STUDY ON THE MANGROVE CARBON POOL IN THE MAJOR RIVERINE STRETCH OF GOA

Final Report on UGC- MRP

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Submitted to University Grants Commission, New Delhi

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Certificate from the Investigators

The project entitled “**STUDY ON THE MANGROVE CARBON POOL IN THE MAJOR RIVERINE STRETCH OF GOA**” has been initiated since 30th November 2015 and completed successfully. Two sites along the estuaries of Mandovi and Zuari were selected for the investigation. Seasonal sampling of the biomass and carbon estimation of the major mangrove species are the main objectives of this project with the goal to identify the potential of major mangroves of Goa as sink of carbon.

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CONTENTS

A. Executive Summary

1. It has been documented that in the last 3–4 decades different ecosystems in the tropical regions contributed maximum trace gases (CH_4 and N_2O) to the atmosphere. Terrestrial ecosystems in tropics, sub-tropics and in temperate regions are the well-known sources and sinks of important GHGs (green house gases). Now-a-days, developing countries of Asia Pacific regions are contributing a maximum amount of these trace gases at the global scale.

2. Trees (producer community) have unique potential to sequester GHG's (preferably C), which has provided them a special status in the vertical of climate change mitigation.

3. Carbon is also stored in the soils/sediments, through the process of mineralisation of plant tissues and biogenic precipitation of inorganic materials. It is dependent on time span, geographic conditions and nutrient availability; higher stocks are reported in short-time scale in the tropical forests and temperate wetlands. It includes SOC (Soil Organic Carbon), microbial biomass, plant biomass and their root exudates, particulate organic matters introduced in to the soil compartment from aboveground structures of plants (in the form of litter) and agricultural runoff to lowlands.

4. Afforestation, reforestation and forest restoration are the key strategies to mitigate climate change (at local level and at regional scale); it is therefore important to estimate the potential of each floral species to sequester GHG's in their vegetative parts, which is the prime target of the present programme preferably with respect to carbon dioxide.

5. The complex network of abiotic and biotic interactions occurring in the soil compartment is integral to forest health and provides habitat to many endogenous species. Therefore in this study, monitoring of the soil compartment has also been carried out not only to estimate the potentiality of the compartment to act as a sink of carbon, but also to evaluate the nature of the soil as the growth promoter of planted vegetation. In this context, parameters like Soil Organic Carbon (SOC) and soil pH were monitored in all the selected plots of the study area.

6. The contrasting variations in DBH (Diameter at Breast Height) and the height of the floral species, age of the species and the edaphic factors may be the reasons for such significant spatial variations of stored carbon.

7. The direct proportionalities of SOC with AGB and AGC of the vegetations in the study area point towards the source of organic matter in the soil, which is undoubtedly the local vegetations (mangroves).

8. The values of stored carbon in the mangroves and soil of intertidal mudflats of Zuari are relatively higher compared to Mandovi estuarine region. The average AGB of Zuari mangroves is 47.33 % and 10.38 % higher than Mandovi mangroves during 2016 & 2017 respectively. The AGC also exhibits the same trend with 99.74% higher value during 2016 and 50.28% higher value in 2017.

9. The litter carbon values of Zuari mangrove system are also higher by 9.72% and 16.21% compared to Mandovi mangroves during 2016 and 2017 respectively.

10. The SOC, being the proxy to litter and detritus biomass exhibits similar trend. The values of SOC in the intertidal mudflats of Zuari are 12.84% and 6.78% higher than Mandovi during 2016 and 2017 respectively.

11. The hydrological parameters (preferably the salinity) may be the key driver behind this contrasting variation between these two estuarine systems in terms of carbon storage. The average salinity of Zuari estuary (~ 27.5 psu) is lower than that of Mandovi (~ 30.5 psu), which may be the causative point behind such contrasting variations in AGB and AGC.

12. The higest value of CO_2 - equivalent in monsoon compared to other two seasons, and higher biomass and stored carbon in the less saline Zuari estuarine region is a confirmatory acid test for the preference of mangroves towards higher dilution factor. These observations call for the management of edaphic factors and salinity through channelization of rain water (after harvesting/storing in small pools in the intertidal mudflats, preferably in the supra-littoral region) to the hypersaline zone of intertidal mudflats, which may serve as a road map to boost up the biomass and stored carbon in the mangrove vegetation.

B. Technical Contents

INTRODUCTION

The phenomenon of global warming has become a vital issue in the present ‘*era*’, which is keenly related to emission of carbon dioxide from varied sectors of human civilization ranging from household activities to industries. The increasing levels of carbon dioxide (Fig. 1) in the atmosphere are of global concern because it can trigger changes in the environment and ecosystem structure. The present CO_2 abundance in the atmosphere recorded for the month of June 2018 is about 410.79 parts per million (https://www.co$_2$.earth/). The issue has been well addressed in Kyoto Protocol and several recommendations were forwarded to reduce the emission rate with the aim to keep the planet Earth safe and reduce the rate of alteration of climate.

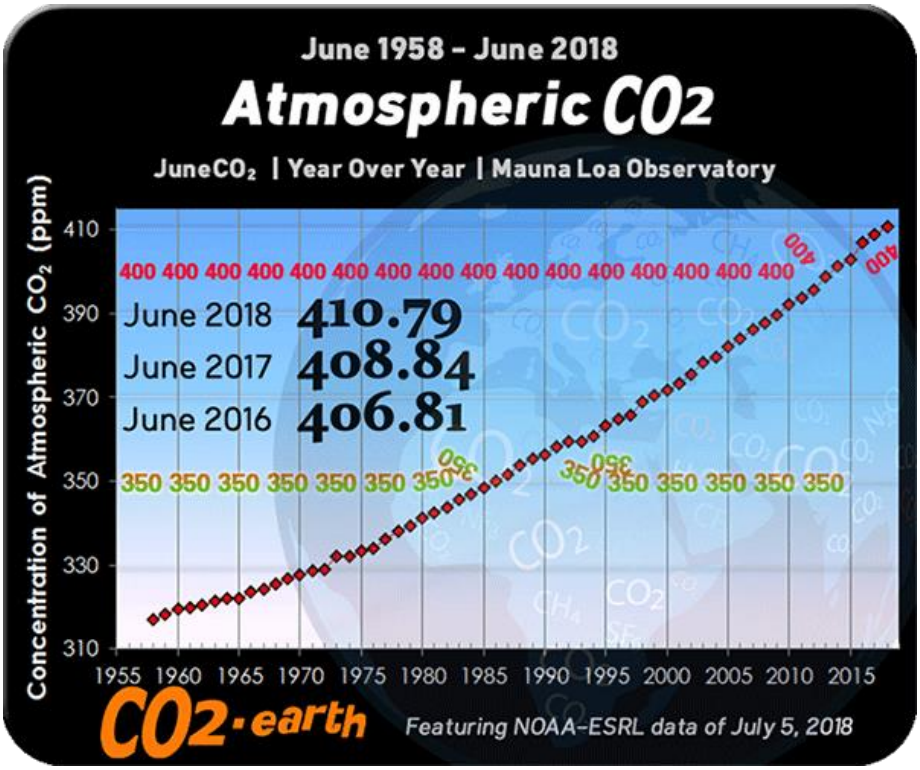


Fig. 1. Rise in concentration of atmospheric carbondioxide
(Source: https://www.co2.earth/)

The ocean plays a vital buffering role in regulating the amount of CO_2 in the atmosphere through air – water interphase. This greenhouse gas diffuses in and out of the ocean depending on the physical and biogeochemical conditions of the surface waters. There is about fifty times more CO_2 in the ocean than the atmosphere. The ocean acts as enormous carbon sink (Doney and Naomi, 2006) because of its present mild basic pH. Global estimates of carbon sources in coastal ecosystems are identified as either allochthonous or *in situ* depending on whether the source of CO_2 is from the atmosphere or of ocean origin.

The primary producer communities (phytoplankton, aquatic vegetation, mangroves, terrestrial herbs, shrubs, trees etc.) are the key players in this context. They are important sinks for atmospheric carbon i.e., carbon dioxide. Among them, forests play an important role in the global carbon cycle. It is estimated that there are 1,146 Gt C stored within the 4.17 billion hectares of tropical temperate and boreal forest areas, a third of which is stored in forest vegetation, and the rest in forest soils (IPCC, 2000). Another 634 Gt C is stored in tropical savannas and temperate grasslands. Tree growth in forests serves as an important means to capture and store carbon dioxide in vegetation, soils and forest products. The IPCC Second Assessment Report (SAR) noted that the potential for carbon sequestration through forestry activities ranged from 55-76 Gt C (Brown *et al.*, 1996). Considering the extent and expansion rate of industry, tourism, transportation and aquaculture, the safe guarding of the environment is a key issue. This can be achieved by carbon sequestration through plantation/afforestation programmes in newly formed islands and mudflats.

Carbon sequestration: An overview

Carbon sequestration may be defined as the extraction of atmospheric carbon dioxide and its storage in different compartments of ecosystems for a very long period of time – many thousands of years. Forests offer some potential to be managed as a sink that is to promote net carbon sequestration. A stock that absorbs carbon is called a “sink” and the one that releases carbon is referred to as “source”. Shifts or flows of carbon from one stock to another, for example, from the atmospheric compartment to forest are commonly known as carbon “fluxes”.

Plants or autotrophic community remove carbon (as CO_2) from the atmosphere through the process of photosynthesis and store it in plant tissue. Until this carbon is cycled back to the atmosphere, it resides in one of a number of “carbon pools”, which may be (a) above ground biomass like stems, leaves, branches, flowers, fruits etc., (b) below ground biomass like root and modified stem in some exceptional cases, and (c) biomass based products (like wood). Carbon can remain in these pools for centuries. An increase in carbon in these pools represents a net removal of carbon dioxide from the atmosphere. A certain fraction of the carbon, from the plant body is also transferred to the soil as litter. Thus on the basis of carbon storage facility of the forest ecosystem, four distinct chambers/compartments can be identified. These are (i) trees growing on the forest floor, (ii) below ground biomass of the trees comprising of root system (and other parts in exceptional case like potato etc.), (iii) detritus such as leaf litter and other decaying matter on the forest floor, and (iv) forest soils. The total forest carbon (T_C) is thus the summation of above–ground biomass (A_C), below-ground (B_C), soil (S_C), and litter (L_C) carbon i.e.,

$$T_C = A_C + B_C + S_C + L_C.$$

Forest transitions from one ecological condition to another will produce substantial carbon flows, and in this context forests can be a “source” or a “sink”. In case of incidences like forest fire, massive deforestation, high rate of decomposition etc., forest biomass is reduced making a net flux of carbon from the forest to the atmosphere. However, the same forest may act as carbon sink as it is restored, systematically managed and plantation is done on regular basis.

Biosequestration is the general term used to describe activities where biota (plants and animals) is used to ‘sequester’ or absorb carbon from the atmosphere. Trees remove carbon dioxide from the atmosphere through the natural process of photosynthesis and store the carbon (C) in their leaves, branches, stems, bark and roots. Approximately half the dry weight of a tree's biomass is carbon. One ton of C = 3.67 tons of 'carbon dioxide equivalent' (http://www.forestrycorporation.com). Trees in forests (including plantations), if well stocked, typically sequester carbon at a maximum rate between the age 10-30. 200 to 520 tons of carbon dioxide is sequestered per hectare in forests. Reforesting cleared areas will create carbon sinks to counteract greenhouse gas emissions, and will assist in other aspects of environmental improvement such as salinity control and creation of wildlife habitat. A number of computer models have been developed over recent years to estimate the carbon sequestered by forests. Their levels of complexity and required input data vary greatly.

The general consensus among climate researchers and environmentalists is that increased emissions of greenhouse gases (GHGs) from human activities and luxurious life styles, burning fossil fuels, and massive deforestation in many regions of the world are changing the climate of the planet Earth. CO_2 plays the major role in absorbing outgoing terrestrial radiation and contributes about half of the total green house effect. Between 1850 and 1900, around 100 gigatons of carbon was released into the air just for land-use changes (Pandey, 2002). Most of the increase has been since 1940 (Hair and Sampson, 1992). The atmospheric CO_2 concentration is currently rising by 4% per decade (Jo and McPherson, 2001). Worldwide concern about climate change has created increasing interest in trees to help reduce the level of atmospheric CO_2 (Dwyer *et al*., 1992). Forests are most critical components for taking carbon out of circulation for long periods of time. Of the total amount of carbon tied up in earthbound forms, an estimated 90% is contained in the world's forests, which includes trees, forest floor (litter) and forest soil. For each cubic foot of merchantable wood produced in a tree, about 33 lb. (14.9 kg) of carbon is stored in total tree biomass (Sampson *et al*., 1992). Tropical forests in general are a disproportionately important component in the global carbon cycle, and are thought to represent 30-40% of the terrestrial net primary production (Clark *et al*., 2001). Although the area covered by mangrove ecosystems represents only a small fraction of tropical forests, their position at the terrestrial-ocean interface and potential exchange with coastal water suggest these forests make a unique contribution to carbon biogeochemistry in coastal ocean (Twilley *et al*., 1992).

Mangrove ecosystems thrive along coastlines throughout most of the tropics and subtropics. These intertidal forests play important ecological and socioeconomic roles by acting as a nutrient filter between land and sea (Robertson and Phillips, 1995), contributing to coastline protection (Vermatt and Thampanya, 2006), providing commercial fisheries resources (Constanza *et al*., 1998) and nursery grounds for coastal fishes and crustaceans. The coastal zone (<200 m depth), covering ~7% of the ocean surface (Gattuso *et al*., 1998) has an important role in the oceanic carbon cycle, and various estimates indicate that the majority of mineralization and burial of organic carbon, as well as carbonate production and accumulation takes place in the coastal ocean (Gattuso *et al*., 1998; Mackenzie *et al*., 2004). The potential impact of mangrove on coastal zone carbon dynamics has been a topic of intense debate during the past decades. The “outwelling” hypothesis, first proposed for mangroves by Odum (1968) and Odum and Heald (1972) suggests that a large fraction of the organic matter produced by mangrove trees is exported to the coastal ocean, where it forms the basis of a detritus food chain and thereby supports coastal fisheries. A number of recent studies, however, have indicated a direct trophic link between mangrove forest production and offshore secondary production is unlikely for many mangrove systems. Despite the large number of case studies dealing with various aspects of organic matter cycling in mangrove systems (Kristensen *et al*., 2008), there is very limited consensus on the carbon sequestering potential of mangroves.

Mangroves constitute an important ecosystem because of their global extent and high productivity. These plants thrive in the intertidal zones of the tropics and subtropics that are characterized by regular tidal inundation and fluctuating salinity. Mangrove species are well adapted, both morphologically and physiologically, to survive under saline conditions. Despite their ecological success in saline environments, however, carbon assimilation capacity and growth are reduced as salinity increases. The carbon storage potential of mangrove floral community has been critically studied and quantified by several researchers (Mitra, 2013; Mitra and Zaman, 2014; Alongi, 2014; Mitra and Zaman, 2016; Murdiyarso *et al*., 2015; Mitra *et al*., 2016; Agarwal *et al*., 2018). The storage of carbon by trees varies spatially and temporally based on abundance of the species, growth rate of the species and environmental conditions. Net annual carbon sequestration is positive for growing forest with considerable Above Ground Biomass (AGB) of the species.

Mangroves can be found in over 118 countries and territories in the tropical and subtropical regions of the world. The largest percentage of mangroves is found between the 5° N and 5° S latitudes. According to the study carried by Giri *et al*. (2011) approximately 75% of world's mangroves are found in 15 countries. Asia has the largest amount (42%) of the world's mangroves, followed by Africa (21%), North/Central America (15%), Oceania (12%) and South America (11%).

The mangroves in the coastal zone are important storehouse of carbon. The global storage of carbon in mangrove biomass is estimated at 4.03 Pg C; and 70% of this carbon occurs in coastal margins from 0^o to 10^o latitude. The average rate of wood production is 12.08 Mg ha-t/yr, which is equal to global estimate of 0.16 Pg C/yr stored in mangrove biomass. Together with carbon accumulation in mangrove sediments (0.02 Pg C/yr), the net ecosystem production in mangroves is about 0.18 Pg C/yr. Global estimates of export from coastal wetlands is about 0.08 Pg C/yr compared to input of 0.36 PgC/yr from rivers to coastal ecosystems. Total allochthonous input of 0.44 PgC/yr is lower than *in situ* production of 6.65 PgC/yr. The trophic condition of coastal ecosystems depends on the fate of this total supply of 7.09 PgC/yr as either contributing to system respiration, or becoming permanently stored in sediments. Accumulation of carbon in coastal sediments is only 0.41 PgC/yr; about 6% of the total input. Accumulation of carbon in wood and sediments of coastal wetlands is 0.205 PgC/yr, half the estimate for sequestrating of carbon in coastal sediments. Burial of carbon in shelf sediments is probably underestimated, particularly in tropical river-dominated coastal margins. Better estimates of these two carbon sinks in the tropics, coastal wetlands and shelf sediments, is needed to understand the contribution of coastal ecosystems to the global carbon budget.

As per the ISFR 2017 report (https://www.rajras.in/index.php/download-india-state-forest-report-2017/), the total area of mangrove cover of India is 4921 km^2, (181 km^2 positively changed with respect to 2015 mangrove cover assessment) which contributes 3.3% to the global mangrove cover (http://fsi.nic.in/isfr2017/isfr-mangrove-cover-2017.pdf). The top 10 mangrove dominated states in India and the total area covered by them is given in the following table (Table 1) (https://www.mapsofindia.com/top-ten/geography/mangrove-forest.html).

Table 1: Prevalence of mangroves in the states of India

Rank	States/UTs with highest mangrove cover in 2017	Total mangrove cover in km^2 in 2015	Total mangrove cover in km^2 in 2017
1	West Bengal	2,106	2114
2	Gujarat	1,107	1140
3	Andaman And Nicobar Islands	617	617
4	Andhra Pradesh	367	404
5	Maharashtra	222	304
6	Odisha	231	243
7	Tamil Nadu	47	49
8	Goa	26	26
9	Kerala	9	9
10	Karnataka	3	10

Goa occupies eighth place among the top ten mangrove dominated states of India. It encompasses an area of 3,702 km^2. It lies between the latitudes 14°53′54″ N and 15°40′00″ N and longitudes 73°40′33″ E and 74°20′13″ E. Most of Goa is a part of the coastal region known as the Konkan, which an escarpment is rising up to the Western Ghats range of mountains, which separate it from the Deccan Plateau. The highest point is the Sonsogor, with an altitude of 1,167 meters. Goa has a coastline of 105 km. Goa's main rivers are Mandovi, Zuari, Terekhol, Chapora and the Sal. The Mormugao harbour on the mouth of the River Zuari is one of the best natural harbours in South Asia. The Zuari and the Mandovi are the lifelines of Goa, with their tributaries draining 69% of its geographic area. The total navigable length of Goa's rivers is 253 km. On this background the present project aims to evaluate stored carbon in the mangrove patches of Mandovi and Zuari estuaries of Goa.

OBJECTIVES

Information on the spatial variation in carbon sequestration in different types of forest cover in the land could achieve further improvements of accuracy of global sinks. Sixty two percent (62%) to 78% of the global terrestrial carbon is sequestered in the forests, and about 70% of this carbon is stored in the soil (Dixon *et al.*, 1994; Schimel, 1995) with slow turnover rate (Guggenberger *et al*., 1994). Tropical forests process about six times as much carbon as the anthropogenic emission. Changes in carbon dynamics in tropical forest with 50% contribution to global terrestrial gross primary production (GPP) (Grace *et al.,* 2001) could alter the pace of climate change (Adams and Piovesan, 2005). Regional studies of carbon exchange vary in showing disequilibrium state of Tropical forest and in increasing stocks of tree carbon (Phillips *et al*., 1998, Lewis *et al*., 2009). Apart from resource availability and pollution stress, succession and global change could have varying importance at different regions to produce different spatial and temporal pattern of carbon uptake by trees (Muller-Landau, 2009).

The carbon uptake by trees during the process of photosynthesis results in carbon sequestration. It is basically the pooling of the atmospheric carbon dioxide and its storage in the producer community of the ecosystems for a long period of time- many thousands of years. Forests offer considerable potential to act as a sink of carbon which is an important roadmap to promote net carbon sequestration. A stock or reservoir that takes up or absorbs carbon is referred to as ‘sink’, and one that releases or emits carbon is called a ‘source’. Shifts or flows of carbon from one stock to another, for example, from the atmosphere to the forest vegetation (as happens during photosynthesis) or from industrial units/several anthropogenic sources to atmosphere (as occurs during emission) are referred to as carbon ‘fluxes’. This process of shifting the carbon from one compartment to other constitutes the carbon cycle. In the carbon cycle, apart from emission from industrial and anthropogenic sources, carbon dioxide is also transferred to the atmosphere through microbial decomposition.

The basic constituent of all organic compounds and a major element involved in the fixation of energy by photosynthesis, carbon is so closely tied to energy flow that the two are inseparable. In fact the measurement of productivity is commonly expressed in terms of grams of carbon fixed per square meter per year. The source of all the fixed carbon in both living organisms and fossils deposits is carbon dioxide, found in the atmosphere and dissolved in the waters of the earth. To trace is cycling to the ecosystem is to redescribe photosynthesis and energy flow.

Once produced by the plant, the polysaccharides and fats synthesized from glucose and stored as tissue are utilized by plant-feeding animals that digest and synthesize the carbon compounds into others. Meat eating animals feed on the herbivores, and the carbon compounds are redigested and resynthesied into other forms. Some of the carbon is returned by these organisms directly because carbon dioxide is a by-product of the respiration of both plants and animals. Some is incorporated into the bones of land animals and the exoskeletons of invertebrates, especially such marine forms as Foraminifera.

The carbon contained in animal wastes and in the protoplasm of plants and animals is eventually released by assorted decomposer organisms. The rate of release depends on environmental conditions such as soil moisture, temperature, and precipitation. In tropical forests most of the carbon in plant remains is quickly recycled, for there is little accumulation in the soil. The turnover rate of atmospheric carbon over peat bogs is somewhere on the order of 3 to 5 years (Leith, 1963).

The cycling of carbon as carbon dioxide involves its assimilation and respiration by plants, its consumption in the form of plant and animal tissue by animals, its release through their respiration, the mineralization of litter and wood, soil respiration, accumulation of carbon in a standing crop, and withdrawal into longer-term reserves such as humus and peat fossil deposits.

At daylight, when photosynthesis begins, plants start to withdraw carbon dioxide from the air and the concentration declines sharply. By afternoon, when the temperature is increasing and the humidity is decreasing, the respiration rate of plants is increased, the assimilation rate of carbon dioxide declines, and the concentration of carbon dioxide in the atmosphere increases. By sunset the light phase of photosynthesis ceases, carbon dioxide is no longer being withdrawn from the atmosphere, and its concentration in the atmosphere increases sharply.

Over the years, forest ecologists have developed various methods to estimate the biomass of forests. Three important methods are usually adopted for estimating forest biomass: the harvest method, the mean-tree method, and the allometric method. In a mature forest, the total weight of an individual tree often reaches several tons (Komiyama *et al*., 2005). Therefore, the harvest method cannot be easily used in mature forests and in itself is not reproducible because all trees must be destructively harvested. The mean-tree method is utilized only in forests with a homogeneous tree size distribution, such as plantations. The allometric method estimates the whole or partial weight of a tree from measurable tree dimensions, including trunk diameter and height, using allometric equations. This is a non- destructive method and is thus useful for estimating temporal changes in forest biomass by means of subsequent measurements. However, the site- and species-specific dependencies of allometric equations pose a problem to researchers because tree weight measurement in forests is labour-intensive. Based on studies of forest biomass using the allometric method and other characters, Kira and Shidei (1967) summarized the so-called ‘‘summation method’’ for estimating the Net Primary Production (NPP) of forests. In this method, the rates of growth increment, death, and consumption by herbivores, are summed to obtain the NPP. The Gross Primary Production (GPP) of forests can then be calculated by adding the rate of metabolic respiration to the NPP. Recently, interest has grown in the study of carbon fluxes of an entire ecosystem, which includes carbon emissions from soil respiration. Net Ecosystem Production (NEP) is a sophisticated criterion to judge carbon fixation from the NPP and the rate of soil respiration. One method for estimating the NEP is through the eddy covariance. Essentially, this consists of taking rapid measurements of the vertical component of air velocity and the concentration of carbon dioxide/water vapour in the air above forest canopies, and taking their covariance. However, this method requires large equipment in forests, high priced instruments, and complex computation (Monji *et al*., 2002).

Allometric equations for trees have been developed for several decades to estimate biomass and subsequent growth. Most studies have used allometric equations for single stemmed trees, but some species have multi-stemmed tree forms, as often seen in *Rhizophora*, *Avicennia*, and *Excoecaria* species (Clough *et al*., 1997; Dahdouh Guebas and Koedam, 2006). Clough *et al.* (1997) showed that the allometric relationship can be used for trunks in a multi-stemmed tree.

Moreover, for dwarf trees, allometric relationships have been used to estimate the biomass (Ross *et al*., 2001). For studies on single-stemmed trees published from 1984 to 2000, Saenger (2002) cited 43 allometric equations on AGB. His review and subsequent studies by Tam and Ong (1995), Ong *et al.* (2004), Comley and McGuinness (2005), and Soares and Schaeffer-Novelli (2005) provide a good overall survey of the relevant literature. They found that species-specific trait of allometry (*i.e*., the allometric equation) is significantly different among forest tree species. Clough *et al.* (1997) found different relationships in different sites, although Ong *et al.* (2004) reported similar equations applied to two different sites for *Rhizophora apiculata*. This issue is important for practical uses of allometric equations. If the equations are segregated by species and site, then different expressions are established for each site.

On both the species and site-specific issues of allometry, Chave *et al.* (2005) and Komiyama *et al.* (2005) proposed the use of a common allometric equation for halophytic tree species. The common allometric equation that Komiyama *et al.* (2005) proposed is based on the pipe model (Shinozaki *et al*., 1964) and the static model of plant form (Oohata and Shinozaki, 1979). These models predict that the partial weight of the trunk at a certain height physically sustains the weight of the upper tree body, regardless of tree species and locality.

By using these two theories, Komiyama *et al.* (2005) derived equations with trunk diameter and wood density as parameters, and found good fits with 104 sample trees comprising 10 tree species from Thailand and Indonesia (the data, Tamai *et al*., 1986; Komiyama *et al*., 1988 are included in this common equation).

The common equation of Chave *et al.* (2005) was established based on statistical analysis but nevertheless consisted of the same two parameters used by Komiyama *et al.* (2005). These two common equations have the advantage of requiring only two parameters, even though Soares and Schaeffer-Novelli (2005) list a large number of parameters in their allometric equations for trees. The measurement of trunk diameter or girth is more practical than other parameters, especially for those working in closed and tall canopies where tree height is difficult to accurately measure. Wood density differs significantly in different tree species, but less for individuals within a species (Komiyama *et al*., 2005).

The issue of carbon sequestration and mitigation of GHG emission has cropped up from the exponential rise of GHG in the atmosphere.

On this background, the prime objectives of the present study are:

1. Monitoring the carbon sequestration pattern in the above ground biomass of six common mangrove species (*Avicennia alba, A. marina, A. officinalis, Excoecaria agallocha*, *Rhizophora apiculata* and *Rhizophora mucronata*) in the Zuari and Mandovi Rivers of Goa through seasons (Pre-monsoon, Monsoon & Post-monsoon).
2. To evaluate CO_2-equivalent of each species to assess the role of the selected tree species in offsetting CO_2.
3. Monitoring carbon in litter of Mangroves from both the sites through season (Pre-monsoon, Monsoon & Post-monsoon).
4. Monitoring the soil organic carbon of the substratum in the sampling sites through seasons (Pre-monsoon, Monsoon & Post-monsoon).
5. Develop allometric equations for each mangrove species site-wise considering the data achieved from all stations of the two sites (Zuari and Mandovi).

LITERATURE REVIEW

Global average CO_2 was about 280 ppm in the 19th century, the concentration of CO_2 fluctuated between 180-280 ppm during ice ages and interglacial warm periods. Today's rate of increase is more than 100 times faster than the increase that occurred when last the ice age ended and the increase has taken an exponential turn since last 3 decades (https://www.co2now.org/Current-CO_2-Trend/acceleration-of-atmosphere-co_2.html/). The predicted increase in carbon dioxide was 700-1000 ppm by the end of the century as a result of fossil fuel consumption (Calderia and Wickett, 2003; IPCC, 2007). There was a gradual increase in atmospheric CO_2 concentration from 314 ppm in the year 1960 to 410.79 ppm in the year 2018 (https://www.co2.earth).

An increase in carbon dioxide concentration of seawater enhances the photosynthetic rate of carbon fixation by some of the phytoplankton groups (Riebesell, 2004).The artificial stimulation of algal blooms could be a useful strategy to remove excess carbon from the oceans and indirectly reducing the concentration of atmospheric CO_2 (Schrope, 2007). Iron enrichment, growth of algae and carbon sequestration was reported by Watson *et al.* (2008). Carbon sequestration by the marine planktonic micro algae and macro algae was estimated under laboratory conditions. It was found that seaweed biomass along the Indian coast was capable of utilizing 9012t CO_2/day against emission of 365t CO_2/day indicating a net carbon credit of 8687t CO_2/day (Kaladharan *et al.*, 2009).

Rivers discharge about 13.5×10^9 tons of particulate material annually to the coastal oceans, over half of which is supplied by the world's 21 largest rivers (Milliman and Meade, 1983). Besides their POC load, rivers carry an approximately equal load of DOC- about 200×10^{12} g per year. In addition, the nutrient load of rivers may enhance the primary productivity of neritic waters, and some of this carbon may accumulate in the sediments of continental margins. Present estimates suggest that there is much more organic matter coming down the rivers than can be accounted for in annual accumulation of sediment carbon in the ocean. Few estimates have synoptically accounted for the other sources of *in situ* carbon, such as mangroves, sea grasses and coral reefs that may accumulate in coastal ecosystems.

More and more research has been coming out recently on how much carbon is being sequestered and thus stored in different ecosystems. Global estimates of carbon sources in coastal ecosystems (Table 2) are identified as either allochthonous or *in situ* depending on whether the source of CO_2 is from the atmosphere or of ocean origin. River input (0.36 Pg C/yr) is terrigenous organic carbon fixed by terrestrial vegetation. TOC export from coastal wetlands also represents C fixed by vegetation directly from the atmosphere, but these are included as part of coastal ecosystems. Coastal wetlands thus should be carefully evaluated in developing carbon budgets of coastal ecosystems since they exchange C directly with the atmosphere and with coastal waters. C export from mangroves is estimated in the study at 0.05 Pg C/yr and marsh export is estimated at 0.03 Pg C/yr using a mean export of 95 gC m-2 yr-1 (Lugo *et al.*, 1990). This is near the average rate of C export (Nixon, 1980). The total contribution of C from coastal wetlands is estimated at 0.08 Pg C/yr. Together with estimate of river input, the total allochthonous input of organic carbon into coastal ecosystems is 0.44 Pg C/yr (Table 2). Estimates of primary production in coastal environments range from approximately 1.0-7.0 Pg C/yr (Walsh, 1984; Smith and Mackenzie, 1987). Walsh (1988) classified coastal production among macrophytes, estuarine, and shelf systems for total *in situ* production of 6.65 Pg C/yr (Table 2). Based on these estimates the total input of organic C to coastal ecosystems is 7.09 Pg/yr (Table 2).

Table 2: Estimates of carbon sources and sinks in coastal ecosystems (Pg C/yr)

SOURCES		
Rivers	0.36	Twilley *et al*. (1992)
Wetlands	0.08	Twilley *et al*. (1992)
Allochthonous	**0.44**	
Shelf Waters	5.40	Walsh (1984)
Estuaries/Deltas	0.92	Walsh (1984)
Macrophytes	0.33	Walsh (1984)
Total *in situ* production	**6.65**	
TOTAL (Allochthonous & *in situ*)	**7.09**	
SEDIMENT SINKS		
Coral Reefs	0.01	Walsh (1984)
Shelf	0.2	Berner (1982)
Estuaries	0.20	Walsh (1984)
TOTAL	**0.41**	
WETLAND SINKS		
Mangroves	0.18	Twilley *et al*. (1992)
Marshes	0.025	Hopkinson (1988)
TOTAL	**0.205**	

The National level work on Climate Change in coastal zone is being carried out by Institute for Ocean Management (IOM). Krithika *et al*. (2008) worked on the emissions of green house gases mainly methane (CH_4) and nitrous oxide (N_2O) from sediments of mangrove ecosystems and concluded that these GHGs seem to be highly variable from one site to another. Studies done by Krithika *et al*. (2008) state that human induced climate change by the production of green house gases (primarily CH_4 and N_2O) due to forestation/deforestation has emerged as an environmental issue related to the global warming problem because forests and especially mangrove wetlands are possible sinks/sources for CO_2 and other related greenhouse gases. Sensitivity of Mangrove flora to changing climate and their role in carbon sequestration was discussed at a length with examples of interesting case studies (Mitra, 2013). Estimation of the balances and fluxes of CH_4 and N_2O, the two key anthropogenically altered gases have become necessary, as these greenhouse gases are normally released from wetlands and are important in order to evaluate the offsetting effects of these GHGs against CO_2 sequestration by mangroves in coastal ecosystems.

Forests play a crucial role in regulating the climate of the planet Earth by acting as important store house of carbon. Forests plant and soils drive the global carbon cycle by sequestering (storing) carbon dioxide through photosynthesis and releasing it through respiration. When the uptake of carbon dioxide (photosynthesis) exceeds losses *via* respiration, harvest and management, then forests store carbon (C sinks). In an undisturbed forest ~ 74% of the carbon dioxide is stored in live stems and branches, 16 % is stored in roots and 10 % in soils. The global sink in forest vegetation and soils (Table 3) is estimated to be 1200 Gt of carbon (1 Gt = 10^9 tonnes). This increases at a rate of 1-3 Gt annually.

Several researchers have estimated the carbon stored in forest vegetation in the pre-industrial and present times (Table 4).

Table 3: Carbon storage totals for global soils

Storage (Gt C)	**Reservoir type**	**Author(s)**
1115 Gt	Soils, present potential ('prehistoric')	Adams *et al*. (1990)
1395 Gt (1.)	Peats + soils, present potential	Adams *et al*. (1990)
1405 Gt (3.)	Soils, present-day	Bazilevich (1974) (s.)
3000 Gt (4.)	Soils (+ peats ?), present-day	Bohn (1978) (s.)
1672 Gt (3.)	Soils, present-day	Bolin *et al*. (1979) (s.)
1477 Gt (5.)	Soils, present-day	Buringh (1983) (s.)
1515 Gt (6.)	Soils (+peat lands?) present-day	Schlesinger (1984)
787 Gt	Forest soils only (+fine debris)	Dixon and Krankina (1993)
1500 Gt (7.)	Soils, in 1989	IPCC (1990) (s.)
1560 Gt (7.)	Soils, in 'pre-industrial' era.	IPCC (1990) (s.)
860 Gt (8.)	Peats, present-day	Bohn (1976) (s.)
300 Gt (8.)	Peats	Sjors (1980) (s.)
202 Gt (8.)	Peats	Post *et al*. (1982)
377 Gt (8.)	Peats	Bohn (1976, 82)
180-227 Gt (8.)	Peats	Gorham (1990) (s.)
461 Gt (9.)	Subarctic and boreal peat	Gorham (1992)
1576 Gt (10.)	Global soils (present-day)	Eswaran *et al*. (1993)
500 Gt (11.)	Global peats	Markov *et al*. (1988) (s.)

Table 4: Previous global carbon storage estimates for vegetation

Storage (Gt C)	Reservoir type	Author(s)
827 Gt (1)	Present actual land vegetation	Whittaker and Likens, 1975 (s)
560 Gt (2)	Present actual land vegetation	Olson *et al*. (1983)
550 Gt (3)	Present actual (1980s) land vegetation	IPCC (1990) (s)
610 Gt (3)	Pre-industrial (pre-1700) vegetation	IPCC (1990) (s)
1080 Gt (4)	Land vegetation, ‘prehistoric’ times	Bazilevich *et al*. (1971)
924 Gt	Present potential (‘prehistoric’) vegetation	Adams *et al*. (1990)
343 Gt (5)	Last Glacial Maximum vegetation	Adams *et al*. (1990)
350 Gt	Coarse woody debris (present potential)	Harmon (1990)
591 Gt (8)	Present-actual land vegetation	Ajtay *et al*. (1979) (s)

The planet Earth sustains some 3.9 billion hectares or 39,000,000 Km^2 of remaining forests (Brown *et al*., 2008) which is approximately 30% of the World's land surface.

The tropical forest zone encompasses 1.76 billion ha or 17,600,000 Km^2, and is divided into six ecofloristic zones: the tropical rain forests, the moist deciduous forests, the dry zone, the very dry zone, the desert zone and the hill and mountain forests.

Tropical rain forests are found in areas with more than 2500 mm of annual rainfall. They are evergreen, luxuriant and rich in animal and plant species. More than half the world's 718.3 million ha of rain forests are located in two countries: Brazil (41 percent) and Indonesia (13 percent). Rain forest composition and structure vary with distance from the ocean, distance from rivers, altitude and geographic position.

Moist deciduous forests occur in areas with an annual rainfall of 1000 to 2000 mm. Forest structure varies depending on the amount and distribution of rain, the type of soil and the length of the dry season. Some dominant tree species may lose their leaves towards the end of the dry season. This forest type is generally less diverse than rain forest.

Dry zone forests are found in tropical areas receiving between 500 and 1 000 mm of rainfall per year. They are relatively open and include thornland, shrubland, savannah and other short and sparse woody vegetation. Dry zone forests tend to be fragile and are easily degraded. More than half are in Africa. Dry forest types include oak, mesquite, piñon-juniper, maquis and acacia.

Tropical upland forests are forests above 800 m and include cloud forests (montane rain forests), which are shorter, floristically simpler and more heavily laden with mosses and lichens than lowland rain forests. Tropical upland species are similar to temperate forest species. The upland zone covers the Himalayas, parts of Myanmar, Thailand and Vietnam, the highlands of Mexico, the Andes and the highlands of Ethiopia and mountains around Lake Victoria.

The total mangrove forest area accounts for 0.7% of the total tropical forest in the world. Most mangroves (42%) are found in Asia, followed by Africa (20%), North and Central America (15%), Oceania (12%) and South America (15%).

According to a study conducted by a team of U.S. Forest Service and University scientists coastal mangrove forests store more carbon than almost any other forest on earth. Their findings are published online in the journal *Nature Geoscience*, (www.nature.com/naturegeoscience.com). The mangrove forest's ability to store such large amounts of carbon can be attributed, in part, to the deep organic-rich soils in which it thrives (Fig. 2).

Fig. 2. Organic carbon – rich soil of mangrove ecosystem

The soil depth mostly increases with time as the silt of the overlying aquatic phase deposit on the existing soil bed (intertidal mudflats). This happens because the intertidal mudflats suffer total submergence by silty water during high tide (Fig. 3)

Fig. 3. Complete submergence of intertidal mudflats during high tide

Mangrove-sediment carbon stores were on average five times larger than those typically observed in temperate, boreal and tropical terrestrial forests, on a per-unit-area basis. The mangrove forest's complex root systems, which anchor the plants into underwater sediment, slow down incoming tidal waters allowing organic and inorganic material to settle into the sediment surface. Low oxygen conditions slow decay rates, resulting in much of the carbon accumulating in the soil. In fact, mangroves have more carbon in their soil alone than most tropical forests have in all their biomass and soil combined.

The capacity of mangroves, sea grasses, and salt marshes to sequester carbon dioxide from the atmosphere is becoming increasingly recognized at an international level. Of all the biological carbon, also termed as ’green carbon’, captured in the world, over half (55%) is captured by mangroves, sea grasses, salt marshes, and other marine living organisms, which are also known more specifically as ‘blue carbon’. Mangroves, salt marshes, and sea grasses form much of the earth’s blue carbon sinks (http://www.recoftc.org/site/resources/Mangroves-more-Carbon-Rich-and-Important-for-Climate-Change.php).

Mangrove ecosystems are concentrated along tropical and subtropical coasts and are the only known woody halophytes. A part of their productivity flows into adjacent ecosystems, or conversely, they receive organic materials from estuarine or oceanic ecosystems (Fig. 4) (Ong, 1993; Kristensen *et al.*, 2008).

Fig. 4. Mangrove forests supply nutrients to the adjacent estuarine water

The biological and ecological aspects of mangroves have been studied worldwide (Lugo and Snedaker, 1974; Boto *et al.*, 1984; Twilley *et al.*, 1986; Odum and Mclvor, 1990; Twilley, 1995; Cox and Allen, 1999). Most researchers deal with patterns of primary productivity, nutrient cycle and detrital export in riverine mangroves, whereas fringe and scrub mangrove have been studied to a lesser extent (Twilley *et al.*, 1992; Alongi *et al.*, 1992; Lee, 1995). The field survey of mangrove biomass and productivity is rather difficult due to muddy soil conditions and the heavy weight of the wood. The peculiar tree form of mangroves, especially their unusual roots, has long attracted the attention of botanists and ecologists (Tomlinson, 1986). The survival of mangroves in soft muddy substratum is basically because of the support of their root system. To maintain a bottom-heavy tree form (Ong *et al*., 2004) or a low ratio of top biomass to root biomass (T/R ratio; Komiyama *et al*., 2000), mangroves might allocate a great deal of biomass to their roots. This phenomenon may produce peculiar conditions for ecosystem processes in root zones owing to the anaerobic conditions.

Over the years, forest ecologists have developed various methods to estimate the biomass of forests. Three important methods are usually adopted for estimating forest biomass: the harvest method, the mean-tree method, and the allometric method. In a mature mangrove forest, the total weight of an individual tree often reaches several tons (Komiyama *et al*. 2005). Therefore, the harvest method cannot be easily used in mature forests and in itself is not reproducible because all trees must be destructively harvested. The mean-tree method is utilized only in forests with a homogeneous tree size distribution, such as plantations. The allometric method estimates the whole or partial weight of a tree from measurable tree dimensions, including trunk diameter and height, using allometric equations. This is a non- destructive method and is thus useful for estimating temporal changes in forest biomass by means of subsequent measurements. However, the site- and species-specific dependencies of allometric equations pose a problem to researchers because tree weight measurement in mangrove forests is labour-intensive. Based on studies of forest biomass using the allometric method and other characters, Kira and Shidei (1967) summarized the so-called ‘‘summation method’’ for estimating the Net Primary Production (NPP) of forests. In this method, the rates of growth increment, death, and consumption by herbivores, are summed to obtain the NPP. The Gross Primary

Production (GPP) of forests can then be calculated by adding the rate of metabolic respiration to the NPP. Recently, interest has grown in the study of carbon fluxes of an entire ecosystem, which includes carbon emissions from soil respiration. Net Ecosystem Production (NEP) is a sophisticated criterion to judge carbon fixation from the NPP and the rate of soil respiration. One method for estimating the NEP is through the eddy covariance. Essentially, this consists of taking rapid measurements of the vertical component of air velocity and the concentration of carbon dioxide/water vapour in the air above forest canopies, and taking their covariance. However, this method requires large equipment in mangrove forests, high priced instruments, and complex computation.

Allometric equations for mangroves have been developed for several decades to estimate biomass and subsequent growth. Most studies have used allometric equations for single stemmed trees, but mangroves sometimes have multi-stemmed tree forms, as often seen in *Rhizophora*, *Avicennia*, and *Excoecaria* sp. (Clough *et al*., 1997; Dahdouh-Guebas and Koedam, 2006). Clough *et al*. (1997) showed that the allometric relationship can be used for trunks in a multi-stemmed tree.

Moreover, for dwarf mangrove trees, allometric relationships have been used to estimate the biomass (Ross *et al*., 2001). For studies on single-stemmed trees published from 1984 to 2000, Saenger (2002) cited 43 allometric equations on AGB. His review and subsequent studies by Tam *et al*. (1995), Ong *et al*. (2004), Comley and McGuinness (2005), and Soares and Schaeffer-Novelli (2005) provide a good overall survey of the relevant literature. They found that species-specific trait of allometry (*i.e*., the allometric equation) is significantly different among mangrove tree species. Clough *et al*. (1997) found different relationships in different sites, although Ong *et al*. (2004) reported similar equations applied to two different sites for *Rhizophora apiculata*. This issue is important for practical uses of allometric equations. If the equations are segregated by species and site, then different expressions can be established for each site (Table 5).

On both the species and site-specific issues of allometry, Chave *et al*. (2005) and Komiyama *et al*. (2005) proposed the use of a common allometric equation for mangroves. The common allometric equation that Komiyama *et al*. (2005) proposed is based on the pipe model (Shinozaki *et al*., 1964) and the static model of plant form (Oohata and Shinozaki, 1979). These models predict that the partial weight of the trunk at a certain height physically sustains the weight of the upper tree body, regardless of tree species and locality. By using these two theories, Komiyama *et al*. (2005) derived equations with trunk diameter and wood density as parameters, and found good fits with 104 sample trees comprising 10 mangrove species from Thailand and Indonesia (the data, Tamai *et al*., 1986; Komiyama *et al*., 1988 are included in this common equation). The common equation of Chave *et al*. (2005) was established based on statistical analysis but nevertheless consisted of the same two parameters used by Komiyama *et al*. (2005) (Table 5). These two common equations have the advantage of requiring only two parameters, even though Soares and Schaeffer-Novelli (2005) list a large number of parameters in their allometric equations for mangroves. The measurement of trunk diameter or girth is more practical than other parameters, especially for those working in closed and tall canopies where tree height is difficult to accurately measure. Wood density differs significantly in different mangrove species, but less for individuals within a species (Komiyama *et al*., 2005).

Table 5: Allometric equations for various mangroves based on DBH (cm)

Species	Above-ground tree weight (Wtop in kg)	References
Avicennia germinans	$W_{top} = 0.140DBH^{2.40}$ $r^2 = 0.97$, n = 45, Dmax = 4 cm	Fromard *et al*. (1998)[a]
	$W_{top} = 0.0942DBH^{2.54}$ $r^2 = 0.99$, n = 21, Dmax: unknown	Imbert and Rollet (1989)[a]
Avicennia marina	$W_{top} = 0.308DBH^{2.11}$ $r^2 = 0.97$, n = 22, Dmax = 35 cm	Comley and McGuinness (2005)
Laguncularia racemosa	$W_{top} = 0.102DBH^{2.50}$ $r^2 = 0.97$, n = 70, Dmax = 10 cm,	Fromard *et al*. (1998)[a]
	$W_{top} = 0.209DBH^{2.24}$ $r^2 = 0.99$, n = 17, Dmax: unknown	Imbert and Rollet (1989)[a]
Rhizophora apiculata	$W_{top} = 0.235DBH^{2.42}$ $r^2 = 0.98$, n = 57, Dmax = 28 cm	Ong *et al*. (2004)
Rhizophora mangle	$W_{top} = 0.178DBH^{2.47}$ $r^2 = 0.98$, n = 17, Dmax: unknown	Imbert and Rollet (1989)[a]
Rhizophora spp.	$W_{top} = 0.128DBH^{2.60}$ $r^2 = 0.92$, n = 9, Dmax = 32 cm	Fromard *et al*. (1998)[a]
	$W_{top} = 0.105DBH^{2.68}$ $r^2= 0.99$, n = 23, Dmax = 25 cm	Clough and Scott (1989)[a]
Bruguiera gymnorrhiza	$W_{top} = 0.186DBH^{2.31}$ $r^2 = 0.99$, n = 17, Dmax = 25 cm	Clough and Scott (1989)[a]
Bruguiera parviflora	$W_{top} = 0.168DBH^{2.42}$ $r^2 = 0.99$, Dmax = 25 cm, n = 16	Clough and Scott (1989)[a]
Ceriops australis	$W_{top} = 0.189DBH^{2.34}$ $r^2 = 0.99$, n = 26, Dmax = 20 cm	Clough and Scott (1989)[a]
Xylocarpus grnatum	$W_{top} = 0.0823DBH^{2.59}$ $r^2 = 0.99$, n = 15, Dmax = 25 cm	Clough and Scott (1989)[a]
Common equation	$W_{top} = 0.251pD^{2.46}$ $r^2 = 0.98$, n = 104, Dmax = 49 cm	Komiyama *et al*. (2005)
	$W_{top} = 0.168pDBH^{2.47}$ $r^2 = 0.99$, n = 84, Dmax = 50 cm	Chave *et al*. (2005)

W_{top} – Above ground tree weight; [a] After Saenger (2002), D_{max}: the upper range of samples

A number of reports are now available on mangrove biomass from different regions of the world. AGB of 460 t ha^{-1} was reported from a forest dominated by *R. apiculata* in Malaysia (Putz and Chan, 1986). AGB of more than 300 t ha^{-1} was documented in mangrove forests in Indonesia (Komiyama *et al*. 1988) and French Guiana (Fromard *et al*., 1998). The AGB was less than 100 t ha^{-1} in most secondary forests or concession areas. In high-latitude areas (>24° 23`N or S), primary forests mostly have an AGB of around 100 t ha^{-1}, however, even at 27° 24' S, an AGB of 341 tha^{-1} was reported for an *Avicennia marina* forest (Mackey, 1993). The lowest AGB reported was 7.9 tha^{-1} for a *Rhizophora mangle* forest in Florida, USA (Lugo nd Snedaker, 1974). The canopy height of mangrove forests is generally lower at higher latitudes (Pool *et al*., 1977; Saenger and Snedaker, 1993) which is a justified reason for relatively lower AGB in higher latitudes (Table 6).

Table 6: Global data of AGB of different mangrove species

Region	**Location**	**Condition or age**	**Species**	**ABG (tha $^{-1}$)**	**Reference**
Australia	$27^{0}24^{/}$S, 153^{0} $8^{/}$ E	Secondary forest	*A. marina* forest	341.0	Mackey 1993
Thailand (Ranong Southern)	9^{0}N, 98^{0} E	Primary forest	*Sonneratia* forest	281.2	Komiyama *et al*. (1987)
Sri Lanka	$8^{0}15^{/}$ N, 79^{0} $50^{/}$ E	Fringe	*Avicennia sp.*	193.0	Amarasinghe and Balasubramaniam (1992)
Indonesia (Halmahera)	$1^{0}10^{/}$N, 127^{0} $57^{/}$ E	Primary forest	*Sonneratia* forest	169.1	Komiyama *et al*. (1987)
Australia	$33^{0}50^{/}$S, 151^{0} $9^{/}$ E	Primary forest	*A. marina* forest	144.5	Briggs (1977)
French Guiana	$4^{0}52^{/}$N, 52^{0} $19^{/}$ E	Matured coastal	*Lagucularia sp., Avicennia sp., Rhizophora sp.*	315.0	Fromard *et al.* (1998)
South Africa	$29^{0}48^{/}$S, 31^{0} $03^{/}$ E	-	*Bruguiera gymnorrhiza,* *A. marina*	94.5	Steinke *et al.* (1995)
French Guiana	$5^{0}23^{/}$N, 52^{0} $50^{/}$ E	Pioneer stage 1 year	*Avicennia sp.*	35.1	Fromard *et al.* (1998)

In contrast at low latitudes, primary or mature mangrove forests generally have high AGB. The AGB is always low in temperate areas and may be related to different climatic conditions, such as temperature, solar radiation, precipitation and frequency of storms. It is interesting to note that AGB in mangroves is primarily influenced by stem, and not by branches and leaves. A study conducted by Mitra *et al*. (2009) on three dominant mangrove species (*Sonneratia apetala*, *Excoecaria agallocha* and *Avicennia alba*) in western and central Indian Sundarbans clearly confirms that stem biomass (which is a direct function of DBH) and is a unique indicator of mangrove AGB unlike branches and leaves that contribute substantially to litter fall and less to permanent biomass.

DESCRIPTION OF STUDY AREA

Goa occupies eighth place among the top ten mangrove dominated states of India. It encompasses an area of 3,702 km^2 (1,429 sq mi). It lies between the latitudes 14°53′54″ N and 15°40′00″ N and longitudes 73°40′33″ E and 74°20′13″ E. Most of Goa is a part of the coastal region known as the Konkan, which an escarpment is rising up to the Western Ghats range of mountains, which separate it from the Deccan Plateau. The highest point is the Sonsogor, with an altitude of 1,167 meters. Goa has a coastline of 105 km. Goa's main rivers are Mandovi, Zuari, Dicholi, Molde, Valvat, Kushavati, Uguem, Guloli, Khandepar etc. (Fig. 5).

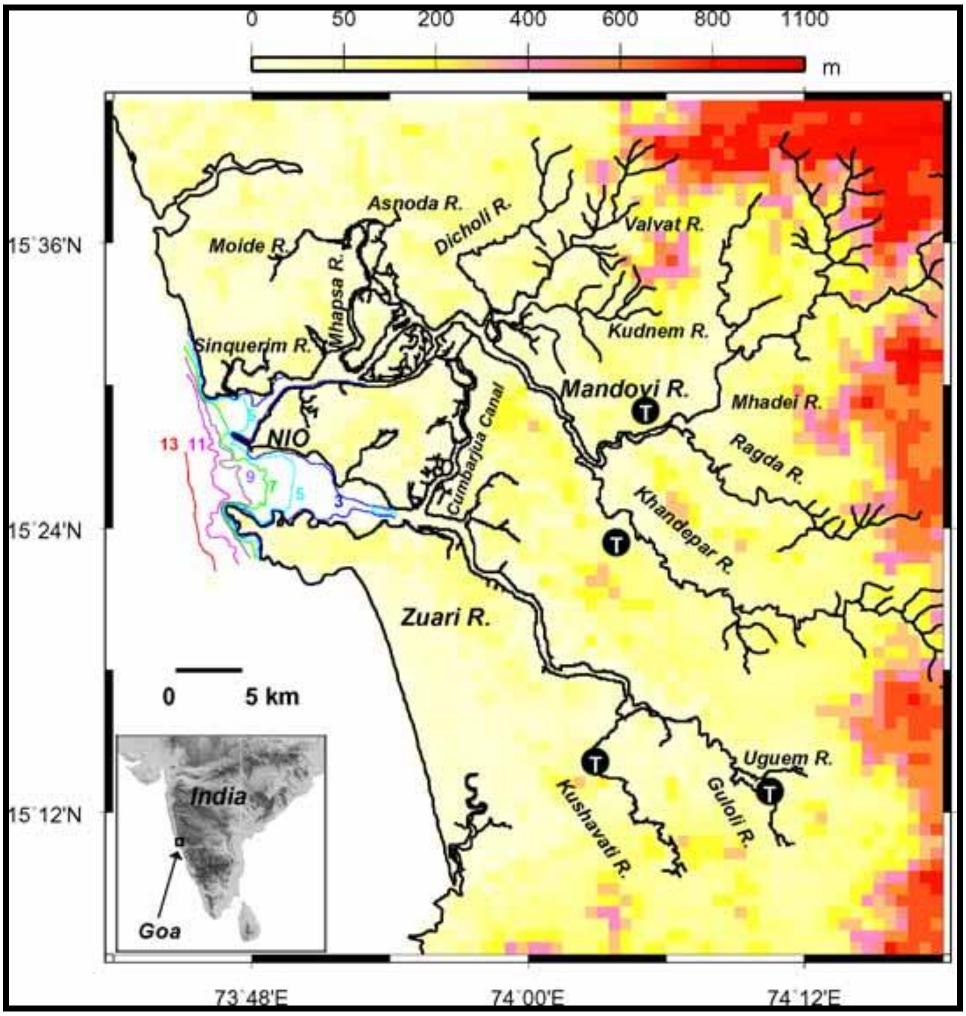
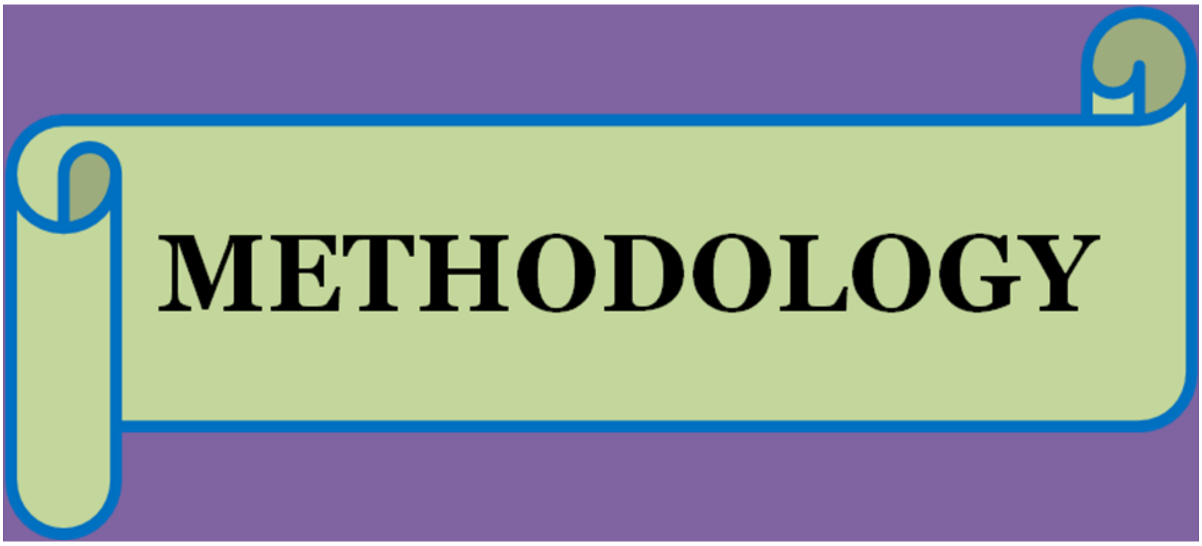


Fig. 5. Map of the Mandovi and Zuari estuaries based on publications from the Survey of India (1967), the Naval Hydrographic Office, India, and the Admiralty, U.K. The depth contours (m) are with respect to mean sea level which is 1.3m above Spring Low Water at Mormugao. To avoid clutter, the depth contours are shown only near the mouths of the Mandovi and the Zuari. "T" in a circle shows location up to which tidal influence is felt in the rivers Kushavati, Uguem, Guloli, Khandepar, and Mandovi. Land elevation is shown in colour, the key for which is given above the figure.

The Mormugao harbour on the mouth of the River Zuari is one of the best natural harbours in South Asia. The Zuari and the Mandovi are the lifelines of Goa, with their tributaries draining 69% of its geographic area. The total navigable length of Goa's rivers is 253 km.

The Mandovi is wider, the width being approximately 4km at the Aguada Bay. The 4 km long stretch of the bay is, on average, marginally deeper than the rest of the estuarine channel, the average depth in the bay being about 5 m. The Sinquerim River joins the bay. The 6 km long stretch immediately upstream of the bay is, on average, 750m wide and 5m deep, i.e., the channel narrows considerably from the bay to this stretch of the estuary. The Mhapsa River joins the Mandovi at the upstream end of this stretch. Farther upstream, Diwar Island, which is approximately 11 km long, bifurcates the Mandovi into two channels. Before rejoining at the upstream end of the island, the two channels lead into an extensive network of narrow channels in a marshy area. The Cumbarjua canal joins the Mandovi about 4 km upstream of Diwar Island. The 30 km stretch of the main channel of the Mandovi, from the eastern edge of Diwar Island to Ganjem, gets progressively narrower and shallower in the upstream direction. Rivers Dicholi, Valvat, Kudnem, and Khandepar join the Mandovi along this stretch. The Khandepar is the largest of the four rivers and is fed by the Dudhsagar River.

A smaller river, Ragda, also joins the Mandovi near Ganjem. The Mhapsa River, which joins the Mandovi at Penha de France, has at its upstream end the rivers Asnoda and Moide. The Mhapsa River and its tributaries are joined by a large network of small rivulets that often flow through marshy areas. The 10 km stretch upstream from the mouth of the Zuari, known as the Mormugao Bay, is approximately 5 km wide and 5m deep. At the upstream end of the bay, the channel narrows to a width less than 1km. The 30 km long channel from Cortalim to Sanvordem narrows progressively. It is less than 50m wide at Sanvordem. The Kushavati River (also known as Paroda) joins the Zuari 4 km downstream of Sanvordem.

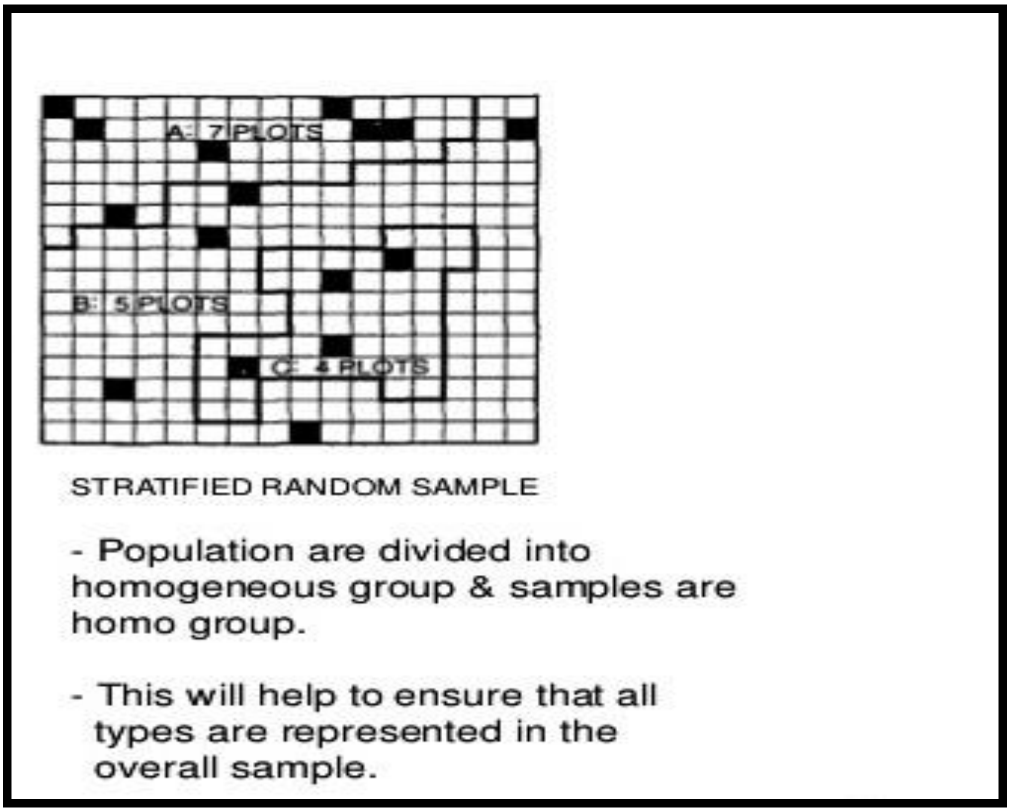


METHODOLOGY

PHASE A: SITE SELECTION and SAMPLING

Three sites were selected in each of these compartments/estuaries (Mandovi and Zuari), where stratified random sampling design was followed considering 10 plots per site. The basic idea in stratified random sampling is to divide a heterogeneous population into sub-populations, usually known as strata, each of which is internally homogeneous in which case a precise estimate of any stratum mean can be obtained based on a small sample from that stratum and by combining such estimates, a precise estimate for the whole population can be obtained.

Stratified sampling provides a better cross section of the population than the procedure of simple random sampling. It may also simplify the organisation of the field work. Geographical proximity is sometimes taken as the basis of stratification. The assumption here is that geographically contiguous areas are often more alike than areas that are far apart. Administrative convenience may also dictate the basis on which the stratification is made. For example, the staff already available in each range of a forest division may have to supervise the survey in the area under their jurisdiction. Thus, compact geographical regions may form the strata. A fairly effective method of stratification is to conduct a quick reconnaissance survey of the area or pool the information already at hand and stratify the forest area according to forest types, stand density, site quality etc. (Scheme 1).



STRATIFIED RANDOM SAMPLE

- Population are divided into homogeneous group & samples are homo group.
- This will help to ensure that all types are represented in the overall sample.

Scheme 1. Stratified Random sampling followed for Relative Density analysis of floral community

If the characteristic under study is known to be correlated with a supplementary variable for which actual data or at least good estimates are available for the units in the population, the stratification may be done using the information on the supplementary variable. For instance, the volume estimates obtained at a previous inventory of the forest area may be used for stratification of the population. In stratified sampling, the variance of the estimator consists of only the ‘within strata’ variation. Thus the larger the number of strata into which a population is divided, the higher, in general, the precision, since it is likely that, in this case, the units within a stratum will be more homogeneous. For estimating the variance within strata, a total of 10 units in each stratum were considered in the present study (depending on the variability of the species).

Before sampling, it is assumed that the population is divided into k strata of N_1, $N_2, \dots, N_k$ units respectively, and that a sample of n units is to be drawn from the population. The problem of allocation concerns the choice of the sample sizes in the respective strata, *i.e.*, how many units should be taken from each stratum such that the total sample is *n*. In this context the species variability /richness has been considered.

Estimation of mean and variance

In this study, the population of N units is first divided into k strata of N_1, $N_2, \ldots, N_k$ units respectively. These strata are non-overlapping and together they comprise the whole population, so that

$N_1 + N_2 + \ldots + N_k = N$

When the strata have been determined, a sample is drawn from each stratum, the selection being made independently in each stratum. The sample sizes within the strata are denoted by $n_1, n_2, \ldots, n_k$ respectively, so that

$n_1 + n_2 + \ldots + n_3 = n$

Let y_{tj} ($j = 1, 2, \ldots, N_t$; $t = 1, 2, \ldots k$) be the value of the characteristic under study for the j the unit in the tth stratum. In this case, the population mean in the stratum is given by the expression:

$$\boxed{\overline{Y}_t = \frac{1}{N_t}\sum_{j=1}^{N_t} y_{tj}, (t = 1, 2, \ldots, k)}$$

The overall population mean is given by

$$\boxed{\overline{Y} = \frac{1}{N}\sum_{t=1}^{k} N_t \overline{Y}_t}$$

The estimate of the population mean $\overline{Y}$, in this case was obtained by

$$\boxed{\hat{\overline{Y}} = \frac{\sum_{t=1}^{k} N_t \overline{y}_t}{N}}$$

Where,

$$\boxed{\bar{y}_t = \sum_{j=1}^{n_t} \frac{y_{tj}}{n_t}}$$

Estimate of the variance of $\hat{\bar{Y}}$ is given by

$$\boxed{\hat{V}(\hat{\bar{Y}}) = \frac{1}{N^2} \sum_{t=1}^{k} N_t (N_t - n_t) \frac{s_{t(y)}^2}{n_t}}$$

Where,

$$\boxed{s_{t(y)}^2 = \sum_{j=1}^{n_t} \frac{(y_{tj} - \bar{y}_t)^2}{n_t - 1}}$$

Stratification, if properly done generates lower variance for the estimated population total or mean than a simple random sample of the same size. This leads to the assurance of quality data, which is followed in all the selected sites to achieve the relative abundance of each species. This is the foundation of assessing site- and species-wise biomass and stored carbon in the study area.

PHASE B: EXPERIMENTAL DESIGN

1. ABOVE GROUND BIOMASS (AGB) ESTIMATION

Above Ground Biomass (AGB) in tree species refers to the sum total of stem, branch and leaf biomass that are exposed above the soil.

i. STEM BIOMASS ESTIMATION

The stem volume of each species in each of the 10 plots (10m × 10m) per site was estimated using the Newton's formula (Husch *et al.*, 1982).

$$V = h/6\ (A_b + 4A_m + A_t)$$

Where V is the volume (in m^3), h the height measured with laser beam (BOSCH DLE 70 Professional model), and A_b, A_m, and A_t are the areas at base, middle and top respectively. Specific gravity (G) of the wood was estimated taking the stem cores by boring 4.5 cm deep. This was converted into stem biomass (B_S) as per the expression $B_S = GV$. The stem biomass of individual tree was finally multiplied by the number of trees of each species in 10 selected plots (per site) in all the selected stations and the mean values are expressed in t ha^{-1}.

ii. BRANCH BIOMASS ESTIMATION

The total number of branches irrespective of size was counted on each of the sample trees. These branches were categorized on the basis of basal diameter into three groups, *viz.* < 6 cm, 6–10 cm and >10 cm. The leaves on the branches were removed by hand. The branches were oven-dried at 70^0C overnight in hot air oven in order to remove moisture content if any present in the branches. Dry weight of two branches from each size group was recorded separately using the equation of Chidumaya (1990).

$$B_{db} = n_1bw_1 + n_2bw_2 + n_3bw_3 = \Sigma\ n_ibw_i$$

Where B_{db} is the dry branch biomass per tree, n_i the number of branches in the ith branch group, b_{wi} the average weight of branches in the ith group and i = 1, 2, 3, …..n are the branch groups. The mean branch biomass of individual tree was finally multiplied with the number of trees of each species in all the 10 plots for each site and expressed in t ha^{-1}.

iii. LEAF BIOMASS ESTIMATION

For leaf biomass estimation, one tree of each species per plot was randomly considered. All leaves from nine branches (three of each size group) of individual trees of each species were removed and oven dried at 70^0C and dry weight (species-wise) was estimated. The leaf biomass of each tree was then calculated by multiplying the average biomass of the leaves per branch with the number of branches in that tree. Finally, the dry leaf biomass of the selected species (for each plot) was recorded as per the expression:

$$\mathbf{L_{db} = n_1Lw_1N_1 + n_2Lw_2N_2 + \ldots\ldots\ldots n_iLw_iN_i}$$

Where L_{db} is the dry leaf biomass of selected urban species per plot, $n_{1..}\ldots n_i$ are the number of branches of each tree of the species, Lw_1 …….Lw_i are the average dry weight of leaves removed from the branches and $N_{1\ldots\ldots\ldots}N_i$ are the number of trees per species in the plots. This exercise was performed for all the sites and the mean results were finally expressed in t ha^{-1}.

The leaf and stem portions of the shrub represents the AGB. These shrubs were handpicked and the AGB was oven dried and directly weighed and expressed in Kg m^{-2}.

2. ABOVE GROUND CARBON (AGC) ESTIMATION

Direct estimation of percent carbon in the AGB (referred to as AGC) was done by CHN analyzer, after grinding and random mixing the oven-dried stem, branches and leaves separately for each species. For this, a portion of fresh sample of stem, branch and leaf from trees (of each species) was oven dried at 70^0C, randomly mixed and ground to pass through a 0.5 mm screen (1.0 mm screen for leaves). The carbon content (in %) was finally analyzed for each part of each species through a *Vario MACRO elementar CHN* analyzer.

The mean carbon values of these vegetative parts were considered as the stored carbon in AGB of each species and finally converted to CO_2 – equivalent by multiplying with a factor of 3.67.

Analysis of Carbon in the vegetation and litter with calibration

Elemental Analyser provides a means for the rapid determination of C, H, N, and S in organic matrices and other type of materials. They are capable of handling wide variety of sample types, including solids, liquids, volatile and viscous samples in the field of pharmaceuticals, polymer, chemicals, environment, food, energy.

In the present study total carbon content of stem, branch and leaf and litter of the floral species was determined.

The Elemental Analyser converts samples into CO_2, N_2, SO_2 and H_2 when used in combustion mode. Dried and powdered samples of 1 to 2.5 mg are taken into small tin capsules. The tin capsules with samples were loaded onto solid auto sampler. When the auto sampler was triggered, the samples fell inside the ball valve which then rotated at a 90^0 angle and got flushed by helium gas. Then the sample was released into combustion tube that was held at $950\text{-}1150^0$C. As the sample was released into the combustion tube the samples got combusted in an atmosphere temporarily enriched with oxygen, where the tin promotes flash combustion. Over here it is essential to optimize the combustion process by ensuring that sufficient amount of oxygen was used otherwise, incomplete combustion of samples result in the mixing of residues of the first sample with the next sample.

The combustion products were then carried through, on oxidation catalyst by a constant flow of helium. The oxidation catalyst used here was CuO, so as the combustion products passed through this, they got converted into their respective oxides. This then was passed through the lead chromate where the sulphur got absorbed. The oxidation products were then passed through a reduction reactor at 550-850°C, depending on operation, containing Cu granules, where oxides of N were reduced to elemental form N_2 and excess oxygen was removed. Then further it was passed through silver wool where halogens were absorbed and then passed through Sicapent *i.e.* potassium pentoxide which absorbs the moisture present. The remaining CO_2, N_2, and SO_2 were then passed into an absorption column that physically absorbs the gas mixture and then release them separately (Gas Chromatography). Then they pass through a thermal conductivity detector for quantification. Sulphonilamide standards were used for calibration.

3. CO_2 - EQUIVALENT ESTIMATION

The weight of CO_2 is C + 2 × O (Oxygen) = 43.99915. Hence, the ratio of CO_2 to C is calculated as: 43.99915/12.001118 = 3.6663. Therefore, in order to determine the weight of carbon dioxide sequestered in the tree (CO_2-equivalent), the weight of carbon in the vegetative parts of the tree is multiplied by 3.6663.

4. LITTER BIOMASS and LITTER CARBON ESTIMATION

The amount of dead plant material in a forest, or detritus, is composed of fine litter on the forest floor, (leaves, fruits, flowers, twigs, bark fragments, branches, standing dead trees and snags, and lying dead wood) greater than 10 cm diameter. The amount of fine litter on the forest floor represents the balance between inputs from litter fall and outputs from decomposition, both of which vary widely across the tropics.

Litter fall was determined by setting 10 rectangular traps (1m × 1m) in each of the selected plots per site. The traps were made of 1 mm mesh size nylon screen, through which rainwater can pass (Brown, 1984). The contents of all the selected quadrats per plot were collected and brought to the laboratory, where it was dried to a constant weight overnight at 80°C. Finally the mean litter weight per site was estimated and expressed in Kg m^{-2} unit. Finally the carbon content (in %) was estimated through CHN analyzer.

5. SOIL ORGANIC CARBON (SOC) ESTIMATION

Soil samples from the upper 5 cm were collected from all the 10 plots of each site and dried at 60^0C for 48 hrs. For analysis, visible plant particles were handpicked and removed from the soil. After sieving the soil through a 2 mm sieve, the samples of the bulk soil (50 gm from each plot) were ground finely in a ball – mill. The fine dried sample was randomly mixed to get a representative picture of the study site. Modified version of Walkley and Black method (1934) was then followed to determine the organic carbon of the soil in %.

The flow chart for determining of SOC is shown in Scheme 2.

SCHEME 2. WALKLEY AND BLACK

↓

1 gm of dried soil was taken in a conical flask

1 ml of phosphoric acid (H_3PO_4) and 1 ml of distilled water were added

↓

The mixture was heated for 10 min at 100 to 110° C

↓

10 ml 1 N potassium dichromate ($K_2Cr_2O_7$) and 20 ml concentrated sulphuric acid (H_2SO_4) with silver sulphate (Ag_2SO_4) were added and mixed.

↓

Allowed the mixture to stand for 30 minutes

↓

The mixture was diluted to 200 ml with distilled water and 10 ml of phosphoric acid (H_3PO_4) and 1 ml of indicator (diphenyl amine) were added.

↓

The colour of the mixture changed to bluish purple

↓

The mixture was titrated with Mohr salt solution [$(NH_4)_2Fe(SO_4)_2.6H_2O$] until the colour of the solution changed to brilliant green

↓

The same titration was repeated without taking soil and the volume of the potassium dichromate required to oxidize organic carbon was calculated from the difference

CALCULATION

% of CARBON = 3.951/g x (1- S/B)

Where, g = weight of sample in grams

S = Mohr salt solution for Sample

B = Mohr salt solution for blank

PHASE C: STATISTICAL ANALYSIS

Models provide compact ways of summarizing observed inter-relationships between variables and which will be essential for making prediction and inferences. The process of choosing the most appropriate model is very complex and requires lot of logics and exercises to mimic the real conditions.

Development of allometric equation has been based on proper selection of dependent and independent variables. In the first step, a subject or dependent variable (in this case AGB of selected mangrove species) has been considered. Then, easily measured attributes or independent variables (here DBH) are estimated. Finally a regression analysis has been performed as per the expression:

$$\mathbf{y = bx + a}$$

Where **y** is the dependent variable, **x** is the independent variable, **b** is the slope and **a** is constant. The accuracy of the model is determined by the magnitude of R^2 values. More the R^2 value approaches towards 1, the better is the accuracy of the model.

RESULTS

It is clear from the results that the carbon budget in stored form is relatively higher in the Zuari estuarine system comared to the Mandovi estuarine system (Tables 7-12).

Table 7: Values and Average values of variables during postmonsoon 2016

	Mandovi				Zuari			
	Site 1	Site 2	Site 3	Avg.	Site 1	Site 2	Site 3	Avg.
AGB (t/ha)	6.22	3.02	18.69	9.31	8.13	4.23	21.45	11.27
AGC (t/ha)	2.9	0.67	8.61	4.06	4.85	2.15	9.23	5.41
CO_2-equivalent (t/ha)	10.63	4.92	31.61	15.72	13.45	7.39	28.14	16.33
SOC	1.05	1.07	1.07	1.06	1.13	1.16	1.2	1.16
Litter Carbon (Kg/m^2)	4.89	5.03	5.1	5.01	5.12	5.37	5.26	5.25

Table 8: Values and Average values of variables during premonsoon 2016

	Mandovi				Zuari			
	Site 1	Site 2	Site 3	Avg.	Site 1	Site 2	Site 3	Avg.
AGB (t/ha)	9.54	52.5	69.38	43.81	10.67	62.34	88.35	53.79
AGC (t/ha)	5.31	2.45	33.4	13.72	5.6	24.67	38	22.76
CO_2-equivalent (t/ha)	19.48	6.78	122.58	49.61	21.23	6.23	139.47	55.64
SOC	1.08	1.11	1.08	1.09	1.25	1.22	1.25	1.24
Litter Carbon (Kg/m^2)	4.92	5.07	5.13	5.04	5.67	5.56	5.59	5.61

Table 9: Values and Average values of variables during monsoon 2016

	Mandovi				Zuari			
	Site 1	Site 2	Site 3	Avg.	Site 1	Site 2	Site 3	Avg.
AGB (t/ha)	12.58	54.74	78.11	48.48	13.67	139	101.24	84.64
AGC (t/ha)	8.12	2.95	41.1	17.39	15.29	61.87	49.03	42.06
CO_2-equivalent (t/ha)	24.23	7.32	127.51	53.02	56.13	192.43	106.16	118.24
SOC	1.11	1.15	1.09	1.12	1.29	1.3	1.29	1.29
Litter Carbon (Kg/m^2)	4.95	5.1	5.15	5.07	5.74	5.72	5.69	5.72

Table 10: Values and Average values of variables during postmonsoon 2017

	Mandovi				Zuari			
	Site 1	Site 2	Site 3	Avg.	Site 1	Site 2	Site 3	Avg.
AGB (t/ha)	35.68	117.23	88.95	80.62	41.23	133.34	86.37	86.98
AGC (t/ha)	9.17	22.3	28.16	19.88	11.67	51.17	39.99	34.28
CO_2-equivalent (t/ha)	27.87	81.85	133.32	81.01	38.98	151.11	110.23	100.11
SOC	1.13	1.17	1.12	1.14	1.21	1.2	1.21	1.21
Litter Carbon (Kg/m^2)	5.01	5.11	5.17	5.10	5.89	5.9	5.89	5.89

Table 11: Values and Average values of variables during premonsoon 2017

	Mandovi				Zuari			
	Site 1	Site 2	Site 3	Avg.	Site 1	Site 2	Site 3	Avg.
AGB (t/ha)	42.35	122.87	93.89	86.37	45.9	135.87	102.3	94.69
AGC (t/ha)	10.98	24.07	43.11	26.05	19.93	53.28	49.22	40.81
CO_2-equivalent (t/ha)	31.21	87.19	145.67	88.02	71.45	161.00	132.44	121.63
SOC	1.17	1.21	1.16	1.18	1.25	1.28	1.27	1.27
Litter Carbon (Kg/m^2)	5.04	5.13	5.20	5.12	5.91	5.95	5.96	5.94

Table 12: Values and Average values of variables during monsoon 2017

	Mandovi				Zuari			
	Site 1	Site 2	Site 3	Avg.	Site 1	Site 2	Site 3	Avg.
AGB (t/ha)	46.17	129.42	97.48	91.02	50.13	137.89	121.33	103.12
AGC (t/ha)	12.31	26.34	34.03	24.23	26.44	56.78	7.9	30.37
CO_2-equivalent (t/ha)	36.99	95.13	151.93	94.68	78.45	153.82	26.49	86.25
SOC	1.22	1.24	1.19	1.22	1.29	1.3	1.3	1.30
Litter Carbon (Kg/m^2)	5.07	5.18	5.21	5.15	5.99	6.01	6.02	6.01

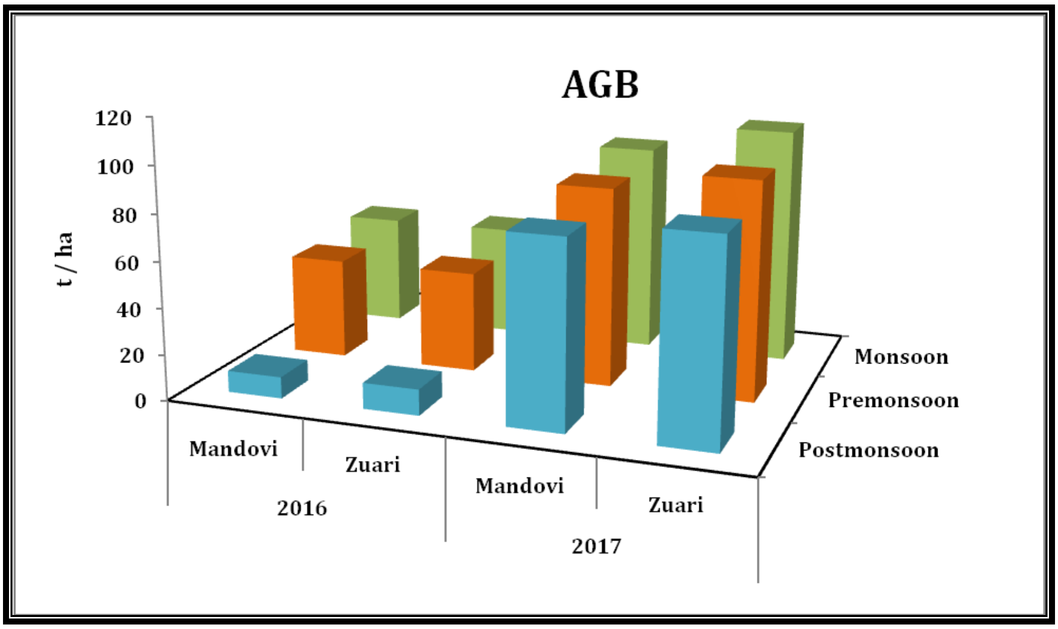


Fig. 6. Average AGB values in Mandovi and Zuari estuaries during 3 seasons in 2016 and 2017

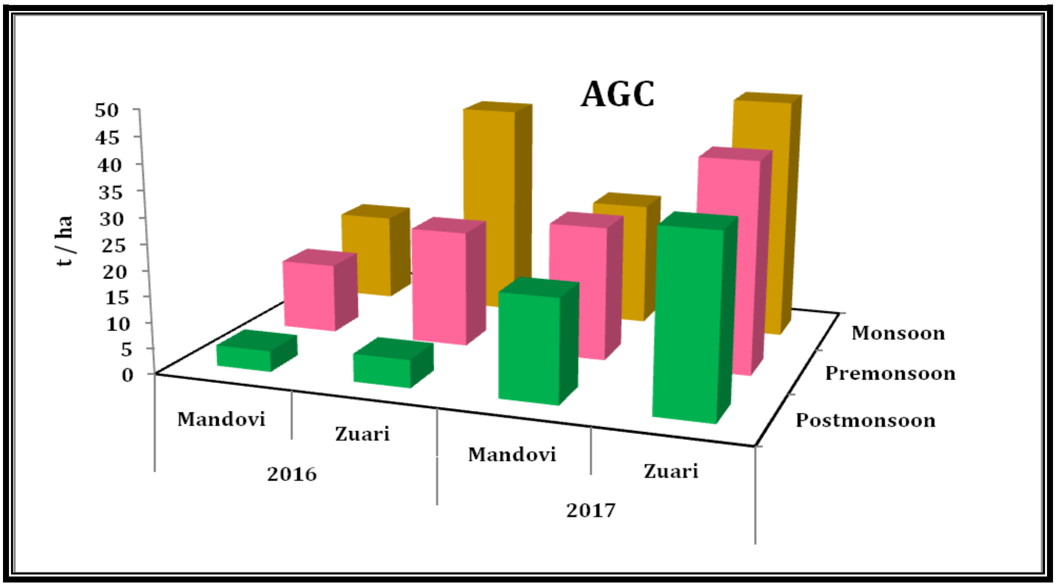


Fig. 7. Average AGC values in Mandovi and Zuari estuaries during 3 seasons in 2016 and 2017

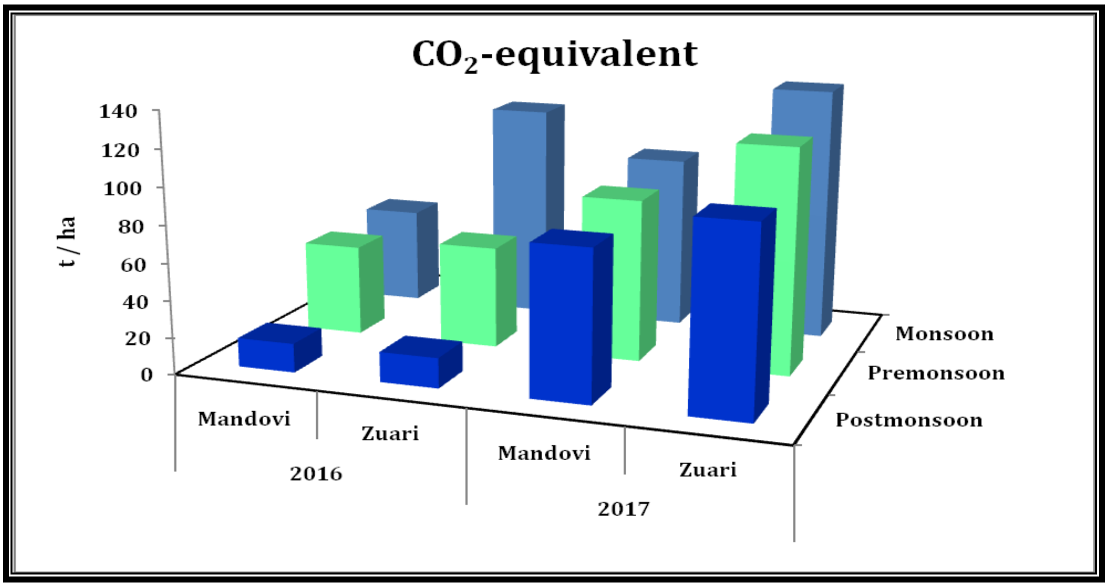


Fig. 8. Average CO_2-equivalent in Mandovi and Zuari estuaries during 3 seasons in 2016 and 2017

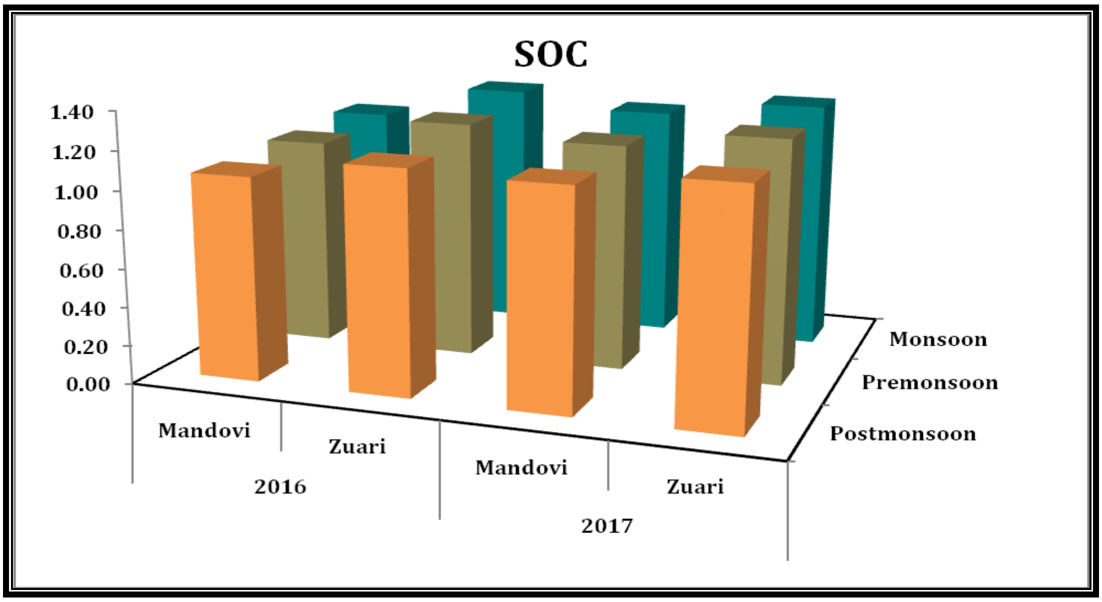


Fig. 9. Average SOC values in Mandovi and Zuari estuaries during 3 seasons in 2016 and 2017

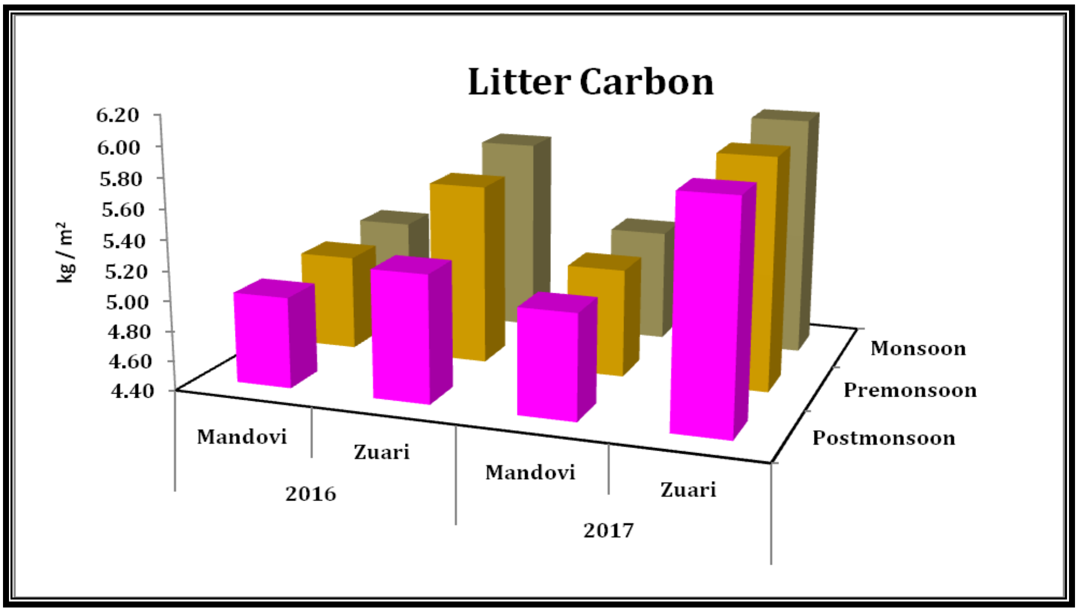


Fig. 10. Average values of litter carbon in Mandovi and Zuari estuaries during 3 seasons in 2016 and 2017

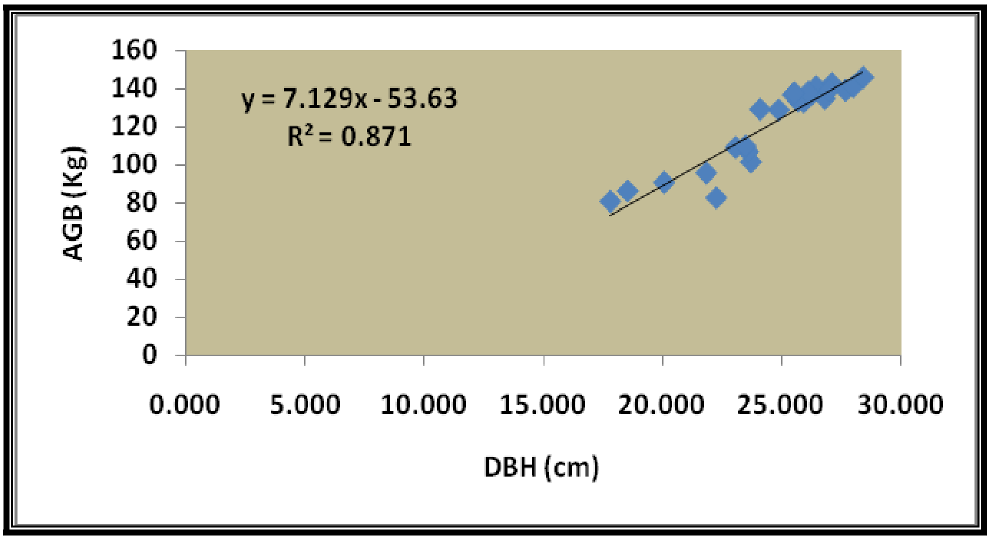


Fig. 11. Scatter plot showing the inter-relationship between DBH and AGB of *Avicennia alba* at Mandovi estuary during 2016

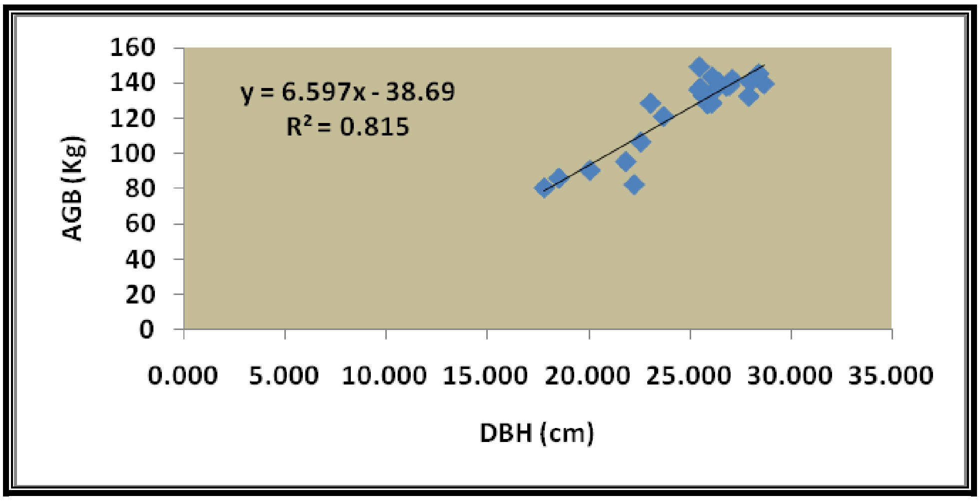


Fig. 12. Scatter plot showing the inter-relationship between DBH and AGB of *Avicennia alba* at Mandovi estuary during 2017

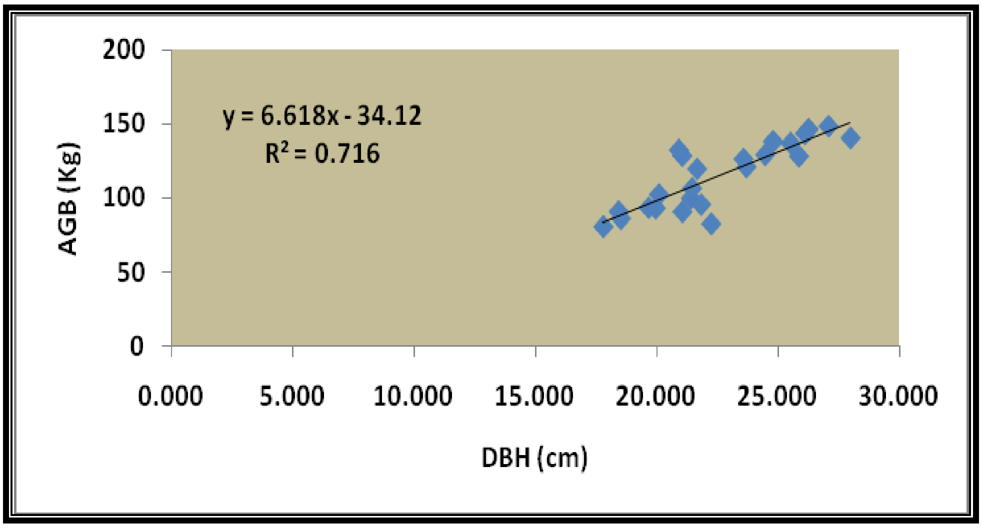


Fig. 13. Scatter plot showing the inter-relationship between DBH and AGB of *Avicennia marina* at Mandovi estuary during 2016

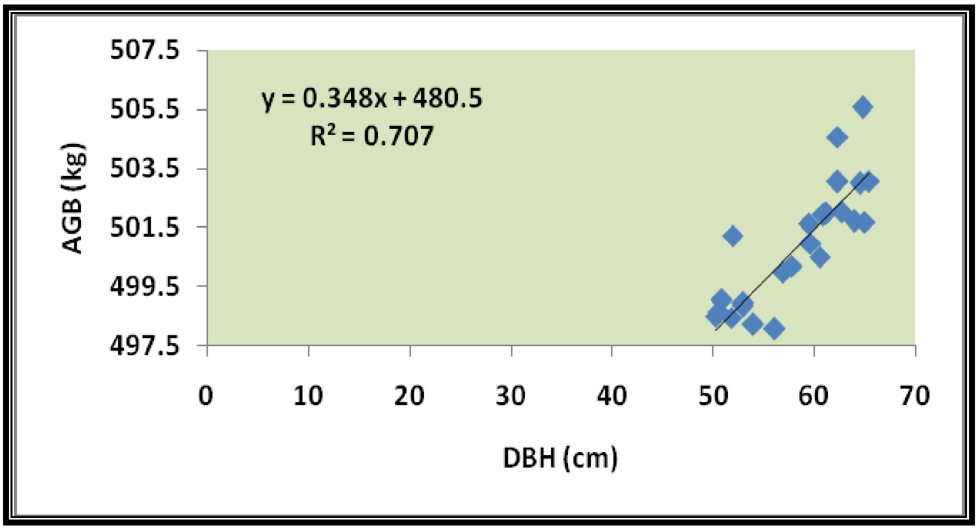


Fig. 14. Scatter plot showing the inter-relationship between DBH and AGB of *Avicennia marina* at Mandovi estuary during 2017

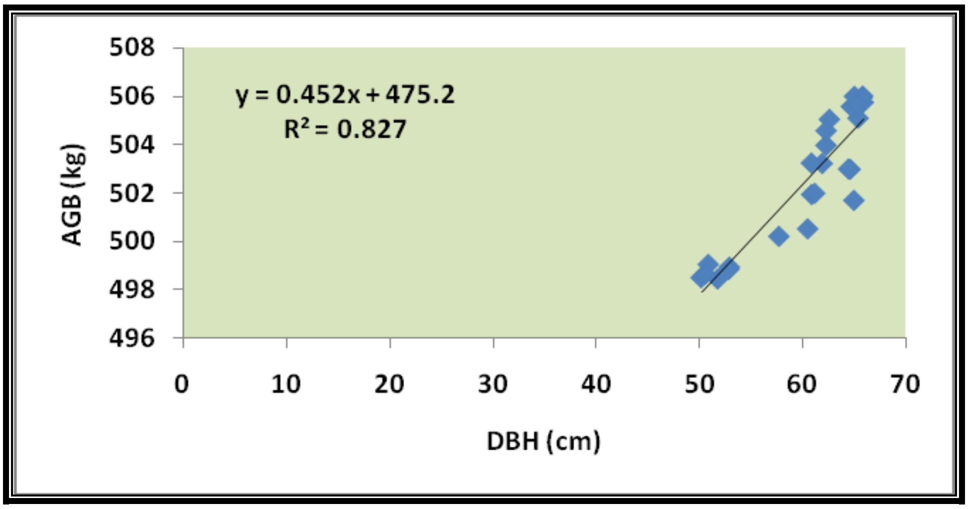


Fig. 15. Scatter plot showing the inter-relationship between DBH and AGB of *Excoecaria agallocha* at Mandovi estuary during 2016

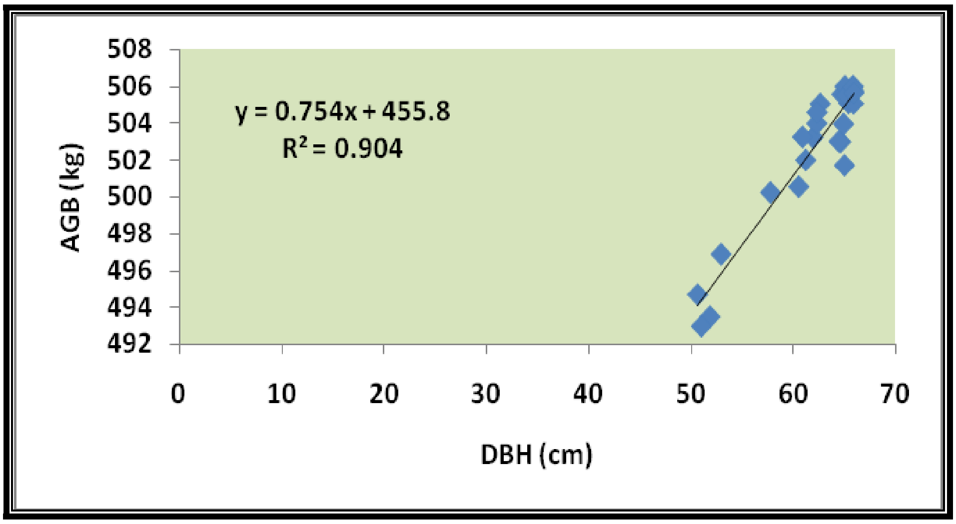


Fig. 16. Scatter plot showing the inter-relationship between DBH and AGB of *Excoecaria agallocha* at Mandovi estuary during 2017

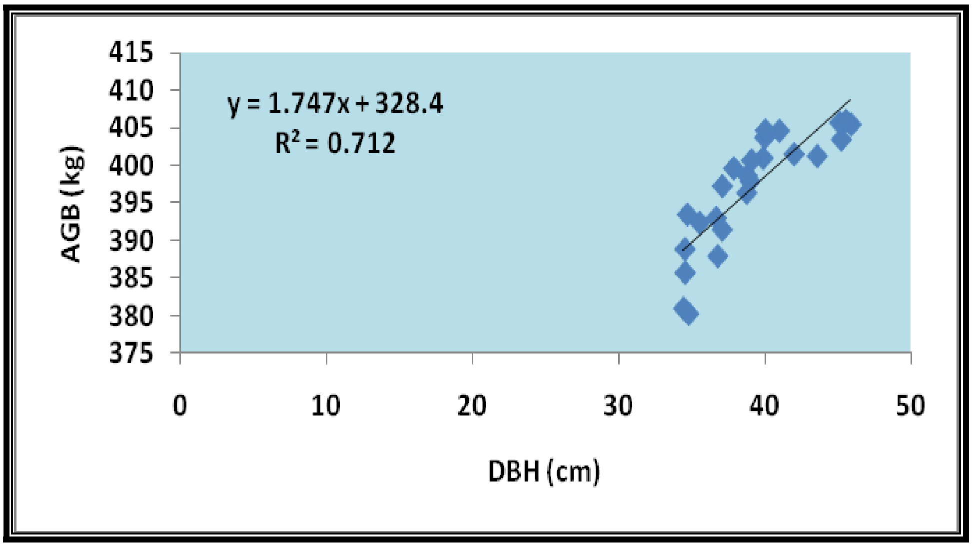


Fig. 17. Scatter plot showing the inter-relationship between DBH and AGB of *Rhizophora mucronata* at Mandovi estuary during 2016

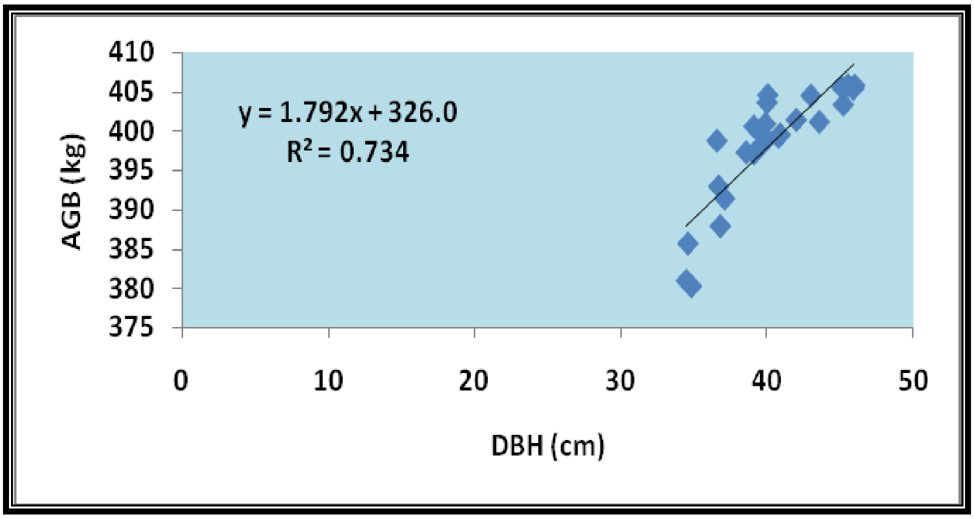


Fig. 18. Scatter plot showing the inter-relationship between DBH and AGB of *Rhizophora mucronata* at Mandovi estuary during 2017

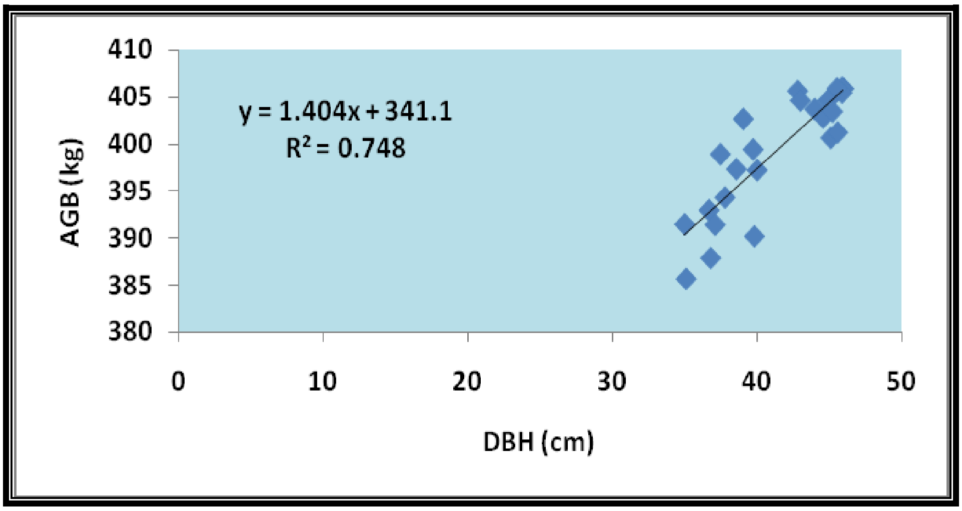


Fig. 19. Scatter plot showing the inter-relationship between DBH and AGB of *Avicennia marina* at Zuari estuary during 2016

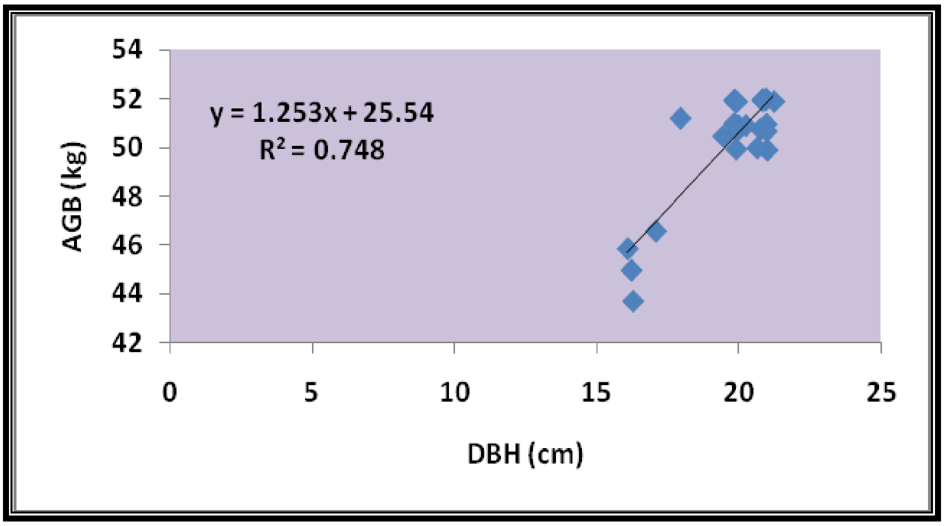


Fig. 20. Scatter plot showing the inter-relationship between DBH and AGB of *Avicennia marina* at Zuari estuary during 2017

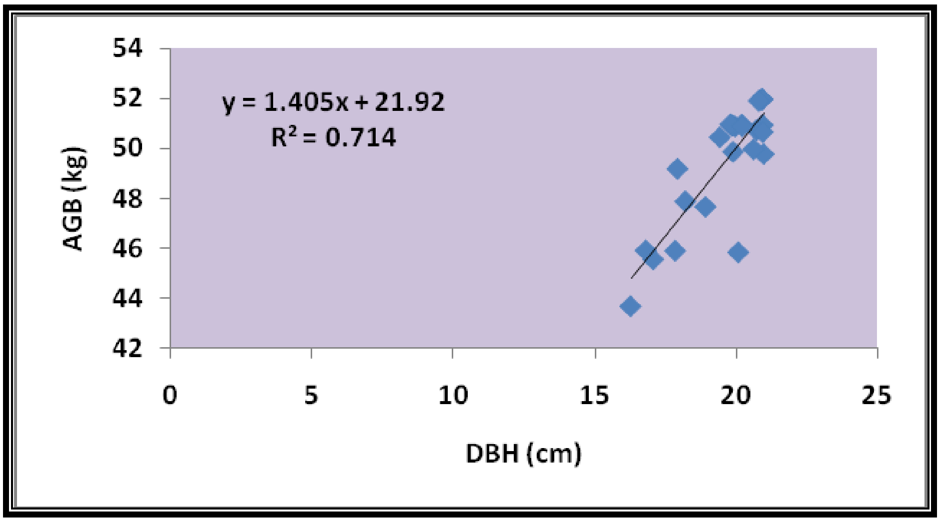


Fig. 21. Scatter plot showing the inter-relationship between DBH and AGB of *Rhizophora mucronata* at Zuari estuary during 2016

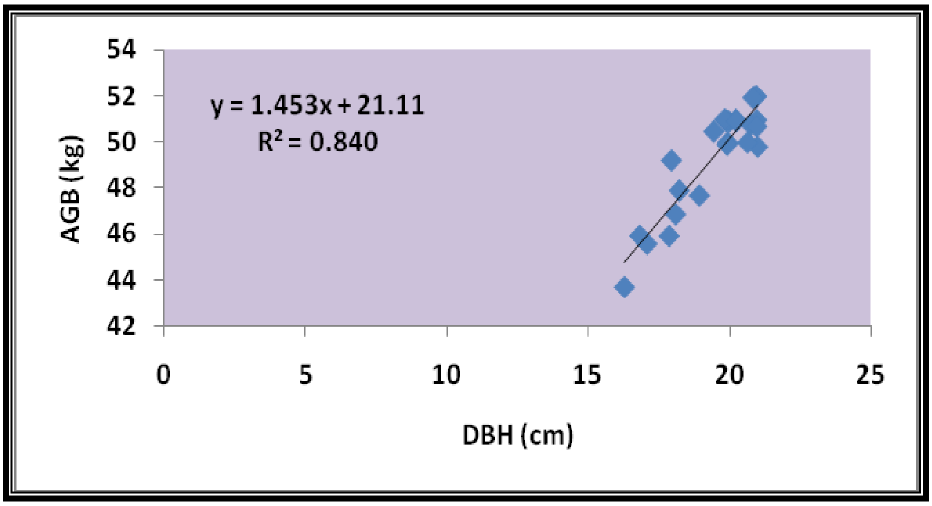


Fig. 22. Scatter plot showing the inter-relationship between DBH and AGB of *Rhizophora mucronata* at Zuari estuary during 2017

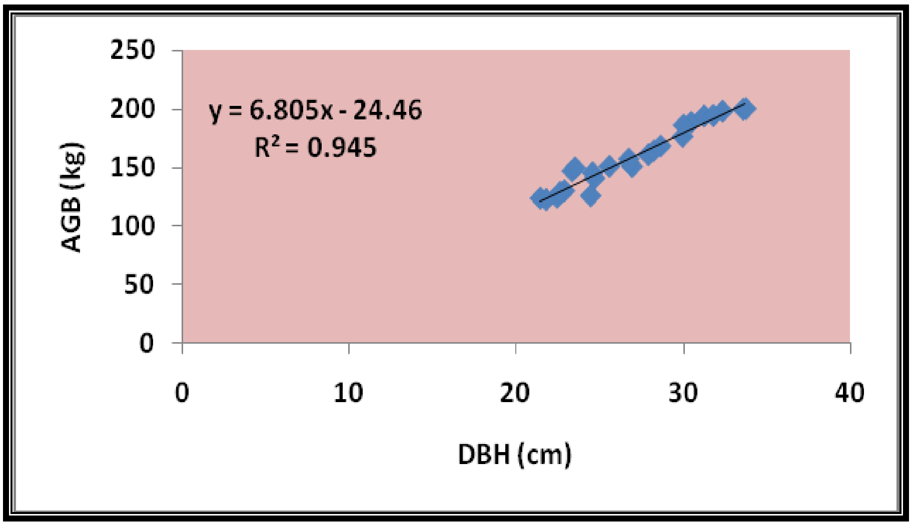


Fig. 23. Scatter plot showing the inter-relationship between DBH and AGB of *Excoecaria agallocha* at Zuari estuary during 2016

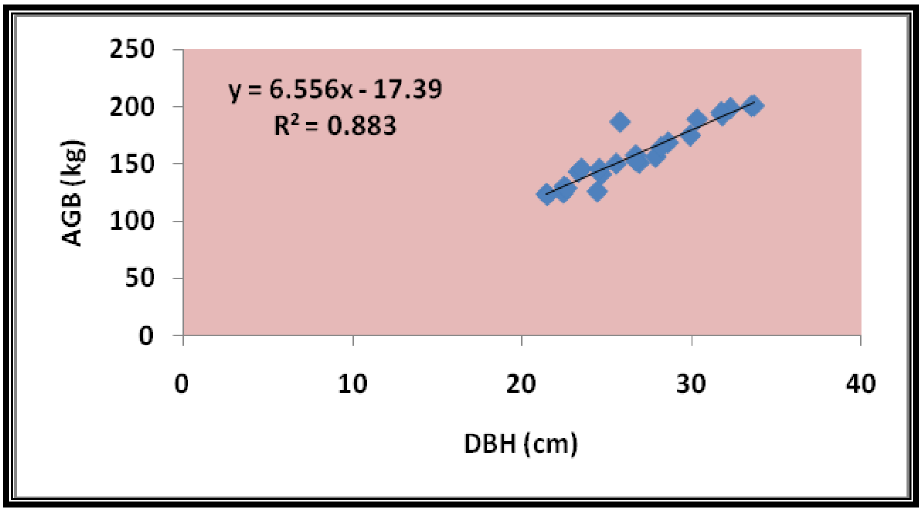


Fig. 24. Scatter plot showing the inter-relationship between DBH and AGB of *Excoecaria agallocha* at Zuari estuary during 2017

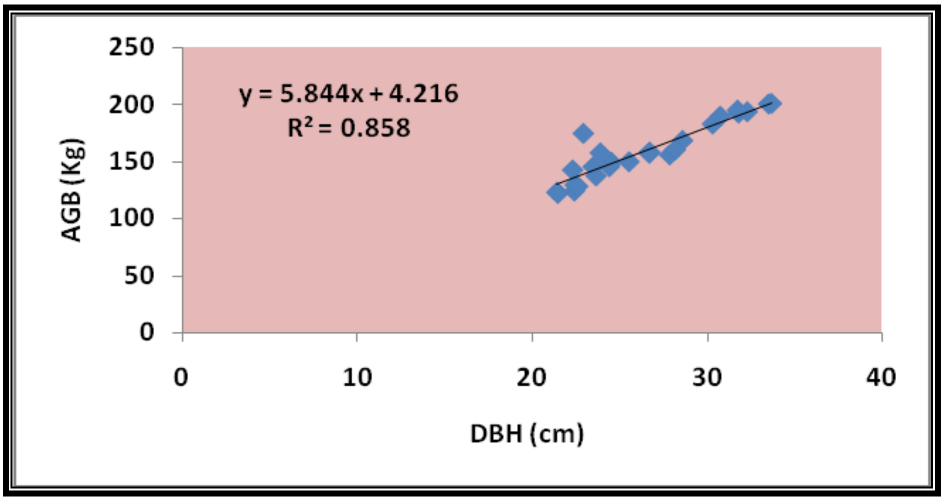


Fig. 25. Scatter plot showing the inter-relationship between DBH and AGB of *Rhizophora apiculata* at Zuari estuary during 2016

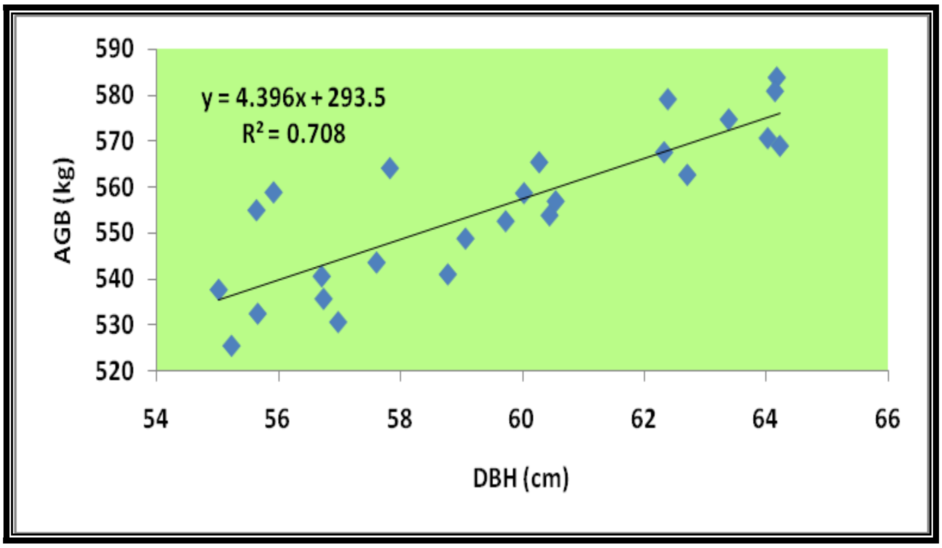


Fig. 26. Scatter plot showing the inter-relationship between DBH and AGB of *Rhizophora apiculata* at Zuari estuary during 2017

DISCUSSION

Over the past few decades, research articles on mangrove ecosystem services primarily focused on four major groups namely 1) nursery services of mangrove forest, 2) fuel, fodder and timber generation as sources of livelihood for adjacent coastal population and island dwellers, 3) Shoreline stabilization and land-building capacity and 4) carbon storage and subsequent sequestration.

Mangroves have several ecosystem services in context to coastal industries and urban developments as listed here:

- Prevent the spread of fugitive dust generated due to industrial and allied activities
- Attenuate noise generated by the port and industrial activities
- Reduce soil erosion
- Help to stabilise the slope of external soil and over-burden dumps
- Increase green cover and improve aesthetics
- Accelerate recolonisation of the area

However, steps have been adopted in recent time to assess the ecosystem service of this green cover in terms of carbon sequestration and this study has the primary mission in this direction in the framework of Goa coast.

A careful observation on the status of stored carbon in the vegetation and soil reservoir of Mandovi and Zuari exhibits a significant difference between the two estuarine areas. The values of stored carbon in the mangroves and soil of intertidal mudflats of Zuari are relatively higher compared to Mandovi estuarine region. The average AGB of Zuari mangroves is 47.33 % and 10.38 % higher than Mandovi mangroves during 2016 & 2017 respectively. The AGC also exhibits the same trend with 99.74% higher value during 2016 and 50.28% higher value in 2017.

The litter carbon values of Zuari mangrove system are also higher by 9.72% and 16.21% compared to Mandovi mangroves during 2016 and 2017 respectively. The SOC, being the proxy to litter and detritus biomass exhibits similar trend. The values of SOC in the intertidal mudflats of Zuari are 12.84% and 6.78% higher than Mandovi during 2016 and 2017 respectively. The variations between the two estuarine systems can be visualized after critically analyzing the figures (Fig. 6 – 10).

The hydrological parameters (preferably the salinity) may be the key driver behind this contrasting variation between these two estuarine systems in the carbon framework. The salinity of Zuari estuary (~ 27.5 psu) is lower than that of Mandovi (~ 30.5 psu). The role of salinity as growth regulator of mangroves has been pointed out by several researchers. Along with biomass/ growth of mangrove species, the magnitude of stored carbon in the vegetation also exhibits variation by the influence of ambient aquatic salinity.

Salinity of the brackish water ecosystem is the consequence of the interaction among the frequency of tidal inundation, evaporation and supply of fresh water (Clarke and Hannon, 1969). Other factors contributing towards the development of salinity include soil type and topography, depth of impervious subsoil, amount and seasonality of rainfall, freshwater discharge in rivers, and run off from adjacent landmasses (Hutchings and Saenger, 1987). Increased temperature enhances evaporation and thereby causes increased salinity. Rainfall through adding freshwater in the ecosystem reduces salinity and makes the environment suitable for mangrove growth and survival. Humidity regulates the evapo-transpiration in the mangrove and thus in turn regulates salt movement in the soil. High salinity accompanied with high temperature and wind causes accumulation of salt at the surface of the soil that makes the site unsuitable for mangroves. The extent of plant cover also has a significant influence on evaporative losses from the mangrove community (Hutchings and Saenger, 1987). Presence of salt is a critical factor for the development of mangrove ecosystems. At lower intensities it favors the development of mangroves eliminating more vigorous terrestrial plants which other wise could compete with. On the contrary at increased level it might cause overall degradation of mangroves. Salinity affects plant growth in a variety of ways: 1) by limiting the availability of water against the osmotic gradient, 2) by reducing nutrient availability, 3) by causing accumulation of Na^+ and Cl^- in toxic concentration causing water stress conditions enhancing closure of stomata, reduced photosynthesis (Jalil, 2002). Salinity is also a controlling factor for mangrove seedling recruitment and the relation is negatively proportional. Siddiqi (2001) noted reduced recruitment of *Heritiera fomes* and *Excoecaria agallocha* seedling in the Sundarbans mangrove forest with increased salinity. Ball and Pidsley (1995) observed adverse impact of increased salinity on canopy development, leaf initiation, and leaf area expansion in *Sonneratia alba* and *Sonneratia lanceolata*. In Indian coastal region, the adverse impact of salinity on the growth of mangrove species has been documented (Mitra *et al.*, 2004). Salinity, therefore, greatly influences the overall growth and productivity of the mangroves (Das and Siddiqi, 1985).

The overall results, however point the mangroves of Mandovi and Zuari as the unique sink of carbon and management of edaphic factors and salinity through channelization of rain water in the hypersaline zone of intertidal mudflats may serve as a road map to boost up the biomass and stored carbon in the mangrove vegetation.

It is interesting to note that in all the two estuaries, the AGB has direct proportionality with the DBH (Diameter at breast height) of the floral species (***vide the scatter plots***: Fig. 11-26). Thus a long term study may be the road map to develop allometric model through which the AGB can be predicted by measuring the DBH of the trees.

In this study it is also interesting to note that the AGC is directly proportional to AGB.

The importance of green cover in reducing GHGs is a burning issue throughout the globe. COP also echoed in the same line of reducing the GHGs. At COP21, held in Paris in November-December 2015, the parties negotiated (what is known as the Paris Agreement), to establish specific actions and targets for reducing greenhouse gases emissions, mitigating and adapting to the effects of climate change, and financing mitigation and adaptation efforts in developing countries. The agreement took effect nearly a year later. Signatory countries agreed to work to limit global temperature rise to below 2°C and to make strong efforts to keep the rise to 1.5°C. The Paris Agreement is especially significant because it is a legally binding agreement. The curbing and retardation pace of GHGs can effectively be carried out through massive plantation and expansion of mangrove forest biome, which is the primary basis of the present study. Seasonal and long term study of this nature can lead to the validation of such scientific exercise in and around the coastal zone with major deliverables like (i) development of carbon sequestration potential series (amongst the mangrove species) (ii) management of edaphic factors to accelerate biomass and (iii) development of long term data bank (archive) on species-wise CO_2-equivalent.

Time has come to recognize and articulate the importance of mangrove trees as a vital component of the coastal landscape. There is a need for greater attention to be paid to the selection of trees in coastal zone, not just with a view to easy maintenance as is currently the case, but to select an appropriate mix of trees because if we view the current trend across the coastal areas for tree diversity, the exotics dominate the native species and the value of native species as an sustainable asset is often ignored therefore challenge towards building native biodiversity is needed as it may bring about ecological integrity and ability to sequester carbon in coastal landscapes. Native and dominant trees are considered ecologically beneficial as they have relatively high efficiency of carbon fixation; these species may be suitable for checking environmental pollution and may provide a good option for maximum carbon fixation.

REFERENCES

Adams, J.M. and Piovesan, G. 2005. Long series relationships between global interannual CO_2 increment and climate: Evidence for stability and change in role of the tropical and boreal temperate zones. Chemosphere, 59, 1595–1612.

Adams, J.M., Faure, H., Faure-Denard, L., McGlade, J.M. and Woodward, F.I. 1990. Increases in terrestrial carbon storage from the last glacial maximum to the present. Nature, 348, 711-714.

Agarwal, S.K., Fazli, P., Zaman, S. and Mitra, A. 2018. Near surface Air temperature and carbon dioxide in Indian Sundarbans: A Time series Analysis. Parana Journal of Science and Education, 4 (1), 10-15.

Ajtay, G.L., Ketner, P. and Duvigneaud, P. 1979. Terrestrial primary production and phytomass. In: B. Bolin, E. T. Degens, S. Kempe and P. Ketner, Eds., The Global Carbon Cycle, John Wiley & Sons, Chichester, 1979, pp. 129-181.

Alongi, D.M. 2014. Carbon cycling and storage in mangrove forests. Annual Review of Marine Science, 6, 195–219.

Alongi, D.M., Boto, K.G. and Robertson, A.I. 1992. Nitrogen and phosphorous cycle's pp. 251-292. In: Robertson, A.I and D.M. Alongi (Eds). Tropical mangrove ecosystems. American Geophysical Union, Washington, D.C.

Amarasinghe, M.D. and Balasubramaniam, S. 1992. Structural properties of two types of mangrove stands on the northwestern coast of Sri Lanka. Hydrobiologia, 247, 17-27.

Ball, M.C., and Pidsley, S.M. 1995. Growth responses to salinity in relation to distribution of two mangrove species, *Sonneratia alba* and *Sonneratia lanceolata* in Northern Australia. *Functional Ecology*, 9:77-85.

Bazilevich, N.I. 1974. Energy flow and biogeochemical regularities of the main world ecosystems. - In: Cave, A.l.(ed.) Proceeding of the First International Congress of

Ecology. Structure, Functioning and Management of Ecosystems, pp. 182-186. Wageningen: Pudoc

Bazilevich, N.I., Rodin, L.Y. and Rozov, N.N., 1971. Geographical aspects of biological productivity. Sov. Geogr. Rev. Transl. 12: 293-317; and Pap. Vth Congr. USSR Geographical Society, Leningrad, 1970.

Berner, R.A. 1982. Burial of organic carbon and pyrite sulfur in the modern ocean: Its geochemical and environmental significance. American Journal of Science, 282, 451–473.

Bohn, H.L. 1976. Estimate of organic carbon in world soils. Soil Science Society of America Journal, 40, 468-470.

Bohn, H.L. 1978. Organic soil carbon and CO_2. Tellus, 30, 472--475.

Bohn, H.L. 1982. Estimate of organic carbon in world soils: II. Soil Science Society American Journal, 46, 1118–1119.

Bolin, B., Degens, E.T., Duvigneaud, P. and Kempe, S. 1979. The Global Biogeochemical Carbon Cycle. In: Bolin, B., Degens, E.T., Kempe, S. and Kenter, P. (Eds.), The Global Carbon Cycle (1st Ed). Chichester, UK: John Wiley and Sons. pp. 1-56.

Boto, K. and Wellington, J. 1984. Soil characteristics and nutrient status in a Northern Australian mangrove forest. Estuaries and Coasts. 7, 61-69.

Briggs, S.V. 1977. Estimates of biomass in a temperate mangrove community. Australian Journal of Ecology, 2, 369-373.

Brown, L.R., Larsen, J., Dorn, J.G. and Moore, F. 2008. Time for Plan B: Cutting Carbon Emissions 80 Percent by 2020, EPI Release, 1-12.

Brown, S. and Lugo, A. E. 1984. Biomass of tropical forests: a new estimate based on forest volumes. *Science*, 223: 1290-1293.

Brown, S, Sathaye, J, Cannel, M and Kauppi, P. 1996. Management of forests for mitigation of greenhouse gas emissions. In: Watson, R T, Zinyowera, M C and R H Moss (eds), Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses, Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge and New York, Cambridge University Press, pp. 775-797.

Buringh, P. 1984. Organic carbon in soils of the world. In: The Role ofTerrestrial Vegetation in the Global Carbon Cycle.Measurements by Remote Sensing, pp. 91 – 109 (ed. G.M. Woodwell). SCOPE 23, JohnWiley & Sons, New York.

Caldeira, K. and Wickett, M.E. 2003. Anthropogenic carbon and ocean pH. Nature, 425, 365 – 365

Chave, J., Andalo, C., Brown, S., Cairns, M.A., Chambers, J.Q., Eamus, D., Fo¨ lster, H., Fromard, F., Higuchi, N., Kira, T., Lescure, J.P., Nelson, B.W., Ogawa, H., Puig, H., Rie´ra, B. and Yamakura, T. 2005. Tree allometry and improved estimation of carbon stocks and balance in tropical forests. Oecologia, 145, 87–99.

Chidumaya, E.N. 1990. Above ground woody biomass structure and productivity in a Zambezian woodland. Forest Ecology and Management, 36, 33-46.

Clark, D.A., Brown, S., Kiicklighter, D.W., Chambers, J.Q., Thomlinson, J.R.J.Ni., Holland, E.A. 2001. Measuring net primary production in forest: An evaluation and synthesis of existing field data. Ecological Applications, 11, 371-384.

Clarke, L.D. and Hannon, N.J. 1969. The mangrove swamp and salt marsh communities of the Sydney district:II. The holocoenotic complex with particulat reference to physiography. Journal of Ecology, 57, 213 – 234.

Clough, B. F. and Scott, K. 1989. Allometric relationship for estimating above ground biomass in six mangrove species. Forest Ecology and Management, 27, 117-127.

Clough, B.F., Dixon, P. and Dalhaus, O. 1997. Allometric relationships for estimating biomass in multi-stemmed mangrove trees. Australian. Journal of Botany, 45, 1023-1031.

Comley, B.W.T. and McGuinness, K.A. 2005. Above- and below-ground biomass and allometry of four common northern Australian mangroves. Australian Journal of Botany, 53, 431-436.

Constanza, R. et al., 1998. The value of the world’s ecosystem service and natural capital. Ecological Economics, 25, 3-15.

Cox, E.F and Allen, J.A. 1999. Stand structure and productivity of the introduced Rhizophora mangle in Hawaii. Estuaries, 22 (2A), 276–284.

Dahdouh-Guebas, F. and Koedam, N. 2006. Empirical estimate of the reliability of the use of the Point-Centred Quarter Method (PCQM): solutions to ambiguous field situations and description of the PCQM+ protocol. Forest Ecology and Management, 228, 1-18.

Das, S. and Siddiqi, N.A. 1985. The Mangroves and Mangrove forest of Bangladesh. Mangrove Silviculture Division, Bulletin No. 2, Bangladesh Forest Research Institute, Chittagong. mangrove plantations of the coast al afforestation project. UNDP Project BGD/85/085, Dhaka. Field document NO. 2. 69 pp.

Dixon, R.K. and Krankina, O.N. 1993. Forest fires in Russia: Carbon dioxide emissions to the atmosphere. Canadian Journal of Forest Research, 23, 700-705.

Dixon R.K., Brown S., Houghton R.A., Solomon A.M., Trexler M.C. and Wisniewski J. 1994. Carbon pools and flux of global forest ecosystems. Science, 263, 185–191.

Doney, S.C. and Naomi, M.L. 2006. How Long Can the Ocean Slow Global Warming? http://www.whoi.edu/oceanus/viewArticle.do?id=17726. Accessed April 24, 2012.

Dwyer, J.F., Mcpherson, E., Gregory, Schroeder, Herbert W., and Rowan, A.R. 1992. Assessing the benefits and costs of the urban forest. J. Arboricult. 18, 227-234.

Eswaran, H., Den Berg, E.V. and Reich, P. 1993. Organic carbon in soils of the world. Soil Science Society of American Journal, 57, 192-194.

Fromard, F., Puig, H., Mougin, E., Marty G., Betoulle, J.L. and Cadamuro, L. 1998. Structure, above-ground biomass and dynamics of mangrove ecosystems: New data from French Guiana. Oecologia, 115, 39–53.

Gattuso, J.P., Frankignoulle, M. and Wollast, R. 1998. Carbon and carbonate metabolism in coastal ecosystems. Annual Review of Ecology, Evolution, and Systematics, 29, 405-434.

Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Masek, J. and Duke, N. 2011. Status and Distribution of Mangrove Forests of the World Using Earth Observation Satellite Data. Global Ecology and Biogeography, 20, 154-159.

Gorham, E. 1990. Biotic impoverishment in northern peatlands. In: The earth in transition: patterns and processes of biotic impoverishment, Woodwell, G.M. (Ed.) Cambridge University, New York, NY, 65–98.

Gorham, E. and Janssens, J.A. 1992. Concepts of fen and bog reexamined in relation to bryophyte cover and the acidity of surface waters. Acta societalis botanicorum poloniae, 61, 7–20.

Grace, J., Malhi, Y., Higuchi, N. and Meir, P. 2001. Productivity of tropical rain forests. Terrestrial global productivity: past, present and future (ed. by H. Mooney, J. Roy and B. Saugier), pp. 401–426. Academic Press, San Diego, CA.

Guggenberger, G., Zech, W. and Schulten, H.R. 1994. Formation and mobilization pathways of dissolved organic matter: evidence from chemical structural studies of organic matter fractions in acid forest floor solutions. Organic Geochemistry, 21, 51–66.

Hair, D. and Sampson, R.N. 1992. Climate Change- History, prospects, and possible impacts. In Forests and Global Change Volume One: Opportunities for Increasing Forest Cover (Dwight Hair and R. Neil Sampson, eds.) American Forests, Washington, DC. pp. 1-10.

Harmon, M.E., Ferrell, W.K. and Franklin, J.F. 1990. Effects on carbon storage conversion of old-growth forests to young forests. Science, 247, 699-702.

Hopkinson, C.S. 1988. Patterns of organic carbon exchange between coastal ecosystems: the mass balance approach in salt marsh ecosystems. In Coastal-offshore ecosystem interactions, Jansson B-O, editor. Berlin: Springer-Verlag, pp. 122–54.

Husch, B., Miller, C.I. and Beers, T.W. 1982. Forest mensuration. Ed. 3. Wiley, New York. 402 p.

Hutchings, P. and Saenger, P. 1987. Ecology of mangroves. University of Queensland Press, St Lucia, London, New York.

Imbert, D. and Rollet, B. 1989. Phytmassaerienne et production primaire dans la mangrove du Grand Cul-de-sac Marine (Guadeloupe, Antilles francaises). Bulletin of Ecology, 20, 27-39.

IPCC, 2000. Land Use, Land Use Change and Forestry. Special Report, Inter-Governmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 127–180.

IPCC-Working Group II. 1990. Chapter 5: World Ocean and coastal zones.

Jalil, AMd. 2002. Impact of salinity on the growth of *Avicennia officinalis* and *Aegicerus corniculatum*. Dissertation submitted to Forestry and Wood Technology Discipline, Khulna University, as partial fulfillment of the 4-years professional

B.Sc. (Honors) in Forestry from Forestry and Wood Technology Discipline, Khulna University, Khulna, Bangladesh.

Jo and McPherson, 2001. Indirect carbon reduction by residential vegetation and planning strategies in Chicago, USA. J. Environmental Management, 61, 165 – 177.

Kaladharan, P., Veena, S. and Vivekanandan, E. 2009. Carbon sequestration by a few marine algae: observation and projection. Journal of Marine Biological Association of India, 51 (1), 107 – 110.

Kira, T. and Shidei, T. 1967. Primary production and turnover of organic matter in different forest ecosystems of the Western Pacific. Jpn. Journal of Ecology, 17, 70-87.

Komiyama, A., Havanond, S., Srisawatt, W., Mochida, Y., Fujimoto, K., Ohnishi, T., Ishihara, S. and Miyagi, T. 2000. Top root biomass ratio of secondary mangrove (Ceriops tagal (Perr.) C.B Rob.) forest. Forest Ecological and Management, 139, 127-134.

Komiyama, A., Moriya, H., Prawiroatmodjo, S., Toma, T. and Ogino, K. 1988. Primary productivity of mangrove forest. In: Ogino, K. and Chihara, M. (Eds). Biological system of mangroves. Ehime University, Matsuyama. pp. 97-117.

Komiyama, A., Ogino, K., Aksomkoae, S. and Sabhasri, S. 1987. Root biomass of a mangrove forest in southern Thailand 1. Estimation by the trench method and the zonal structure of root biomass. Journal of Tropical Ecology, 3, 97-108.

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

Kristensen, E., Bouillon, S., Dittmar, T. and Marchand, C. 2008. Organic matter dynamics in mangrove ecosystems. Aquatic Botany, 89, 201-219.

Krithika, K., Purvaja, R. and Ramesh, R. 2008. Fluxes of methane and nitrous oxide from an Indian mangrove. Current Science, 94, 218–224.

Lee, S.Y. 1995. Mangrove outwelling: A review, Hydrobiologia, 295, 203– 212.

Leith, H. 1963. The role of vegetation in the carbon dioxide content of the atmosphere. Journal of Geophysical Research, 68, 3887–3898.

Lewis, S.L. et al. 2009. Increasing carbon storage in intact African tropical forests. Nature, 477, 1003–1006.

Lugo, A.E. and Snedaker, S.C. 1974. The ecology of mangroves. Annual Review of Ecology and Systematics, 5, 39–64.

Lugo, A.F., Brown, S. and Brinson, M.M. 1990. Concepts in Wetland Ecology. In-Forested Wetlands. Ecosystems of the World 15, eds. A. E. Lugo; M. Brinson and S. Brown. Elsevier Science, 171-184.

Mackenzie, F.T., Lerman, A. and Andersson, A.J. 2004. Past and present of sediment of carbon biogeochemical cycling models. Biogeoscience, 1, 11-32.

Mackey, A.P. 1993. Biomass of the mangrove Avicennia marina (Forsk.) Vierh, near Brisbane, south eastern Queensland. Australian Journal of Marine Freshwater Research, 44, 721-725.

Markov, V.D., Olunin, A.S., Ospennikova, L.A., Skobeeva, E.I. and Khoroshev, P.I. 1988. World Peat Resources. Moscow 'Nedra'. pp. 383 (in Russian).

Milliman, J.D. and Meade, R.H. 1983. World-wide delivery of river sediment to the oceans. Jounal of Geology, 91, 1-21.

Mitra, A. 2013. In: Sensitivity of Mangrove ecosystem to changing Climate. Springer DOI: 10.1007/978-; 81-322-1509-7, pp. 323.

Mitra, A. and Zaman, S. 2014. Carbon sequestration by Coastal Floral Community, India. Published by The Energy and Resources Institute (TERI) TERI Press. ISBN 978-81-7993-551-4.

Mitra, A. and Zaman, S. 2016. Basics of Marine and Estuarine Ecology, 2016, Springer, ISBN 978-81- 322-2705-2.

Mitra, A., Banerjee, K., Bhattacharyya, D. P.: In: The other face of mangroves, Department of Environment, Govt. of West Bengal publication. 2004.

Mitra, A., Banerjee, K., Sengupta, K. and Gangopadhyay, A. 2009. Pulse of climate change in Indian Sundarbans: A myth or reality? National Academy Science Letters, 32, 1-2.

Mitra, A., Sundaresan, J., Banerjee, K. and Agarwal, S.K. 2016. Environmental Coastgurds - Understanding Mangrove Ecosystem and Carbon sequestration. Published by CSIR-National Institute of Science Communication and Information Resources (CSIR-NISCAIR), New Delhi. ISBN: 978-817236-352-9.

Monji, N., Hamotani, K., Tosa, R., Fukagawa, T., Yabuki, K., Hirano, T., Jintana, V., Piriyayota, S., Nishimiya, A. and Iwasaki, M. 2002. CO_2 and water vapor flux evaluations by modified gradient methods over a mangrove forest. Journal of Agricuultural Meterology, 58, 63-69.

Muller-Landau, H.C. 2009. Carbon cycle: sink in the African jungle. Nature, 457, 969-970.

Murdiyarso, D., Purbopuspito, J., Kauffman, J.B., Warren, M.W., Sasmito, S.D., Donato, D.C., Manuri, S., Krisnawati, H., Taberima, S. and Kurnianto, S. 2015. The potential of Indonesian mangrove forests for global climate change mitigation. Nature Climate Change, 5, 1089–1092.

Nixon, S. W. 1980. Between coastal marshes and coastal waters - a review of twenty years of speculation and research on the role of salt marshes in estuarine productivity. In P. Hamilton & K. B. MacDonald (eds.), Estuarne wetland Processes. Plenum Publishing Corporation, New York: 437-520.

Odum, E.P. 1968. A research challenge: Evaluating the productivity of coastal and estuarine waters. In Proceedings of the 2nd Sea Grant Conference, Univ. of Rhode Island Kingston. pp. 63-64.

Odum, W.E. and Heald, E.J. 1972. Trophic analysis of an estuarine mangrove community. Bulletin of Marine Science, 22, 671-738.

Odum, W.E. and McIvor, C.C. 1990. Mangroves. In: Ecosystems of Florida. Ewel, J. and Myers, R. (Eds.). University of Central Florida Press. USA. Chapter 15, pp. 517-548.

Olson, J.S., Watts, J.A. and Allison, L.J. 1983. Carbon in Live Vegetation of Major World Ecosystems. Oak Ridge, Tennessee: Oak ridge National Laboratory, ORNL-5862.

Ong, J.E. 1993. Mangroves -a carbon source and sink. Chemosphere, 27, 1097-1107.

Ong, J.E., Gong, W.K. and Wong, C.H. 2004. Allometry and partitioning of the mangrove, Rhizophora apiculata. Forest Ecology and Management, 188, 395-408.

Oohata, S. and Shinnozaki, K. 1979. A statical model of plant form – further analysis of the pipe model theory. Japanese Journal of Ecology, 29, 323–335.

Pandey, D.N. 2002. Global climate change and carbon management in multifunctional forests. Current Science, 83, 593-602.

Phillips, O.L., Mahli, Y., Higuchi, N., Laurance, W.F., Nunez, P.V., Vasquez, R.M., Laurance, S.G., Ferreira, L.V., Stern, M., Brown, S. and Grace, J. 1998. Changes in the carbon balance of tropical forests: evidence from long-term plots. Science, 282, 439–442.

Pool, D.J, Snedaker, S.C and Lugo, A.E. 1977. Structure of mangrove forests in Florida, Puerto Rico, Mexico and Costa Rica. Biotropica, 9, 195-212.

Post, W.M., Emanuel, W.R., Zinke, P.J. and Stangenberger, A.G., 1982. Soil carbon pools and world life zones. Nature, 298, 156-159.

Putz, F.E. and Chan, H.T. 1986. Tree growth Dynamics and productivity in a mature mangrove forest in Malaysia. Forest Ecology and Management, 17, 211-230.

Riebesell, U. 2004. Effects of CO_2 enrichment on marine phytoplankton. Journal of Oceanography, 60, 719–729.

Robertson, A.I. and Phillips, M.J. 1995. Mangroves as filters of shrimp pond effluent-Prediction and biogeochemical research needs. Hydrobiology, 295, 311-321.

Ross, M.S., Ruiz, P.L., Telesnicki, G.J. and Meeder, J.F. 2001. Estimating above-ground biomass and production in mangrove communities of Biscayne National Park, Florida (USA). Wetlands Ecology and Management, 9 (1), 27–37.

Saenger, P. 2002. Mangrove ecology, silviculture, and conservation, Kluwer Academic Publishers, Dordrecht.

Saenger, P. and Snedaker, S.C. 1993. Pantropical trends in mangrove above-ground biomass and annual litterfall. Oecologia, 96 (3), 293-299.

Sampson, R.N., Moll., Gary, A., Kielbaso, James, J. 1992. Opportunities to increase urban forests and the potential impacts on carbon storage and conservation. In Forests and Global Change Volume One: Opportunities for Increasing Forest Cover (Dwight Hair and R Neil Sampson, eds.). American Forests, Washington, DC. pp. 51-72.

Schimel, D.S. 1995. Terrestrial ecosystems and the carbon-cycle. Global Change Biology, 1, 77–91.

Schlesinger, W.H. 1984. Soil Organic Matter: a Source of Atmospheric CO_2, in: Woodwell, G.M. (Eds.), The Role of Terrestrial Vegetation in the Global Carbon Cycle: Measurement by Remote Sensing. E-publishing, John Wiley & Sons Ltd., pp. 111-127.

Schrope, M. 2007. Digging deep. Nature, 447, 246–247.

Shinozaki, K., Yoda, K., Hozumi, K. and Kira, T. 1964. A quantitative analysis of plant forms the pipe model theory. I. Basic analysis. Japanese Journal of Ecology, 14, 97–105.

Siddiqi, N.A. 2001. Mangrove Forestry in Bangladesh. Institute of Forestry and Environmental Science, University of Chittagong. 1-201 pp.

Sjors, H. 1980. Peat on Earth: multiple uses or conservation? Ambio, 9, 303-308.

Smith, S.V. and Mackenzie, F.T. 1987. The ocean as a net heterotrophic system: Implications from the carbon biogeochemical cycle. Global Biogeochem Cycles, 1, 187-198.

Soares, M.L.G. and Schaeffer-Novelli, Y.S. 2005. Estuarine, Coastal and Shelf Science, 65, 1-18.

Steinke, T.D., Ward, C.T. and Raijh, A. 1995. Forest structure and biomass of mangrove in the Mgemi estuary, South Africa. Hydrobiologia, 295 (1-3), 159-166.

Tam, N.F.Y. and Wong, Y.S. 1995. Spatial and temporal variations of heavy metal contamination in sediments of a mangrove swamp in Hong Kong. Marine Pollution Bulletin, 31, 254–261.

Tamai, S., Nakasuga, T., Tabuchi, R. and Ogino, K. 1986. Standing biomass of mangrove forests in Southern Thailand. Journal of the Japanese Forest Society, 68, 384-388.

Tomlinson, P.B. 1986. The botany of mangroves. Cambridge University Press, Cambridge.

Twilley, R., Lugo, A.E. and Zucca, C.P. 1986. Litter production and turnover in basin mangrove forest in South- West Florida, USA. Ecology, 67, (3), 670-683.

Twilley, R.R. 1995. Properties of mangroves ecosystems and their relation to the energy signature of coastal environments. In: Hall C. A. S. (Ed.). Maximum Power: The ideas and applications of H. T. Odum. Colorado Press, Colorado, pp. 43-62.

Twilley, R.R., Chen, R.H. and Hargis, T. 1992. Carbon sinks in mangrove forests and their implications to the carbon budget of tropical coastal ecosystems. Water Air Soil Pollution, 64, 265-288.

Vermatt, J.E. and Thampanya, U. 2006. Mangroves mitigate tsunami damage: A further response. Estuarine, Coastal and Shelf Science, 69, 1-3.

Walkley, A. and Black, I.A. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Science, 37, 29-38.

Walsh, J.J. 1984. The role of the ocean biota in accelerated ecological cycles: a temporal view. Bioscience, 34, 499-507.

Walsh, J.J. 1988. On the Nature of Continental Shelves. San Diego. Academic Press, London, 520 pp.

Watson, A.J., Boyd, P.W., Turner, S.M., Jickells, T.D. and Liss, P.S. 2008. Designing the next generation of ocean iron fertilization experiments. Marine Ecology Progress Series, 364, 303-309.

Whittaker, R.H. and Likens, G.E. 1975. The biosphere and man. In: Lieth, H. and Whittaker, R.H. (Eds), Primary Productivity of the Biosphere. Springer-Verlag, Berlin, Heidelberg, New York. Ecological Studies. 14: 305-328.

Webliography

https://www.co2.earth

https://www.co$_2$now.org/Current-CO$_2$-Trend/acceleration-of-atmosphere-co$_2$.html/

http://www.earth-policy.org/press_room/C68/80by2020.

http://www.forestrycorporation.com

http://fsi.nic.in/isfr2017/isfr-mangrove-cover-2017.pdf

https://www.mapsofindia.com/top-ten/geography/mangrove-forest.html

https://www.nature.com/naturegeoscience.com

https://www.rajras.in/index.php/download-india-state-forest-report-2017/

http://www.recoftc.org/site/resources/Mangroves-more-Carbon-Rich-and-Important-for-Climate-Change.php

PLATES

PLATE 1

Fig. A. Esturine region of Zuari

Fig. B. Intertidal mudflat of Zuari estury with mangrove patches

PLATE 2

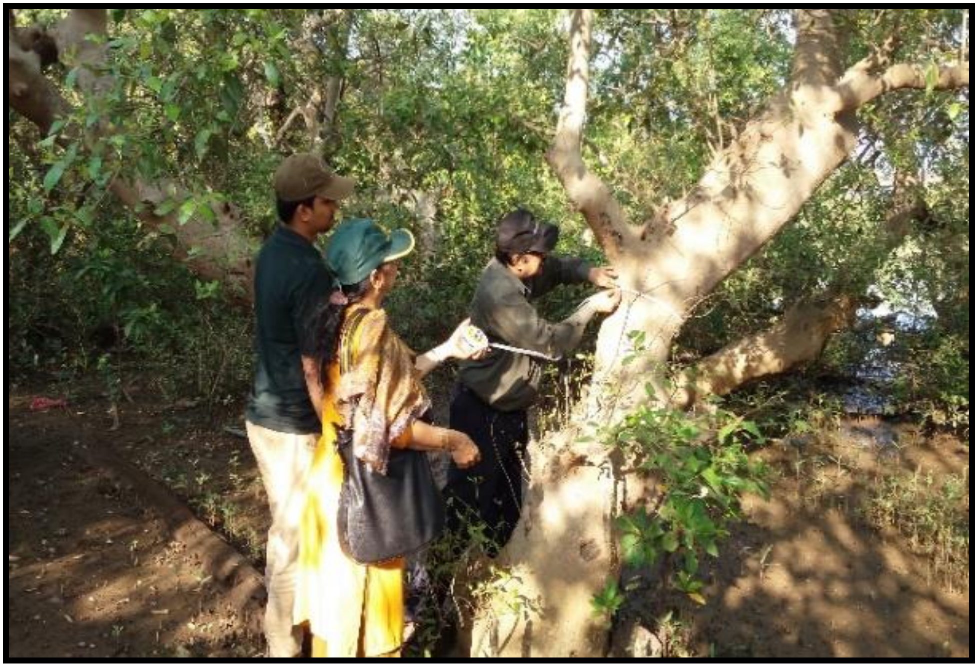


Fig. C. Measuring DBH of mangrove trees in sampling stations

Fig. D. Litter collection from sampling stations

PLATE 3

Fig. E. Estuarine region of Mandovi

Fig. F. Intertidal mudflat of Mandovi estuary

PLATE 4

Fig. G. Population density estimation through quadrat

Fig. H. Project members in the field