# Assessment of 'Blue carbon' in sediment of Indian mangrove (*Avicennia officinalis*) in selected locations of Vembanad lake ecosystem in Kerala

*by*

AARATHY. G. S
(2013-20-123)

**THESIS**

**Submitted in partial fulfillment of the**

**requirements for the degree of**

**B.Sc.-M.Sc. (Integrated) CLIMATE CHANGE ADAPTATION**

**Faculty of Agriculture**

**Kerala Agricultural University**

**ACADEMY OF CLIMATE CHANGE EDUCATION AND RESEARCH**

**VELLANIKKARA, THRISSUR - 680 656**

**KERALA, INDIA**

**2018**

# DECLARATION

I, Aarathy.G.S (2013-20-123) hereby declare that this thesis entitled **"Assessment of 'Blue carbon' in sediment of Indian mangrove (*Avicennia officinalis*) in selected locations of Vembanad lake ecosystem in Kerala"** is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

Vellanikkara

Aarathy. G. S

Date: 15/12/18

(2013-20-123)

# CERTIFICATE

Certified that this thesis entitled **"Assessment of 'Blue carbon' in sediment of Indian mangrove (*Avicennia officinalis*) in selected locations of Vembanad lake ecosystem in Kerala"** is a record of research work done independently by Ms. Aarathy. G. S (2013-20-123) under my guidance and supervision and that it has not previously formed the basis for the award of any degree, diploma, fellowship or associateship to her.

Kochi
Date: 14 - 12 - 2018

DPrema

**Dr. D. Prema**
(Major Advisor, Advisory committee)
Principal Scientist,
Fishery environment Management Division
Central Marine Fisheries Research Institute, Kochi - 682018

# CERTIFICATE

We, the undersigned members of the advisory committee of **Ms. Aarathy. G. S (2013-20-123)**, a candidate for the degree of **BSc - MSc (Integrated) Climate Change Adaptation**, agree that the thesis entitled **"Assessment of 'Blue carbon' in sediment of Indian mangrove (*Avicennia officinalis*) in selected locations of Vembanad lake ecosystem in Kerala"** may be submitted by Ms. Aarathy.G.S, in partial fulfillment of the requirement for the degree.

**Dr. D. Prema**
(MajorAdvisor,Advisory committee)
Principal Scientist,
Fishery Environment Management
Division
Central Marine Fisheries Research
Institute, Kochi

**Prof. Nameer. P.O, Ph.D.**
(Member, Advisory committee)
Special Officer & Head
Academy of Climate Change
Education and Research
Vellanikkara, Thrissur

**Dr. V. Kripa**
(Member, Advisory committee)
Principal Scientist and Head,
Fishery Environment Management
Division
Central Marine Fisheries Research
Institute, Kochi

**Dr. Shelton Padua**
(Member, Advisory committee)
Scientist,
Fishery Environment Management
Division
Central Marine Fisheries Research
Institute, Kochi

28/11/2018

**EXTERNAL EXAMINER**

Dr. BETTY BASTIN
Professor
Dept. Soil Science & Agrl. Chemistry
College of Horticulture
KAU. P.O., Thrissur - 680 656

# *Acknowledgement*

*I express my heartfelt respect, sincere gratitude and thanks to my Ma'am* ***Dr.D.Prema****; Principal scientist, Fishery Environment Management Division, Central Marine Fisheries Research Institute, Kochi and my major advisor for her scholastic guidance, valuable suggestions, continuous supervision and kind help rendered during the entire research programme. This work would not have been possible without her guidance and involvement, her support and encouragement on daily basis from the start of the project till date.*

*I eloquent my deepest gratitude and thanks to* **Dr.Shelton Padua***, Scientist, Fishery Environment Management Division, Central Marine Fisheries Research Institute, Kochi and member of my advisory committee for his scholastic guidance, treasured suggestions and kind help equivalent to a major guide and also timely support during statistical analysis, spatial mapping and acquainting me with the GIS and Remote sensing, without the knowledge about which I would not have completed this project.*

*I express my sincere gratitude to* ***Dr.V. Kripa,*** *Principal Scientist & Head, Fishery Environment Management Division, Central Marine Fisheries Research Institute, Kochi and member of my advisory committee for her valuable suggestions, kind cooperation and help throughout the period of research work.*

*I express my sincere gratitude to, special officer* ***Prof.Nameer.P.O****, Academy of Climate Change Education and Research, KAU, Vellanikkara and member of my advisory committee for his helpful directions, Advices, motivation and kind cooperation during my entire work.*

*I express my deep gratitude to former special officers* ***Dr.E.K.Kurian****,* ***Dr.P.Indira Devi****,* ***Dr.T.K.Kunhamu****, Academy of Climate Change Education and Research, Kerala Agricultural University for their support.*

*I owe my heartfelt thanks to* ***Mrs.Lavanya.s,*** *senior technical assistant, FEMD, Central Marine Fisheries Research Institute, Kochi, for her perpetual support, ever willing assistance and guidance given to me in sample analysis and throughout my research work.*

*I extent my heartfelt thanks to* ***Mr.Vysakhan.P****, Skilled supporting staff, FEMD, Central Marine Fisheries Research Institute, Kochi,* **Mr.Seban John,** *Skilled support staff,FEMD, Central Marine Fisheries Research Institute, Kochi,* ***Ms.Prajitha.P****,FEMD, Lab Assistant, Central Marine Fisheries Research Institute,* ***Mr.Akhil Babu****,FEMD,Skilled support staff, Central Marine Fisheries Research Institute for their help during sample collection and special thanks for their moral support, suggestions and assistance during period of study.*

*I am very graceful to* ***Dr.Jenni.B****, senior technical officer, Molluscan Fisheries Department, Central Marine Fisheries Research Institute for her great support, advice and assistance helped me in crossing through the tougher times during my research.*

*I am graceful to my beloved senior* ***Mr.Ananth C babu,*** *at a very high level for laying out the foundation stone for my work at CMFRI, for his tips, help and moral support in the hours of need.*

*It is a matter of immense privilege for me to express my whole hearted thanks to my beloved and ever encouraging teachers,* ***Mrs. Krishna priya****,* ***Mr.Sreekumar, Mrs.Nisha****, whose moral support, advice and assistance helped me in cruising through the tougher times during my research.*

*Let me thank* ***Ms.Shamiya Hasan, Ms.Haritha J, Ms.Athira Prasad and Ms.Mary Agnus K A*** *for their help, support and generous care throughout the study. More personally I thank to my friend* **- Chandhu** *to his everlasting mental support, inspiration, care and joyous company rendered to me.*

*I respectfully thank* ***Kerala Agricultural University, Academy of Climate Change Education and Research*** *and all scientists and staff members of* ***Central Marine Fisheries Research Institute*** *for providing all the support needed to complete this work.*

*I personally thankful to all my classmates of* ***Kauravas-2013*** *for all their company and support given to me during the five years of college days.*

*I am sincerely thankful to all the* ***seniors****,* ***Teaching staff*** *and* ***Non - Teaching staff*** *of Academy of Climate Change Education and Research for their support.*

*My words are few to express the love towards* ***my parents - Appa and Amma*** *and* ***my sister Neelima*** *for their inspiration and moral support, deep concern, prayers and blessings. I salute you all for your pain and personal sacrifices you did to shape my life.*

*I humbly and whole heartedly bow my head before God Almighty the supreme power that guide me throughout the five years of my study, protected me in all my difficult times and giving ability to complete my thesis work on time.*

***Aarathy. G. S***

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF PLATES

# LIST OF FIGURES

15

# SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| **ANOVA** | Analysis of variance technique |
| ***A. officinalis*** | *Avicennia officinalis* |
| **CCC** | Climate Change Commission |
| **CHNS** | Carbon Hydrogen Nitrogen Sulfur |
| **Cm** | Centimetre |
| **C: N** | Carbon by Nitrogen |
| **$CO_2$** | Carbon dioxide |
| **DBD** | Dry bulk density |
| **Eh** | Redox potential |
| **FAO** | Food and Agriculture Organization |
| **FSI** | Forest survey of India |
| **GIS** | Geographic information system |
| **$g/cm^3$** | gram/ centimetre cube |
| **ha** | Hectare |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **MAP** | Mangrove Action Project |
| **Mg C $ha^{-1}$** | megagram carbon per hectare |
| **NCSCM** | National Centre for Sustainable Coastal Management |
| **OM** | Organic matter |
| **pH** | Pouvoir hydrogène |
| **SPSS** | Statistics is a software package |
| **T** | Treatment |
| **TOC** | Total organic carbon |
| **USDA** | United States Department of Agriculture |

# INTRODUCTION

# CHAPTER 1

# INTRODUCTION

In essence, the term blue carbon denotes the carbon stored by coastal and oceanic ecosystems. The coastal blue carbon includes the stored carbon in mangroves, salt tidal marshes and sea grass meadows within the soil, the living biomass above ground (leaves, branches, stems), the living biomass below ground (roots) and the non-living biomass (litter and deadwood (Mcleod *et al.*, 2011).

Coastal ecosystems play a major role in the national wealth of maritime countries, providing ecosystem goods and services to the coastal community.The coastal ecosystems sequester more carbon than terrestrial ecosystems and it remains trapped for a very long period of time resulting in very large carbon stocks. Unlike forests, their carbon storage is in the sediment (rather than in the above ground plant materials) where it can remain stored of several meter depths for centuries or more. Here, the captured atmospheric carbon is stored in the ground at rates 10 times greater than forests on a per area basis (CCC, 2017).

Mangrove habitats are forests found in tidally inundated areas, observed as dense or fragmented vegetative stand(Saenger *et al.*, 2013).They are seen along coastlines throughout most of the tropics and subtropics, mainly distributed over the river mouths, fringing sheltered bays, around lagoons and ponds, and on islets and cays. Mangroves form a major part of the coastal ecosystem providing various services to the nearby population including coastal protection as bio shields (Das, 2009; Kathiresan, 2010). Mangroves come up well mostly at the land-sea interface and estuarine delta and they naturally sequester carbon dioxide during photosynthesis. In due course of time, carbon accumulates in the mangrove trees, in the mangrove forest-floor (in form of litter) and in mangrove sediment (Mitra *et al.,* 2015).

The mangrove ecosystems are already well known for various advantages and services that they offer which essentially benefit for climate change adaptation along the coasts. These ecosystem services by mangroves include, protection from storms and sea level rise, prevention of shoreline erosion, regulation of coastal water quality, providing essential habitat for nursery for commercially significant fisheries and marine species under threat of extinction, as well as food security for many coastal communities. Mangroves also capture and stock up good amounts of coastal blue carbon from the atmosphere and the sea and consequently help in mitigating climate change (Kennedy, 1984; Beck *et al.*, 2001; Yee, 2010).

Carbon sequestration potential of various ecosystems is presently of public and scientific concern as the atmospheric $CO_2$ concentration increase steadily. But studies on carbon sequestration potential were mainly on agriculture and forest ecosystems, and wetlands such as mangroves were not given enough consideration (Patil *et al.*, 2012). In contrast to other land forests, mangrove ecosystems accrue more sequestered carbon in their sediment (Wojick, 1999). Mangroves act as significant sink for $CO_2$ and so have a considerable role in sequestering of carbon and reducing greenhouse gases (Patil *et al.*, 2012).Though marine mangroves occupy only less than 0.5% of global coastal ocean area, they contribute towards 50% of carbon burial in marine sediment sand the soil carbon pools of mangroves amount to 75% of their total carbon sequestration (Duarte *et al.*, 2013; Alongi, 2014).

Total area of mangroves in India is 4921km$^2$ (FSI, 2017). Mangroves in India account for about 5 per cent of the world's mangrove vegetation and the extent of mangroves of Kerala is 2502 ha. Ernakulam district occupies second highest extent of mangroves in the state after Kannur district (Vidyasagaran and Madhusoodanan, 2014). Vembanad lake, the second largest brackish water lake in India, encircled by mangroves, mudflats, swamps and marshes, is one among the most dynamic, life-supporting coastal wetlands of Kerala. Mangrove patches in

21

the Vembanad lake facilitate production of detritus, organic matter, recycling of nutrients and improvement of coastal production (Mogalekar *et al.*, 2015).The Vembanad lake was declared as a RAMSAR Wetland Site on 19th August 2002 (ENVIS, 2015). The present study scrutinized the blue carbon stocks of Vembanad lake mangrove patches of Ernakulam district of selected locations.

The present investigation, focused on the estimation of blue carbon stocks in the sediment pool of the mangrove species *Avicennia officinalis*, known commonly as Indian mangrove, in selected locations of Vembanad lake. *Avicennia officinalis* is one of the common species which could be able to establish in different mangrove formations in the state of Kerala (Vidyasagaran and Madhusoodanan, 2014). As per Duke *et al.* (2010), this species is extensive and common and globally there has been an estimated 24% decline in mangrove area within this species range since 1980, due to extraction and coastal development. Dominance of *Avicennia spp.* is high (70%) and are found in the proximal zones of Vembanad Lake (Mogalekar *et al.*, 2015). Among the different mangroves, *Avicennia officinalis* represents 41% of the total Important Value Index in Kerala (George *et al.*, 2018).

Some of the most threatened ecosystems on the earth are the coastal blue carbon ecosystems. It was estimated that around 3.4 to 9.88 lakhs hectares of them are being lost every year (Murray *et al.*, 2011). Situated mostly in sediments, this blue carbon can be freed to the atmosphere when these ecosystems are converted or degraded (Pendleton *et al.*, 2012).

Loss of vegetated coastal ecosystems through changed land-use pattern has happened for centuries and has hastened in recent decades. Estimates of cumulative loss over the last 50-100 years ranged from 25-50% of the total global area of each type (Mcleod *et al.*, 2011). Decline in this way continues and the estimated annual losses amount to ~8000 km$^2$at the rate of ~0.5-3% area lost per year according to ecosystem type. If this land conversion rates persist, almost 100% of mangroves could be lost in the next 100 years (Pendleton *et al.*, 2012).

22

More attention is needed for the conservation of carbon sequestration capabilities as well as other ecosystem services of mangroves. According to Avelar *et al.,* (2017), determining carbon stocks in sediment is essential for climate change mitigation actions. Potential changes in carbon stocks in soil / sediment in response to anthropogenic activities highlights the importance of considering and safeguarding carbon stocks on land, as well as carbon stocks "hidden" in the coastal / ocean sediment. Both stocks may be substantial in size and vulnerable to human interference. Study of carbon stock in soil /sediment is for a better understanding of the quantity and vulnerability of carbon stocks in both systems and the results can give potential implications for the management of human activities on coastal environments.

The Intergovernmental Panel on Climate Change (IPCC) estimated that by the year 2050, global $CO_2$ emissions must come down by 85% from its levels seen in 2000 to restrict the global mean temperature increase to $2^{\circ}C$ (IPCC, 2007). To diminish atmospheric $CO_2$ levels, they suggested reducing the anthropogenic $CO_2$ sources (ie., mitigation) with supporting $CO_2$ uptake and storage through the conservation of natural ecosystems with high C sequestration rates and capacity. The role of marine and coastal ecosystems such as mangroves, tidal marshes, and seagrasses are recognized in the partial mitigation of global climate change through the storage and sequestration of carbon dioxide. Scientific evaluation of carbon sequestration capacity of coastal ecosystems and their potential role in climate mitigation in comparison to terrestrial systems has not been carried out in India in detail (NCSCM, 2017).

The present study is hence very relevant in analyzing the carbon stock in sediment in selected mangrove ecosystems, anticipating indications for mitigation of climate change adversities on marine ecosystems, through mangrove restoration wherever applicable. The outcome of the present investigation can also be the basis for future studies, in addition to its usefulness for policy guidelines for climate change mitigation.

Hence the study was undertaken in this background, with the specific objectives:

To estimate the blue carbon stocks of Indian mangrove in sediment in selected locations of Vembanad lake ecosystem, Ernakulam, Kerala

To evaluate the impact of age and health of Indian mangrove, in its blue carbon stocks in sediment

Spatial mapping of sequestered carbon in sediment in the selected mangrove ecosystems.

# REVIEW OF LITERATURE

# CHAPTER 2

# REVIEW OF LITERATURE

## 2.1 Blue carbon ecosystems

The world's oceans contain around 55% of all the carbon in living organisms. Blue carbon is the carbon stored in the marine and coastal ecosystems. This carbon is stored in the sediments of mangroves, salt marshes and seagrasses are major blue carbon sinks (Nellemann *et al.*, 2009).These blue carbon ecosystems are autotrophic. They take up $CO_2$ and bind it in organic matter photosynthetically in excess of the $CO_2$ exhaled by biota (Duarte and Cebrian, 1996). A part of the excess carbon enter into the nearby ecosystems comprising of open ocean and beach ecosystems thus contributing to net removal of $CO_2$ from the atmosphere (Duarte *et al.*, 2008).The rest of surplus $CO_2$ from mangrove forests, salt-marshes and seagrass meadows remain hidden in the sediments, where it can stay for millions of years and thus they become, well built in its carbon sinks (Mateo *et al.*, 1997).

### 2.1.1 Mangrove ecosystem

Mangroves are transition zones (true ecotones) having adaptation to come up in marine as well as terrestrial environments and they have distinctive adjustment mechanisms such as viviparous embryos , salt tolerance, aerial roots for respiration in anoxic, submerged soils (Alongi, 2012). According to (Blasco *et al.,* 1996), the most favourable habitats for mangroves include intertidal, sheltered and muddy sediments. Mangroves are salt tolerant plants which flourish under saline environments (Krishnamurthy *et al.*, 2014). Mangroves ecosystems are precious in biodiversity preservation with both of ecological and economical significance, but these ecosystems have not gained attention for policy decisions (Hema and Devi, 2015).

26

The mangroves fix the global and coastal carbon, the intensity of carbon fixation by mangroves vary within the trees depending upon light intensity, species composition, nutrient and water availability, salinity, tides, waves, temperature and climate. The mangroves help in storing carbon to reduce the impact of climate change (Alongi, 2014). In India, Patil *et al.*, (2012) had reviewed the potential of mangroves to sequester carbon.

### 2.1.2 Threats to mangrove ecosystem

Globally the mangroves are one of the most threatened ecosystems facing the danger of disappearance, due to human activities, urbanization, overexploitation, mining and aquaculture, the major reasons for the loss of mangroves.

Coastal ecosystems have sediments with high organic matter which bind up carbon due to low oxygen conditions and other factors that slow down organic matter decomposition at depth. When these ecosystems are degraded or converted for other uses, the sediment carbon comes in contact with oxygen, and facilitate the microbial activity liberating large amounts of greenhouse gases to the atmosphere or water bodies (Pendleton *et al.*, 2012). The origin and amount of organic carbon in mangrove sediments are influenced by physical and biological factors. The quality and availability of food sources for benthic faunal communities in these ecosystems may also be controlled by the organic carbon content in the sediments.

Loss of vegetated coastal ecosystems through land-use change had occurred for centuries and had hastened in recent decades. Estimates of cumulative loss over the last 50-100 years ranged from 25-50% of total global area of each type (Mcleod *et al.*, 2011).

### 2.1.3 Importance of *Avicennia officinalis*

*Avicennia officinalis* is a very common mangrove species in almost all the coastal states of India. It is also present in most of the Kerala coasts

(Thirunavukkarasu *et al.,* 2011). The soils of Avicennia spp had more degradable organic matter and maintain higher rates of microbial activity (Mongia and Ganesahamurthy, 1989). *Avicennia officinalis* is a tropical mangrove tree species which can come under variable salinities (0.7–50.0 dS $m^{-1}$) at intertidal regions. *Avicennia officinalis* with its salt-secreting glands help to study the changes in salt and water regulation through salt glands (Tan *et al.,* 2013). Mangrove plants are found all through the tropical regions (Laffoley and Grimsditch, 2009). Organic carbon and nitrogen contents were also higher in *Avicennia* soils (Lacerda *et al.*, 1995).

*Avicennia officinalis* is used by coastal communities as the traditional medicine for rheumatism, paralysis, asthma, snake-bites, skin disease and ulcer. Salt tolerant plants have more antioxidant effect. *A. officinalis* extracts have high amount of phenolic compounds. The antioxidative constituents of the *A. officinalis* can be treated for their efficiency as anti-diabetic, anti-cancer and anti-cardiac vascular disease properties (Thirunavukkarasu e*t al.,* 2011).

### 2.1.4 Mangroves and climate change

Mangroves are more common in warm humid region compared to drier coastlines. In equator and tropics mangroves grow tall, dense and diverse. In subtropical dry regions mangroves are short, scattered and intermittent. Mangroves are seen abundantly in areas of higher rainfall, due to runoff of sedimentation and nutrient supply (Ellison, 2000).

Due to global warming, mangroves extent to poleward region and expand to temperate climate. Avicennia species get more affected by sea-level rise due to its horizontal root structure. A sea level rise of between 9 and 12cm over 10 yrs can affects mangroves and seriously threaten the mangrove ecosystems (Ellison and Stoddart, 1991). High rates of sea level rise can threaten mangrove ecosystem. Sea level rise can cause anoxia, sulfide toxicity etc. (Snedaker, 1995). In the historic part,

28

mangroves had shown high resilience capacity against large sea level fluctuations (Woodroffe, 1990).

Ellison (2000) was of view that increase in $CO_2$ in atmosphere and rise in temperature will increase the productivity of mangroves and, change in Phenological patterns (i.e. timing of flowering and fruiting). The intertidal ecosystems predicts the climate change because of their sensitivity to changes in temperature (Saenger and Moverley 1985, Duke 1990), salinity (Ball, 1988), and ambient $CO_2$ levels (Farnsworth *et al.*, 1996), In addition, intimate connection between the health of intertidal vegetation communities and sea-level also cause these ecosystems to act as climate change predictors (Woodroffe 1990; Ellison and Stoddart 1991).

The salt stress of mangroves can happen through many factors in addition to sea-level rises *viz.*, groundwater depletion due to lessened freshwater flux, groundwater extraction, and low rainfall. Salt excluding mangroves can decrease or stop the transpiration and photosynthesis when exposed to higher saline water and continue photosynthesizing using ocean water in transpiration, because of their salt glands in the leaves. When the inundation is increased, low oxygen conditions occur and can lead to mortality of mangroves (Ellison, 2000).

## 2.2 Total organic carbon (TOC) in sediment

According to Batley and Simpson (2016), the total organic carbon (TOC) indicates the total amount of oxidisable organic material. The organic carbon in mangrove sediments is contributed by tree litters and subsurface root growth of mangroves (Alongi, 1998).The carbon sequestered in coastal soils can be extensive and remains captured for a very long period of time resulting in very large carbon stocks compared to terrestrial soils (Duarte *et al.,* 2005,Lo lacono *et al.,* 2008). The organic carbon content of mangrove areas are higher in surface soil than in terrestrial areas showing higher capacity for that organic matter production and storage in the areas of mangrove ecosystems (Matsui *et al.*, 2015).The ecosystems store organic carbon mainly in living biomass and soil organic matter whereas in coastal vegetations the main storage of organic carbon in sediment (Fourqurean *et al.*, 2012, Mcleod *et al.*, 2011) and when allowed to remain undisturbed, they remain safe for millions of years (NCSCM, 2017).

Prema *et al.,* (2013) observed that in the top layer (0-5 cm) sediment, the organic carbon percentage was substantially high (>1.5) in stations with good growth of transplanted mangroves than in the stations with scarce growth (<0.5) at selected locations of Vembanad lake in Ernakulam District. It implies that at least 1.5% organic carbon in sediment is essential for the initial growth and survival of transplanted mangrove seedlings. Soil organic carbon is a recognized indicator of accumulated soil organic matter. Kathiresan *et al.*, (2014) found that the total organic carbon in sediment was as much as 2.5 times higher in aged mangroves and 2 times greater in saplings during quantification of sediment characteristics of planted and / or natural mangrove forests in comparison with un-vegetated soil for four seasons of the year 2009-2010 in the Vellar-Coleroon estuarine complex, India.

## 2.3 Total organic matter in sediment

For biogeochemical cycling of carbon and associated elements along tropical continental margins, mangroves have an active role because of their high productivity turnover rate of organic carbon and its interchanges with other ecosystems both of marine and terrestrial origins (Jennerjahn and Ittekkot, 2002). Mangrove ecosystems produce large amount of organic matter which get often transferred to nearby coastal waters in the form of detritus and living organisms. (Robertson AI, Duke NC, 1990).Organic matter (OM) content in mangrove soils influences the growth of associated plants and animals by providing nutrients of the ecosystems (Prema e*t al.*, 2013). The OC contents in mangrove sediment was higher in the mud layer compared to other layers due to the higher accumulation of OM provided by the mangrove forest (Matsui *et al.*, 2015).

Chaikaew and Chavanich (2017) worked on organic matter and organic carbon of mangrove soils in Thailand. They observed that high amounts of organic matter was found to the limited to the soil surface. Surface soil (0-5cm) contained higher organic carbon compared to subsurface soil (5-10 cm).Organic matter gets bound to fine particles in clayey soils, thus preventing soil carbon loss. Avnimelech and Wodka (1988) stated that organic matter (OM) content increases with time before it reaches an equilibrium state, depending on the accumulation and decomposition rates.

## 2.4 Bulk density of sediment

Buchanan *et al* (1993) and USDA (2008) reported that the sediment bulk density is closely related with the mineral - organic content of the sediment (Lagoon and Lanka, 2015).In mangrove soils, the bulk density depends upon the relative proportion of sand, silt and clay and also with the specific gravity of solid organic and inorganic particles and porosity of the soil (Mitra *et al*, 2012).The bulk density of the soil varies with the age, depth and location (Howard *et al* , 2014) .In case of blue carbon stock estimation, bulk density is used for the conversion of organic carbon concentrations to mass per soil area at a chosen depth (Avelar *et al*, 2017). In Senegal, the mean bulk density was higher at all sampled soil depths in low mangroves compared to medium mangroves (Kauffman and Bhomia, 2017).

## 2.5 Sediment salinity

The mangrove species has the ability to tolerate high salinity. They have adaptation strategies for salinity variation due to their differential ability of salt tolerance. Hence there is a survival advantage for them in a saline environment (Liang e*t al.,*2008).Both salinity and geomorphic habitat influence the distribution of mangrove communities (López-Portillo and Ezcurra, 1989).Highly saline mangrove soils are not feasible for microbial activities and the organic matter decomposition becomes slow, keeping the soil at an anaerobic state (Chmura *et al*., 2003).The mangrove soil salinity was found significantly higher in the dry season than in the rainy season (Wakushima *et al.,* 1994).Mangrove vegetation is usually denser at lower salinities (Prema e*t al*., 2013).

McMillan (1975) stated that soil texture may have a salinity buffering effect since fine particles and organic matter act as chelators during cation exchange. Most of the halophytic species like mangroves are grown under low to moderate salinities. When the salinity increases, carbon allocation to roots increases at the expense of leaf area and specific leaf area decreases. These changes in the carbon allocation, together with the increase in salinity and decrease in irradiance would lower the fraction of assimilated carbon that is available for growth (Ball, 2002).

Pal *etal.* (1996) noted that *A.officinalis* dominated in soils with high salinity in Sundarbans during tidal inundation. The complexity of mangrove vegetation increased with a decrease in soil salinity in the Sundarbans (Joshi and Ghose, 2003).Cintron *et al.* (1978) reported that salt-tolerant species like *Avicennia* along the south coast of Puerto Rico, Culebra, and Mona Island could adjust even upto 90 ppt salinity (*i.e.,* about 2.5 times the concentration of seawater) .Soil salinity (13.0 to 31.2 ppt) decreased with increasing distance from the tidal coast. Salinity ranged from 13.01 ppt to 31.25 ppt (Joshi and Ghosh, 2003).

## 2.6 Sediment pH

Wakushima *et al.* (1994a, 1994b) found that Soil pH and salinity in the dry season are the important factors governing the zonal distribution of Japan and Thai mangroves. The area where *A. officinalis* was growing abundantly showed soil pH optima ranging from 7.07 and 7.65 in Sundarban mangroves (Joshi and Ghose, 2003).They also stated that the Soil pH had no uniform rise or fall with increasing distance from the tidal coast. The average soil pH was slightly alkaline (7.53) ranging from 7.05 to 7.89 in Sundarbans mangroves.

According to Prema *et al*, 2013, the pH of a soil significantly affects plant growth, mainly due to the change in the availability of both essential elements as well as non-essential elements. Sediment pH is an important factor affecting growth of mangroves as well affecting the chemical transformation of most nutrients and their availability to mangroves. When the sediment pH is lower than 6 the growth transplanted mangrove seedlings was retarded growth (Prema e*t al.*, 2013).

## 2.7 Oxidation reduction potential of sediment

Jennerjahn and Ittekkot (1997) found that oxidation reduction potential (Eh) of the mangrove surface soils varied based on the type of vegetation in the ecosystem. The organic carbon stock of the mangrove mud layer was affected by the Eh gradient. Due to the waterlogged condition of mangrove soils, anaerobic microbial decomposition takes place by a series of oxidation-reduction (redox) processes. The anoxic sediments have redox potentials below -0.2 V, while typical oxygenated soils have the potential of above +0.3V (Prema e*t al.*, 2013). Oxidation reduction potential was found to be an important factor in the mobilization/ uptake of chemical elements in the mangrove mud layer. Slight increase in Eh was noticed in the area having *Avicennia* spp. Also the change in litter composition and OM decomposability resulted in significant difference in the Eh values where Avicennia spp were found (Matsui *et al.*, 2015).

## 2.8 Sediment grain size analysis

The proportions of clay, silt, and sand, together with the grain size, direct the permeability of the soil to water, which affects soil salinity and water content. Nutrient status also plays a major role in the physical composition of the soil, where clayey soils having higher nutrients than sandy soils. Mangrove soils are mostly formed when sediment derived from coasts, river banks, or from upland areas aggregates after being transported down rivers and creeks. The topsoil of mangroves generally contains clay (fine-grained) whereas the soil beneath the surface is a mixture of silt and clay (known as mud).Sediment grain size along with other environmental factors (*e.g.*, salinity, inundation, and nutrient availability or pollution level) can influence the presence and distribution of floral or faunal species. Atleast

11% clay in sediment is essential for the initial growth and survival of transplanted mangroves (Prema e*t al.*, 2013).

## 2.9 Total carbon in sediment

The intertidal habitats are the major contributors of carbon stocks to the ecosystems. They store a huge proportion of carbon in their sediment. Field measurements help to calculate the carbon stocks in each habitat of the ecosystem while total carbon stocks were assessed for the entire intertidal ecosystem (Phang *et al*, 2015). Mangrove is considered as the most carbon-dense tropical forests. The assessments carried out in northern Madagascar, revealed that the highly closed canopy of mangroves had an average total vegetation carbon of 146.8 Mg/ha (±10.2) (Jones *et al*, 2014).

At Senegal, the nitrogen and carbon concentration was lower at all sediment depths in low mangroves, while taller statured mangroves tend to have higher soil nitrogen and carbon concentrations(Kauffman and Bhomia, 2017).The carbon nitrogen relationship indicates that carbon was the main source of nitrogen (Matsui *et al.*, 2015).Total carbon was 98.2% in developed and aged mangroves and 41.8% in saplings during quantification of sediment characteristics of planted and / or natural mangrove forests in comparison with un-vegetated soil in the Vellar-Coleroon estuarine complex, India (Kathiresan *et al.,* 2014).

## 2.10 Total nitrogen in sediment

Inorganic nitrogen is at low concentrations in the mangrove sediments. Due to the high rate of CN ratio in the mangrove ecosystems, the inorganic nitrogen cycle becomes fast and effective, but it is not sufficient for the optimal growth of microorganisms (Kristensen *et al*, 2000). The total nitrogen is higher in Avicennia soils. It helps to ensure information on the microbial degradation (Lacerda *et al,* 1995).Bouillon *et al* (2003) confirmed that the mangrove sediments are observed to

34

be one of the nitrogen enrichment sources.The major portion of the nitrogen in the soil samples occurred in the organic form. After the mineralization, organic nitrogen was converted to inorganic nitrogen. The major source of nitrogen released to maintaining high primary production in mangrove forests are due to this mineralization (Matsui *et al.*, 2015).Due to the high C/N Ratio, sometimes the N regulating the mangrove growth (Weiss *et al*, 2016).

## 2.11 C/N ratio

In mangroves, leaves are the major portion of detritus having a C: N ratio between 20 and 95.The C/N ratio was regularly used as an indicator of the OM sources in aquatic sediments. The low C/N ratio in *Avicennia spp.* sediment can be due to the carbon originating from biological sources, such as plankton or algae (Jennerjahn and Ittekkot, 1997). The C: N ratio decreases due to the colonization of bacteria incorporated with the nitrogen from the indigenous particulate organic nitrogen pool in the sediments (Holmer and Olsen, 2002).

Mangrove litters having high C/N Ratios >200 brought problems for the decomposition processes. Sediments of marine mangroves had higher C: N ratio when compared with estuarine mangroves (Weiss *et al*, 2016).A value for C: N ratio of 10 or less are the normal conditions of heterotrophic bacteria for their maintenance and growth in an organic substrate, at the same time the mangrove and seagrass litter having highly insufficient substrate due to C: N ratios of up to 100 (Kristensen *et al*, 2000).

## 2.12 Blue carbon in mangroves

The carbon capture ability of the blue carbon sinks is estimated at 329 Tg C year$^{1}$ (Nellemann and Corcoran, 2009). Mangroves forests are the major carbon producers in the tropics, containing an average 1,023 Mg C ha$^{-1}$ (Donato *et al.*, 2011). Chen *et al.* (2017) found that the mangroves are the important exporters of both organic and inorganic carbon.

35

Total carbon and total organic carbon are rich in mangrove soils (Kathiresan *et al.*, 2014). According to Ong *et al.* (2002) sediments in mangrove ecosystems held 700 tons of carbon per meter depth per hectare. Thailand mangrove sediments can release carbon ranging from 70 t C/ha/yr (256.6 mt $CO_2$/ha/yr) (Yee, 2010). Bouillon *et al.*, (2008) and Kristensen *et al.* (2008) reported that the highest carbon density throughout the profile is the major factor which affects the soil carbon pool. Carbon density in the sediment depth of mangroves is the indication of high organic matter input rates from mangroves and sedimentation, along with low decomposition rates (Stringer *et al.*, 2016). Donato *et al.* (2011) stated that mangrove soil organic carbon decreased below 1 m. The soil organic carbon content decreased with depth. Significant seasonal variations were observed in soil organic carbon. The organic carbon rate increased gradually through years which showed the ability of sundarban mangrove as potential sink of carbon dioxide (Biswas *et al.*, 2017).

Lacerda *et al.* (1995) reported that the *Avicennia* soil carbon content decreased with increasing depth. *Avicennia* sediment showed a decline in organic carbon by about 40% from the surface to a depth of 15cm. Pachpande and Pejaver (2015) observed that the top layer of mangrove surface sediment (approximately 15cm depth) contained high percentage of organic carbon reaching up to 6%.

The source of OC in a mangrove forest soil was primarily allochthonous (Wooller *et al.,* 2003).The mangrove carbon stored in the soil and the belowground pools of dead roots (Alongi *et al.*, 2004), which helps to the conservation and recycling process of nutrients under the soil (Alongi, 2014).Organic-rich soils ranged from 0.5m to more than 3 m in depth and accounted for 49–98% of carbon storage in these systems. The thick submerged suboxic layer of the mangrove soils hold up the anaerobic decomposition and having moderate to high C concentration. Below-ground C storage in mangrove soils are the integration of variable deposition, transformation, and erosion dynamics associated with fluctuating sea levels and episodic disturbances of millennia (Donato *et al.*, 2011).

Due to the complex rooting structures of mangrove ecosystems, they have the potential to trap and store large amount of carbon compared to many freshwater wetlands ecosystems (Marchio *et al.*, 2016).The storage capacity can be improved by maintaining the future sea level rise (Krauss *et al.*, 2017).

# MATERIALS AND METHODS

# CHAPTER 3

# MATERIALS AND METHODS

## 3.1 Location

Samples were collected from selected locations of Vallarpadam, Kundanoor, Kumbalam, Mangalavanam, Thevara, Malipuram and Puthuvype areas of Vembanad lake. Altogether 25 stations were fixed for the study as depicted in the location maps (Fig. 1 and Fig. 2), making use of Google Earth imageries and delineating the micro-level boundaries. The sampling was done in two seasons *viz.* post monsoon (October – November 2017) and pre monsoon (February – March 2018).

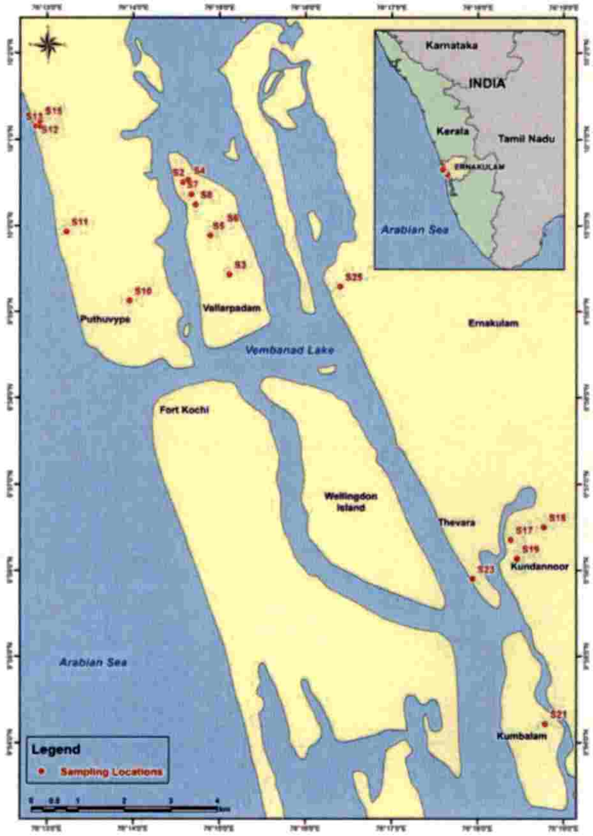


**Fig. 1. Locations for sediment sampling in the post monsoon**

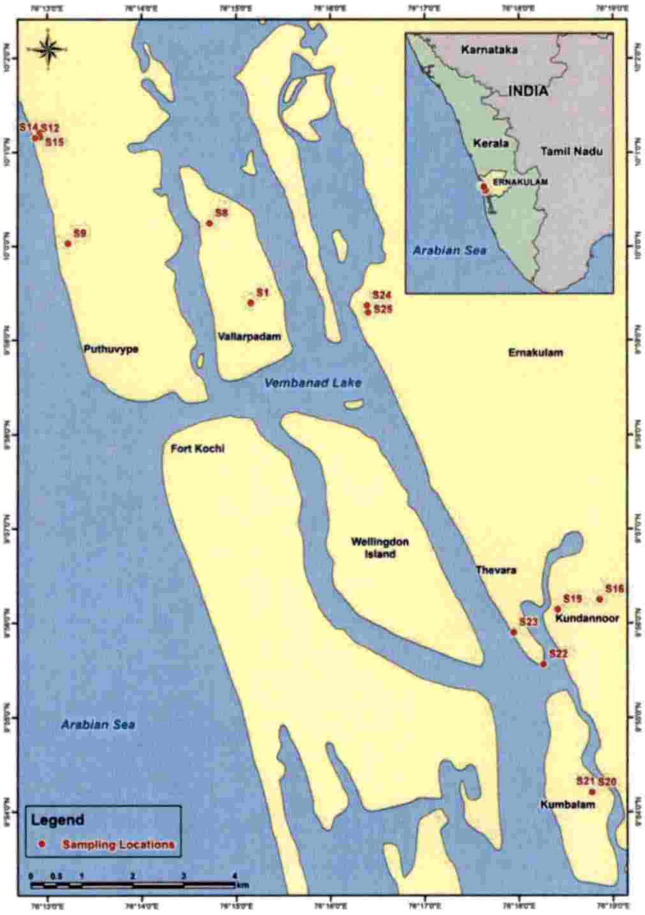


Fig. 2. Locations for sediment sampling in the premonsoon

Based on the objective of the study, the observed stand of *A. officinalis* (Indian mangrove) were classified into four treatments *viz*. aged, recent, healthy and degraded. Control stations were taken from the same areas selected for the study, but without mangrove covers. The control was introduced as reference station for the purpose of comparison of blue carbon stocks of the treatments. The treatments are detailed in table 1.

40

**Table 1. Treatment details of mangroves based on age and canopy cover**

| TREATMENT | DESCRIPTION |
|---|---|
| **$T_1$** | Control (No Mangroves) |
| **$T_2$** | Aged (*Avicennia officinalis*) |
| **$T_3$** | Recent (*Avicennia officinalis*) |
| **$T_4$** | Healthy (*Avicennia officinalis*) |
| **$T_5$** | Degraded (*Avicennia officinalis*) |

The sites having *Avicennia officinalis* with age > 15 years were considered as 'aged' and < 5 years as 'recent', the age being found out through local enquiry. The treatments 'healthy' and 'degraded' were classified based on their canopy cover, initially while fixing sampling locations through the visual interpretation of Google Earth imageries and further verifying through *in situ* visual observation. The *A. officinalis* stands, having dense canopy cover, were considered as "healthy" whereas the *A. officinalis* stands having sparse canopy cover, as a result of anthropogenic activities were considered as "degraded'. The general stand of *Avicennia officinalis* in the areas taken as treatments is shown in plates 1 to 4.

The treatments were replicated unequally, as per the availability of *Avicennia officinalis* in each treatment category in each area. As the center of attention of the assessment was blue carbon stocks in mangrove sediments and as the chance of variations in the carbon stocks of control stations were practically nil, within a short period of time, control stations were not repeatedly sampled.

**Plate 1. Typical sampled area with aged *Avicennia officinalis* cover**

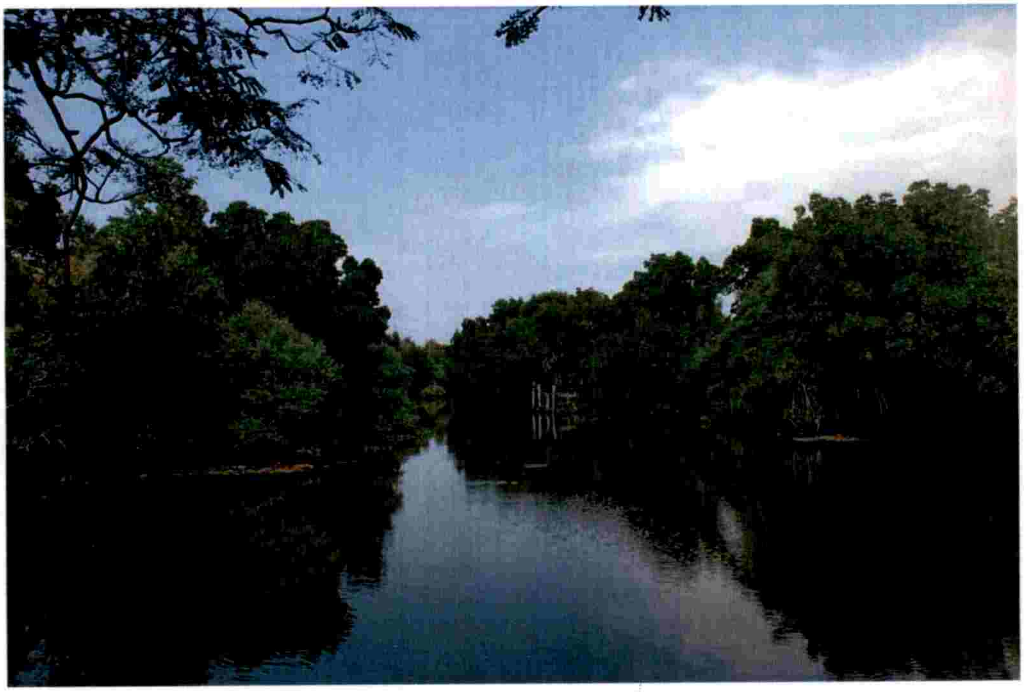


**Plate 2. Typical sampled area with healthy *Avicennia officinalis* cover**

**Plate 3.Typical sampled area with degraded *Avicennia officinalis* cover**

**Plate 4. Typical sampled area with recent *Avicennia officinalis* cover**

### 3.2 Sediment collection

The sediment samples were collected using custom made soil core samplers of 1 m height and 5 cm diameter, closed with screwing lid for both open ends. The core pipes were inserted into the sediment (Plate 5) to a depth of 1m after removing the lower cap. In each station, two cores were taken, one exclusively for analyzing bulk density and other for analysis of all other sediment characteristics.

### 3.3. Sediment processing

In the laboratory, the cores were cut into 10 cm long sections (0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm, 50-75 cm and 75-100 cm) as per availability of intact sediment in the cores and transferred into labeled trays for air drying (Plate 6). For the determination of pH and Eh, the wet samples were used. The samples kept for air drying were used for measuring salinity, total organic carbon, total organic matter, total nitrogen, total carbon, C/N ratio and texture. For bulk density, the samples were cut into 10 cm long sections (0-10 cm, 10-20 cm, 20-30 cm, 30-40 cm, 40-50 cm, 50-75 cm and 75-100 cm) as per availability of intact sediment in the cores and transferred into labeled previously weighed glass containers. Then the samples were kept for oven drying at 60°C, till attaining constant dry weight.

The samples having core compression and also core sections having water in place of sediment were not taken for laboratory analysis. Wherever, intact sediment samples were available in the core, blue carbon stocks up to the maximum available depth was measured. Core samples up to 30 cm depth with 10 cm interval were uniformly available in all cores and were subjected to all laboratory analytical procedures and these results were used for data analysis and interpretation.

Plate 5.Sediment sample collection using cores

Plate 6.  Collected samples kept for air drying

## 3.4. Sediment analysis

### 3.4.1. Analysis of wet sediment samples

#### *3.4.1.1 pH*

The pH of the sediment samples was determined on the same day of sample collection in the laboratory using EUTECH pH meter (model PC 5500) as per the method described by Boyd and Tucker (1992). The pH meter was calibrated initially and the accurate probe measurements were recorded.

#### *3.4.1.2 Oxidation reduction potential (Eh)*

The oxidation reduction potential of the sediment samples was determined on the same day of sample collection in the laboratory using EUTECH ORP tester (model ORP Testr 10) as described by Hesse (1971). The ORP tester was calibrated initially and the accurate probe measurements were recorded.

### 3.4.2 Analysis of air dried sediment samples

#### *3.4.2.1 Organic carbon*

The organic carbon of the sediment was estimated by Walkley and Black's titration method as described by Jackson (1958).

#### *3.4.2.2 Organic matter*

Based on the assumption that organic matter (OM) of the sediment contains 58% of organic carbon as per Sprengel (1826), the OM was estimated by multiplying % carbon with the empirical factor 1.724 (Jackson, 1958).

Percentage organic matter in sediment = 1.724 × % organic carbon in sediment

Plate 7. Reagent preparation for organic carbon analysis

Plate 8.Organic carbon analysis of sediment samples

### *3.4.2.3 Salinity*

The Salinity of the sediment was estimated by Mohr and Knudsen (1856) titration method as described by Jackson (1958) using silver nitrate solution.

### *3.3.2.4 Texture*

Sediment texture was estimated, using mechanical analysis by International pipette method as described by FAO (1976). The relative proportion various sized particles of the sediment *viz.* sand, silt and clay, were found out as percentage. The size classification of sand, silt and clay as defined by USDA (2008), was followed.

### *3.4.2.5 Dry bulk density*

Dry bulk density (DBD) was estimated by collecting a known quantity of sediment dried to a constant weight in an oven at 60°C.This was determined from the mass of a fully dried sediment sample and its original volume, as per Howard *et al.* (2014).

Dry bulk density ($g/cm^{-3}$) = Mass of dry soil (g) / Original volume sampled ($cm^3$)

### *3.3.2.6 Total carbon and total nitrogen*

Total carbon and total nitrogen of the sediment was determined by CHNS analyzer (model Vario EL CUBE). A known weight of the dried sample was loaded into an automatic analyzer at a temperature of 300°C. The data was transferred to a computer with dedicated software of Vario EL CUBE in CHNS mode for further processing and calculation of % total carbon and total N.

**Plate 9. Estimation of sediment salinity**

**Plate 10: Textural analysis of sediment samples**

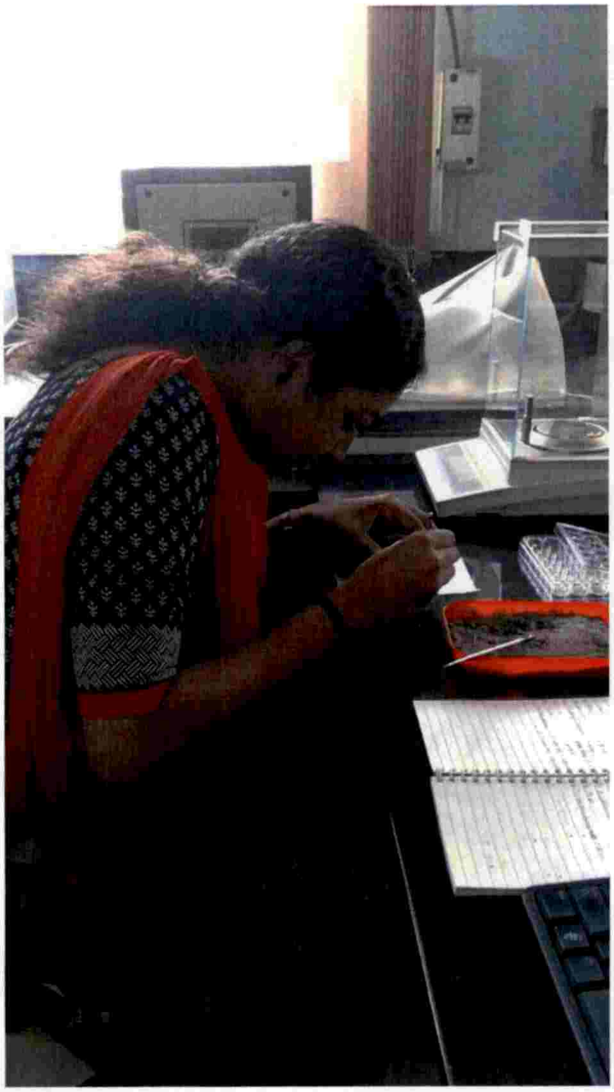


**Plate 11. Samples preparation for estimation of C and N in CHN analysis**

### *3.4.2.7 C/N ratio*

C: N ratio is the ratio of total organic carbon (TOC) to total nitrogen and it was derived from the analysed results of TOC and total nitrogen.

$$\text{C: N Ratio} = \frac{\text{Total organic carbon (\%)}}{\text{Total nitrogen (\%)}}$$

### *3.3.2.8 Blue carbon stock assessment*

Stock assessment of blue carbon pool of mangrove sediment in selected mangrove ecosystems of Vembanad lake was done as per Howard *et al*., (2014), using the standard protocols for assessing blue carbon stocks in coastal ecosystems. Carbon stocks were calculated based on soil organic carbon concentration and dry bulk density, for the different depth increments. The total soil carbon stock within an area was determined by the amount of carbon within a defined area and soil depth as follows.

For each interval of the core sampled/analysed, calculated the soil organic carbon density;

Soil carbon density (g/cm$^3$) = dry bulk density (g/cm$^3$) * (% organic carbon/100).

The amount of carbon in the various sections of core sampled was calculated by multiplying each soil carbon density value by the thickness of the sample interval (cm) as follows.

Amount of carbon in core section (g/cm$^3$) = Soil carbon density (g/cm$^3$) * thickness interval (cm). The amount of carbon in core sections were summed over the total sampling depth.

Core #1 summed = Amount of carbon in core section A (g/cm$^3$) + Amount of carbon in core section B (g/cm$^3$) + Amount of carbon in core section C (g/cm$^3$) + …. all the samples from a single core.

Converted the total core carbon into the units commonly used in carbon stock assessment (Mg C ha$^{-1}$) using the following unit conversion factors:

(There are 1,000,000 g per Mg (mega gram), and 100,000,000 cm$^2$ per hectare)

Total core carbon (Mg C $ha^{-1}$) = Summed core carbon ($g/cm^3$) *(1 Mg/1,000,000 g) * (100,000,000 $cm^2$/ ha).

The above steps were repeated for calculation of total carbon stock of each core.

### 3.5. Statistical analysis

Statistical tools *viz.* analysis of variance technique (ANOVA) and correlation were applied on the data of blue carbon stock and selected auxiliary parameters of sediment samples collected from the different treatments at selected depths.

Two way ANOVA with unequal replications was done to find out significant difference among the treatments and among the depths. Wherever ANOVA result showed significant difference, post hoc analysis was carried out for critical difference test between specific treatments and specific depths.

The statistical software *viz.* R 3.5.1 and Microsoft – Excel 2013 were used for the various statistical analyses.

### 3.6. Mapping

The blue carbon content in sediment at different location was mapped using Arc GIS 10.0 Software.

# RESULTS

# CHAPTER 4

# RESULTS

## 4.1 Blue carbon

### 4.1.1 *Cumulative stock of blue carbon*

In post monsoon, the treatment mean values of cumulative carbon stock in sediment (Table 2) varied at depths 0-10 cm, 0-20 cm and 0-30 cm with value ranging from 8.25 ($T_5$ Degraded) to 25.33 Mg ha$^{-1}$( $T_4$ Healthy), 16.97 ($T_5$ Degraded) to 45.09 ($T_4$ Healthy) and 25.26 ($T_5$ Degraded) to 62.47 Mg ha$^{-1}$ (($T_4$ Healthy). The highest stock of carbon was seen in healthy mangroves.

**Table 2.Cumulative stock of mean blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

| Depth | 0-10 cm | 0-20 cm | 0-30 cm |
|---|---|---|---|
| $T_1$ | 14.33 | 29.34 | 48.22 |
| $T_2$ | 19.94 | 35.31 | 49.59 |
| $T_3$ | 17.00 | 37.80 | 61.99 |
| $T_4$ | 25.33 | 45.09 | 62.47 |
| $T_5$ | 8.25 | 16.97 | 25.26 |

In pre monsoon, the treatment mean values of cumulative carbon stock in sediment varied at depths 0-10 cm, 0-20 cm and 0-30 cm ranged from 11.55 ($T_3$ Recent) to 14.99 Mg ha$^{-1}$( $T_2$ Aged), 22.63 ($T_5$ Degraded) to 47.36 ($T_4$ Healthy) and 33.61 ($T_3$ Recent) to 66.00 Mg ha$^{-1}$ (T4 Healthy). The highest stock of carbon (Table 3) was seen in healthy *A. Officinalis.*

52

**Table 3.Cumulative stock of mean blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in pre-monsoon.**

| Depth | 0-10 cm | 0-20 cm | 0-30 cm |
|---|---|---|---|
| $T_1$ | 14.33 | 29.33 | 44.98 |
| $T_2$ | 14.99 | 33.41 | 56.85 |
| $T_3$ | 11.55 | 22.63 | 33.61 |
| $T_4$ | 26.90 | 47.36 | 66.00 |
| $T_5$ | 14.58 | 29.78 | 45.79 |

### 4.1.2 *Layer wise blue carbon*

In post monsoon, the treatment mean values of layer wise carbon in sediment varied at depths 0-10 cm, 10-20 cm and 20-30 cm ranged from 0.08 ($T_5$ Degraded) to 0.25 g cm$^{-3}$ ( $T_4$ healthy), 0.09 ($T_5$ Degraded) to 0.21 ($T_3$ Aged) and 0.08 ($T_5$ Degraded) to 0.24 g cm$^{-3}$ ($T_4$ Healthy). The highest value (Table 4) of blue carbon was seen in healthy *A. officinalis* ($T_4$) at 0-10 cm core section followed by $T_2$ and $T_3$.

**Table 4. Layer wise mean blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 0.14 | 0.15 | 0.19 |
| $T_2$ | 0.20 | 0.15 | 0.14 |
| $T_3$ | 0.17 | 0.21 | 0.24 |
| $T_4$ | 0.25 | 0.20 | 0.17 |
| $T_5$ | 0.08 | 0.09 | 0.08 |

In pre monsoon, the treatment mean values of layer wise carbon in sediment varied at depths 0-10 cm, 10-20 cm and 20-30 cm ranged from 0.12 ($T_3$ Recent) to 0.27 g cm$^{-3}$ ( $T_4$ Healthy), 0.11 ($T_3$ Aged) to 0.3 ($T_5$ Degraded) and 0.11 ($T_3$ Recent) to 0.30g cm$^{-3}$ ($T_5$ degraded). The highest stock (Table 5) of carbon was seen in degraded *A. officinalis* at core section 10-20 cm and 20 – 30 cm followed by $T_2$ and $T_4$.

**Table 5. Layer wise mean blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30cm |
|---|---|---|---|
| $T_1$ | 0.14 | 0.15 | 0.16 |
| $T_2$ | 0.15 | 0.18 | 0.23 |
| $T_3$ | 0.12 | 0.11 | 0.11 |
| $T_4$ | 0.27 | 0.20 | 0.19 |
| $T_5$ | 0.15 | 0.30 | 0.30 |

### 4.2 Total organic carbon (TOC) in sediment

The treatment mean values of layer wise organic carbon in sediment ranged at depths 0-10 cm, 10-20 cm and 20-30 cm from 1.19 ($T_5$ Degraded) to 4.71 % ( $T_4$ Healthy), 0.72 ($T_5$ Degraded) to 2.41 ($T_1$ Control) and 0.64 ($T_5$ Degraded) to 2.28% ($T_1$ Control) in post monsoon. The highest value of organic carbon in sediment was seen in healthy *A. officinalis* ($T_4$) at 0-10 cm core section (Table 6).

**Table 6. Mean organic carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 2.34 | 2.41 | 2.28 |
| $T_2$ | 3.16 | 1.44 | 1.51 |
| $T_3$ | 2.90 | 2.35 | 1.57 |
| $T_4$ | 4.71 | 2.30 | 1.97 |
| $T_5$ | 1.19 | 0.72 | 0.64 |

In pre-monsoon, the treatment mean values (Table 7) of layer wise organic carbon in sediment ranged at depths 0-10 cm, 10-20 cm and 20-30 cm

Sh

from 1.21 ($T_5$ Degraded) to 3.57 % ( $T_4$ Healthy), 1.56 ($T_2$ Aged and $T_3$ Recent) to 2.41 ($T_1$ Control) and 1.48 ($T_3$ Recent) to 2.28 % ($T_1$ Control). The highest value of organic carbon in sediment was seen in healthy *A. officinalis* ($T_4$) at 0-10 cm core section.

**Table 7. Mean organic carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in premonsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 2.34 | 2.41 | 2.28 |
| $T_2$ | 1.86 | 1.56 | 1.50 |
| $T_3$ | 2.31 | 1.56 | 1.47 |
| $T_4$ | 3.57 | 1.75 | 1.50 |
| $T_5$ | 1.21 | 2.15 | 2.13 |

### 4.3 Dry bulk density of sediment

The treatment mean values of layer wise organic carbon in sediment at depths 0-10 cm, 10-20 cm and 20-30 cm ranged from 0.54 ($T_4$ Healthy) to 0.85 g cm$^{-3}$ ( $T_5$ Degraded), 0.72 ($T_1$ Control) to 1.27g cm$^{-3}$ ($T_5$ Degraded) and 0.91 ($T_1$ Control) to 1.41g cm$^{-3}$ ($T_3$ Recent) in post monsoon. The highest value of bulk density was seen in sediment of recent stand of *A. officinalis* ($T_3$) at 20-30 cm core section (Table 8).

**Table 8. Mean bulk density in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 0.83 | 0.72 | 0.91 |
| $T_2$ | 0.69 | 1.06 | 1.06 |
| $T_3$ | 0.69 | 0.89 | 1.41 |
| $T_4$ | 0.54 | 1.08 | 1.16 |
| $T_5$ | 0.85 | 1.27 | 1.30 |

In pre-monsoon, the treatment mean values of layer wise bulk density in sediment at depths 0-10 cm, 10-20 cm and 20-30 cm ranged (Table 9) from 0.50 ($T_3$ Recent) to 1.26 g cm$^{-3}$($T_5$ Degraded), 0.72 ($T_1$ Control and $T_3$ Recent) to 1.43g cm$^{-3}$ ($T_5$ Degraded) and 0.74($T_3$ Recent) to 1.65g cm$^{-3}$($T_4$ Healthy) respectively.

**Table 9. Mean bulk density in sediment of *A. officinalis* at selected locations of Vembanad lake in premonsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 0.83 | 0.72 | 0.81 |
| $T_2$ | 0.77 | 1.19 | 1.64 |
| $T_3$ | 0.50 | 0.72 | 0.74 |
| $T_4$ | 0.80 | 1.36 | 1.65 |
| $T_5$ | 1.26 | 1.43 | 1.43 |

### 4.4 Total organic matter in sediment

The treatment mean values (Table 10) of layer wise total organic matter in sediment at depths 0-10 cm, 10-20 cm and 20-30 cm ranged from 2.05 ($T_5$ Degraded) to 8.11% ($T_4$ Healthy), 1.23 ($T_5$ Degraded) to 4.15 % ($T_1$ Control) and 1.10 ($T_5$ Degraded) to 3.93 % ($T_1$ Control) respectively in post monsoon.

**Table 10. Mean organic matter in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 4.04 | 4.15 | 3.93 |
| $T_2$ | 5.44 | 2.47 | 2.61 |
| $T_3$ | 5.00 | 4.05 | 2.70 |
| $T_4$ | 8.11 | 3.96 | 3.39 |
| $T_5$ | 2.05 | 1.23 | 1.10 |

In pre-monsoon, the treatment mean values of layer wise total organic matter in sediment at depths 0-10 cm, 10-20 cm and 20-30 cm ranged (Table 11) from 2.09 ($T_5$ Degraded) to 6.16 % ( $T_4$ Healthy), 2.69 ($T_2$ Aged and $T_3$ Recent) to 4.15 % ($T_1$Control) and 2.54 ($T_3$ Recent) to 3.93 % ($T_1$ Control).

**Table 11. Mean organic matter in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 4.04 | 4.15 | 3.93 |
| $T_2$ | 3.21 | 2.69 | 2.58 |
| $T_3$ | 3.98 | 2.69 | 2.54 |
| $T_4$ | 6.16 | 3.02 | 2.59 |
| $T_5$ | 2.09 | 3.71 | 3.66 |

### 4.4 Sediment salinity

The treatment mean values of layer wise sediment salinity varied at depths 0-10 cm, 10-20 cm and 20-30 cm from 8.68 ($T_1$ Control) to 16.15 ppt ($T_5$ Degraded), 8.11 ($T_3$ Recent) to 18.81ppt ($T_4$ Healthy) and 6.26 ($T_3$ Recent) to 17.16 ppt ($T_4$ Healthy) in post monsoon (Table 12).

**Table 12. Mean sediment salinity of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 8.68 | 11.85 | 9.57 |
| $T_2$ | 14.34 | 15.37 | 11.62 |
| $T_3$ | 14.23 | 8.11 | 6.26 |
| $T_4$ | 14.06 | 18.81 | 17.16 |
| $T_5$ | 16.15 | 12.32 | 11.49 |

In pre-monsoon, the treatment mean values of layer wise sediment salinity (Table 13) at depths 0-10 cm, 10-20 cm and 20-30 cm ranged from 6.64 ($T_5$ Degraded) to 12.54 ppt ( $T_4$ Healthy), 5.62 ($T_3$ Recent) to 14.04 ppt ($T_4$ Healthy) and 4.08 ($T_2$ Aged) to 15.32 ppt ($T_4$ Healthy).

**Table 13. Mean sediment salinity of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 8.68 | 11.85 | 7.49 |
| $T_2$ | 10.42 | 5.81 | 4.08 |
| $T_3$ | 4.60 | 5.62 | 5.23 |
| $T_4$ | 12.51 | 14.04 | 15.32 |
| $T_5$ | 6.64 | 10.98 | 12.28 |

### 4.5 Sediment pH

The treatment mean values of layer wise sediment pH varied at depths 0-10 cm, 10-20 cm and 20-30 cm from 6.74 ($T_1$ Control) to 7.43 ($T_5$ Degraded), 6.67 ($T_1$ Control) to 7.30 ($T_4$ Healthy) and 6.65 ($T_1$ Control) to 7.55 ($T_2$ Aged) in post monsoon (Table 14).

**Table 14. Mean sediment pH of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 6.74 | 6.67 | 6.65 |
| $T_2$ | 7.15 | 7.27 | 7.55 |
| $T_3$ | 6.84 | 7.14 | 7.19 |
| $T_4$ | 7.43 | 7.30 | 7.48 |
| $T_5$ | 7.10 | 6.97 | 7.28 |

In pre-monsoon, the treatment mean values of layer wise sediment pH (Table 15) at depths 0-10 cm, 10-20 cm and 20-30 cm ranged from 6.56 ($T_3$ Recent) to 7.19 ($T_4$ Healthy), 6.64 ($T_3$ Recent) to 7.09 ($T_5$ degraded) and 6.34 ($T_2$ Aged) to 7.05 ($T_5$ Degraded).

**Table 15. Mean sediment pH of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 6.74 | 6.67 | 6.65 |
| $T_2$ | 6.74 | 6.73 | 6.34 |
| $T_3$ | 6.56 | 6.64 | 6.46 |
| $T_4$ | 7.19 | 6.76 | 6.75 |
| $T_5$ | 6.88 | 7.09 | 7.05 |

### 4.6 Oxidation reduction potential of sediment

The treatment mean values of layer wise oxidation reduction potential of sediment (Eh) varied (Table 16) at depths 0-10 cm, 10-20 cm and 20-30 cm from -317 mV ($T_4$ Healthy) to -118 mV ($T_3$ Recent), -233 mV($T_4$ Healthy) to -47 mV ($T_5$ Degraded) and -141 mV($T_1$ Control) to -33 mV ($T_5$ Degraded) in post monsoon.

**Table 16. Mean oxidation reduction potential of sediment in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | -152 | -161 | -141 |
| $T_2$ | -151 | -110 | -94 |
| $T_3$ | -118 | -98 | -81 |
| $T_4$ | -317 | -233 | -33 |
| $T_5$ | -158 | -47 | -33 |

In pre-monsoon, the treatment mean values of layer wise sediment Eh (Table 17) at depths 0-10 cm, 10-20 cm and 20-30 cm ranged from -152 mV ($T_1$ Control) to -56 mV ($T_4$ Healthy), -259 mV ($T_5$ Degraded) to 10 mV ($T_2$ Aged) and -186 mV ($T_5$ Degraded) to 30 mV ($T_2$ Aged).

**Table 17. Mean oxidation reduction potential of sediment in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | -152 | -161 | -141 |
| $T_2$ | -92.8 | 10 | 30 |
| $T_3$ | -122.4 | -75.5 | -55.5 |
| $T_4$ | -56 | -125 | -142 |
| $T_5$ | -116 | -259 | -186 |

## 4.7 Sediment grain size analysis

### 4.7.1. *Clay*

In post monsoon, the treatment mean values of layer wise clay in sediment at depths 0-10 cm, 10-20 cm and 20-30 cm ranged from 9.27 ($T_5$ Degraded) to 18.54% ($T_4$ Healthy), 7.69 ($T_5$ Degraded) to 17.82 % (T1 Control) and 2.16 ($T_4$ Healthy) to 18.43 % ($T_1$ Control) in post monsoon (Table 18).

**Table 18. Mean clay content in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 15.92 | 17.82 | 18.43 |
| $T_2$ | 13.00 | 12.50 | 9.60 |
| $T_3$ | 13.69 | 12.61 | 6.20 |
| $T_4$ | 18.54 | 11.56 | 2.16 |
| $T_5$ | 9.27 | 7.69 | 4.32 |

The treatment mean variation of clay content of sediment (Table 19) in pre monsoon at the depths 0-10 cm, 10-20 cm and 20-30 cm was 10.34 ($T_5$ Degraded) to 27.64 % ($T_2$ Aged), 8.62 ($T_5$ Degraded) to 22.93% ($T_2$ Aged) and 6.32 ($T_5$ Degraded) to 18.43 % ($T_1$ Control).

**Table 19. Mean clay in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 15.92 | 17.82 | 18.43 |
| $T_2$ | 27.64 | 22.93 | 13.56 |
| $T_3$ | 18.87 | 18.48 | 10.75 |
| $T_4$ | 18.39 | 16.93 | 15.66 |
| $T_5$ | 10.34 | 8.62 | 6.32 |

### 4.7.2. *Silt*

In post monsoon, the treatment mean values of layer wise silt in sediment varied at depths 0-10 cm, 10-20 cm and 20-30 cm from 6.94 ($T_1$ Control) to 34.76 % ( $T_5$ Degraded), 9.82 ($T_1$ Control) to 36.96 % (T4 Healthy) and 13.57 ($T_1$ Control) to 41.88 % ($T_4$ Healthy) in post monsoon (Table 20).

**Table 20. Mean silt content in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 6.94 | 9.82 | 13.57 |
| $T_2$ | 29.99 | 23.28 | 26.00 |
| $T_3$ | 31.37 | 27.25 | 33.18 |
| $T_4$ | 33.62 | 36.96 | 41.88 |
| $T_5$ | 34.76 | 30.25 | 27.94 |

The treatment mean variation of silt content of sediment in pre monsoon (Table 21) at the depths 0-10cm, 10-20cm and 20-30cm was 6.94 ($T_1$ Control) to 22.58 % ($T_4$ Healthy), 8.67 ($T_3$ Recent) to 22.36% ($T_4$ Healthy) and 8.38 ($T_3$ Recent) to 22.50 % ($T_1$ Control).

**Table 21. Mean silt content in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 6.94 | 9.82 | 13.57 |
| $T_2$ | 20.26 | 21.19 | 20.93 |
| $T_3$ | 11.05 | 8.67 | 8.38 |
| $T_4$ | 22.58 | 22.36 | 18.77 |
| $T_5$ | 13.63 | 18.61 | 22.5 |

### 4.7.3. *Sand*

The variation of treatment means of sand content of sediment in post monsoon (Table 22) at the depths 0-10 cm, 10-20 cm and 20-30 cm was from 44.91 ($T_4$ Healthy) to 70.44 % ($T_1$ Control), 49.56 ($T_4$ Healthy) to 68.02% ($T_1$ Control) and 34.75 ($T_4$ Healthy) to 67.60 % ($T_5$ Degraded).

**Table 22. Mean sand in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 70.44 | 68.02 | 62.75 |
| $T_2$ | 56.6 | 61.17 | 60.33 |
| $T_3$ | 53.71 | 58.65 | 61.83 |
| $T_4$ | 44.91 | 49.56 | 34.75 |
| $T_5$ | 54.67 | 60.56 | 67.60 |

In pre monsoon, the treatment mean values of layer wise sand in sediment ranged (Table 23) at depths 0-10 cm, 10-20 cm and 20-30 cm from 50.80 ($T_3$ Recent) to 7.44 % ($T_1$ Control), 45.4 ($T_2$ Aged) to 68.02 % ($T_1$ Control) and 46.07($T_2$ Aged) to 62.75 % ($T_1$ Control).

**Table 23. Mean sand in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 70.44 | 68.02 | 62.75 |
| $T_2$ | 51.21 | 45.40 | 46.07 |
| $T_3$ | 50.80 | 52.60 | 53.17 |
| $T_4$ | 55.48 | 57.80 | 58.49 |
| $T_5$ | 64.19 | 57.04 | 50.47 |

## 4.8 Total carbon in sediment

The variation of treatment means of total carbon content of sediment in post monsoon (Table 24) at the depths 0-10 cm, 10-20 cm and 20-30 cm was from 1.37 ($T_5$ Degraded) to 4.87 % ($T_4$ Healthy), 1.11 ($T_5$ Degraded) to 3.44% ($T_3$ Recent) and 0.96 ($T_5$ Degraded) to 7.95 % ($T_4$ Healthy).

**Table 24. Mean total carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 2.49 | 2.45 | 2.66 |
| $T_2$ | 3.28 | 1.59 | 1.65 |
| $T_3$ | 3.54 | 3.44 | 2.13 |
| $T_4$ | 4.87 | 2.86 | 7.95 |
| $T_5$ | 1.37 | 1.11 | 0.96 |

In pre monsoon, the treatment mean values of layer wise total carbon in sediment (Table 25) at depths 0-10 cm, 10-20 cm and 20-30 cm ranged from 1.25 ($T_5$ Degraded) to 3.89% ( $T_4$ Healthy), 1.96 ($T_3$ Recent and $T_4$ Healthy) to 2.98 % ($T_2$ Aged) and 1.68 ($T_3$ Recent) to 2.66 % ($T_1$ Control).

**Table 25. Mean total carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 2.49 | 2.45 | 2.66 |
| $T_2$ | 2.18 | 2.98 | 1.75 |
| $T_3$ | 2.79 | 1.96 | 1.68 |
| $T_4$ | 3.89 | 1.96 | 1.72 |
| $T_5$ | 1.25 | 2.56 | 2.24 |

### 4.9 Total nitrogen in sediment

The variation of treatment means of total nitrogen content of sediment (Table 26) in post monsoon at the depths 0-10 cm, 10-20 cm and 20-30 cm was from 0.08 ($T_2$ Aged) to 0.22 % ($T_4$ Healthy), 0.08 ($T_2$ Aged) to 0.18 % ($T_1$ Control) and 0.07 ($T_2$ Aged) to 0.35 % ($T_4$ Healthy).

**Table 26. Mean total nitrogen in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 0.22 | 0.18 | 0.18 |
| $T_2$ | 0.08 | 0.08 | 0.07 |
| $T_3$ | 0.13 | 0.12 | 0.27 |
| $T_4$ | 0.10 | 0.09 | 0.35 |
| $T_5$ | 0.15 | 0.14 | 0.16 |

In pre monsoon, the treatment mean values of layer wise total nitrogen (Table 27) in sediment at depths 0-10 cm, 10-20 cm and 20-30 cm ranged from 0.08 ($T_5$ Degraded) to 0.21% ( $T_4$ Healthy), 0.08 ($T_5$ Degraded) to 0.18 % ($T_1$ Control) and 0.10 ($T_5$ Degraded) to 0.18 % ($T_1$ Control and $T_4$ Healthy).

**Table 27. Mean total nitrogen in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 0.22 | 0.18 | 0.18 |
| $T_2$ | 0.14 | 0.24 | 0.11 |
| $T_3$ | 0.12 | 0.11 | 0.15 |
| $T_4$ | 0.21 | 0.13 | 0.18 |
| $T_5$ | 0.08 | 0.13 | 0.10 |

### 4.10 C/N ratio

The mean values of C/N ratio of sediment in post monsoon (Table 28) at the depths 0-10 cm, 10-20 cm and 20-30 cm ranged from 8.09 ($T_5$ Degraded) to 48.68 ($T_4$ Healthy), 5.12 ($T_5$ Degraded) to 25.51 ($T_4$ Healthy) and 3.92 ($T_5$ Degraded) to 22.44 ($T_2$ Aged) respectively.

**Table 28. Mean C/N ratio in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 10.72 | 13.09 | 12.50 |
| $T_2$ | 39.45 | 17.94 | 22.44 |
| $T_3$ | 21.88 | 19.18 | 5.76 |
| $T_4$ | 48.68 | 25.51 | 5.63 |
| $T_5$ | 8.09 | 5.12 | 3.92 |

In pre monsoon, the mean values of layer wise C/N ratio in sediment (Table 29) at depths 0-10 cm, 10-20 cm and 20-30 cm ranged from 10.72 ($T_1$ Control) to 19.26 ( $T_3$ Recent), 6.65 ($T_2$ Aged) to 16.56 ($T_5$ Degraded) and 8.34 ($T_4$ Healthy) to 21.25 ($T_5$ Degraded).

**Table 29. Mean C/N ratio in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

| Depth | 0-10 cm | 10-20 cm | 20-30 cm |
|---|---|---|---|
| $T_1$ | 10.72 | 13.09 | 12.50 |
| $T_2$ | 13.51 | 6.65 | 13.60 |
| $T_3$ | 19.26 | 14.18 | 9.83 |
| $T_4$ | 17.01 | 13.46 | 8.34 |
| $T_5$ | 15.16 | 16.56 | 21.25 |

# DISCUSSION

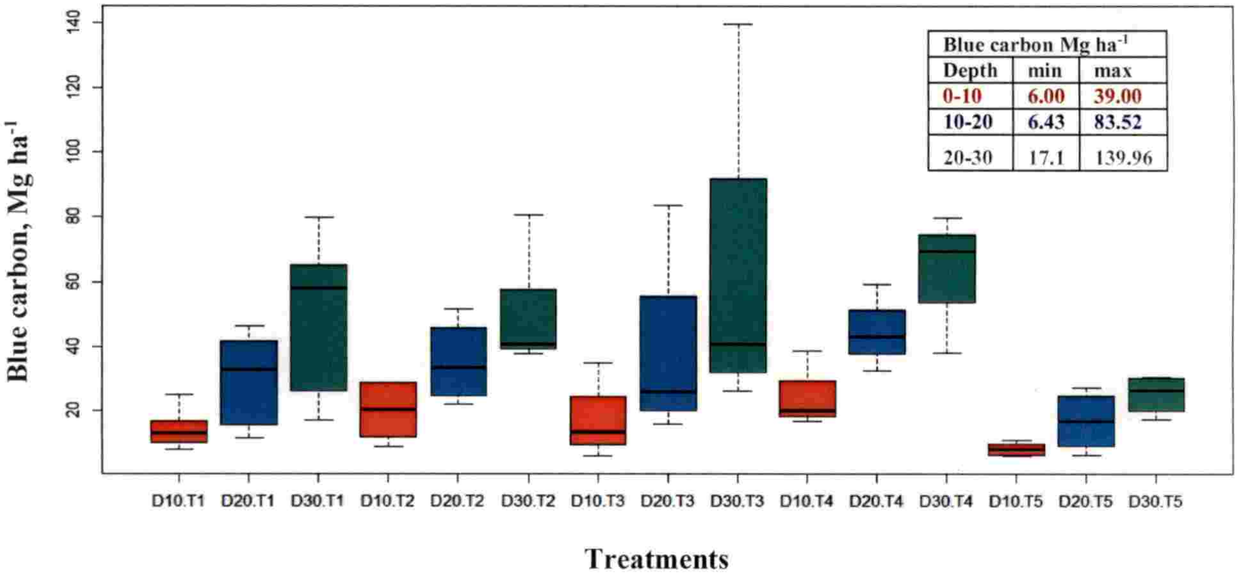
## CHAPTER 5

## DISCUSSION

### 5.1 Blue carbon

#### 5.1.1 *Cumulative stock of blue carbon*

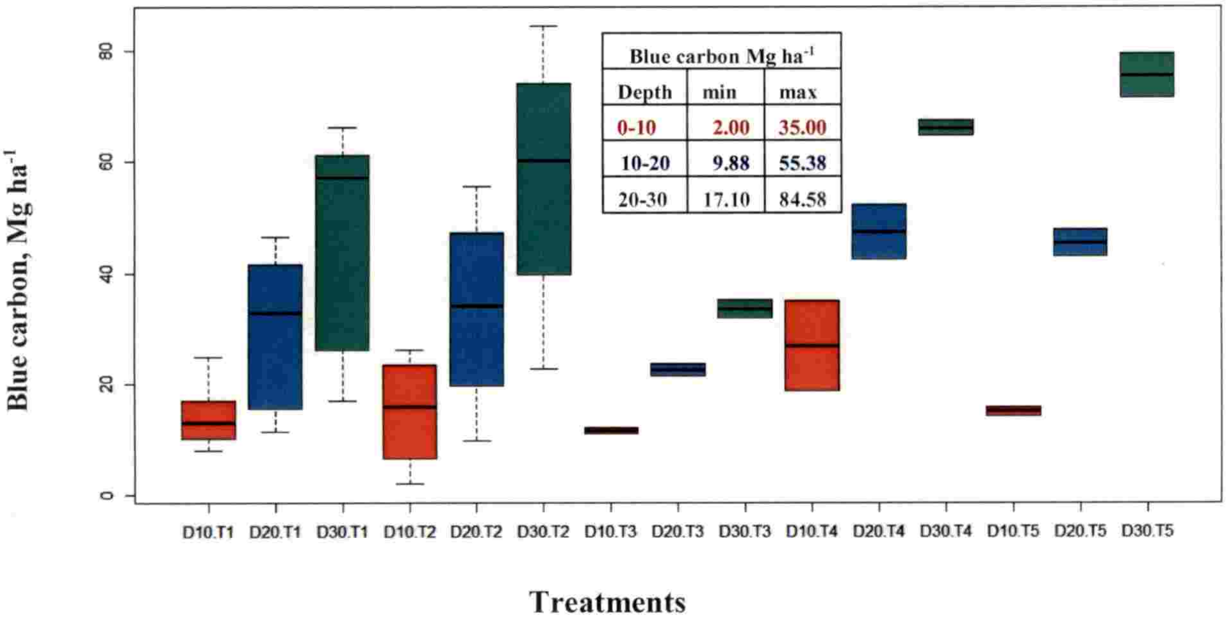
Cumulative stock of blue carbon in sediment of *Avicennia officinalis* in all sampling locations ranged from 6.00 to 39.00 Mg ha$^{-1}$ , 6.43 to 83.52 Mg ha$^{-1}$ and 17.10 to 139.96 Mg ha$^{-1}$ at 0-10 cm, 0-20 cm and 0-30 cm of depth respectively in post monsoon (Fig.3).



| Blue carbon Mg ha$^{-1}$ | | |
|---|---|---|
| Depth | min | max |
| 0-10 | 6.00 | 39.00 |
| 10-20 | 6.43 | 83.52 |
| 20-30 | 17.1 | 139.96 |

**Fig.3 Cumulative stock of blue carbon in sediment of *A. officinalis* selected locations of Vembanad lake in post monsoon.**

In premonsoon, the variation of blue carbon stock was from 2.00 to 35.00 Mg ha$^{1}$, 9.88 to 55.38 Mg ha$^{-1}$ and 17.10 to 84.58 Mg ha$^{-1}$ at 0-10 cm, 0-20 cm and 0-30 cm of depth respectively (Fig. 4).



| Blue carbon Mg ha$^{-1}$ | | |
|---|---|---|
| Depth | min | max |
| 0-10 | 2.00 | 35.00 |
| 10-20 | 9.88 | 55.38 |
| 20-30 | 17.10 | 84.58 |

**Fig.4 Cumulative stock of blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

The overall mean carbon storage in the *A. officinalis* sediments in selected locations of Vembanad lake area was found to be 62.35 Mg ha$^{-1}$. This value is very low compared to the mean global soil organic carbon stock in the mangrove ecosystem (386 Mg ha$^{-1}$) (IPCC, 2013), which offers the opportunity to sequester more carbon in the selected mangrove ecosystems in Vembanad lake there by contributing to climate change mitigation efforts.

Kauffman *et al.*, (2014) justified inclusion of conservation of mangrove ecosystems for climate-change mitigation strategies, based on the high carbon stocks of mangroves, the high emissions of $CO_2$ by their conversion or destruction or disturbance and also based on the other important services they provide. The term mangrove includes both the ecosystem and the plant families that got adaptations to live in the tidal environment which are inundated twice daily by the tides (IUCN, 2007).

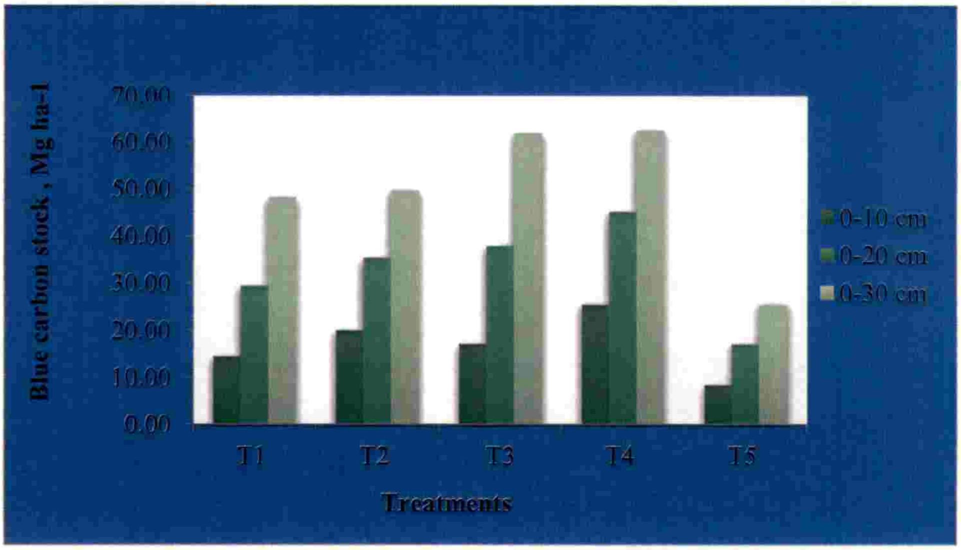


**Fig.5 Cumulative stock of mean blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

The results of two way ANOVA with unequal replications in post monsoon showed treatments differed significantly ($p < 0.05$). There was also very highly significant variation among depths ($p < 0.001$). The highest stock (62.47 Mg ha $^{-1}$) was in $T_4$ (Healthy) at 0-30 cm depth. The highest stock was seen in 0-30 cm as the cumulative carbon stock is the sum of layered stocks (Fig.5).

Post hoc analysis revealed that there was a highly significant difference between $T_4$ (Healthy) and $T_5$ (Degraded), higher stock being found in $T_4$ sediment.
Weiss *et al.*, (2016) compared healthy and degraded marine and estuarine mangroves in Indonesia for soil organic carbon stocks and found that the mangrove degradation caused a decrease in soil organic carbon stocks to 80–132 Mg ha$^{-1}$ m$^{-1}$ from the original values of 271–572 Mg ha$^{1}$ m$^{-1}$ in marine mangroves. Mangrove loss reduces carbon stock in the ocean by about 30 Tg
Year $^{-1}$ (Duarte *et al.,* 2005). On degradation, the mangrove soils have $CO_2$ emissions that contribute to climate change (IUCN, 2018). By such loss in carbon sequestration capacity, the soil carbon stock in degraded mangroves get much reduced compared to healthy mangroves. There was also significant difference between $T_3$ (Recent) and $T_5$ (Degraded), higher stock seen in Recent than in Degraded *A.officinalis.*

Patil *et al.*, (2012) described that for $CO_2$ sequestration, in the mangrove ecosystem, the pertinent carbon sinks under consideration are carbon buried in mangrove sediments nearby or in adjacent systems as well as the net growth of mangrove biomass during growth stage. As $T_3$, being recent (<5 years old) mangroves, they are in growing stage and contribute towards the sediment carbon pool carbon sequestration. On the other hand, $T_5$ being degraded mangroves contribute more towards carbon loss from soil. The disturbed mangrove soils liberate more than an additional 11 million metric tons of carbon annually (MAP, 2018).

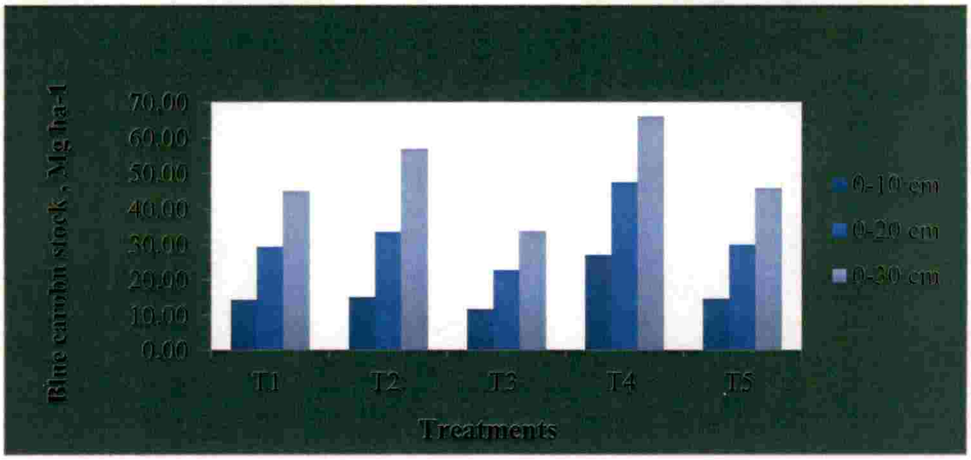
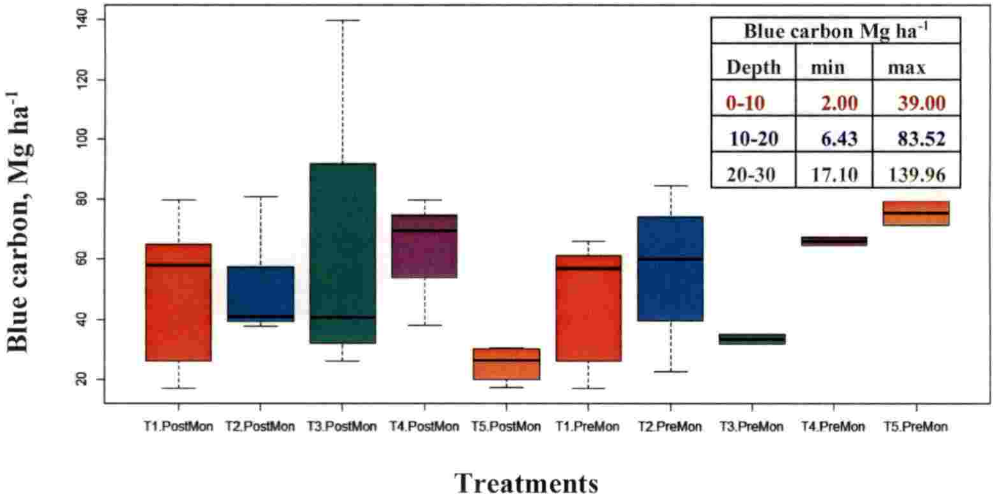


**Fig.6 Cumulative stock of mean blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in pre-monsoon.**

There was no statistically significant increase in the sediment carbon stocks of $T_2$ (Aged) compared to that of $T_3$ (Recent) in the present investigation. Lunstrum and Chen (2014) while comparing soil carbon stocks in young mangrove forest in China, in relation to age, observed that though soil carbon increased with age of mangroves, only the 70 year old showed statistical difference signifying that local ecological variations may mask age-related pattern in soil carbon accumulation.

A similar trend as in post monsoon, was seen in the results of two way ANOVA with unequal replications in pre-monsoon also. The treatments differed significantly ($p < 0.05$) and there was also very highly significant variation among depths ($p < 0.001$). The highest stock was in 0-30 cm since the cumulative carbon stock is the sum of layered stocks (Fig.6).

The values of cumulative stock of blue carbon in sediment in both seasons, at depth 0-30 cm are depicted (Fig.7).



| Blue carbon Mg ha$^{-1}$ | | |
|---|---|---|
| Depth | min | max |
| 0-10 | 2.00 | 39.00 |
| 10-20 | 6.43 | 83.52 |
| 20-30 | 17.10 | 139.96 |

**Fig.7 Cumulative stock of blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake at 0-30 cm.**

The cumulative stock of blue carbon in sediment at 0-30 cm was subject to two way ANOVA, to compare the difference between seasons. The ANOVA showed no significant difference in the cumulative stock of blue carbon in sediment at 0-30 cm depths.

### 5.1.1.1 *Mapping*

The map showing stock of blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake at 0-30 cm, in post monsoon and premonsoon are given below (Fig.8 and 9).

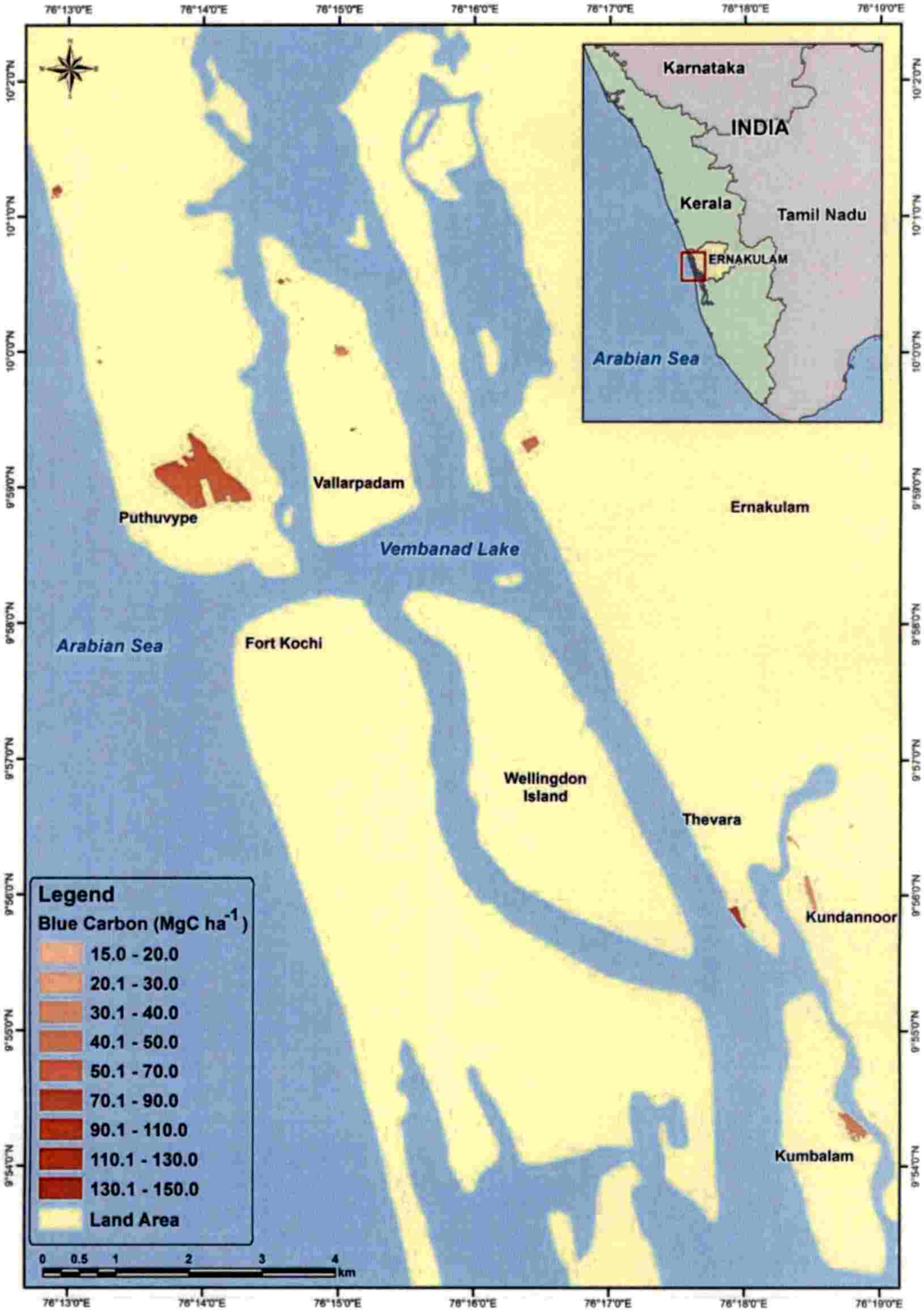


**Fig.8 Map showing stock of Blue carbon in sediment of *A.officinalis* at selected locations of Vembanad lake at 0-30 cm, in post monsoon.**

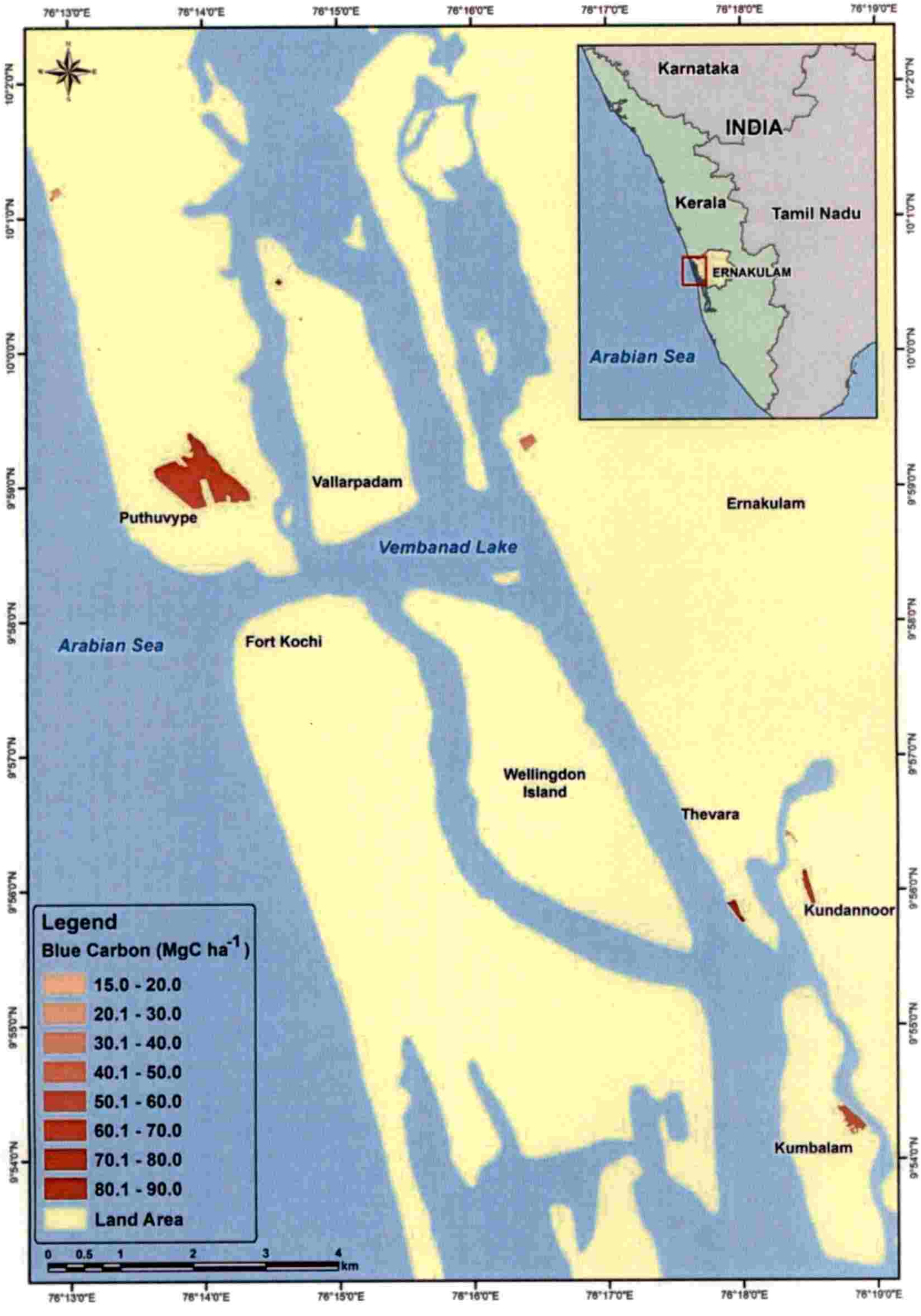
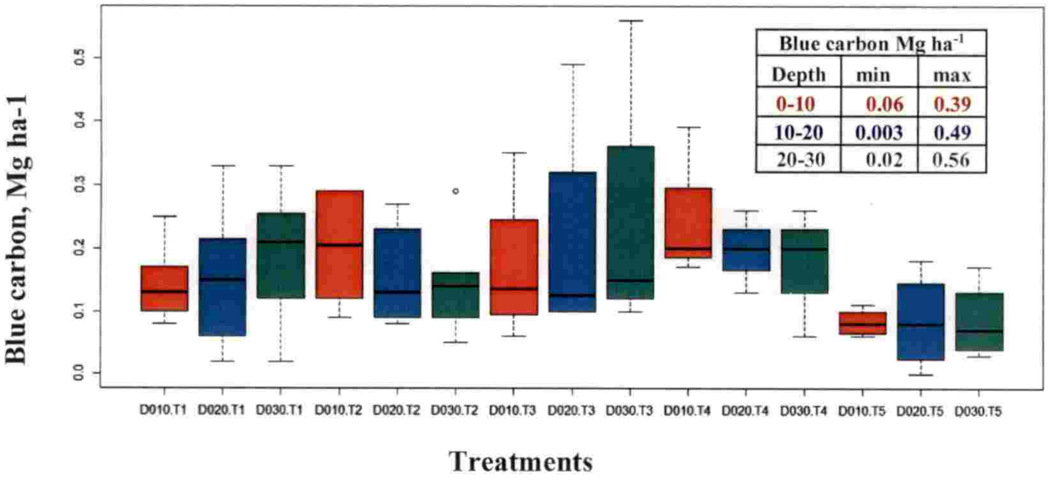


**Fig.9 Map showing stock of blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake at 0-30 cm, in pre monsoon**

It was observed that the cumulative stock of carbon in sediment up to 30 cm depth was higher in post monsoon than in pre monsoon. Kathiresan *et al*., (2013) found that the rate of carbon sequestration was 7.3 fold higher in post-monsoon, than that in pre monsoon in the Vellar-Coleroon estuarine complex in India. Patil *et al.* (2012) opined that carbon accumulating in the mangrove soils need not be fully of the local production by mangroves, but organic matter can be brought in during high tide or by run-off. In the present study, the mean local (district level) rainfall (IMD, 2018) during post monsoon (October – November, 2017) was 473.7 mm and that during pre-monsoon (February – March 2018) was 39.5 mm, which indicated carbon addition by run- off. Mitra *et al.,* (2012) attributed seasonal variation of carbon stocks in mangrove soil to climatic factors that manipulate physical processes such as waves, current pattern and tidal amplitude.

### 5.1.2 *Layer wise blue carbon*

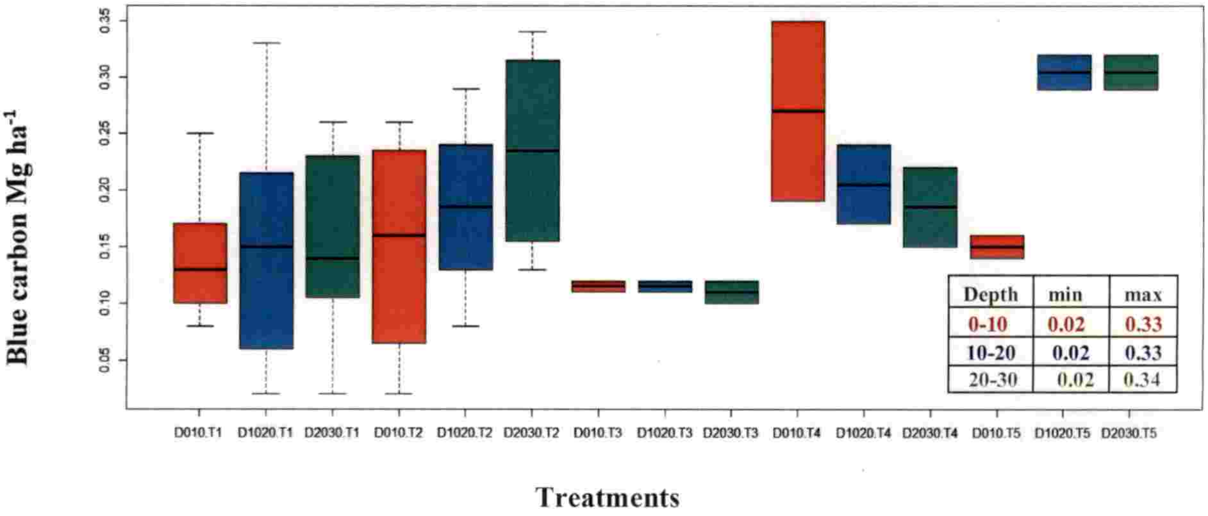
Layer wise blue carbon in sediment core sections of all sampling locations ranged from 0.06to 0.39 g $cm^{-3}$, 0.003 to 0.49 g $cm^{-3}$ and 0.02 to 0.56g $cm^{-3}$ at 0-10 cm, 10-20 cm and 20-30 cm of depth respectively in post monsoon (Fig. 10).



| Blue carbon Mg ha$^{-1}$ | | |
|---|---|---|
| Depth | min | max |
| 0-10 | 0.06 | 0.39 |
| 10-20 | 0.003 | 0.49 |
| 20-30 | 0.02 | 0.56 |

**Fig.10 Layer wise stock of blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon**

In pre monsoon, the variation of layer wise blue carbon was from 0.02 to 0.35 g cm$^{-3}$, 0.02 to 0.33 g cm$^{-3}$ and 0.02 to 0.34 g cm$^{-3}$ at 0-10 cm, 10-20 cm and 20-30 cm of depth respectively (Fig.11).



| Depth | min | max |
|---|---|---|
| 0-10 | 0.02 | 0.33 |
| 10-20 | 0.02 | 0.33 |
| 20-30 | 0.02 | 0.34 |

**Fig.11 Layerwise stock of blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

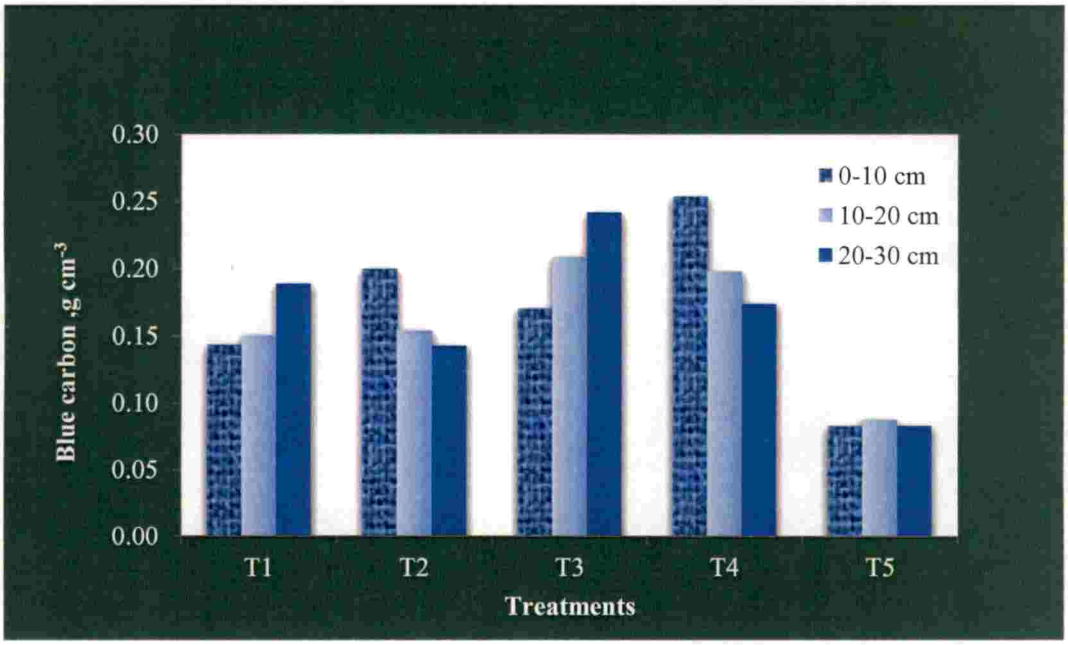


**Fig.12 Layer wise mean blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

In layer wise blue carbon, the results of two way ANOVA with unequal replications in post monsoon showed that the treatments differed significantly ($p < 0.05$). The highest value (0.25 g cm$^{-3}$) was seen in $T_4$ (Healthy) at 0-10 cm sediment layer (Fig.12). There was no significant variation among depths in the layer wise blue carbon.

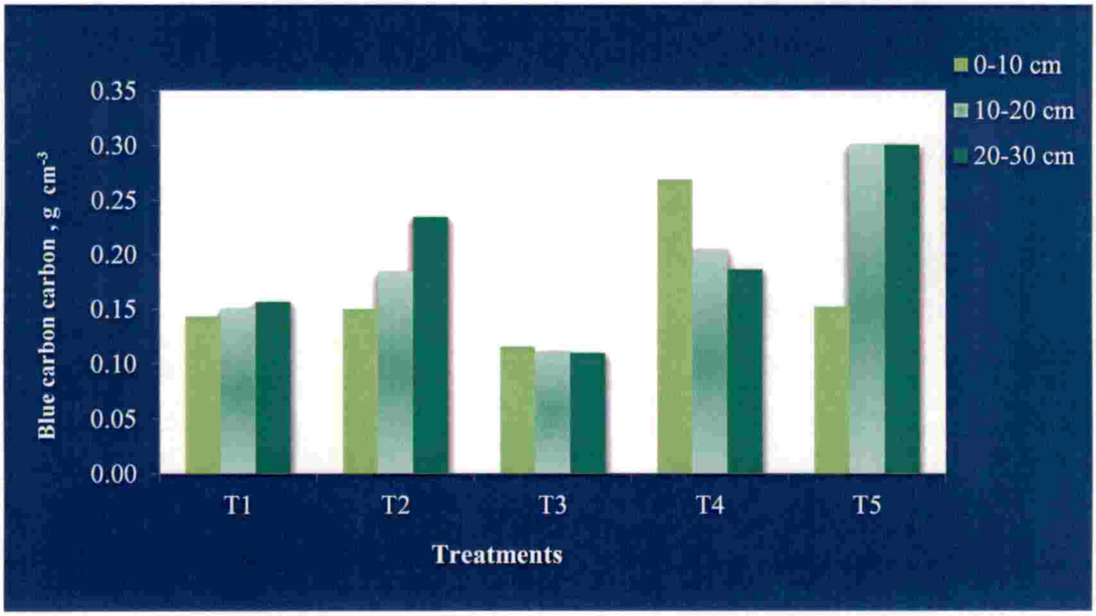
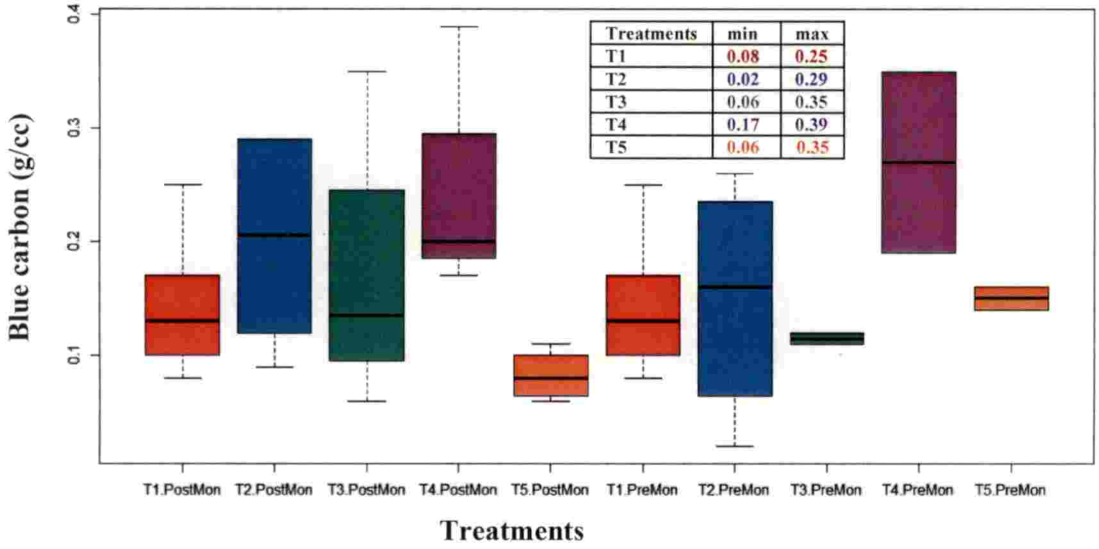


**Fig.13 Layer wise mean blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

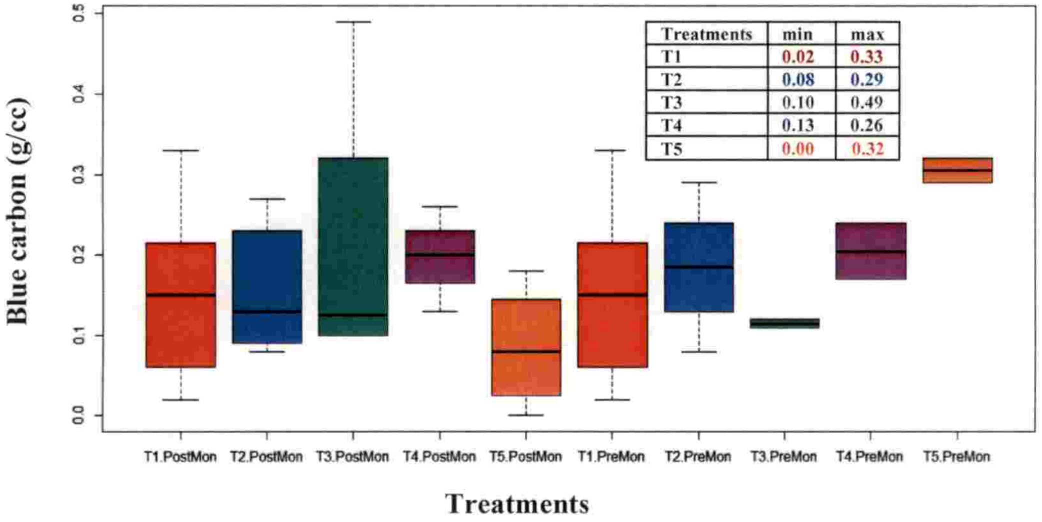
The two way ANOVA results of layer wise blue carbon, in pre monsoon showed that the treatments differed significantly ($p < 0.05$). The highest value (0.30 g cm$^{3}$) was seen in $T_5$ (Degraded) at 10-20 cm and 20-30 cm sediment layers (Fig.13). There was no significant variation among depths in the layer wise blue carbon.

The layer wise blue carbon in sediment between seasons was compared using two way ANOVA. The values of layer wise blue carbon in sediment in both seasons, at depths 0-10 cm, 10-20 cm and 20-30 cm are depicted in Figs.14 to 16. In the top layer (0-10 cm), the ANOVA showed significant difference among treatments.



| Treatments | min | max |
|---|---|---|
| T1 | 0.08 | 0.25 |
| T2 | 0.02 | 0.29 |
| T3 | 0.06 | 0.35 |
| T4 | 0.17 | 0.39 |
| T5 | 0.06 | 0.35 |

**Fig.14 Layer wise (0-10 cm) mean blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake.**



| Treatments | min | max |
|---|---|---|
| T1 | 0.02 | 0.33 |
| T2 | 0.08 | 0.29 |
| T3 | 0.10 | 0.49 |
| T4 | 0.13 | 0.26 |
| T5 | 0.00 | 0.32 |

**Fig.15 Layer wise (10-20 cm) mean blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake.**

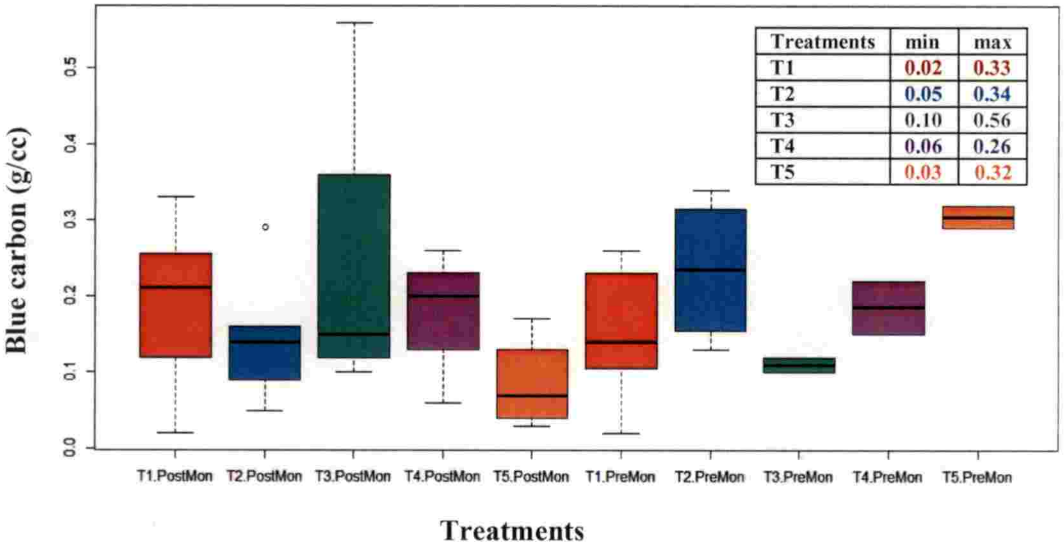


**Fig.16 Layer wise (20-30 cm) mean blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake.**

The ANOVA showed no significant difference in the layer wise blue carbon in sub surface sediment at 10-20 cm and 20-30 cm depths.

The top layer (0-10 cm) being the dynamic layer subjected to more physio chemical and biological interactions was found to be influenced by the seasonal changes.

### 5.1.2.1 *Mapping*

The maps showing layer wise blue carbon in sediment of *A. officinalis* at selected locations of Vembanad Lake at 0-10 cm, 10-20 cm and 20-30 cm in post monsoon are given below (Figs. 17 to 19).

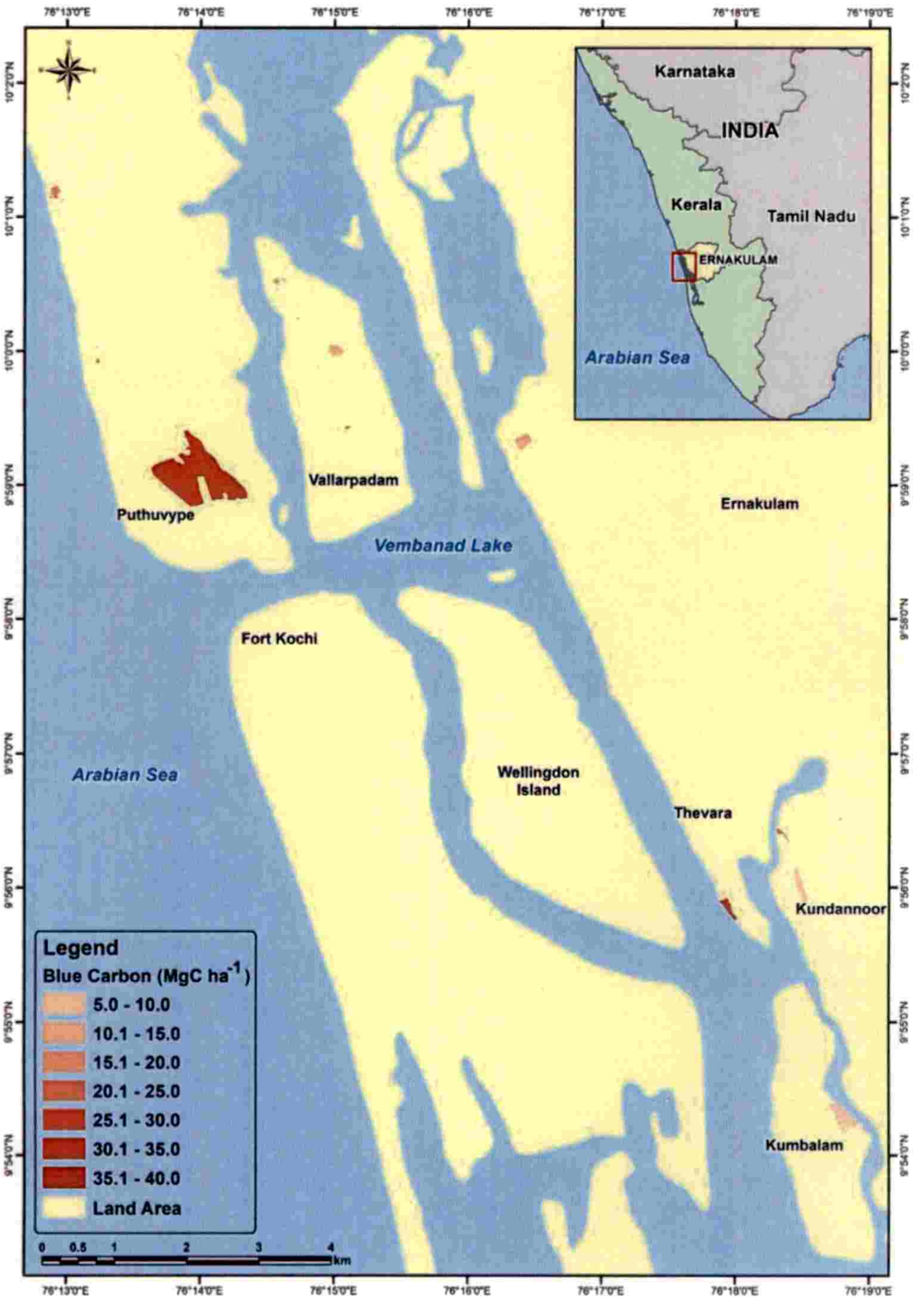


**Fig.17 Map showing layerwise (0-10 cm) blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

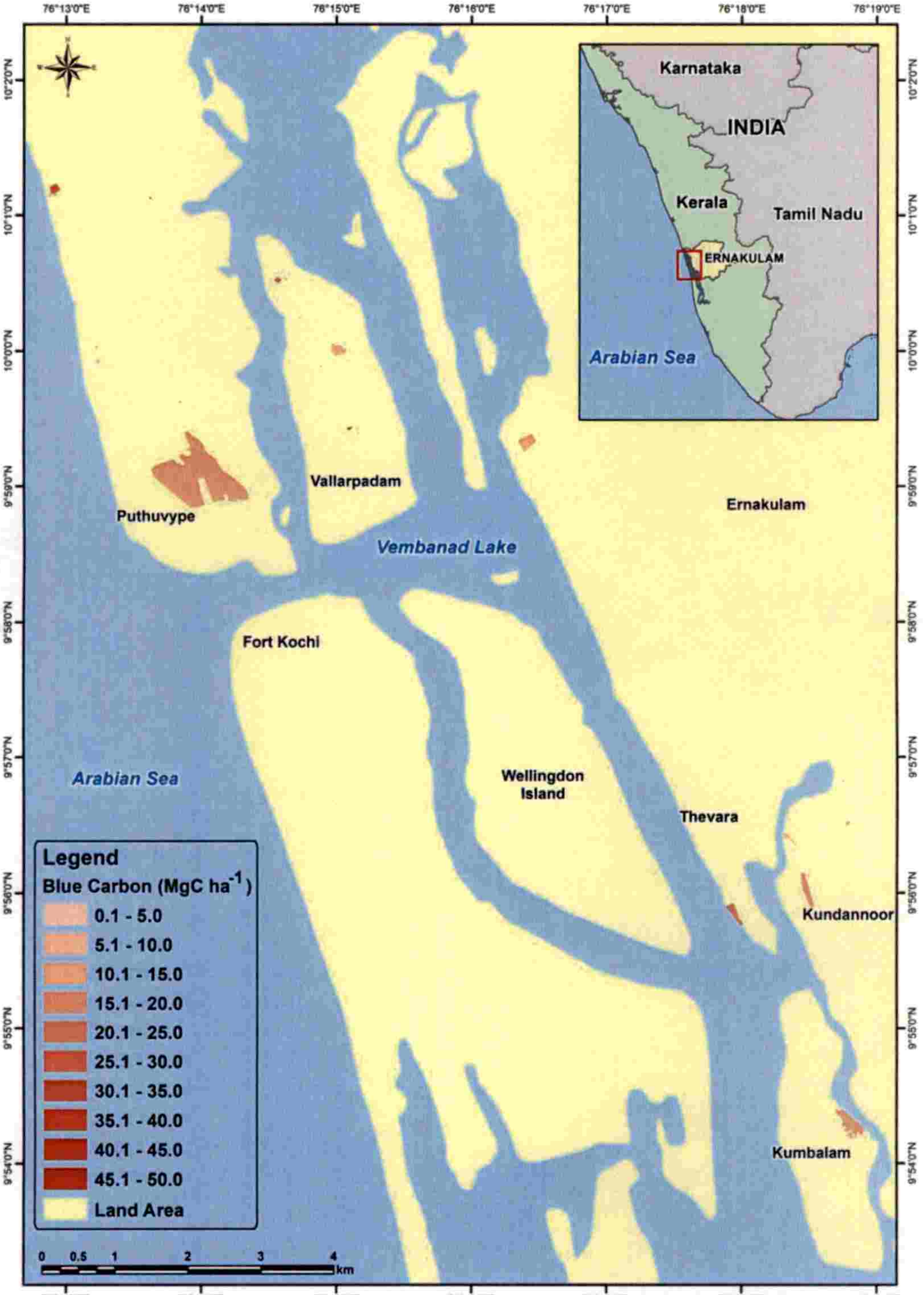


**Fig.18 Map showing layer wise (10-20 cm) blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon**

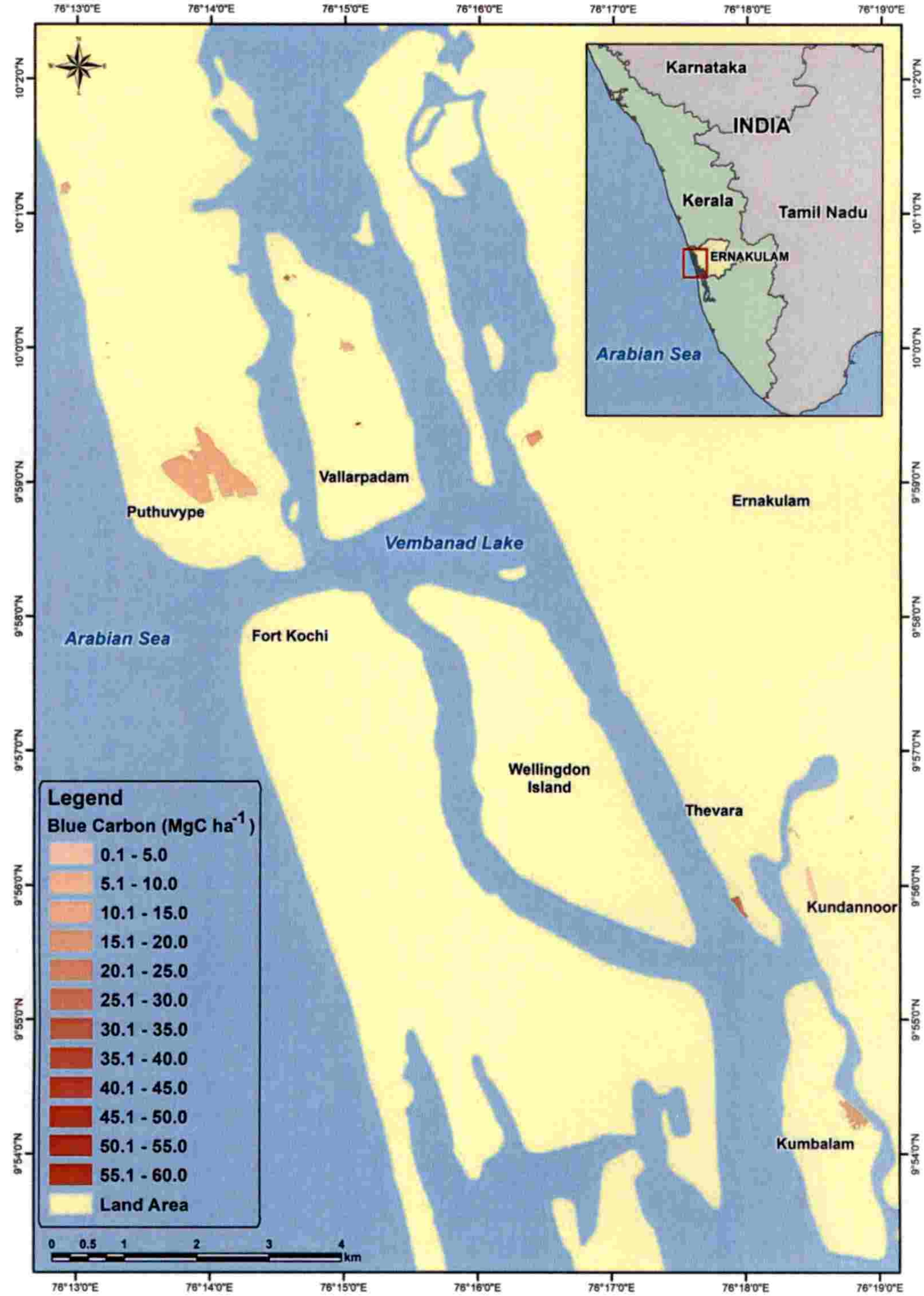


**Fig.19 Map showing layer wise (20-30 cm) blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon**

The maps showing layer wise blue carbon in sediment of *A. officinalis* at selected locations of Vembanad Lake at 0-10 cm, 10-20 cm and 20-30 cm in pre monsoon are given below (Figs. 20 to 22).

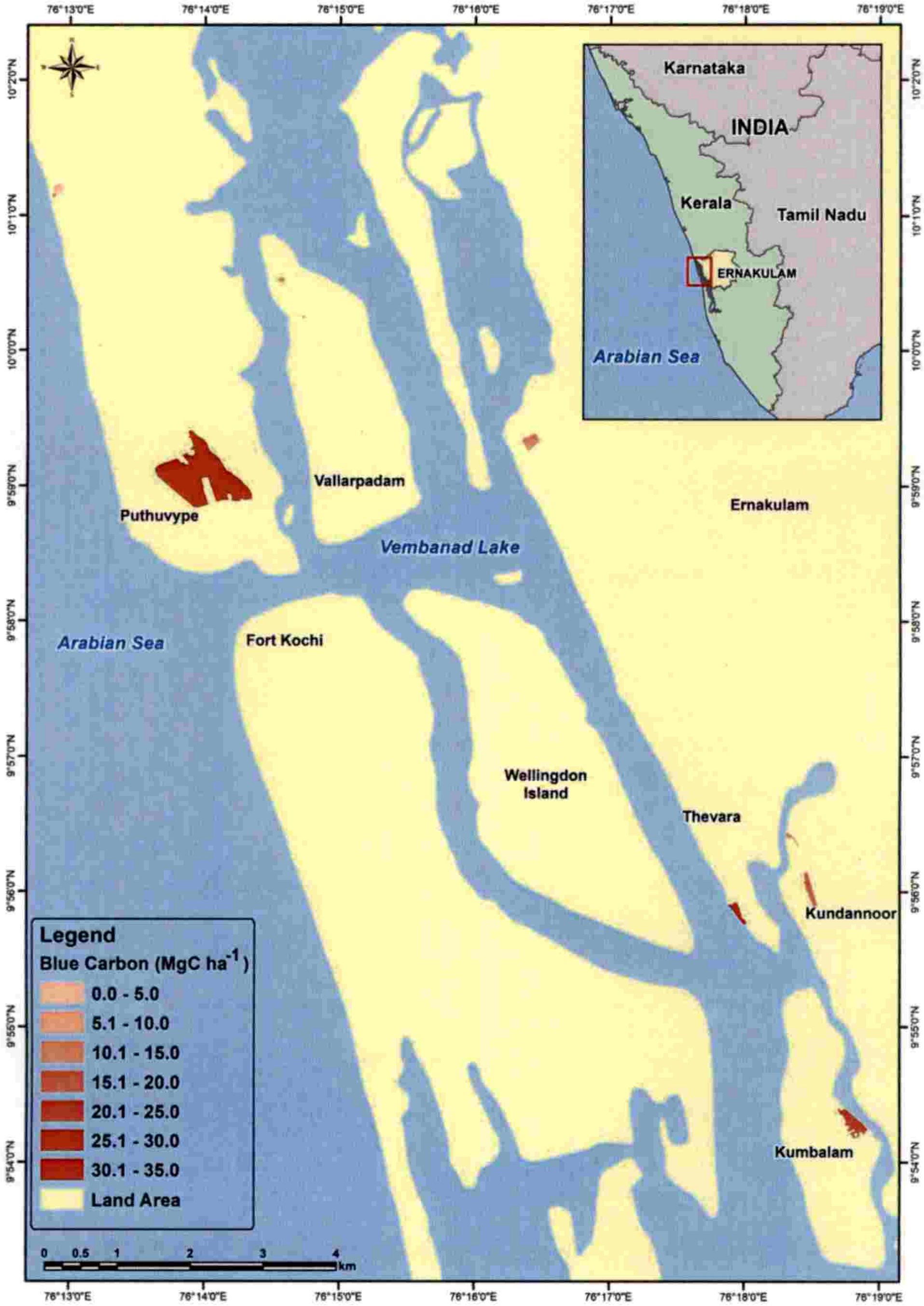


**Fig.20 Map showing layer wise (0-10 cm) blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon**

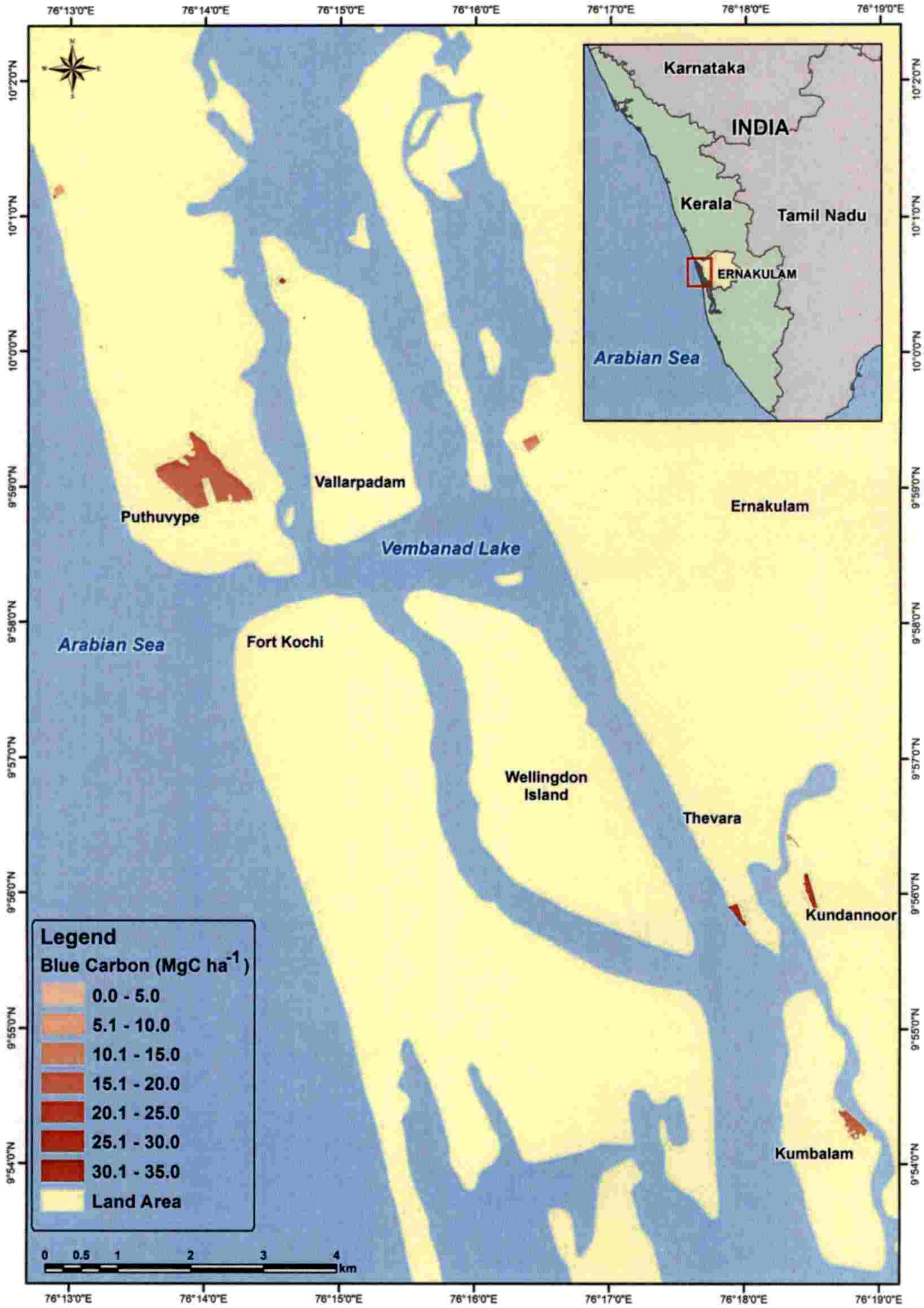


**Fig.21 Map showing layer wise (10-20 cm) blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon**

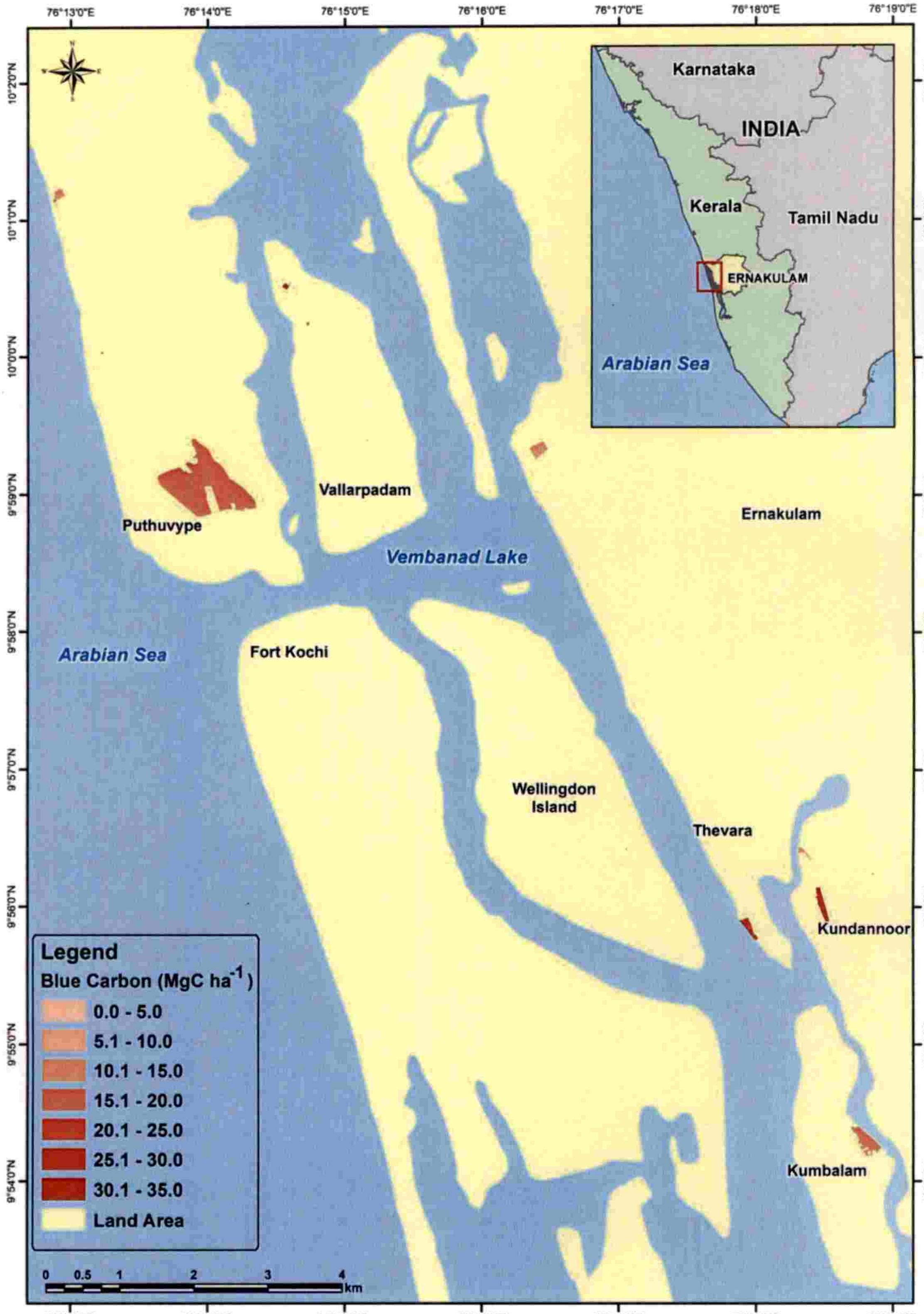


**Fig.22 Map showing layer wise (20-30 cm) blue carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon**

The maps clearly indicate the higher amounts of layer carbon in post monsoon. In post monsoon there was a depth wise increase in layer wise carbon, though it was not statistically significant. This stratification in layered carbon showing depth wise increase noted only in post monsoon can be endorsed to the higher amount of rainfall received in post monsoon which would have facilitated export of carbon downwards.

### 5.1.3. *Measured stock of sediment blue carbon upto maximum possible depth*

The samples having core compression and also core sections having water in place of sediment were not taken for laboratory analysis. Wherever, intact sediment samples were available in the core, blue carbon stocks up to the maximum available depth was measured. The values of measured stock of blue carbon at maximum possible depth are depicted in Fig.23.

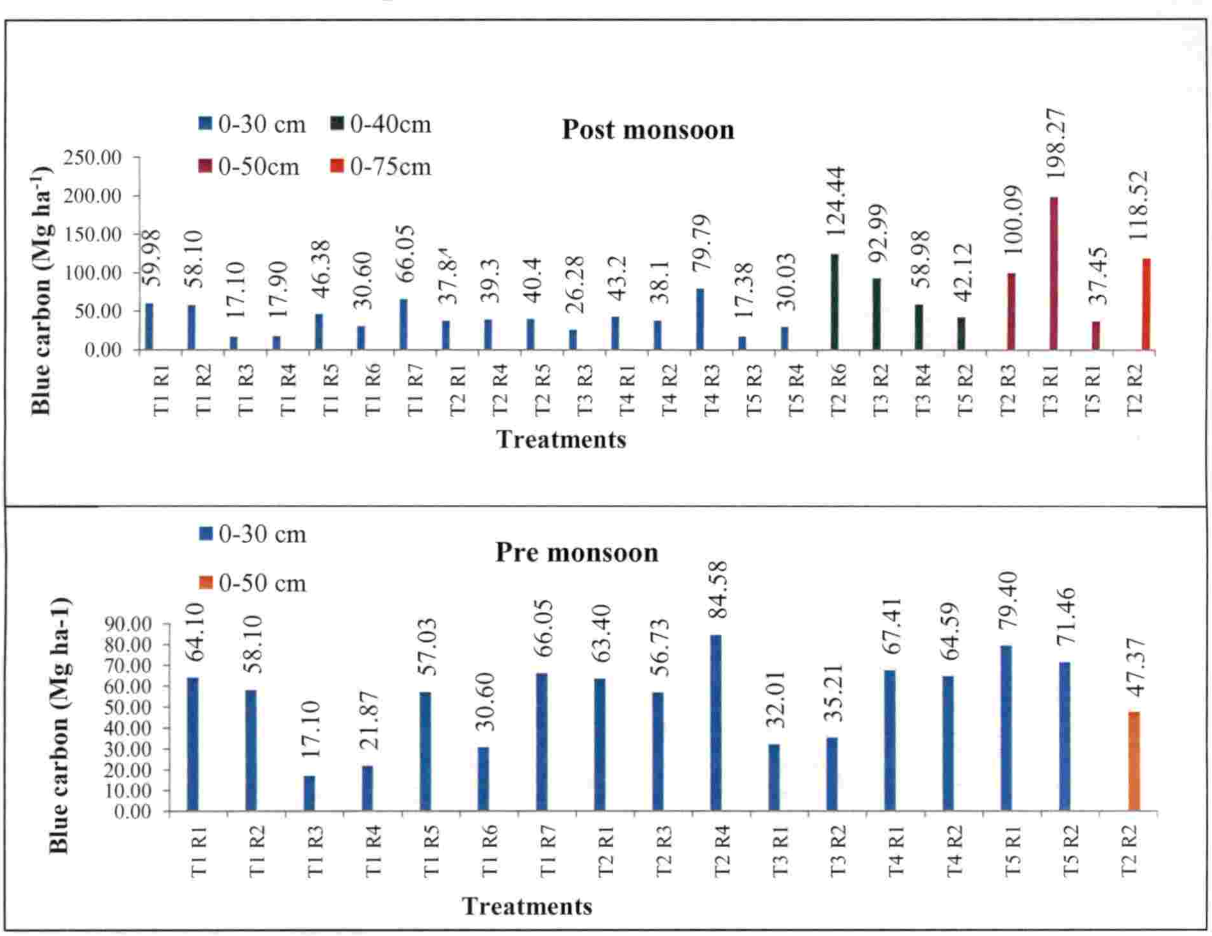


**Fig.23 Measured stock of sediment blue carbon up to maximum possible depth, at selected locations of Vembanad lake during post and pre monsoon**

It was seen that the highest carbon stock was at 0-50 cm depth in post monsoon. The data showed that, the depth wise variation in stock not according to any obvious trend. The factors controlling depth wise variation of soil carbon stock in mangroves is difficult to identify (Alongi, 2008). The variation is not a simple function, but a complex dynamic one affected by many environmental factors and eventful disturbances (Chumura *et al.*, 2003).

## 5.2 Total organic carbon (TOC) in sediment

Layer wise organic carbon in sediment core sections of all sampling locations ranged from 0.52 to 6.48% 0.03 to 5.49%and 0.18 to 4.11% at 0-10 cm, 10-20 cm and 20-30 cm of depth respectively in post monsoon (Fig.24).

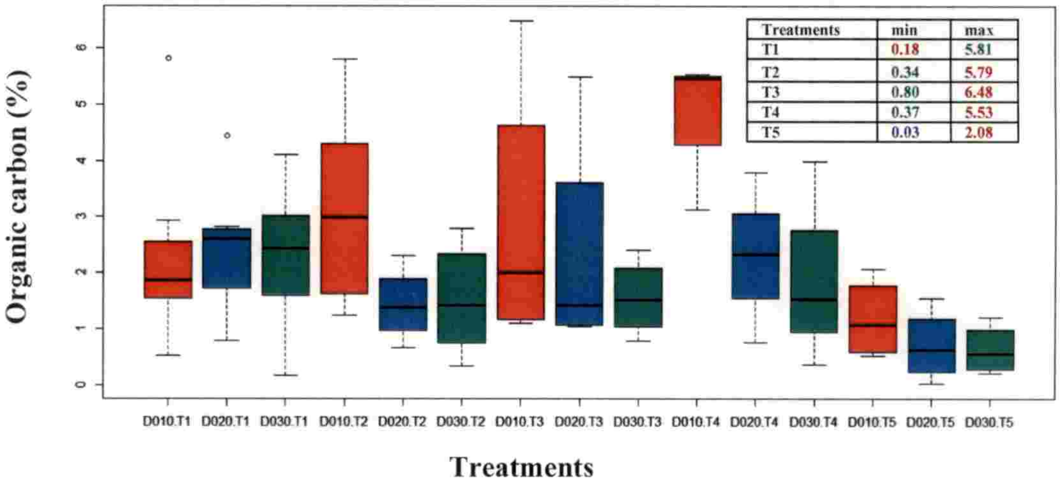
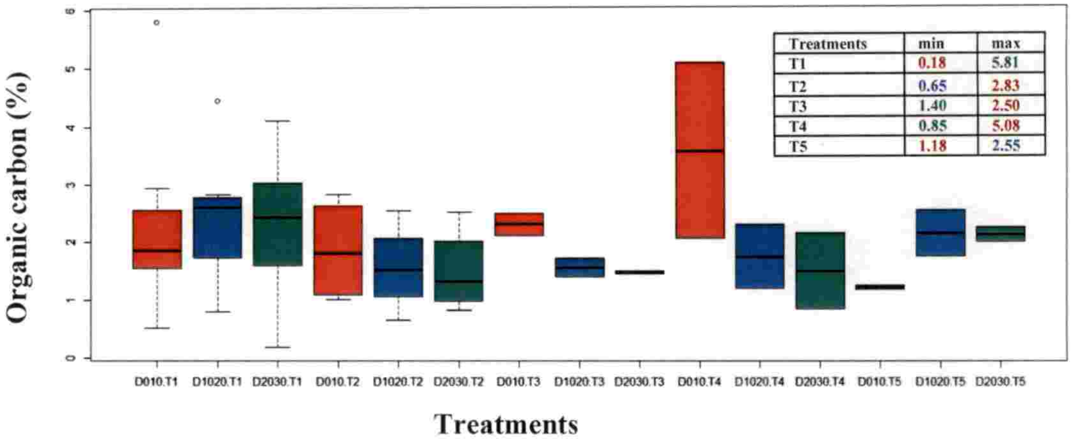


**Fig.24 Layer wise organic carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

The corresponding values in pre-monsoon for layer wise organic carbon were 0.52 to 5.81 %, 0.65 to 4.45 % and 0.18 to 4.11% at 0-10 cm, 10-20 cm and 20-30 cm of depth respectively (Fig.25).



| Treatments | min | max |
|---|---|---|
| T1 | 0.18 | 5.81 |
| T2 | 0.65 | 2.83 |
| T3 | 1.40 | 2.50 |
| T4 | 0.85 | 5.08 |
| T5 | 1.18 | 2.55 |

**Fig.25 Layer wise organic carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in premonsoon.**

The results of two way ANOVA for layer wise organic carbon in sediment, in post monsoon showed that there was highly significant variation among treatments ($p < 0.01$). Depth wise variation of organic carbon in sediment layers was also significant ($p < 0.05$).The top layer (0-10 cm) was having highest content of organic carbon in all the treatments (Fig.26). The decrease in organic carbon in sub surface sediment layers (10-20 cm and 20-30 cm) was more prominent in $T_4$ (Healthy) and $T_3$ (Recent) mangroves. Post hoc analysis showed that 0-10 cm and 20-30 cm differed significantly in the organic carbon content, showing depth wise decrease in mean organic carbon. Mitra *et al.* (2008) also obtained a depth wise decrease in soil organic carbon in mangroves of western and eastern Indian Sunderbans.

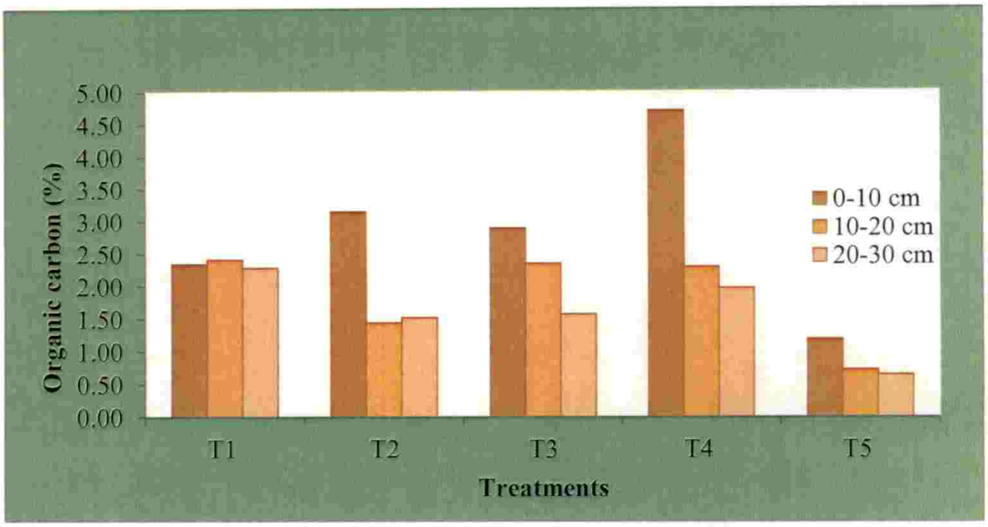


**Fig.26 Mean organic carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

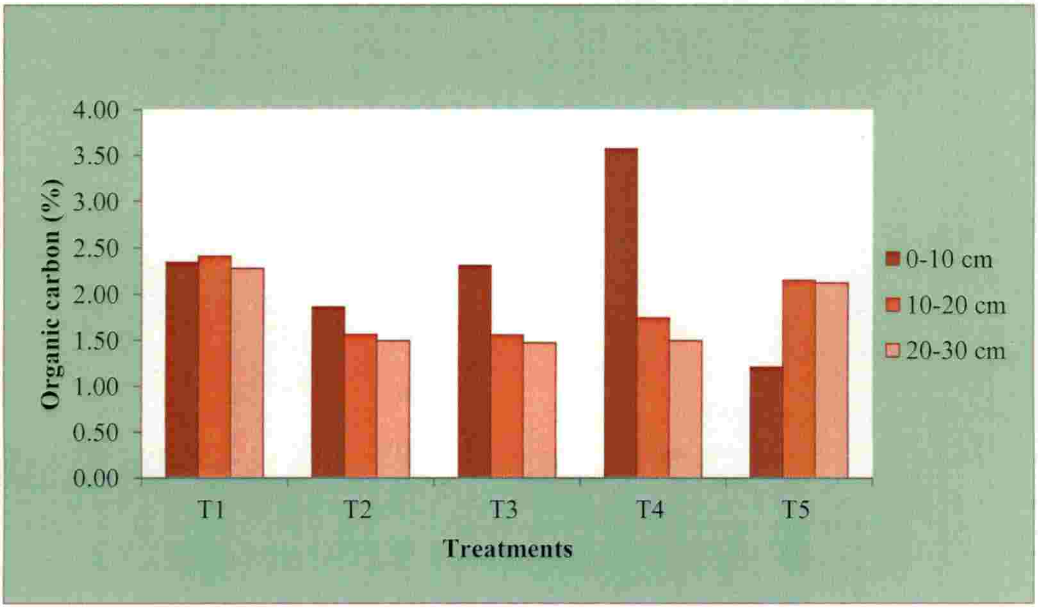
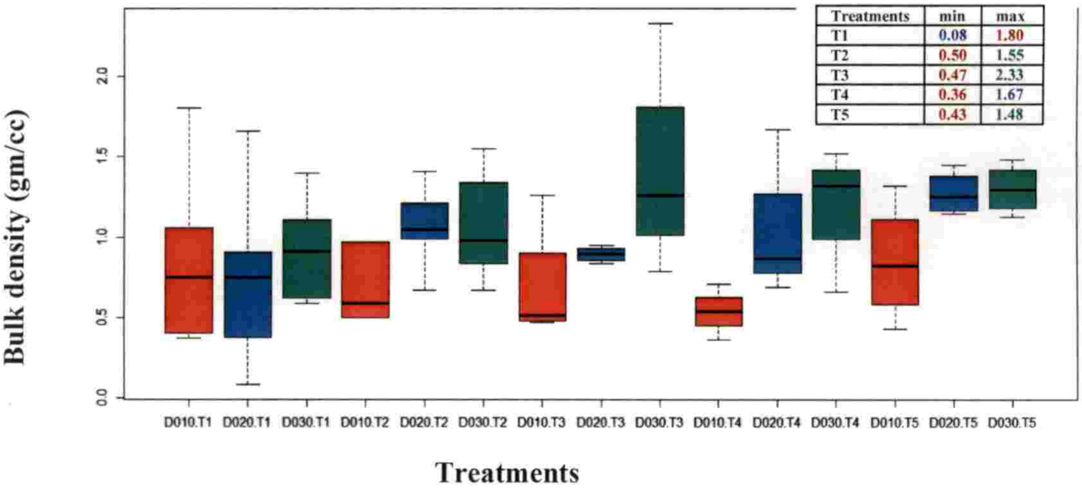


**Fig.27 Mean organic carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in premonsoon.**

The results of two way ANOVA for layer wise organic carbon in sediment in premonsoon did not show significant variation among treatments. Depth wise variation of organic carbon in sediment layers (Fig.27) was also not statistically significant.

### 5.3 Dry bulk density of sediment

Layer wise bulk density in sediment core sections of all sampling locations ranged from 0.36 to 1.80 g cm$^{-3}$ 0.08 to 1.67g cm$^{-3}$ and 0.59 to 2.33g cm$^{-3}$at 0-10 cm, 10-20 cm and 20-30 cm of depth respectively in post monsoon (Fig. 28).



| Treatments | min | max |
|---|---|---|
| T1 | 0.08 | 1.80 |
| T2 | 0.50 | 1.55 |
| T3 | 0.47 | 2.33 |
| T4 | 0.36 | 1.67 |
| T5 | 0.43 | 1.48 |

**Fig. 28 Layer wise bulk density of sediment of *A. officinalis* at selected locations of Vembanad Lake in post monsoon.**

The values for bulk density in sediment in pre-monsoon were 0.17 to 1.80 g cm$^{-3}$, 0.08 to 1.98 g cm$^{-3}$and 0.33 to 2.60 g cm$^{-3}$at 0-10 cm, 10-20 cm and 20-30 cm of depth respectively (Fig.29).

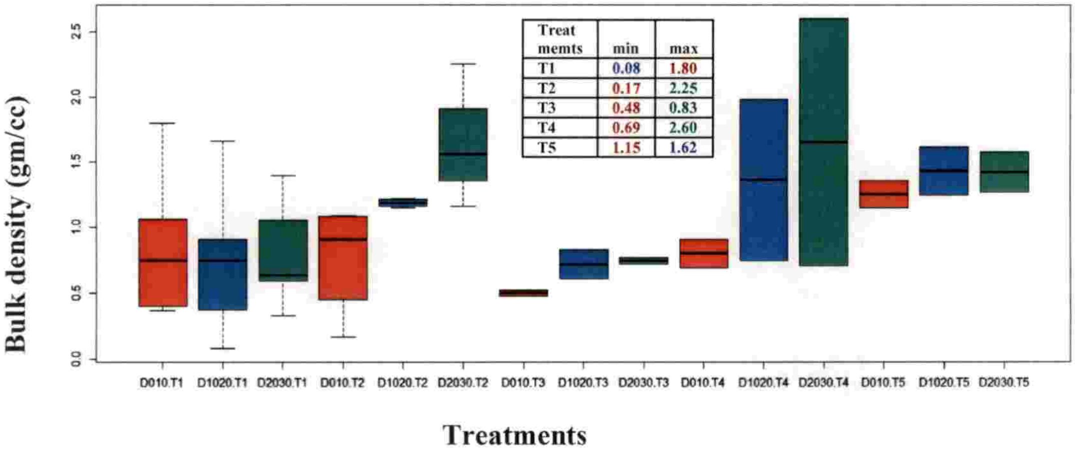


**Fig.29 Layer wise bulk density of sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

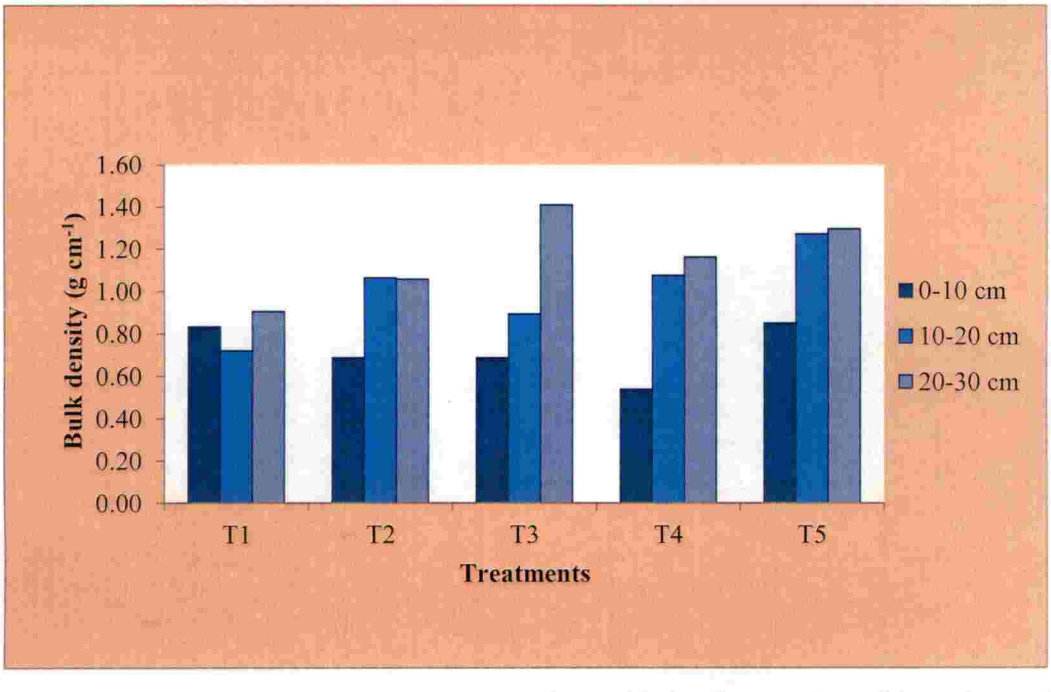


**Fig.30 Mean bulk density in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

The results of two way ANOVA for layer wise bulk density in sediment, in post monsoon showed that there was no significant variation among treatments. Depth wise variation in bulk density in sediment layers was highly significant ($p < 0.01$). The deeper layer (20-30 cm) of sediment was having higher bulk densities, (Fig 30) the maximum being 1.41 g $cm^{-3}$. The bulk density was seen negatively correlated with total organic carbon (-0.56**) in the present study (Table 30). The increased bulk density in deeper layer shows the increased compaction of soil with depth. The bulk density of mangrove soil is related to the solid inorganic and organic particles as well as the porosity of the soil (Mitra *et al.*, 2008).

The highest value of bulk density in sediment was seen in healthy *A. officinalis* ($T_4$) at 20-30 cm core section (Fig.31). In pre monsoon, no significant variation was seen in bulk density, both treatment wise and depth wise, but higher bulk density was seen at 20-30 cm depth.

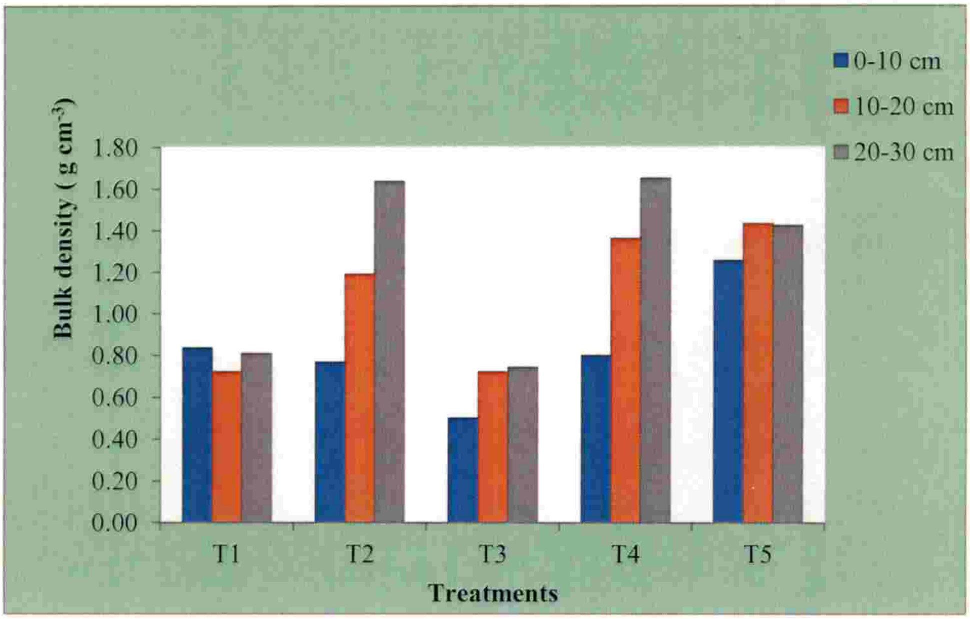


**Fig.31 Mean bulk density in sediment of *A. officinalis* at selected locations of Vembanad lake in premonsoon.**

### 5.4 Total organic matter in sediment

Layer wise organic matter in sediment core sections of all sampling locations ranged from 0.89 to 11.16 %, 0.05 to 9.47% and 0.31 to 7.09% at 0-10 cm, 10-20 cm and 20-30 cm of depth respectively in post monsoon (Fig. 32).

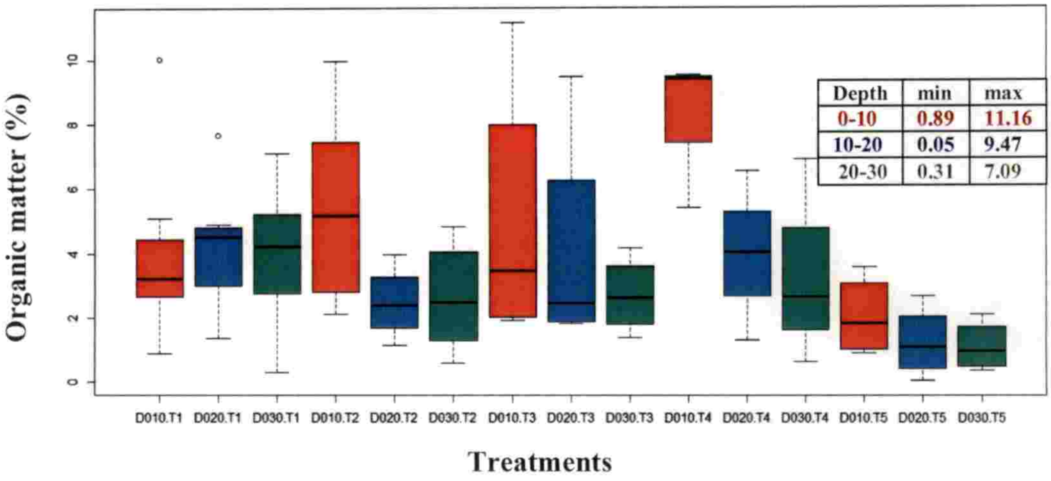


**Fig.32 Layer wise total organic matter in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

The total organic matter in sediment in pre-monsoon ranged from0.89 to 10.02 %, 1.12 to 7.66 % and 0.31 to 7.09 % at 0-10 cm, 10-20 cm and 20-30 cm of depths respectively (Fig.33).

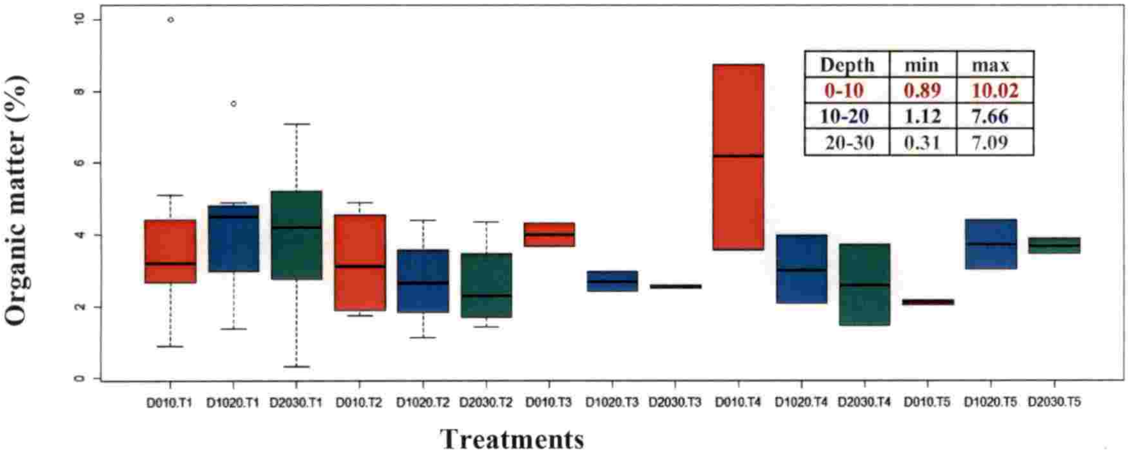


**Fig.33 Layer wise total organic matter in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

The highest value of total organic matter was seen in sediment of healthy *A. officinalis* (T4) at 0-10 cm core section (Fig.34).

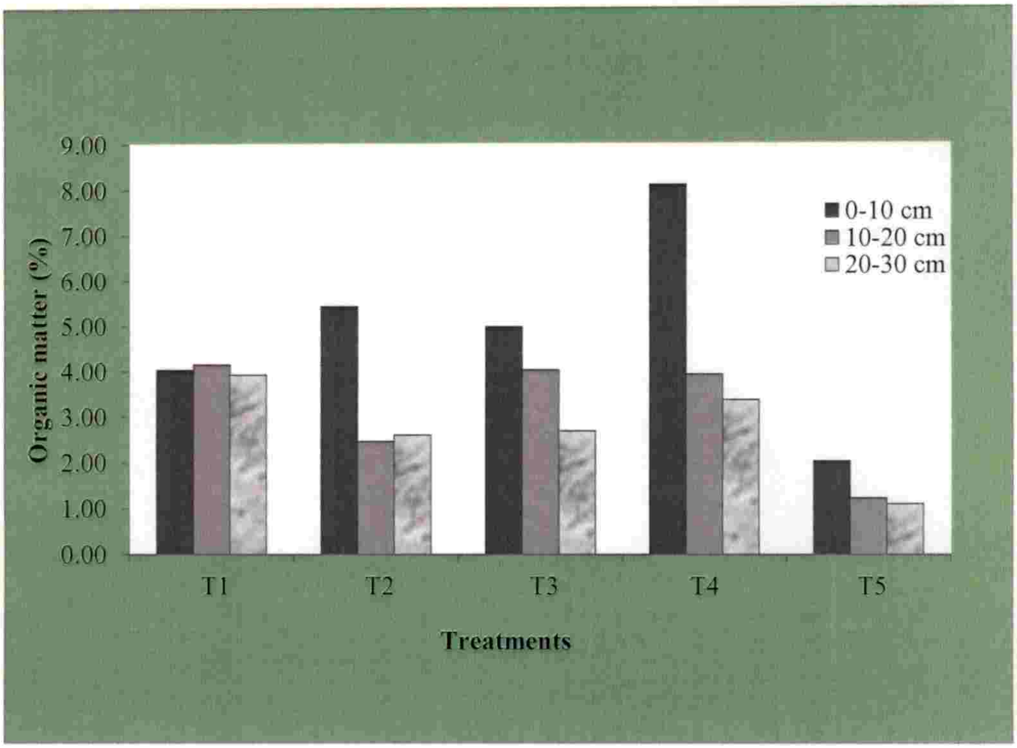


**Fig.34 Mean organic matter in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

The results of two way ANOVA for layer wise organic matter in sediment, in post monsoon showed that there was highly significant variation among treatments ($p < 0.01$). Depth wise variation organic matter in sediment layers was also significant ($p < 0.05$). The top layer (0-10 cm) was having highest content of organic matter in all treatments except for control. The decrease in organic matter in sub surface sediment layers (10-20 cm and 20-30 cm) was more prominent in $T_4$ (Healthy) and $T_2$ (Aged) mangroves.

The variation in total organic matter was similar to that of total organic carbon in sediment, as the value of organic matter in sediment was derived from the organic carbon content based on the empirical relationship between them.

94

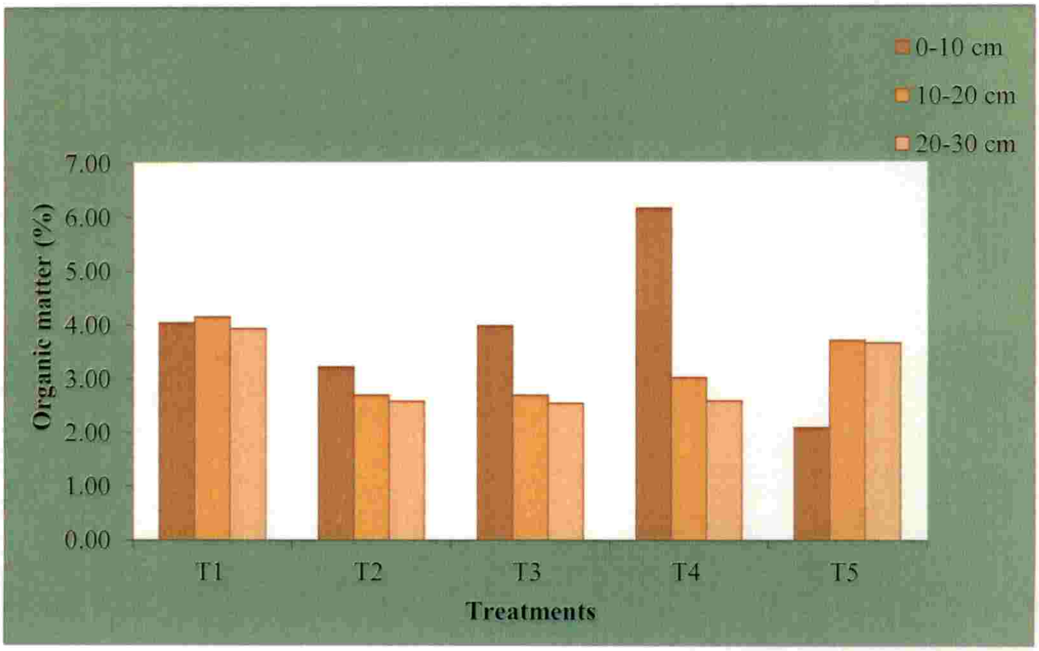


**Fig.35 Mean organic matter in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

The highest value of organic matter in sediment was seen in healthy *A. officinalis* ($T_4$) at 0-10 cm core section (Fig.35).

The results of two way ANOVA for layer wise organic matter in sediment, in pre monsoon did not show significant variation among treatments. Depth wise variation of organic matter in sediment layers was also not statistically significant.

### 5.4 Sediment salinity

The highest value of sediment salinity was seen in sediment of healthy *A. officinalis* ($T_4$) at 10-20 cm core section (Fig.36).

There was no obvious trend in variation of sediment salinity among treatments or among depths. Soil salinity variation is according to the geophysical aspects of the ecosystem (Biswas *et al.*, 2017), affected also by base saturation of soil, rain fall, run off as well as by anthropogenic activities. In the present study, soil salinity was positively correlated (Table 30) with silt content of soil (0.61***) and also with pH (0.62***).

95

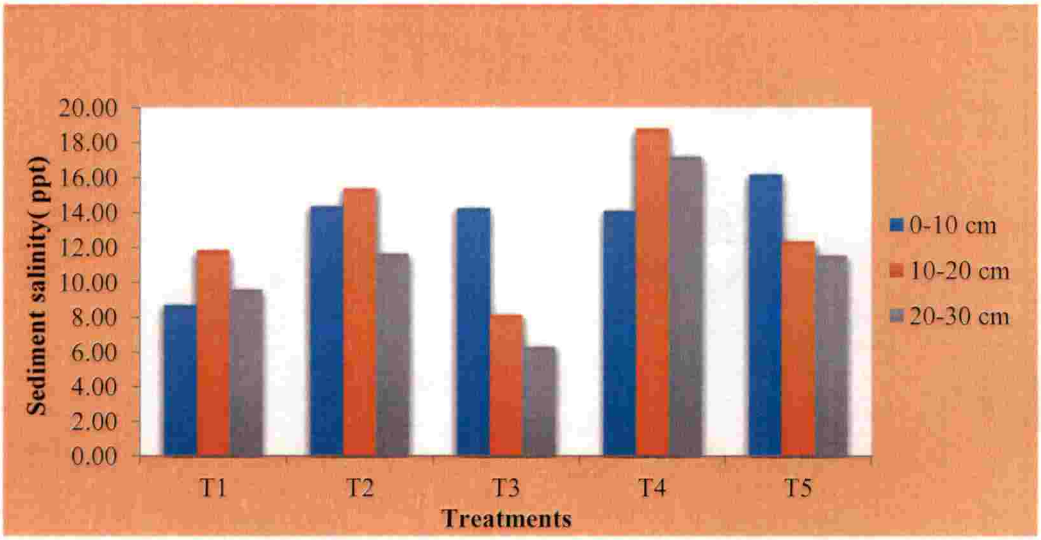


**Fig.36 Mean sediment salinity of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

The highest value of sediment salinity was seen in healthy *A. officinalis* (T4) at 20-30 cm core section (Fig.37).

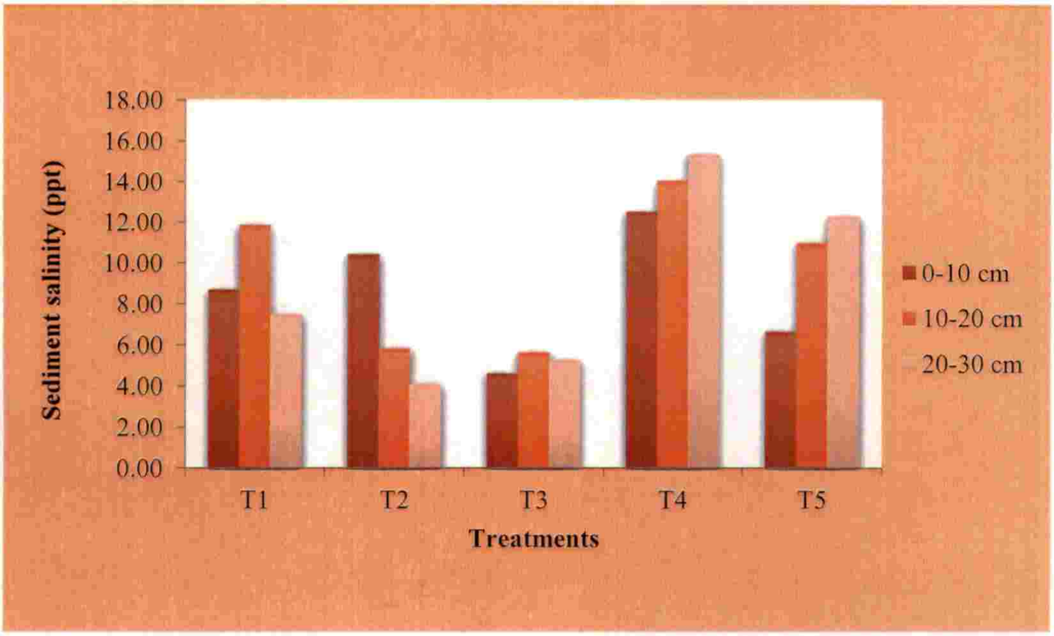


**Fig.37 Mean sediment salinity of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

### 5.5 Sediment pH

The highest value of pH was seen in sediment of aged *A. officinalis* ($T_2$) at 10-20 cm core section (Fig.38).

There was no clear cut trend in variation of sediment pH among treatments and among depths in the present study. The mangrove soil seemed to be more in the neutral to alkaline range compared to control in post monsoon. This was in concordance with finding of Phang *et al.*, (2015) being within the range of pH optima for *A. officinalis*.

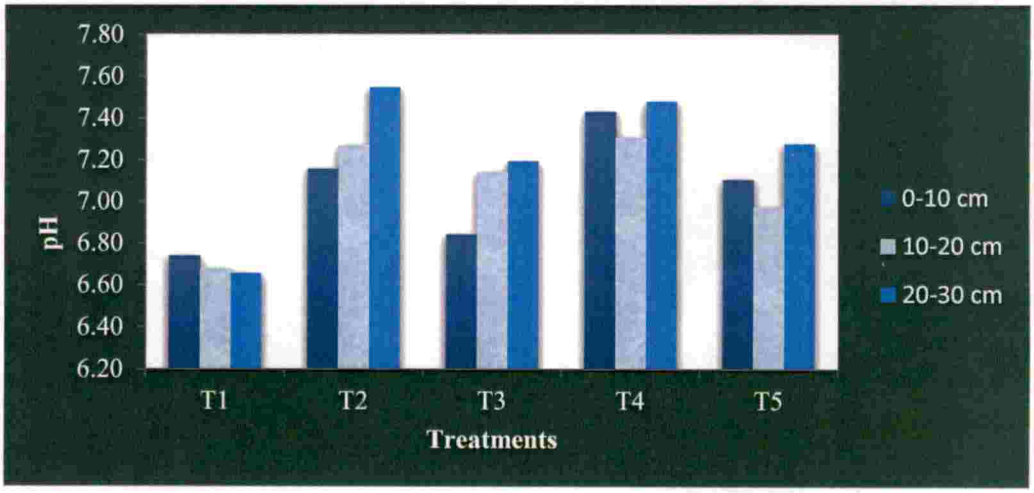


**Fig.38 Mean sediment pH of *A. officinalis* at selected locations of Vembanad Lake in post monsoon.**

The highest value of sediment pH was seen in healthy *A. officinalis* ($T_4$) at 0-10 cm core section (Fig.39). In pre monsoon, the overall range of sediment pH was from 6.43 to 7.19, the range being slightly lower than that of post monsoon. In the present study, pH was positively correlated (Table 30) with silt (0.75***) and salinity (0.62***), indicating pH regulation by the acidic / basic salts present in soil and also the base saturation of the soil.

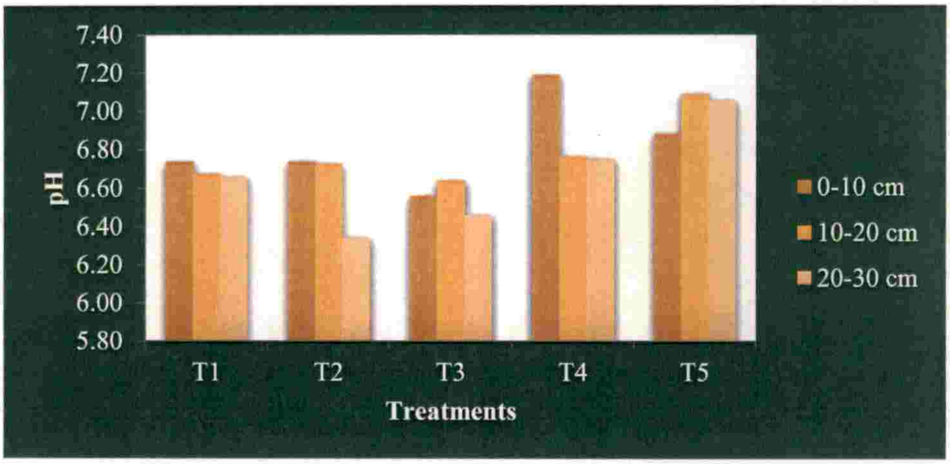


**Fig.39 Mean sediment pH of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

### 5.6 Oxidation reduction potential of sediment

The highest value of Eh was seen in sediment of degraded *A. officinalis* ($T_5$) at 10-20 cm core section (Fig.40).

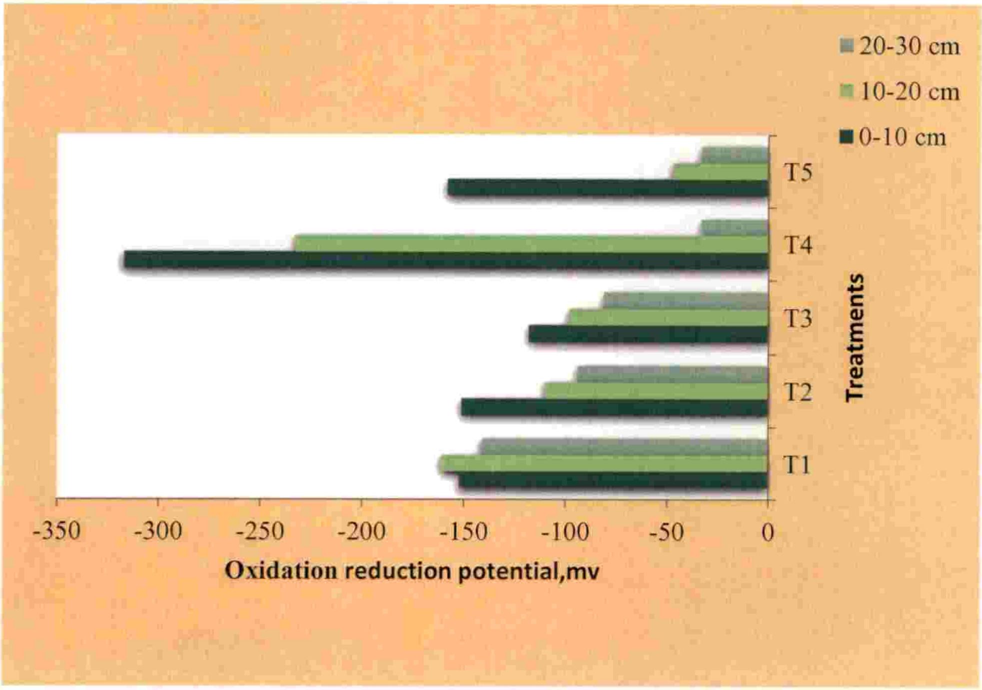


**Fig.40 Mean oxidation reduction potential of sediment in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

The highest value of sediment Eh was seen in aged *A. officinalis* ($T_2$) at 20-30 cm core section (Fig.41).

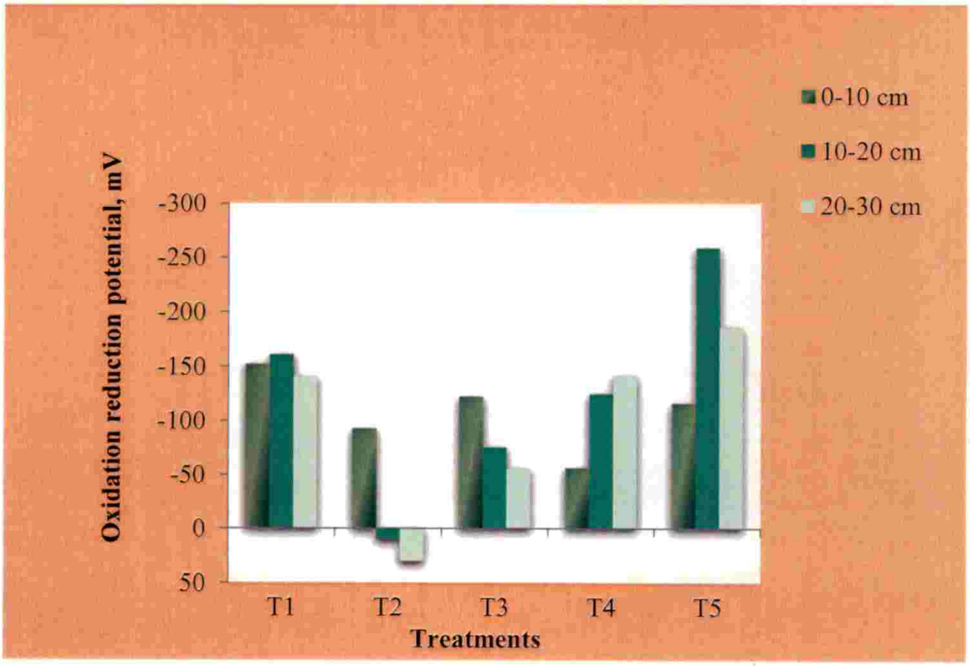


**Fig.41 Mean oxidation reduction potential of sediment in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

The Eh in post monsoon showed value donating reducing condition of sediment. This can be attributed to the submerged condition of soil in post monsoon. In all mangrove treatments there was an increasing trend of Eh towards subsurface layers of sediment in post monsoon consequent to the decrease in organic carbon content. The subsurface layers of sediment showed a tend towards oxidizing condition in pre monsoon. The seasonal difference can be due to the more aerated condition of soil in pre monsoon, sediment having more exposure rather than submergence, which favoured decomposition of organic matter. Similar results were obtained by Kathiresan *et al.* (2014) in mangrove sediment in Vellar estuary. The correlations of Eh obtained in the present investigation, with organic matter (Table 30) (-0.56**), organic carbon (-0.56**) and C/N ratio (-0.60***), further substantiate the relation between Eh and organic matter decomposition in mangrove sediment.

## 5.7 Sediment grain size analysis

### 5.7.1. *Clay*

The highest value of clay was seen in sediment of healthy stands of *A. officinalis* ($T_4$) at 0-10 cm core section (Fig.42).

Healthy mangroves were having higher clay content in the surface layer (0-10 cm). The sediment with at least 11% clay in the top layer showed good growth of mangroves (Prema *et al.,* 2013).

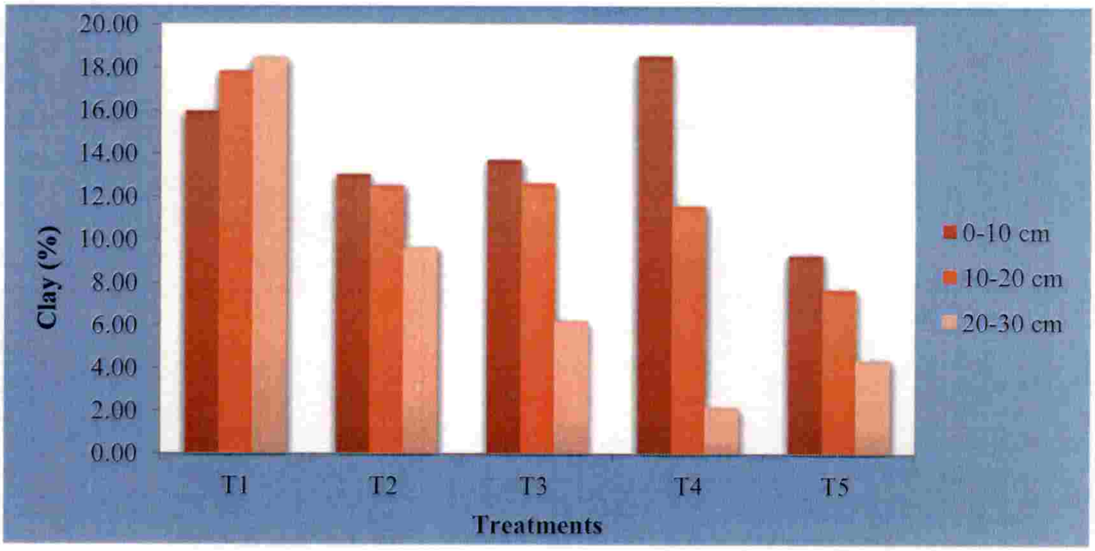


**Fig.42 Mean clay content in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

The highest value of clay was seen in sediment of aged *A. officinalis* ($T_2$) at 0-10cm core section (Fig.43).

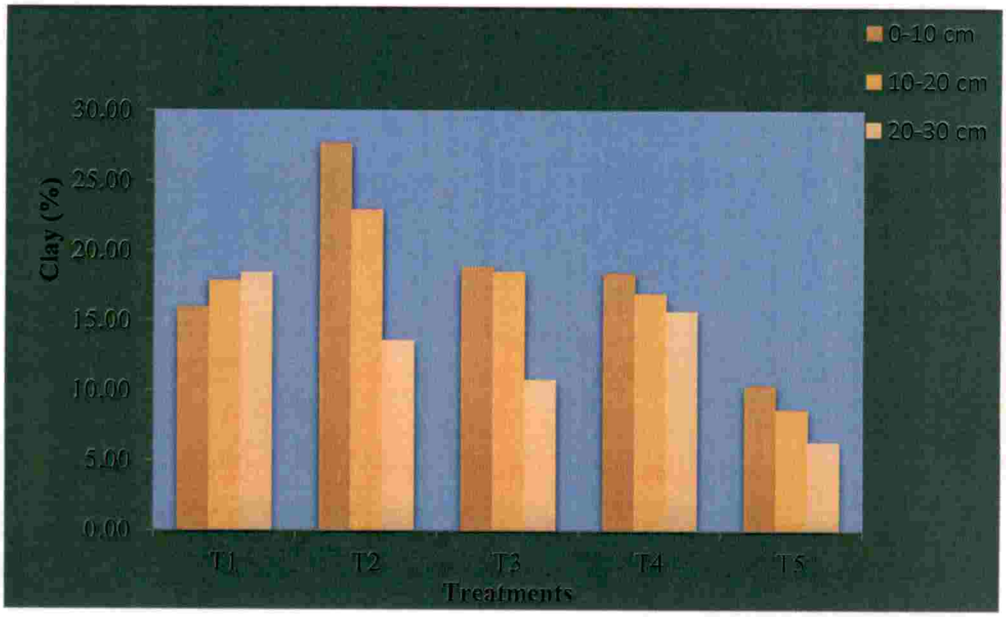


**Fig.43 Mean clay in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

### 5.7.2. *Silt*

The highest value of silt was seen in sediment of healthy *A. officinalis* ($T_4$) at 20-30 cm core section (Fig.44).

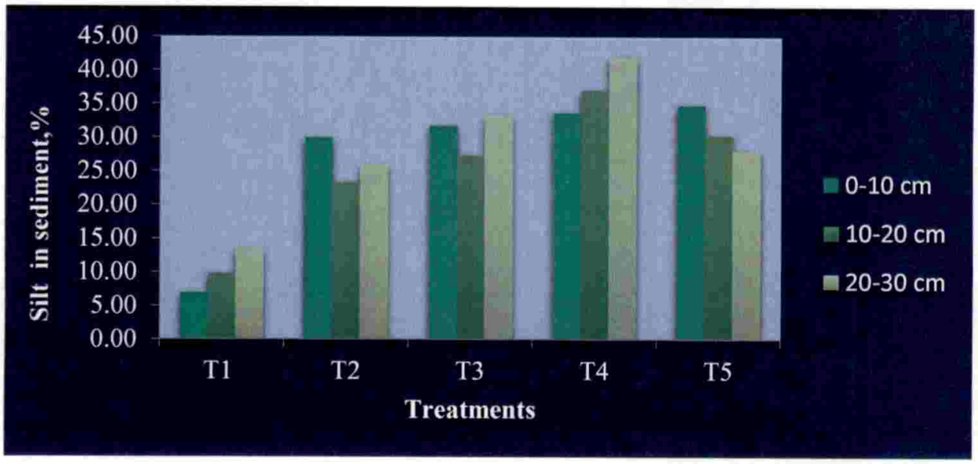


**Fig. 44 Mean silt content in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

The highest value of silt was seen in sediment of healthy *A. officinalis* ($T_4$) at 0-10 cm core section (Fig.45).

101

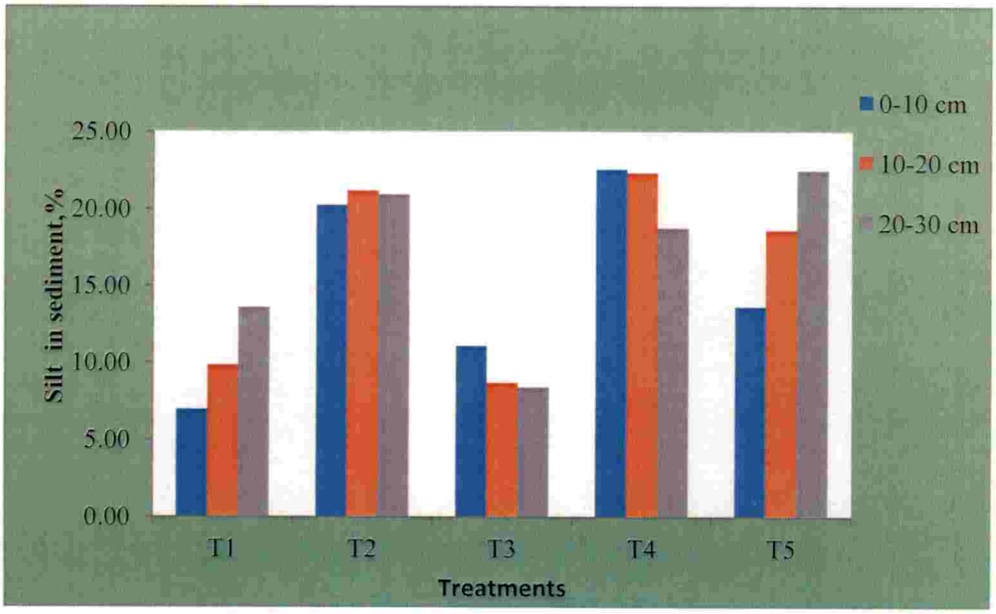


**Fig. 45 Mean silt content in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

In general, mangrove sediments were having more silt content compared to control. Mangroves trap fine and coarse sediment and organic matter driven by storm waves, causing high sedimentation rate in mangrove ecosystems (Patil *et al.*, 2012).

### 5.7.3. *Sand*

The highest value of sand was seen in sediment of control ($T_1$) at 0-10 cm core section (Fig.46).

Sand content was less in $T_4$ (healthy) compared to other treatments. Reduced sand content with increased organic matter improves the water and nutrient holding capacity of soil. Through carbon sequestration in soil, benefits such as increased soil water holding capacity, better soil structure, reduced erosion, improved soil quality and nutrient cycling in the ecosystem are also achieved (Derner and Schuma, 2007 ; Kambale and Tripathi, 2010 ; Sethi *et al.,* 2011).

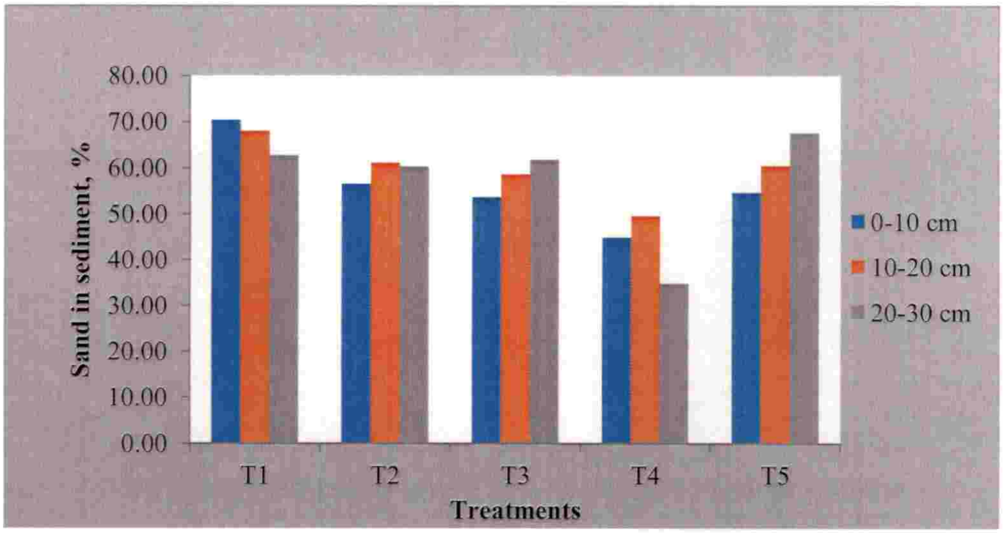


**Fig.46 Mean sand in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

The highest value of sand was seen in sediment of control ($T_1$) at 0-10 cm core section (Fig.47).

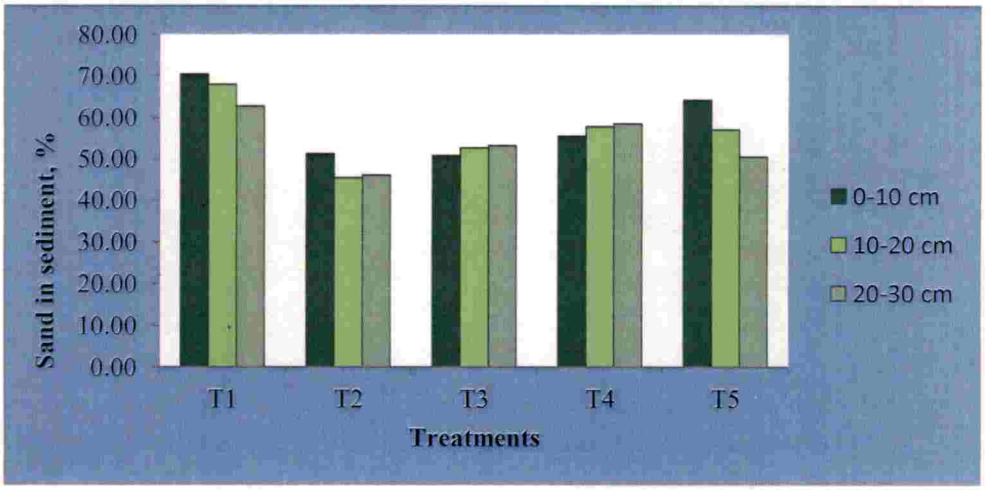


**Fig.47 Mean sand in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

### 5.8 Total carbon in sediment

The highest value of total carbon was seen in sediment of $T_4$ at 20-30 cm core section. There was no obvious trend in depth wise variation of total carbon in sediment among treatments. The range for total carbon in mangrove sediments globally is <0.5 % to 40 % with a median 2.2 % (Kristensen *et al.*, 2008).

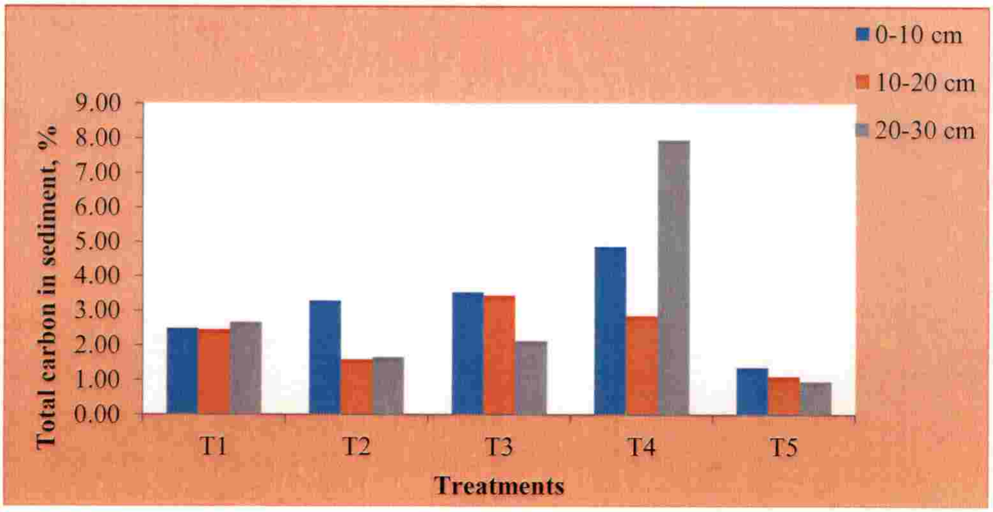


**Fig.48 Mean total carbon in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon.**

The highest value of total carbon was seen in sediment of $T_4$ at 0-10 cm core section (Fig.49). Depth wise decrease in total carbon in sediment was seen in healthy and recent mangroves.

### 5.9 Total nitrogen in sediment

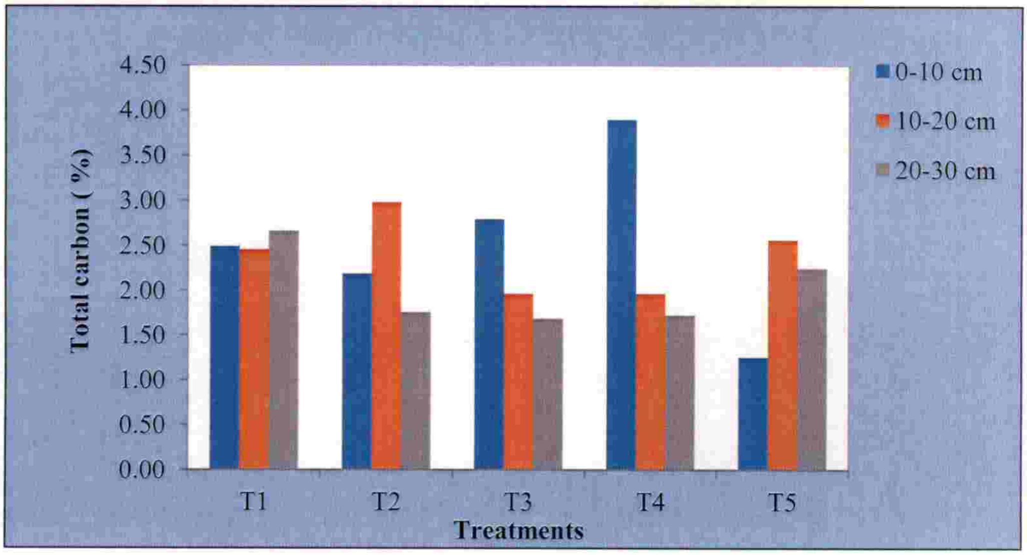


**Fig.49 Mean total carbon content in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon**

10

The highest value of total nitrogen was seen in sediment of treatment $T_4$ at 20-30 cm core section (Fig.50). There was obvious trend in depth wise variation of total nitrogen in sediment among treatments.

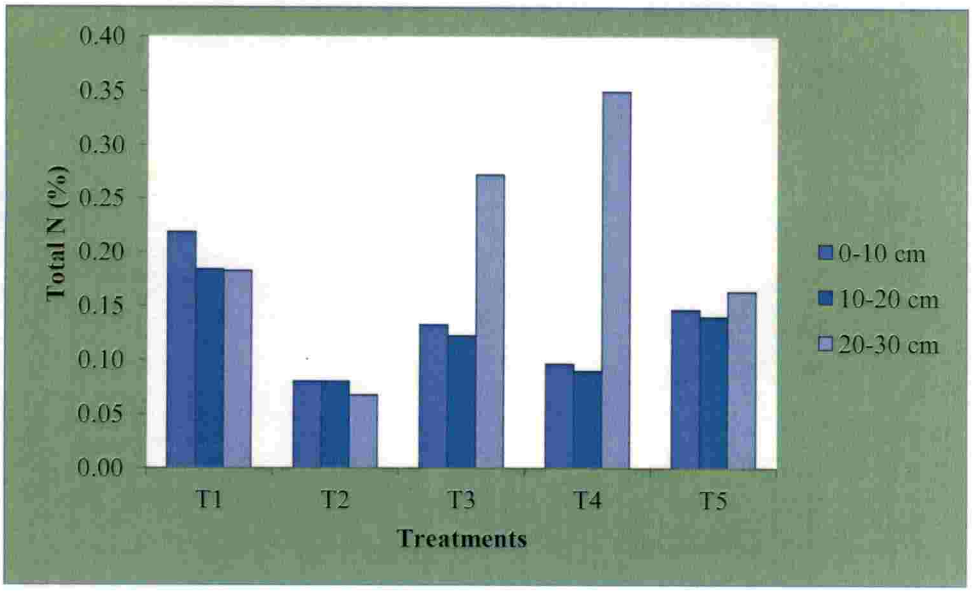


**Fig.50 Mean total nitrogen content in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon**

The highest value of total nitrogen was seen in sediment of $T_2$ at 10-20 cm core section (Fig.51). No evident trend in depth wise variation of total nitrogen in sediment was seen among treatments.

10

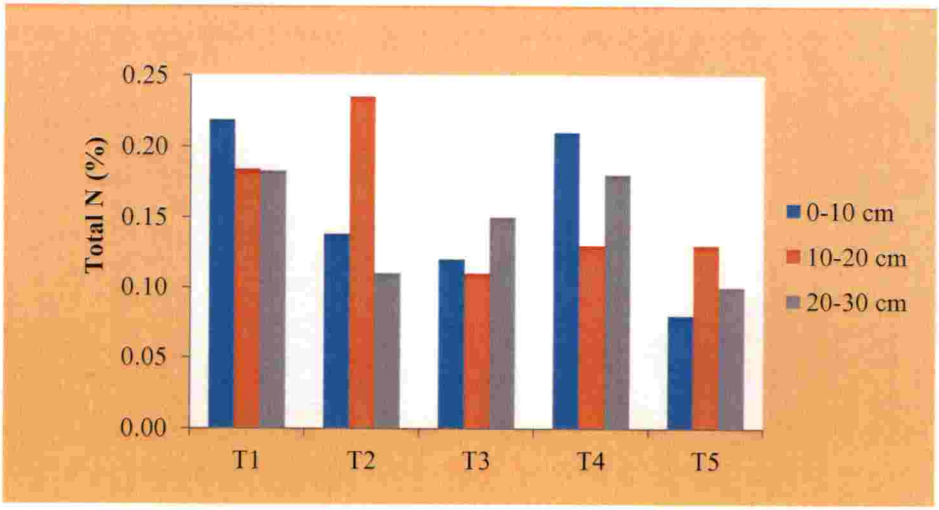


**Fig.51 Mean total nitrogen content in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon.**

In the present study, total nitrogen in sediment gave positive correlation (Table 30) with total carbon (0.48**). The abundance of fine particles in mangrove soil (silt and clay) will increase the concentration of carbon and nitrogen in soil due to the greater surface area of silt and clay (Ramanathan, 1997).

### 5.10 C/N ratio

The highest value of C/N ratio was seen in sediment of $T_4$ at 0-10 cm core section. There was a depth wise decrease t in C/N ratio in sediment in $T_3$ and $T_4$.

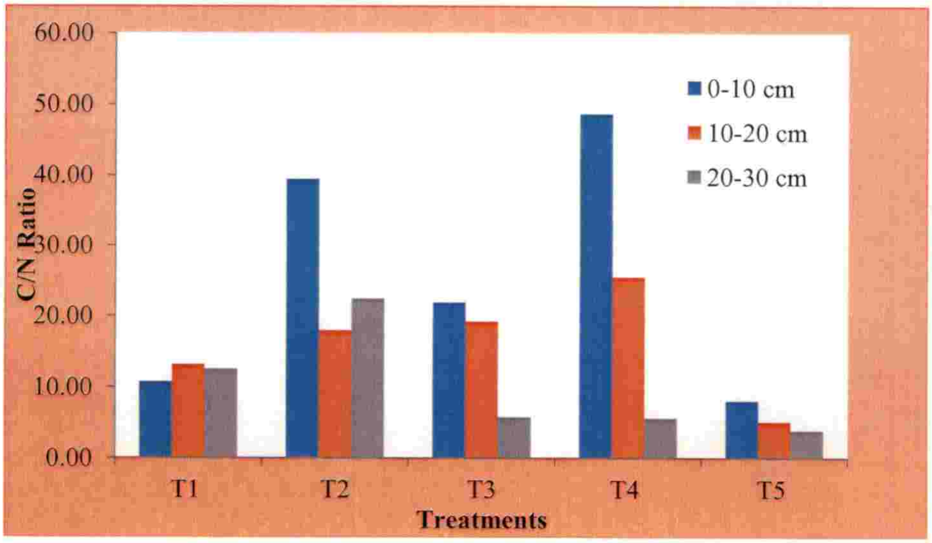


**Fig.52 Mean C/N ratio in sediment of *A. officinalis* at selected locations of Vembanad lake in post monsoon**

The highest value of C/N ratio was seen in sediment of $T_5$ at 20-30 cm core section. There was a depth wise decreasing trend in C/N ratio in sediment in $T_3$ and $T_4$ (Fig.53).

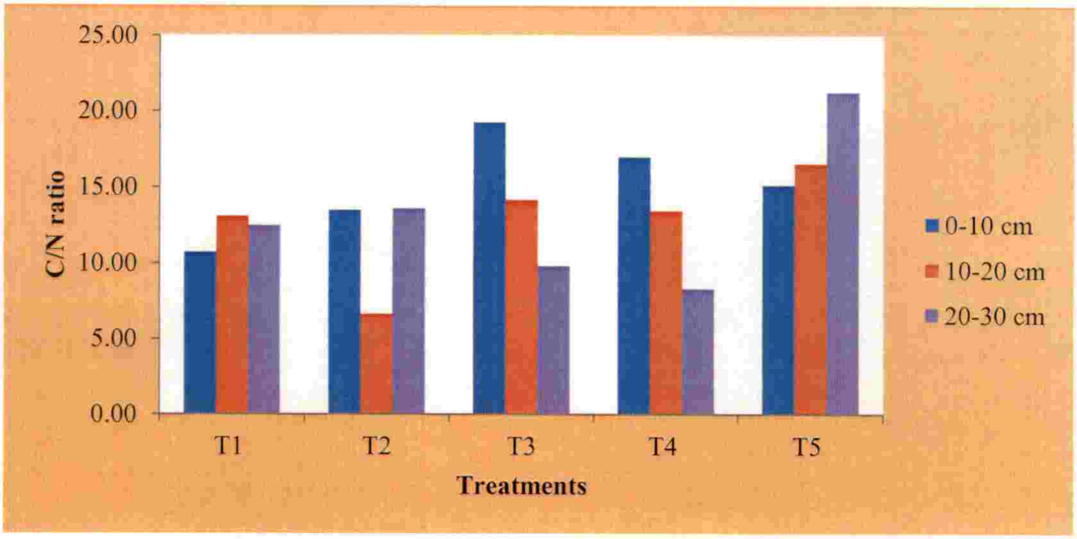


**Fig.53 Mean C/N ratio in sediment of *A. officinalis* at selected locations of Vembanad lake in pre monsoon**

The layer wise blue carbon in sediment showed significant positive correlation with C/N ratio ($p < 0.05$). Kathiresan *et al.* (2014) got significant positive correlation of mangrove sediment carbon with C/N ratio of sediment.

### 5.11. Correlation analysis

Correlation analysis (Table 30) revealed that layer wise blue carbon was highly significantly correlated with total organic carbon and organic matter in the sediment layer ($p<0.01$) positively. There was also significant positive correlation between layer wise blue carbon and C/N ratio in the sediment ($p < 0.05$).

The present study suggests total organic carbon and C/N ratio of the sediment as possible predictive indicators of blue carbon in mangrove sediments with further investigation in depth.

Blue carbon stock was found to be highly significantly correlated ($p < 0.001$) positively with layer wise bulk density. All other significant correlations observed in the correlation matrix are relevant and explainable based on the sediment chemistry and mathematical calculations used in the study.

The present study is of limited extent and preliminary in nature and more depth in investigation needs to be done to assess the sediment carbon stock and carbon sequestration potential of mangrove blue carbon ecosystems in the Vembanad lake.

Table 30. Correlation matrix showing interrelationship of various parameters during the study period

| Correlation | BCstock | BClayer | OClayer | BDlayer | OMlayer | TClayer | TNlayer | CNratioLR | Ehlayer | Sandlayer | Siltlayer | Claylayer | Sallayer |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BCstock | | | | | | | | | | | | | |
| BClayer | 0.43* | | | | | | | | | | | | |
| OClayer | -0.13 | 0.51** | | | | | | | | | | | |
| BDlayer | 0.60*** | 0.33 | -0.56** | | | | | | | | | | |
| OMlayer | -0.13 | 0.51** | 1.00*** | -0.56** | | | | | | | | | |
| TClayer | 0.2 | 0.34 | 0.60*** | -0.26 | 0.60*** | | | | | | | | |
| TNlayer | 0.27 | -0.01 | -0.03 | 0.08 | -0.03 | 0.48** | | | | | | | |
| CNratioLR | -0.15 | 0.40* | 0.75*** | -0.40* | 0.75*** | 0.28 | -0.58*** | | | | | | |
| Ehlayer | 0.17 | -0.33 | -0.56** | 0.26 | -0.56** | -0.11 | 0.31 | -0.60*** | | | | | |
| Sandlayer | -0.25 | -0.29 | -0.18 | -0.06 | -0.18 | -0.57** | -0.04 | -0.24 | -0.14 | | | | |
| Siltlayer | 0.25 | 0.21 | 0.06 | 0.23 | 0.06 | 0.39* | 0.03 | 0.23 | 0.00 | -0.51** | | | |
| Claylayer | -0.27 | -0.03 | 0.37* | -0.47** | 0.37* | -0.03 | -0.07 | 0.17 | -0.07 | 0.03 | -0.49** | | |
| Sallayer | 0.1 | 0.1 | 0.2 | 0.05 | 0.2 | 0.3 | -0.04 | 0.27 | -0.41* | -0.14 | 0.61*** | -0.26 | |
| pHlayer | 0.14 | 0.22 | 0.16 | 0.09 | 0.16 | 0.35 | -0.03 | 0.34 | -0.24 | -0.17 | 0.75*** | -0.53** | 0.62*** |

***p < .001; ** p < .01; * p < .05

# SUMMARY AND CONCLUSION

# CHAPTER 5

# SUMMARY AND CONCLUSION

Blue carbon is the carbon stored by coastal and oceanic ecosystems. The coastal blue carbon includes the stored carbon in mangroves, salt tidal marshes and sea grass meadows within the soil as well as in the living biomass above ground and below ground. The coastal ecosystems sequester more carbon in sediment than terrestrial ecosystems and the carbon remain trapped for very long time adding up the carbon stocks to huge amounts, if allowed to remain undisturbed. This blue carbon can be freed to the atmosphere as $CO_2$ when these ecosystems are converted or degraded. Hence these ecosystems need to be conserved in order to assist in climate change mitigation measures.

Mangroves form a major part of the coastal ecosystem providing goods and ecosystem services to the nearby coastal communities. Mangroves also capture and stock up amounts of coastal blue carbon from the atmosphere and the sea and consequently help in mitigating climate change. Mangroves in India account for about 5 per cent of the world's mangrove vegetation and the extent of mangroves of Kerala is 2502 ha. Ernakulam district occupies the second highest extent of mangroves in Kerala. Vembanad lake, the second largest brackish water lake in India, supports a very dynamic coastal ecosystems in Kerala, encircled by mangroves, swamps, marshes mudflats etc. enhancing coastal life and coastal production.

The present investigation was focused on the estimation of blue carbon stocks in the sediment pool of the most prevalent mangrove species in this area *Avicennia officinalis* also known as Indian Mangrove, in selected locations of Vembanad lake. The present study is hence very relevant in analyzing the carbon stock in sediment in selected mangrove ecosystems of Vembanad lake, resulting in the estimation of blue carbon stock of *A. officinalis* sediment in selected locations revealing its potential for climate change mitigation through the mangrove ecosystem conservation or restoration wherever applicable. The results of the present investigation can also be a baseline data for related future studies in this region, in addition to its usefulness for policy guidelines for climate change mitigation.

Sediment core samples were collected from the sediment of *A. officinalis* stands from selected locations of Vembanad lake, up to 1m depth. The sampling was done in two seasons *viz.* in post monsoon (October – November 2017) and pre monsoon (February – March 2018). The treatments included aged, recent, healthy and degraded mangroves of the selected species ie., *Avicennia officinalis* (Indian Mangrove). Control stations were taken from the same areas selected for the study, but without mangrove covers.

Core samples up to 30 cm depth at 10 cm interval were collected using cores and were subjected to laboratory analysis for the estimation of blue carbon in sediment wherever, intact sediment samples could be obtained or collected. Blue carbon stocks up to the maximum available depth was measured.

The salient results of the study are presented below.

- The overall mean carbon storage the two seasons in the *A. officinalis* sediments in selected locations of Vembanad lake area was found to be 62.35 Mg ha$^{-1}$. This value was very low compared to the mean global soil organic carbon stock in the mangrove ecosystem (386 Mg ha$^{-1}$) (IPCC, 2013), which offers the opportunity to sequester more carbon in the selected mangrove ecosystems of Vembanad lake, there by contributing to climate change mitigation efforts.

- The treatments differed significantly in the cumulative stock of blue carbon in sediment ($p < 0.05$) and the highest mean stock was in T4 (Healthy) at 0-30 cm depth in both seasons.
- Post hoc analysis revealed that there was highly significant difference between $T_4$ (Healthy) and $T_5$ (Degraded), higher stock being found in $T_4$ sediment in both seasons.
- It was observed from the spatial maps that the cumulative stock was higher in post monsoon than in pre monsoon.
- The range of layer wise blue carbon in sediment was 0.06 to 0.56 g $cm^{-3}$ in post monsoon and 0.02 to 0.35 g $cm^{-3}$ in pre monsoon.
- The treatments differed significantly for layer wise blue carbon in sediment in both seasons and there was no significant variation among depths. There was significant difference between $T_4$ (Healthy) and $T_5$ (Degraded), the value of T4 being higher.
- The results showed significant difference among treatments at 0-10 cm depth in layer wise blue carbon in two seasons together, and no significant variation was observed among treatments in the sub surface depth (10-20 cm and 20-30 cm).
- Spatial maps indicated that there was depth wise increase in the layer wise blue carbon in post monsoon, though it was not statistically significant.
- Higher amount of layer wise blue carbon was seen in post monsoon compared to pre monsoon, but the values were not statistically significant.
- Layer wise blue carbon was significantly correlated with total organic carbon and organic matter ($p < 0.01$) positively and with C/N ratio in the sediment ($p < 0.05$).
- The study suggested total organic carbon and C/N ratio as possible predictive indicators of blue carbon in sediment, with further investigation.

- More in depth investigation needs to be done to assess the sediment carbon stock and carbon sequestration potential of mangrove blue carbon ecosystems in the Vembanad lake which will conserve these precious habitats.

# REFERENCES

# CHAPTER 6

## REFERENCS

Alongi, D.M. 1998. Coastal Ecosystem Processes. CRC Press, 419p.

Alongi, D.M., Wattayakorn, G., Tirendi, F. and Dixon, P. 2004. Nutrient capital in different aged forests of the mangrove *Rhizophora apiculata*. *Bot. Mar.* 47:116–24.

Alongi, D.M. 2008.Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. *Estuar Coast Shelf Sci.* (76):1–13

Alongi, D. M. 2012. Carbon sequestration in mangrove forests. *Carbon manag.3* (3):313-322.

Alongi, D. M. 2014. Carbon cycling and storage in mangrove forests. *Annual review of mar. sci.6*:195-219.

Avelar S., van der Voort, T.S., and Eglinton, T.I. 2017. Relevance of carbon stocks of marine sediments for national greenhouse gas inventories of maritime nations. *Carbon Balance Manag* 2017 Dec.12 (1):10.

Avnimelech, Y. and Wodka, M. 1988. Accumulation of nutrients in the sediments of Maaleh Hakishon reclaimed effluents reservoir. *Water Res.*22 (11): 1437-1442.

Ball, M. C. 1988. Salinity tolerance in mangroves *Aegiceras corniculatum*, and *Avicennia marina* I. Water use in relation to growth, carbon partitioning, and salt balance. *Australian J. Plan.* 15, 447-464.

Ball, M. C. 2002. Interactive effects of salinity and irradiance on growth: implications for mangrove forest structure along salinity gradients. *Trees*, *16*(2-3):126-139.

Batley, G. and Simpson, S.2016. *Sediment quality assessment: a practical guide.* (Eds), CSIRO PUBLISHING.

Beck, M.W., Heck, K.L., Able, K.W., Childers, D.L., Eggleston, D.B., Gillanders, B.M., Halpern, B., Hays, C.G., Hoshino, K., Minello, T.J. and Orth, R.J. 2001. The identification, conservation, and management of estuarine and marine nurseries for fish and invertebrates: a better understanding of the habitats that serve as nurseries for marine species and the factors that create site-specific variability in nursery quality will improve conservation and management of these areas. *AIBS Bulletin*, *51*(8):633-641.

Biswas, S., Zaman, S. and Mitra, A.2017.Soil Characteristics of Indian Sundarbans: The Designated World Heritage site. *Sci J. Biomed. Eng. BiomedSci*. 1(2): 053-059.

Blasco, F., Saenger, P. and Janodet, E. 1996. Mangroves as indicators of coastal change. *Catena*. *27*(3-4):167-178.

Bouillon, S., Dahdouh-Guebas, F., Rao, A. V. V. S., Koedam, N. and Dehairs, F. 2003. Sources of organic carbon in mangrove sediments: variability and possible ecological implications. *Hydrobiologia.495* (1-3): 33-39.

Boyd, C.E. and Tucker, C. S. 1992. *Water quality and pond soil analysis for Aquaculture,* Alabama Agricultural Experiment station. Auburn University: 183 p.

Buchanan, B., Khresat, S., Lindermann, W., Pelletier-Hunyadi, M., Purves, P., Shelton, P., Vinson, J., Williams, B., Jones, T. and McCaslin, B. 1993. Introduction to soils - A laboratory Manual. New Mexico State: Department of Agronomy and Horticulture, New Mexico State University. Download on 2018-05-17 URL http://hydrology1.nmsu.edu/teaching_Material/soil252/Chapt5.htm

CCC (Climate Change Commission). 2017. CCC pushes for the protection and conservation of coastal blue carbon. http://climate.gov.ph/knowledge-bank/newsroom/press-release/379-ccc-pushes-for-the-protection-and-conservation-of-coastal-blue-carbon-ecosystems. Downloaded on 08 December 2017.

Chaikaew, P. and Chavanich, S. 2017. Spatial Variability and Relationship of Mangrove Soil Organic Matter to Organic Carbon. *Applied and Environmental Soil Science, 2017.*

Chen, G., Azkab, M. H., Chmura, G. L., Chen, S., Sastrosuwondo, P., Ma, Z. and Chen, B. 2017. Mangroves as a major source of soil carbon storage in adjacent seagrass meadows. *Scientific reports*, *7*: 42406.

Chmura, G. L., Anisfeld, S. C., Cahoon, D. R. and Lynch, J. C. 2003. Global carbon sequestration in tidal, saline wetland soils. *Glob. Biogeochemical Cycles. 17*(4).

Cintron, G., Lugo, A. E., Pool, D. J. and Morris, G. 1978. Mangroves of arid environments in Puerto Rico and adjacent islands. *Biotropica*. 110-121.

Das, S. 2009. *Can Mangroves Minimize Property Loss During Big Storms? An Analysis of House Damage Due to the Super Cyclone in Orissa*. SANDEE Working Paper No. 42-09 South Asian Network for Development and Environmental Economics (SANDEE), 44p.

Derner, J.D. and Schuman, G.E. 2007. Carbon sequestration and rangelands: A synthesis of land management and precipitation effects. *J. Soil Wat. Conser.*62 (2): 1-2.

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

Duarte, C. M. and Cebrian, J. 1996. The fate of marine autotrophic production. *Limnology and Oceanography.41* (8):1758-1766.

Duarte, C.M., Middelburg, J.J.and Caraco, N. 2005. Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences* 2: 1–8.

Duarte, C. M., Dennison, W. C., Orth, R. J. and Carruthers, T. J. 2008. The charisma of coastal ecosystems: addressing the imbalance. *Estuaries and coasts*. *31*(2):233-238.

Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I. and Marbà, N. 2013. The role of coastal plant communities for climate change mitigation and adaptation. *Nature Climate Change*. *3*(11):961.

Duke, N.C. 1990. Phenological Trends with Latitude in the Mangrove Tree *Avicennia marina*. *J. Ecol*. 78: 113-133.

Duke, N., Kathiresan, K., Salmo III, S.G., Fernando, E.S., Peras, J.R., Sukardjo, S. and Miyagi, T. 2010. *Avicennia officinalis*. The IUCN Red List of Threatened Species 2010:e.T178820A7616950.http://dx.doi.org/10.2305/IUCN.UK.20102.RLTS.T178820A7616950.

Ellison, J. C.and Stoddart, D. R. 1991. Mangrove ecosystem collapse during predicted sea-level rise: Holocene analogues and implications. *J. Coastal res*. 151-165.

Ellison, J. C. 2000. How South Pacific mangroves may respond to predicted climate change and sea-level rise. In *Climate change in the South Pacific: impacts and responses in Australia, New Zealand, and Small Island states*, pp. 289-300.

ENVIS (Environmental Information System). 2015. ENVIS Centre on Wildlife & Protected Areas. . Ministry of Environment, Forests & Climate Change, Govt. of India. http://wiienvis.nic.in/Database/ramsar_wetland_sites_8224.aspx

Farnsworth, E. J., Ellison, A. M. and Gong, W. K., 1996. Elevated $CO_2$ alters anatomy, physiology, growth and reproduction of red mangrove (*Rhizophora mangle L.*). *Oecologia* 108: 599-609.

FAO (Food and Agricultural organization of the United Nations). 1976. *Soil bulletin No: 10, Physical and chemical methods of soil and water analysis:* 275p.

Fourqurean, J.W., Duarte, C.M., Kennedy, H., Marba, N., Holmer, M., Mateo, M.A., Apostolaki, E.T., Kendrick, G.A., Krause-Jensen, D., McGlathery, K.J., and Serrano, O .2012. Seagrass ecosystems as a globally significant carbon stock. *Nat Geosci.* 5: 505–509.

FSI (Forest Survey of India). 2017. India State of Forest Report, 2017, Dehradun. pp. 61.

George, G., Krishnan, P., Mini, K.G., Salim, S.S., Ragavan, P., Tenjing, S.Y., Muruganandam, R., Dubey, S.K., Gopalakrishnan, A., Purvaja, R. and Ramesh, R. 2018. Structure and regeneration status of mangrove patches along the estuarine and coastal stretches of Kerala, India. *J. For. Res*. 1-12.

Hema, M. and Devi, P. 2015. Economic Valuation of Mangrove Ecosystems of Kerala, India. *J of Environ. Professionals Sri Lanka*, *4*(1).

Hesse, P.R.1971. *A textbook of soil chemical analysis.* Chemical publishing Co Inc. New York, 520p.

Holmer, M. and Olsen, A. B.2002. Role of decomposition of mangrove and seagrass detritus in sediment carbon and nitrogen cycling in a tropical mangrove forest. *Mar. Ecol. Prog. Ser.*230:87-101.

Howard, J., Hoyt, S., Isensee, K., Telszewski, M. and Pidgeon, E.2014.Coastalblue carbon: methods for assessing carbon stocks and emissions factors in mangroves, tidal marshes, and seagrasses.

IMD (India Meteorological Department).2018.Daily weather report, Kerala and Lakshadweep 1st October and November 2017-1st February and March 2018.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate change 2007: the physical science basis. In: Solomon, S., Qin, D. and Manning, M. (Eds). Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, UK, and New York, NY: Cambridge University Press.

IPCC (Intergovernmental Panel on Climate Change). 2013. Coastal Wetlands. In: 2013 Supplement to the 2006 IPCC guidelines for National Greenhouse Gas Inventories (eds. Alongi, D, Karim, A, Kennedy, H, Chen, G, Chmura, G, Crooks, S *et al.*).

120

IUCN (International Union for Conservation of Nature). 2007. Environmental and socio economic value of mangroves in tsunami affected areas rapid mangrove valuation study, Panama village in South eastern coast of Sri Lanka, *IUCN Report*,2007.

IUCN (International Union for Conservation of Nature).2018. Blue carbon. https://www.iucn.org/resources/issues-briefs/blue-carbon Downloaded on 31 May, 2018.

Jackson, M. L. 1958. Soil Chemical Analysis. Engle-wood Cliffs. *NT Prentice Hall Inc.*

Jennerjahn, T. C. and Ittekkot, V .1997. Organic matter in sediments in the mangrove areas and adjacent continental margins of Brazil. I. Amino acids and hexosamines. *Oceanol. Acta.* 20:359–369.

Jennerjahn, T. C. and Ittekkot, V. 2002. Relevance of mangroves for the production and deposition of organic matter along tropical continental margins. *Naturwissenschaften.89* (1):23-30.

Jones, T. G., Ratsimba, H. R., Ravaoarinorotsihoarana, L., Cripps, G. and Bey, A. 2014. Ecological variability and carbon stock estimates of mangrove ecosystems in northwestern Madagascar. *For.5* (1):177-205.

Joshi, H. and Ghose, M. 2003. Forest structure and species distribution along soil salinity and pH gradient in mangrove swamps of the Sundarbans. *Trop.Ecol.44* (2): 195-204.

Kambale, J. B. and Tripathi, V. K. 2010. Biotic and abiotic processes as a carbon sequestration strategy, *J.Environ.Res.Develop.* 5 (1):240- 251.

Kathiresan, K. 2010. Importance of mangroves forest of India. *J. Coast. Environ.* 1:1-26.

Kathiresan, K., Anburaj, R., Gomathi, V. and Saravanakumar, K. 2013. Carbon sequestration potential of *Rhizophora mucronata* and *Avicennia marina* as

121

influenced by age, season, growth and sediment characteristics in southeast coast of India. *J. coastal conserv.* 17(3):397-408.

Kathiresan, K., Gomathi, V., Anburaj, R. and Saravanakumar, K. 2014. Impact of mangrove vegetation on seasonal carbon burial and other sediment characteristics in the Vellar-Coleroon estuary, India. *J. for. Res. 25*(4): 787-794.

Kauffman, J.B., Heider, C., Norfolk, J. & Payton, F. 2014. Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. Ecological Applications, 24:518–527.

Kauffman, J.B. and Bhomia, R.K .2017.Ecosystem carbon stocks of mangroves across broad environmental gradients in West-Central Africa: Global and regional comparisons. PLoSONE 12(11): e0187749. https://doi.org/10.1371/journal.pone.0187749.

Kennedy, V.S. 1984. The estuary as a filter. Academic Press, New York, NY, USA

Kokkal, K., Harinarayanan, P. and Sahu, K. K. 1889. Wetlands of Kerala. In *Proceeding of Taal 2007 The 12th World Lake Conference*, Vol. 1893.

Krauss, K. W., Cormier, N., Osland, M. J., Kirwan, M. L., Stagg, C. L., Nestlerode, J. A. and Harvey, J. E. 2017. Created mangrove wetlands store belowground carbon and surface elevation change enables them to adjust to sea-level rise. *Scientific Reports*, *7*(1):1030.

Krishnamurthy, P., Jyothi-prakash, P. A., Qin, L. I. N., He, J. I. E., Lin, Q., Loh, C. S.and Kumar, P. P.2014. Role of root hydrophobic barriers in salt exclusion of a mangrove plant Avicennia officinalis. *Plant, cell and environ. 37*(7):1656-1671.

Kristensen, E., Andersen, F. O., Holmboe, N., Holmer, M. and Thongtham, N. 2000. Carbon and nitrogen mineralization in sediments of the Bangrong mangrove area, Phuket, Thailand. *Aquat. Microbial Ecol. 22*(2):199-213.

Kristensen, E., Bouillon, S., Dittmar, T. and Marchand, C., 2008. Organic carbon dynamics in mangrove ecosystems: a review. *Aquat. Bot.89* (2):201-219.

Lacerda, L. D., Ittekkot, V. and Patchineelam, S. R. 1995. Biogeochemistry of Mangrove Soil Organic Matter: a Comparison between Rhizophora and Avicennia Soils in South-eastern Brazil. *Estuarine, Coastal and Shelf Sci. 40*(6): 713-720.

Laffoley, D. and Grimsditch, G.D. 2009. *The management of natural coastal carbon sinks*. IUCN, Gland, Switzerland.

Liang, S., Zhou, R., Dong, S. and Shi, S. 2008. Adaptation to salinity in mangroves: Implication on the evolution of salt-tolerance. Chinese Science Bulletin. 53(11):1708.

Lo Iacono, C., Mateo, M.A., Gràcia, E., Guasch, L., Carbonell, R., Serrano, L., Serrano, O. and Danobeitia, J. 2008. Very high-resolution seismo-acoustic imaging of seagrass meadows (Mediterranean Sea): Implications for carbon sink estimates. *Geophys. Res.Lett.35* (18).

Lagoon, B. and Lanka, S.2015.Carbon stock assessment of Mangrove forests in a local geographical aspect.

López-Portillo, J. and Ezcurra, E.1989. Response of three mangroves to salinity in two geoforms. *Funct. Ecol.* 355-361.

Lunstrum, A. and Luzhen, C. 2014. Soil carbon stocks and accumulation in young mangrove forests. *Soil Biol. Biochem.* 75:223-232. ISSN: 0038-0717

MAP (Mangrove Action Project).2018. Mangrove action project 2013- 2018. http://mangroveactionproject.org/issues/climate-change Downloaded on 02 August 2018.

Marchio, D. A., Savarese, M., Bovard, B. and Mitsch, W. J. 2016. Carbon sequestration and sedimentation in mangrove swamps influenced by hydrogeomorphic conditions and urbanization in Southwest Florida. *Forests*, *7*(6):116.

Mateo, M. A., Romero, J., Pérez, M., Littler, M. M. and Littler, D. S. 1997. Dynamics of millenary organic deposits resulting from the growth of the Mediterranean seagrass *Posidonia oceanica. Estuarine, Coastal and Shelf Sci.44* (1):103-110.

Matsui, N., Meepol, W. and Chukwamdee, J. 2015. Soil organic carbon in mangrove ecosystems with different vegetation and sedimentological conditions *.J. MarSci. Eng. 3*(4):1404-1424.

Mcleod, E., Chmura, G.L., Bouillon, S., Salm, R., Björk, M., Duarte, C.M., Lovelock, C.E., Schlesinger, W.H. and Silliman, B.R. 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. *Front. Ecol. Environ.* 9: 552–560.

McMillan, C. 1975. Interaction of soil texture with salinity tolerances of *Avicennia germinans* (L.) Lam. and *Laguncularia racemosa* (L.) Gaertn. f. from North America. In: *Proceedings of the International Symposium on Biology and Management Resource Management Systems Program, Univ. Florida*, pp. 561-566.

Mitra, A., Santra, S. C. and Mukherjee, J. 2008. Distribution of actinomycetes, their antagonistic behaviour and the physico-chemical characteristics of the world's largest tidal mangrove forest. *Appl. Microbial. Biotechnol.* 80(4):685-695.

Mitra, A., Banerjee, K. and Sett, S. 2012. Spatial Variation in Organic Carbon Density of Mangrove Soil in Indian Sundarbans. *Natl. Acad. Sci. Lett.35* (3): 147-154.doi: 10.1007/s40009-012-0046-6.

Mitra A., Kakoli B. and Cazzolla-Gatti R. 2015. Do all mangrove species exhibit uniform resilience to climate change induced salinity alteration? *Economology J.* Vol.5 Year III, September 2015.

124

Mogalekar, H. S., Adnankhan, G., Ansar, C. P., Raman, N. N. and Devkate, A. 2015. Temporal variation in the hydrobiology of Vembanad lake at Panangad Kumbalam mangrove patches of Kochi, Kerala. *Res. J. Anim. Vet. Fish. Sci.3*:1-7.

Mongia, A. D. and Ganeshamurthy, A. N. 1989. Typical differences between the chemical characteristics of Rhizophora and Avicennia mangrove forest soils in South Andamans [Indian islands]. *Agrochimica. (Italy).*

Murray, B.C., Pendleton, L. and Sifleet, S. 2011. State of the Science on Coastal Blue Carbon: A Summary for Policy Makers. In: *Nicholas Institute for Environmental Policy Solutions Report NIR 11-06*, pp. 1–43.

NCSCM (National Centre for Sustainable Coastal Management) .2017. www.ncscm.res.in/cms/ftr/pdf/research/Blue%20Carbon.pdf . Downloaded on 1 July 2017.

Nellemann, C. and Corcoran, E. (eds). 2009. *Blue carbon: the role of healthy oceans in binding carbon: a rapid response assessment*. UNEP/Earthprint, pp.1-82

Ong, J.E. 2002. The Hidden Costs of Mangrove Services: Use of Mangroves for Shrimp Aquaculture. International Science Roundtable for the Media. June 2002. Bali, Indonesia, pp.1-3

Pachpande, S. C. and Pejaver, M. 2015. Natural carbon sequestration by dominant mangrove species *Avicennia marina* var. Accutissima ex Staf and Moldenke ex Moldenke found across Thane Creek, Maharashtra, India. *Int. J. Sci. Eng. Res. 6*:1162-1165.

Pal, D., A.K. Das, S.K., Gupta. and A.K. Sahoo. 1996. Vegetation pattern and soil characteristics of some mangrove forest zones of the Sundarbans, West Bengal. *Indian Agric.*40: 71-78.

Patil V., Singh A., Naik N., Seema U. and Sawant B. 2012. Carbon sequestration in Mangrove Ecosystems. *J. Environ. Res. Develop.* Vol. 7 (1A):576-583.

125

Pendleton, L., Donato, D.C., Murray, B.C., Crooks, S., Jenkins, W.A., Sifleet, S., Craft, C., Fourqurean, J.W., Kauffman, J.B., Marbà, N. and Megonigal, P. 2012. Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. *PloS one*, *7*(9):p.e43542.

Phang, V. X., Chou, L. M. and Friess, D. A. 2015. Ecosystem carbon stocks across a tropical intertidal habitat mosaic of mangrove forest, seagrass meadow, mudflat and sandbar. *Earth Surface Processes and Landforms*. *40*(10): 1387-1400.

Prema, D., Anilkumar, P.S., Valsala, K.K., Khambadkar, L.R., Sharma, R., Mohan, A., Bose, J. and Kripa, V. 2013. Sediment quality evaluation towards developing scientific restoration protocol for mangroves. *Mar. Fish. Inf. Serv. Tech. Ext. Ser.* (212):3-4.

Ramanathan. A.L. 1997. Sediment characteristics of the Pichavaram mangrove environment, south east coast of India. *Indian J. Geo-Mar. Sci*. 26(3):319-322

Robertson, A.I. and Duke, N.C.1990. Mangrove fish-communities in tropical Queensland, Australia: spatial and temporal patterns in densities, biomass and community structure. *Mar. Biol. 104*(3):369-379.

Saenger P. and Moverley J. 1995 Vegetative phenology of mangroves along the Queensland coastline. *Proc. Ecol. Soc. Aust.* 13:257-265.

Saenger, P., Gartside, D. and Funge-Smith, S. 2013, A review of mangrove and seagrass ecosystems and their linkage to fisheries and fisheries management, report to Food and Agriculture Organization of the United Nations Regional Office for Asia and the Pacific Bangkok, Thailand. ISBN: 9789251077733.

Sethi V. K., Vyas S., Jain P. and Gour Anurag.2011. A novel approach for CO2 sequestration and conversion into useful multipurpose fuel, J.Environ.Res.Develop. 5(3A):732-736.

Snedaker, S. C. 1995. Mangroves and climate change in the Florida and Caribbean region: scenarios and hypotheses. *Hydrobiologia.295* (1-3):43-49.

Stringer, C. E., Trettin, C. C. and Zarnoch, S. J. 2016. Soil properties of mangroves in contrasting geomorphic settings within the Zambezi River Delta, Mozambique. *Wetlands ecol. manag. 24*(2): 139-152.

Tan, W. K., Lin, Q., Lim, T. M., Kumar, P.and Loh, C. S. 2013. Dynamic secretion changes in the salt glands of the mangrove tree species *Avicennia officinalis* in response to a changing saline environment. *Plant, cell & environ.36* (8): 1410-1422.

Thirunavukkarasu, P., Ramanathan, T., Ramkumar, L., Shanmugapriya, R.and Renugadevi, G. 2011. The antioxidant and free radical scavenging effect of *Avicennia officinalis*. *J. Med. Plants Res.5* (19):4754-4758.

USDA (United States Department of Agriculture).2008. Soil Quality Indicators: Bulk Density.Collected02-05-2015fromURL http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_053256.pdf

Vidyasagaran, K. and Madhusoodanan, V. K. 2014. Distribution and plant diversity of mangroves in the west coast of Kerala, India. *J. Biodivers. Environ. Sci. 4*:38-45.

Wakushima, S., Kuraishi, S. and Sakurai, N. 1994. Soil salinity and pH in Japanese mangrove forests and growth of cultivated mangrove plants in different soil conditions. *J. Plant Res.107* (1):39-46.

Wakushima, S., Kuraishi, S., Sakurai, N., Supappibul, K. and Siripatanadllok, S. 1994. Stable soil pH of Thai mangroves in dry and rainy seasons and its relation to zonal distribution of mangroves. *J. Plant Res. 107*(1):47-52.

Weiss, C., Weiss, J., Boy, J., Iskandar, I., Mikutta, R. and Guggenberger, G.2016. Soil organic carbon stocks in estuarine and marine mangrove ecosystems are driven by nutrient colimitation of P and N. *Ecol. evol.6* (14):5043-5056.

Wojick D.E. 1999. Carbon storage in soils: The ultimate no-regrets policy? A report to greening earth society. *http://www.greening earth society.org/pdf/carbon.pdf.*

Wooller, M., Smallwood, B., Jacobson, M. and Fogel, M.2003. Carbon and nitrogen stable isotopic variation in *Laguncularia racemosa* (L.) (White mangrove) from Florida and Belize: implications for trophic level studies. *Hydrobiologia,* 499**:**13–23.

Woodroffe, C. D. 1990. The impact of sea-level rise on mangrove shorelines. *Prog. Phys.Geogr.14* (4):483-520.

Yee, Shannon M. 2010. REDD and BLUE Carbon: Carbon payments for mangrove conservation, MAS *Mar. Biodivers. Conserv. Capstone Project:* 13.

# Assessment of 'Blue carbon' in sediment of Indian mangrove (*Avicennia officinalis*) in selected locations of Vembanad lake ecosystem in Kerala

*by*

**AARATHY. G. S**
**(2013-20-123)**

**ABSTRACT OF THE THESIS**

**Submitted in partial fulfillment of the**

**requirements for the degree of**

**B.Sc.-M.Sc. (Integrated) CLIMATE CHANGE ADAPTATION**

**Faculty of Agriculture**

**Kerala Agricultural University**

**ACADEMY OF CLIMATE CHANGE EDUCATION AND RESEARCH**

**VELLANIKKARA, THRISSUR - 680 656**

**KERALA, INDIA**

**2018**

# ABSTRACT

The present investigation, focused on the estimation of the sediment pool of the blue carbon stocks of the mangrove species *Avicennia officinalis* (Indian Mangrove) in selected locations of Vembanad lake. Sediment core samples were collected in post monsoon (October – November 2017) and pre monsoon (February – March 2018). The treatments included 'aged', 'recent', 'healthy' and 'degraded' mangroves of the selected species and 'control' without mangroves. Sediment core samples up to 30 cm depth with 10 cm interval were subjected to standard laboratory and statistical analytical procedures.

The cumulative stock of blue carbon in sediment ranged from 6.00 to 139.96 Mg ha $^{-1}$ in post monsoon and 2.00 to 84.58 Mg ha $^{-1}$ in pre monsoon. The treatments differed significantly in the cumulative stock of blue carbon in sediment ($p < 0.05$), highest seen in 'healthy' at 0-30 cm depth in both seasons. Highly significant difference was observed between 'healthy' and 'degraded', 'healthy' having more stock in both seasons. These two treatments differed significantly for layer wise blue carbon in sediment also in both seasons, higher content being seen in 'healthy' and there was no significant variation among depths. The range of layer wise blue carbon in sediment, considering all treatments was 0.06 to 0.56 g cm$^{-3}$ in post monsoon and 0.02 to 0.35 g cm$^{-3}$ in pre monsoon. Significant difference among treatments was observed at 0-10 cm depth for layer wise blue carbon in two seasons together, and no significant variation was found in sub surface (10-20 cm and 20-30 cm) depth.

Spatial maps were prepared for the cumulative stock of blue carbon and layer wise blue carbon in sediment during post monsoon and pre monsoon seasons. The cumulative stock and layer wise blue carbon were higher in post monsoon. Depth wise increase was seen in layer wise blue carbon in post monsoon, though they were not statistically significant.

Layer wise blue carbon was significantly correlated with total organic carbon and organic matter ($p < 0.01$) positively and with C/N ratio in the sediment ($p < 0.05$). The study suggests total organic carbon and C/N ratio as possible predictive indicators of blue carbon in sediment, with further investigation.

**Keywords:** Blue carbon, *Avicennia officinalis,* Cumulative stock, Total organic carbon and Organic matter.