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The age and species composition of mangrove forest directly influence the net primary productivity and carbon sequestration potential

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ABSTRACT

Although mangroves inhabit only 0.7% of global coastal zone, but they have a significant contribution to the global carbon. Primary production by mangroves provides a substantial source of energy for aquatic food webs. Net primary productivity and carbon sequestration potential play a pivotal role in understanding the characteristics of the forest ecosystem. Therefore, in order to assess whether the age of mangrove forest and species composition has any influence on the net primary productivity and carbon sequestration potential; six plots of different age group (2, 7, 8, 12, 13 yrs and natural population), and mangrove species combinations were studied in Pichavaram mangrove forest, Tamil Nadu, India. Soil temperature, net canopy photosynthesis and forest functional index significantly varied between mangrove species and age. Regression analysis showed that the soil pH and bulk density positively influenced the carbon sequestration potential which was significant between age group. Higher age group (13yrs) and the natural site showed two-fold higher (21.52 ± 0.72 gC/m^2/day) net canopy photosynthesis. Forest functional index, shoot Biomass, root Biomass, plant biomass, carbon biomass and CO_2 equivalent showed significant variation with species or age having maximum value in natural plot. Net primary productivity was significant between mangrove species or age. However, carbon sequestration potential increased with the increase in age of plants. Maximum carbon sequestration potential was found in *Xylocarpus mekongensis*. The data obtained from the present study can be effectively used for drafting conservation and management policies for the fragile mangrove forest ecosystem.

1. Introduction

The growing evidence of climate change resulting from the continued increase of greenhouse gas concentrations in the atmosphere has made it a powerful political, social, and trade issue. In response to climate change threats, interest in increasing carbon stocks in trees, and minimizing the increase of atmospheric carbon concentration, has been growing among scientists, policymakers, and governments (Baral and Guha, 2004; Kathiresan et al., 2013; Alongi, 2016). Mangrove ecosystems are a significant carbon sink in terms of forest biomass as well as organic sediment accumulation (Donato et al., 2011; Bouillon et al., 2008; Hamilton and Friess, 2018). Although mangrove forests colonize only 0.7% of the global coastal zone they contribute significantly to the global carbon (Estrada and Soares, 2017; Ola et al., 2019). The mangroves are known to remove CO_2 from the atmosphere through photosynthesis and fix greater amounts of CO_2 per unit area, than what the phytoplankton do in the tropical Oceans (Kathiresan and Bingham, 2001; Laanbroek et al., 2018).

There are growing efforts to accurately map carbon stocks and fluxes at global scales (Saatchi et al., 2011; Baccini et al., 2012), but it has been greatly ignored due to the small spatial extent and the mapping challenges posed by mangroves (Estrada and Soares, 2017). Field studies have shown mangroves to have high above-ground biomass, productivity (Matsui, 1998; Alongi et al., 2004), soil carbon (Donato et al., 2011), below-ground to above-ground biomass ratios (Komiyama et al., 2008; Lovelock, 2008), and high rates of carbon sequestration (Mcleod et al., 2011; Alongi, 2012; Breithaupt et al., 2012; Kathiresan et al., 2013; Collins et al., 2017).

Mangroves are well adapted to the inter-tidal conditions and primary production by mangroves provides a significant source of energy for aquatic food webs (Day et al., 1996; Amarasinghe and Balasubramaniam, 1992; Along, 2016). They play a vital role in the sustainability of tropical and subtropical coastal ecosystems; especially for fisheries sustainability, breeding grounds for various fish and prawn

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species, and food source (Gong et al., 1991; Sahu et al., 2016). Mangrove productivity, however, has shown a wide variation among sites (Brown and Lugo, 1982; Amarasinghe and Balasubramaniam, 1992). Apart from climatic, edaphic, hydrological and anthropogenic factors, mangrove forest structure may have an effect on their primary productivity as it has direct relevance to its photosynthetic capacity (Okimoto et al., 2007).

During the past 20 years, a paradigm shift has occurred concerning ideas about factors influencing mangrove forest structure and ecosystem dynamics. Forces such as frequency and duration of tidal flooding, salinity, and sediment characteristics (nutrient availability, redox) were viewed as the primary drivers (s). The outwelling hypothesis stated that mangrove primary production was removed via tidal action and carried to adjacent nearshore ecosystems where it fuelled detrital based food-webs (Odum and Heald, 1975). Studies found that quantification of tree biomass can be very difficult and expensive since it involves tree felling, unearthing root systems, weighing and drying samples (Specht and West, 2003). Therefore, attention has been paid to develop techniques to estimate tree biomass from easily measured tree characteristics known as 'allometry'. Allometry is a powerful non-destructive method for estimating biomass production from easily measured tree characteristic such as stem diameter and height that is quantifiable in the field (Komiyama et al., 2005, 2008). Therefore, allometric equations for mangroves have been developed for several decades to estimate biomass and subsequent growth (Clough et al., 1997a,b; Chave et al., 2005; Komiyama et al., 2005; Dahdouh-Guebas and Koedam, 2006).

Vegetation structure is determined by the species diversity, relative densities of constituent species, the overall density of the stand, a basal area that represents the size of the plant stems and their height. Thus, the structure of vegetation provides an indication of its functional capacity which has a bearing on fisheries, forestry and global climate change due to potential high carbon sequestration. The estimation of aboveground biomass of mangrove not only provides increasingly valuable means for making comparisons among ecosystems but could also use to evaluate the productivity pattern, nutrient cycle and energy flow (Kusmana et al., 1992; Laanbroek et al., 2018). Likewise, in order to understand the forest ecosystem characteristics, the measurement of net primary productivity plays a pivotal role. Therefore, this study was designed to assess net primary productivity and vegetative characteristic of Pichavaram mangrove forest in relation to various age group and mangrove species.

2. Materials and methods

2.1. Study area

The Pichavaram mangrove forest (latitude 11° 25′ N and longitude 79° 47' E) located along the Bay of Bengal on the southeastern coast of the state of Tamil Nadu, India is a shallow estuarine complex sandwiched between two prominent estuaries, the Vellar estuary in the north and Coleroon estuary in the south (Fig. 1) with a total area of 1100 ha (Sahu et al., 2015). The tides in the Pichavaram mangroves are semi-diurnal and vary in amplitude from 0.15 to 1 m (Kathiresan, 2000). The climate is sub-humid and the ratio of precipitation to evapotranspiration (P/Etp) ranges from 0.5 to 0.75 (Selvam, 2003) with maximum precipitation during the northeast monsoons. The annual temperature variation is 18.2–36 °C. The biogeochemical processes in this ecosystem are ruled by a heavy input of sediments and anthropogenic discharges from the Vellar and Coleroon River. Six plots with different age groups were selected for experimental study as per the data obtained by the forest department, Cuddalore district, Tamil Nadu, India. The GPS details about the plot are presented in Table S1. Randomly five quadrates of 10 m^2 were made by using nylon rope at each plot to collect the data.

2.2. Data collection and analysis

2.2.1. Sediment parameters

Sediment parameters such as temperature, hydrogen ion concentration (pH) and redox potential (Eh), the salinity of pore water was *in situ* analyzed at each sampling plot during the low tide. The temperature was measured by using a thermometer with 0.5 °C accuracy, while pH was recorded using platinum electrode (pH 315i/SET, Wissenschaftlich Technische Werkstatten, Germany). A small amount of sediment was filtered using a Whatman No.1 filter paper in a syringe to measure the pore water salinity using a hand refractometer (Atago hand refractometer, Japan). The sediment samples were collected in sterile plastic container and transferred to the laboratory, and sediment samples were oven dried at 60 °C for further experiments.

2.2.2. Analysis of sediment bulk density

The bulk density of sediment is necessary to calculate the concentration of carbon stock in soils. 10 g of the dried sample was measured for their volume by immersing it into a measuring cylinder with a known volume of water. The volume of water displaced was noted down for further calculations. The bulk density was determined by dividing the weight of oven-dried sediment sample by the volume increased after immersing the sample (Miller and Donahue, 1990).

Bulk density ($g.cm^{-3}$) = M_d/V

$M_{d=}$ Mass of dry soil samples (Soil dry weight-tare weight (g))

V = Soil volume (cm^3)

2.2.2.1. Total organic carbon in mangrove sediment. Total organic carbon in sediment was estimated by adopting the method of El Wakeel and Riley (1961). The procedure involves chromic acid digestion and subsequent titration with ferrous ammonium sulfate solution in the presence of phenanthroline indicator. The values calculated were expressed as mg C/g of sediment.

2.2.2.2. Calculation of total carbon in sediment. Total organic carbon was converted into total carbon by dividing TOC with a factor of 1.87

Total carbon in sediment (%) = TOC ÷ 1.87

2.2.2.3. Calculation of carbon stock in sediment. Carbon stock in sediment was calculated by multiplying bulk density and total carbon.

Carbon stock in sediment (%) = Bulk density × Total carbon

2.2.2.4. Calculation of CO_2 equivalent. Carbon stock value was converted into carbon dioxide equivalent by multiplying carbon stock with a factor of 3.67

CO_2 equivalent (%) = Carbon stock × 3.67

2.3. Forest functional index estimation

The most spectacular functional aspects of any mangrove forest are the densities of seedlings and crab holes on the mangrove substrates, which is a good indicator of the dynamic eco-function of mangrove habitat. This assessment is simple, consume less time, energy and cost as well universally applicable. Data were recorded for a number of seedlings (< 1 m in height) and converted to 1-ha area by multiplying with a factor of 100 (Kathiresan, 2013). Data on a number of crab holes were counted in 1 m × 1 m quadrate and converted to 1-ha area by multiplying with a factor of 10,000. Forest functional index was then calculated by summing up as follows:

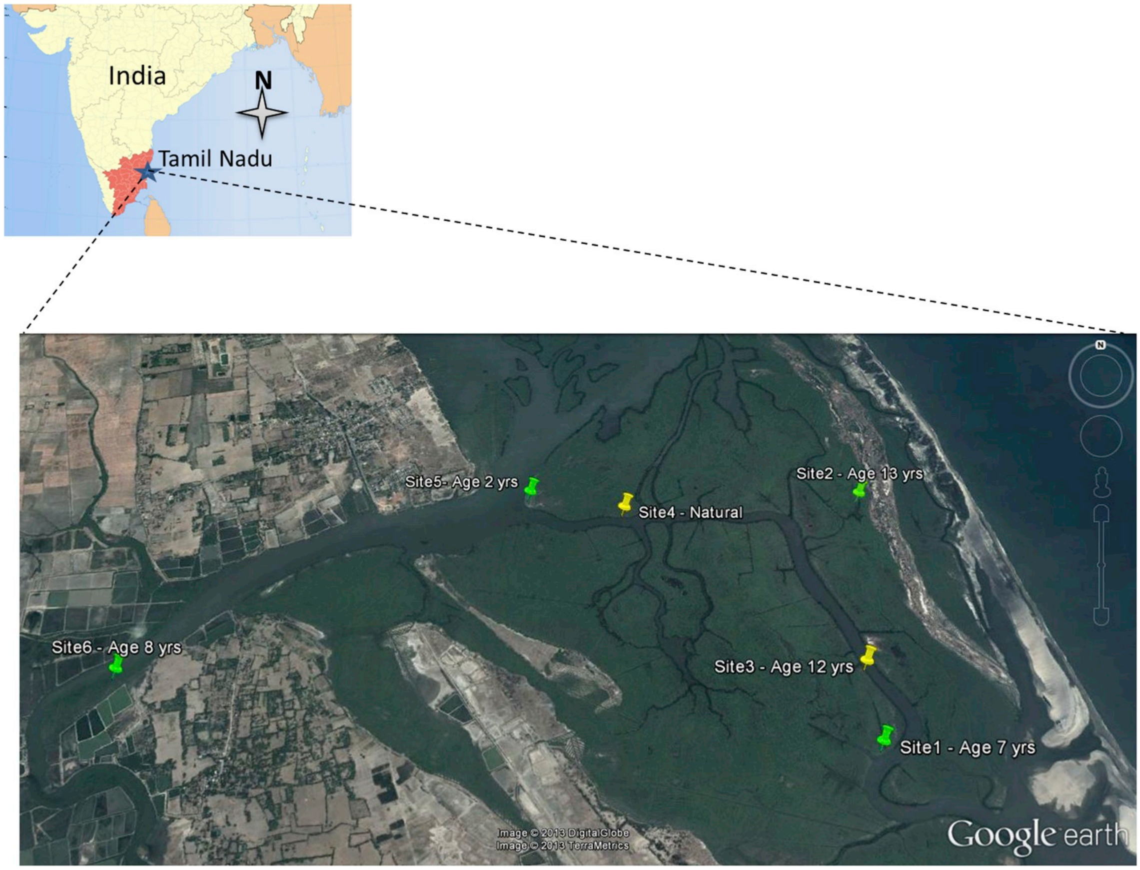

Fig. 1. Map showing the study plots of different age groups in Pichavaram mangrove forest, Tamil Nadu, India.

Forest functional Index = Number of seedlings/hectare + Number of crab holes/hectare

2.4. Net canopy production

The light intensity at the above canopy and below canopy was measured using a lux meter (Light Meter LX1010B, 50,000 Lux Luxmeter with lcd display by Mastech, China). From these measures, leaf area index, net canopy photosynthesis, the biomass of aboveground (AGB), belowground (BGB), total and AGB/BGB were calculated using the Internationally recognized scientific procedures recommended by the Australian Institute of Marine Sciences (AIMS) (English and Wilkinson Basker, 1997). A number of saplings/seedlings and crab holes per m^2 were also enumerated to calculate the forest functional index. The field survey was made during post-monsoon season (March 2013) in all the six plots.

Net canopy production was estimated using the light interception method of Bunt et al. (1979) as modified by Clough (1997). Measurements of light absorption by the forest canopy, 100–250 light readings per plot on a sunny day between 1000 and 1400 h were used to estimate leaf area index, L (= m^2 leaf area m^{-2} ground area) using the formula.

$$L = [\log_e (I)_{mean}] - [\log_e (I_o)_{mean}] / \text{-}k$$

Where, $(I)_{mean}$ = the mean photosynthetically active radiation (PAR) under the canopy; $(I_o)_{mean}$ = incident PAR; and k = canopy light extinction coefficient (0.5). L was corrected to a solar zenith angle (θ) for the latitude of the forests.

The leaf area index (L) was then converted to net canopy photosynthesis (P_N) using the formula.

$$P_N = A \times d \times L$$

Where, d = day length (hrs) and A = average rate of photosynthesis per unit leaf area are 0.3456 for *R. apiculata,* 0.4752 for *A. marina* (Clough et al., 2000a).

The biomass was estimated using the following allometric equation, proposed by Komiyama et al. (2005).

$$\text{Leaf weight} = 0.135\ \rho\ D_B^{1.696}$$

$$\text{Above-ground weight} = 0.251\ \rho\ D^{2.46}$$

$$\text{Below-ground weight} = 0.199\ \rho^{0.899}\ D^{2.22}$$

Where D – Trunk diameter in centimeter at breast height at 30 cm above ground in *R. mucronata* and at 130 cm above ground in *A. marina*

D_B – Trunk diameter in centimeter at the lowest living branch

H – Tree height in meter

ρ – the Wood density of trunk in ton per m^3

The total biomass per tree was converted to carbon biomass per tree by multiplying with a factor 0.42, as the average carbon content is 42% of total biomass (Kathiresan et al., 2013). The latter was converted to carbon biomass per year, based on the forest age, as the rate of carbon sequestration in the tree biomass. The standard mean wood density used for calculation is presented in Table S2.

2.5. Biomass and carbon stock estimation

Plant girth was measured in cm at the tree height of 30 cm for Rhizophoraceae and at 1.3 m for all other mangroves. Tree diameter (D) was calculated by multiplying the girth with a factor of 0.318 (Kathiresan, 2013).

2.5.1. Calculation of biomass and carbon content

The biomass was estimated using the following allometric equation, proposed by Komiyama et al. (2005).

Shoot biomass (SB) = 0.251 x ρ x $D^{2.46}$

Root biomass (RB) = 0.199 x $\rho^{0.899}$ x $D^{2.22}$

Total biomass (X) = SB + RB (kg/ plant)

Where,

D – Tree diameter

ρ – the Wood density of trunk in ton per m^3

2.5.2. Carbon biomass

The shoot biomass was converted into carbon biomass by multiplying a factor of 0.42

Carbon biomass = Total biomass × 0.42

2.5.3. Calculation of CO_2 equivalent

Carbon biomass value was converted into carbon dioxide equivalent by multiplying carbon biomass with a factor of 3.67.

CO_2 equivalent (%) = carbon biomass × 3.67

2.6. Determination of ecological status

Several field inventories were made to study the mangrove distribution pattern, frequency and species abundance, which were ultimately used to determine the ecological status of the mangrove vegetation. Line transects of varying 10 m × 10 m were laid on each plot and data from each were recorded from five quadrats per plot.

2.7. Vegetation and net primary productivity analysis

2.7.1. Frequency

Frequency, as introduced by Raunkiaer (1934), indicates the number of sampling units in which a given species occurs. Frequency and relative frequency of species in the study area were measured by using the formulae of Curtis (1933). It was calculated by the equation:

$$Frequency\,(\%) = \frac{\text{Number of occurrence of a species}}{\text{Total number of sites studied}} \times 100$$

$$\text{Relative frequency}(\%) = \frac{\text{Number of occurrence of a particular species}}{\text{Total number of occurence of all the species}} \times 100$$

The values of relative frequency were calibrated on a 10-point scale to assign a status to the species in each region. Four distinct groups were derived from this 10-point scale and each group in each region was designated as follows: Very Frequent (7-10); Frequent (5–7); Less Frequent (3–5) and Rare (< 3).

2.7.2. Abundance

The abundance and density represent the numerical strength of species in the community (Mishra, 1968). Abundance is described as the number of individuals occurring per sampling unit and density as the number of individuals per sampling unit. Abundance and density were calculated using the following formulae:

$$Abundance\,(A) = \frac{\text{Total number of individuals}}{\text{Total number of sampling unit of occurrence}} \times 100$$

$$\text{Re}\,lativeabundance\,(A) = \frac{\text{Abundance of a particular species}}{\text{Sum of abundance of all the species}} \times 100$$

$$Density = \frac{\text{Total number of individuals of a species in all quadrates}}{\text{Total number of quadrats samples}} \times 100$$

$$\text{Relative density} = \frac{\text{Density of a particular species}}{\text{Sum of the densities of all the species}} \times 100$$

The abundances were grouped to assign abundance-categories, as suggested by Dagar et al. (1991) (Table S3).

2.7.3. Importance value index (IVI)

$$\text{VI} = \text{Relative frequency} + \text{Relative abundance} \\ + \text{Relative density Maturity Index Value(MIV)}$$

The concept of 'Important Value Index' (IVI) has been developed for expressing the dominance and ecological success of any species, with a single value (Mishra, 1968). This index utilizes three characteristics, viz. Relative frequency, relative density and relative abundance and can be calculated by using the following formula:

2.7.4. Complexity index (CI)

Complexity index (CI) was used as an overall estimate of the structural complexity of the vegetation in sample plots and it was calculated by using the formula proposed by Holdridge et al. (1971).

CI = Species richness x stand density x stand basal area x stand height

2.8. Estimation of carbon sequestration potential (CSP)

Carbon sequestration rate (CSR) was estimated based on sediment rates and total organic carbon (TOC) content of sediment (Xiaonan et al., 2008)

CSR = ρ × TOC × R

Where.

ρ is the bulk density of sediment, g/cm3; TOC is TOC content, %; R is the sediment rate of wetland (3.93 mm a^{-1} for Pichavaram mangrove forest) (Ranjan et al., 2010)

Evaluations of carbon sequestration potential (CSP) of different study plots were made based on the area of quadrate studied by using the formula:

CSP = CSR × A

Where, A is the distribution area.

2.9. Statistical analysis

A suite of statistical analysis (SPSS 11.5) was made to assess the significance for each variable between the plant age groups or plot and mangroves species. Post hoc multiple comparison tests (Tukey's, S–N–K), were also used to identify significance between different combinations.

3. Results

Vegetative characteristics, primary productivity and carbon sequestration potential of mangrove forest were assessed at six plots of various age group and different mangrove species combinations in Pichavaram. The obtained data were statistically analyzed and the results are shown in Table 1 and Table 2. Sediment temperature significantly varied between mangrove species and age ($p < 0.01$). Sediment temperature (°C) was recorded maximum (28.06 ± 0.71) in 14 years old mangrove and minimum (27.13 ± 0.46) in natural mangrove plot. Sediment pH was significant between age group ($p < 0.01$) (Table 1). Maximum pH of 6.84 ± 0.07 was recorded in 14 old

Table 1
Various ecological factors in six sites with different age group and species composition.

Sources	Sediment temperature (°C)	Sediment pH	Pore water salinity (ppt)	Sediment bulk density (g.m-3)	Total Organic Carbon in soil (%)	Total Carbon in soil (%)	Sediment Carbon stock (%) (Million grams/hectare)	CO_2 equivalent	carbon sequestration potential (GgC/hectare)
Name of the species									
AC	26.14 ± 1.23^{a}	7.74 ± 0.13^{a}	31.80 ± 3.43^{a}	0.56 ± 0.02^{bc}	0.46 ± 0.26^{a}	0.24 ± 0.14^{a}	0.14 ± 0.08^{a}	0.51 ± 0.31^{a}	130.2 ± 62.50^{a}
AM	27.97 ± 0.50^{a}	7.80 ± 0.05^{a}	22.00 ± 1.40^{a}	0.56 ± 0.00^{b}	0.92 ± 0.10^{b}	0.49 ± 0.05^{b}	0.28 ± 0.03^{a}	1.04 ± 0.12^{a}	245.1 ± 25.51^{a}
BC	27.30 ± 0.87^{a}	7.78 ± 0.09^{a}	28.80 ± 2.43^{a}	0.62 ± 0.01^{b}	0.75 ± 0.18^{b}	0.40 ± 0.10^{b}	0.25 ± 0.06^{a}	0.92 ± 0.22^{a}	194.3 ± 44.19^{a}
CD	28.46 ± 1.23^{a}	7.82 ± 0.13^{a}	29.20 ± 3.43^{a}	0.70 ± 0.02^{c}	1.11 ± 0.26^{b}	0.59 ± 0.14^{b}	0.42 ± 0.08^{b}	1.53 ± 0.31^{b}	260.4 ± 62.50^{b}
EA	29.60 ± 1.23^{a}	7.82 ± 0.13^{a}	26.80 ± 3.43^{a}	0.52 ± 0.02^{a}	0.58 ± 0.26^{b}	0.31 ± 0.14^{b}	0.16 ± 0.08^{a}	0.59 ± 0.31^{a}	151.4 ± 62.50^{a}
LR	26.73 ± 0.87^{a}	7.81 ± 0.09^{a}	28.30 ± 2.43^{a}	0.54 ± 0.01^{a}	0.60 ± 0.18^{b}	0.32 ± 0.10^{b}	0.17 ± 0.06^{a}	0.63 ± 0.22^{a}	162.3 ± 44.19^{a}
RA	27.82 ± 1.23^{a}	7.74 ± 0.13^{a}	29.60 ± 3.43^{a}	0.70 ± 0.02^{c}	0.87 ± 0.26^{b}	0.46 ± 0.14^{b}	0.33 ± 0.08^{b}	1.20 ± 0.31^{b}	204.4 ± 62.50^{b}
Ran	26.14 ± 1.23^{a}	7.74 ± 0.13^{a}	26.80 ± 3.43^{a}	0.70 ± 0.02^{c}	1.18 ± 0.26^{b}	0.63 ± 0.14^{b}	0.44 ± 0.08^{b}	1.62 ± 0.31^{b}	275.8 ± 62.50^{b}
RM	26.96 ± 0.51^{a}	7.80 ± 0.05^{a}	31.43 ± 1.43^{a}	0.57 ± 0.00^{b}	0.84 ± 0.11^{b}	0.45 ± 0.05^{b}	0.26 ± 0.03^{a}	0.93 ± 0.13^{a}	212.13 ± 26.04^{a}
XM	26.78 ± 1.23^{a}	7.82 ± 0.13^{a}	27.20 ± 3.43^{a}	0.70 ± 0.02^{c}	1.53 ± 0.26^{b}	0.81 ± 0.14^{b}	0.57 ± 0.08^{b}	2.10 ± 0.31^{b}	357 ± 62.50^{b}
Age									
2	27.30 ± 0.62^{a}	7.78 ± 0.06^{a}	27.70 ± 1.71^{a}	0.54 ± 0.01^{a}	0.74 ± 0.13^{a}	0.25 ± 0.04^{a}	0.21 ± 0.04^{a}	0.78 ± 0.15^{a}	198.75 ± 31.25^{a}
7	28.06 ± 0.71^{a}	7.79 ± 0.07^{a}	27.06 ± 1.98^{a}	0.53 ± 0.01^{a}	0.68 ± 0.15^{a}	0.21 ± 0.04^{a}	0.19 ± 0.04^{a}	0.71 ± 0.18^{a}	182.73 ± 36.08^{a}
12	27.30 ± 0.87^{a}	7.78 ± 0.09^{a}	28.90 ± 2.43^{a}	0.56 ± 0.01^{a}	0.88 ± 0.18^{a}	0.26 ± 0.06^{a}	0.26 ± 0.06^{a}	0.95 ± 0.22^{a}	206 ± 44.19^{a}
13	27.72 ± 0.74^{a}	7.83 ± 0.08^{a}	27.93 ± 2.06^{a}	0.54 ± 0.01^{a}	0.82 ± 0.16^{a}	0.26 ± 0.05^{a}	0.24 ± 0.51^{a}	0.89 ± 0.18^{a}	228 ± 37.56^{a}
14	27.17 ± 0.71^{a}	7.84 ± 0.07^{a}	27.86 ± 1.98^{a}	0.54 ± 0.01^{a}	0.87 ± 0.15^{a}	0.24 ± 0.04^{a}	0.26 ± 0.04^{a}	0.93 ± 0.18^{a}	239.33 ± 36.08^{a}
Natural	27.13 ± 0.46^{a}	6.77 ± 0.05^{a}	27.00 ± 1.29^{a}	0.70 ± 0.00^{b}	1.02 ± 0.10^{a}	0.19 ± 0.03^{a}	0.38 ± 0.04^{a}	1.41 ± 0.11^{a}	282.72 ± 23.62^{a}
Significance									
Age	NS	NS	NS	[a]	NS	NS	NS	NS	*
Mangroves species	NS	NS	[a]	NS	NS	NS	NS	NS	NS
Age * Mangroves species	[a]	NS	NS	NS	NS	NS	NS	NS	NS

Sources	Net canopy photosynthesis (gC/m2/day)	Forest Functional Index	Shoot Biomass (kg/plant)	Root Biomass (kg/plant)	Plant biomass (kg/plant)	Carbon Biomass (MgC/ha)	CO_2 equivalent	Complexity Index	Primary Productivity (t/ha/yr)
Name of the species									
AC	18.99 ± 1.45^{a}	19.50 ± 1.48^{a}	0.22 ± 0.23^{a}	0.18 ± 2.48^{a}	0.38 ± 7.99^{a}	0.32 ± 6.71^{a}	1.18 ± 24.65^{a}	NA	13.35 ± 1.54^{a}
AM	14.18 ± 0.59^{b}	15.22 ± 0.60^{b}	12.61 ± 2.25^{b}	6.45 ± 1.01^{b}	19.07 ± 3.26^{b}	16.02 ± 2.74^{b}	58.81 ± 10.06^{b}	32.01 ± 1.23^{a}	26.76 ± 3.12^{a}
BC	15.99 ± 1.02^{b}	16.91 ± 1.04^{b}	1.31 ± 3.90^{a}	0.89 ± 1.75^{a}	2.19 ± 5.65^{a}	1.85 ± 4.75^{a}	6.79 ± 17.43^{a}	NA	13.35 ± 2.13^{a}
CD	19.05 ± 1.45^{b}	20.58 ± 1.48^{b}	0.38 ± 5.51^{a}	0.28 ± 2.48^{a}	0.66 ± 7.99^{a}	0.56 ± 6.71^{a}	2.02 ± 24.65^{a}	NA	13.35 ± 1.43^{a}
EA	21.56 ± 1.45^{b}	22.16 ± 1.48^{b}	0.30 ± 0.12^{a}	0.22 ± 2.48^{a}	0.54 ± 7.99^{a}	0.44 ± 6.71^{a}	1.68 ± 24.65^{a}	NA	13.35 ± 2.13^{a}
LR	20.23 ± 1.02^{b}	20.87 ± 1.04^{b}	0.28 ± 3.90^{a}	0.19 ± 1.75^{a}	0.45 ± 5.65^{a}	0.40 ± 4.75^{a}	1.43 ± 17.43^{a}	2.4 ± 0.23^{a}	14.36 ± 4.23^{a}
RA	21.05 ± 1.45^{b}	22.25 ± 1.48^{b}	26.42 ± 5.51^{b}	13.0 ± 2.48^{b}	39.40 ± 7.99^{b}	33.10 ± 6.71^{b}	121.52 ± 24.65^{b}	NA	13.35 ± 3.23^{a}
Ran	19.80 ± 1.45^{b}	21.43 ± 1.48^{b}	95.96 ± 5.51^{c}	42.48 ± 2.48^{c}	138.44 ± 7.99^{c}	116.26 ± 6.71^{c}	426.72 ± 24.65^{c}	NA	13.35 ± 2.13^{a}
RM	19.18 ± 0.60^{b}	20.11 ± 0.61^{b}	11.67 ± 2.29^{b}	5.98 ± 1.03^{b}	17.66 ± 3.33^{b}	14.83 ± 2.80^{b}	54.45 ± 10.27^{b}	29.59 ± 1.32^{a}	25.75 ± 4.23^{a}
XM	18.86 ± 1.45^{b}	20.96 ± 1.48^{b}	0.56 ± 5.51^{a}	0.40 ± 2.48^{a}	0.98 ± 7.99^{a}	0.82 ± 6.71^{a}	3.02 ± 24.65^{a}	NA	13.35 ± 2.54^{a}
Age									
2	17.59 ± 1.02^{c}	18.55 ± 1.04^{c}	12.69 ± 3.90^{b}	6.50 ± 1.75^{c}	19.19 ± 5.65^{bc}	16.12 ± 4.75^{b}	59.18 ± 17.43^{b}	30.80 ± 2.13^{a}	26.25 ± 4.23^{a}
7	11.60 ± 0.87^{bc}	12.49 ± 0.89^{bc}	9.76 ± 3.31^{a}	5.22 ± 1.49^{a}	14.98 ± 4.80^{a}	12.58 ± 4.03^{a}	46.20 ± 14.81^{a}	20.53 ± 3.12^{a}	21.95 ± 2.54^{a}
12	11.06 ± 0.84^{b}	12.00 ± 0.85^{b}	3.62 ± 3.18^{b}	2.09 ± 1.43$^{b c}$	5.71 ± 4.61^{b}	4.81 ± 3.88^{b}	17.64 ± 14.23^{b}	21.34 ± 2.43^{a}	22.29 ± 1.43^{a}
13	21.52 ± 0.72^{a}	22.30 ± 0.74^{a}	15.52 ± 2.75^{b}	7.39 ± 1.24$^{b c}$	22.90 ± 3.99^{bc}	19.24 ± 3.36^{b}	70.62 ± 12.32^{b}	16.00 ± 4.32^{a}	20.05 ± 3.23^{a}
14	19.85 ± 0.84^{a}	20.56 ± 0.85^{a}	1.74 ± 3.18^{a}	1.06 ± 1.43^{b}	2.80 ± 4.61^{a}	2.36 ± 3.88^{a}	8.70 ± 14.23^{a}	20.53 ± 1.43^{a}	21.95 ± 2.54^{a}
Natural	20.44 ± 0.55^{c}	21.85 ± 0.56^{c}	19.98 ± 2.08^{b}	9.38 ± 0.93^{c}	29.37 ± 3.02^{bc}	24.66 ± 2.54^{b}	90.53 ± 9.31^{b}	8.800 ± 2.43^{a}	17.04 ± 1.43^{a}
Significance									
Age	[a]	[a]	[a]	[a]	[a]	[a]	[a]	NS	NS
Mangroves species	[a]	[a]	[a]	[a]	[a]	**	**	[a]	[a]
Age * Mangroves species	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] = $p < 0.01$; NS = Not Significant; values not sharing a common superscript are differ significantly at $p > 0.05$; NA = data not available; AC: *Aegiceras corniculatum*; AM: *Avicennia marina*; BC: *Bruguiera cylindrica*; CD: *Ceriops decandra*; EA: *Excoecaria agallocha*; LR: *Lumnitzera racemosa*; RA: *Rhizophora apiculata*; Ran: *Rhizophora annamalayana*; RM: *Rhizophora mucronata*; XM: *Xylocarpus mekongensis*.

Table 2
Correlation matrix of various ecological factor influencing net primary productivity and carbon sequestration.

	Temperature (°C)	pH	Salinity (ppt)	Sediment bulk density (g.m-3)	Total Organic Carbo (%)	Total Carbon (%)	sediment Carbon stock (Million grams/hectare)	CO_2 equivalent	Net canopy photosynthesis (gC/m2/day)
Temperature	1								
pH	-.119	1							
Salinity (ppt)	.015	-.010	1						
Sediment bulk density	-.100	-.061	.063	1					
Total Organic Carbon	.070	-.089	-.004	.144	1				
Total Carbon	.070	-.089	-.004	.144	1.000 ([a])	1			
Sediment Carbon stock	.038	-.104	-.003	.341 ([a])	.969 ([a])	.969 ([a])	1		
CO_2 equivalent	.038	-.104	-.003	.341 ([a])	.969 ([a])	.969 ([a])	1.000 ([a])	1	
Net canopy photosynthesis	.007	-.084	.087	.242 (*)	-.096	-.096	-.044	-.044	1
Forest Functional Index	.012	-.097	.086	.285 ([a])	.029	.029	.085	.085	.992 ([a])
Shoot Biomass	-.106	-.003	-.006	.211 (*)	.175	.175	.207 (*)	.207 (*)	.098
Root Biomass	-.105	-.001	-.008	.207 (*)	.175	.175	.203 (*)	.203 (*)	.094
Plant biomass	-.106	-.002	-.007	.210 (*)	.175	.175	.206 (*)	.206 (*)	.096
Carbon Biomass	-.106	-.002	-.007	.210 (*)	.175	.175	.206 (*)	.206 (*)	.096
CO_2 equivalent in plant	-.106	-.002	-.007	.210 (*)	.175	.175	.206 (*)	.206 (*)	.096
Complexity Index	.039	.030	-.137	.294 ([a])	.033	.033	-.054	-.054	.227 (*)
Primary Productivity	.039	.030	-.137	.294 ([a])	.033	.033	-.054	-.054	.227 (*)
carbon sequestration potential	.038	-.104	-.003	.341 ([a])	.969 ([a])	.969 ([a])	1.000 ([a])	1.000 ([a])	-.044

	Forest Functional Index	Shoot Biomass (kg/plant)	Root Biomass (kg/plant)	Plant biomass (kg/plant)	Carbon Biomass (MgC/ha)	CO_2 equivalent in plant	Complexity Index	Primary Productivity (t/ha/yr)	carbon sequestration potential ($GgC.h^{-1}$)
Temperature									
pH									
Salinity (ppt)									
Sediment bulk density									
Total Organic Carbon									
Total Carbon									
Sediment Carbon stock									
CO_2 equivalent									
Net canopy photosynthesis									
Forest Functional Index	1								
Shoot Biomass	.124	1							
Root Biomass	.120	.999 ([a])	1						
Plant biomass	.123	1.000 ([a])	.999 ([a])	1					
Carbon Biomass	.123	1.000 ([a])	.999 ([a])	1.000 ([a])	1				
CO_2 equivalent in plant	.123	1.000 ([a])	.999 ([a])	1.000 ([a])	1.000 ([a])	1			
Complexity Index	.234 (*)	-.021	.007	-.012	-.012	-.012	1		
Primary Productivity	.234 (*)	-.021	.007	-.012	-.012	-.012	1.000 ([a])	1	
carbon sequestration potential	.085	.207 (*)	.203 (*)	.206 (*)	.206 (*)	.206 (*)	-.054	-.054	1

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

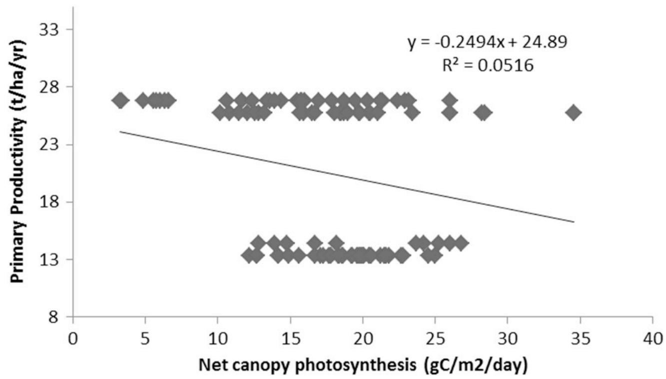

Fig. 2. Regression between primary productivity and net canopy photosynthesis.

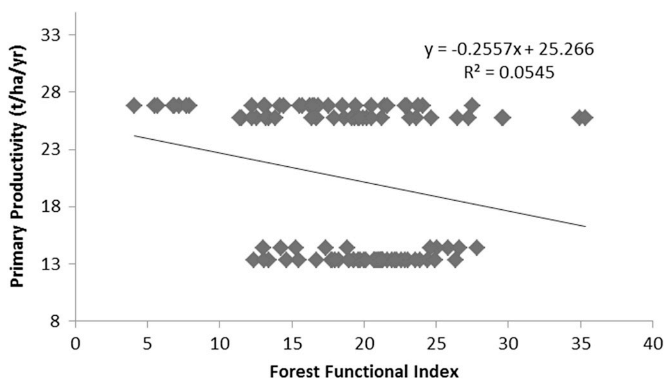

Fig. 3. Regression plot between primary productivity and forest functional index.

mangroves plot and minimum of 6.77 ± 0.13 was recorded from natural mangrove plot. Pore water salinity varied between mangrove species ($p < 0.01$); where maximum salinity of 31.80 ± 3.43 was recorded from *A. corniculatum* zone and minimum of 22.00 ± 1.40 from *A. marina* zone. Sediment bulk density was significant between age ($p < 0.01$) (Table 1) and it was 0.70 $g\,m^{-3}$ in natural plot and minimum (0.53 $g\,m^{-3}$) in plot 1 (age 7). It positively influenced the carbon sequestration potential and negatively influenced the primary productivity of mangrove plants as evident by regression plots displayed in Fig. S1 and Fig. S2.

Total organic carbon was not significant between age or mangrove species and it ranged from 0.68 ± 0.15 to 1.02 ± 0.10 in the age group 7 and natural plot respectively. Similarly, there was no significant difference with respect to total carbon in sediment in relation to age and species. Moreover, sediment carbon stock and CO_2 equivalent did not showed significance between species or age. Net canopy photosynthesis was significant between species and age ($p < 0.01$) (Table 1 and Fig. 2.). *E. agallocha* exhibited the highest net canopy photosynthesis (21.565 $gC/m^2/day$) followed by *R. apiculata* (21.05 $gC/m^2/day$). However, the least net canopy photosynthesis was observed in *B. cylindrica* (15.99 $gC/m^2/day$). In case of age, it showed two fold higher (21.52 ± 0.72 $gC/m^2/day$) in the age group 13 and natural plot than the age group 12 (11.56 ± 1.45 $gC/m^2/day$).

Forest functional index was significant between species or age ($p < 0.01$). It was maximum in the age group 13 (22.30 ± 0.74) followed by the natural plot (21.85 ± 0.56) and minimum in plot 3 (age 12). Congruently, shoot Biomass (Kg/plant), root Biomass (Kg/plant), plant biomass (Kg/plant), carbon biomass (MgC/ha) and CO_2 equivalent showed significant variation with age and species (Table 1 and Fig. 3). In all the age groups these parameters were recorded maximum in natural plot and minimum in the age group 14. Similarly, among species the maximum value was observed for *R. annamalayana* and the minimum was documented for *A. corniculatum.*

Complexity index (CI) was significant ($p < 0.01$) between mangrove species. It was recorded maximum in the plot 2 (30.80 ± 2.13) where the CI was also observed highest for *A. marina* (32.01 ± 1.23). Net Primary Productivity (t/ha/yr) significant between mangrove species ($p < 0.01$) it was maximum of 30.80 ± 2.13 t/ha/yr was beheld in a youngest plot with age group 2, and minimum in natural mangrove plot (17.04 ± 1.43 t/ha/yr). Based on collected data, significant variations of carbon sequestration potential were found between plots or age ranging from 143.62 ± 36.08 (age group 7) to 282.72 ± 23.62 $gCm^{-2}a^{-1}$ (natural plot) (Tables 1 and 2). Among mangrove species the maximum (420.90 ± 62.50) carbon sequestration potential was found in *X. mekongensis* and minimum in *A. corniculatum* (102.33 ± 62.50).

3.1. Importance value index (IVI)

Species dominance was calculated based on the importance value index (IVI). The maximum IVI value was observed for *Avicennia marina* (101.67) followed by *Rhizophora mucronata* (18.55). This dominance could be due to the availability of soft substratum and higher salinity, which is actually favorable for these two species for their growth and development. A similar dominance of *Avicennia* species was observed by Bando et al. (2017) in Indonesia. However, among all the species IVI value was least for *Ceriops decandra* and *Aegiceras corniculatum* (0.74). Table 3 shows the IVI value for all the species observed.

Table 3
Importance Value Index of mangrove species observed in the study sites.

S. No.	Species	Importance Value Index
1	*Avicennia marina*	101.67
2	*Rhizophora mucronata*	18.55
3	*Rhizophora apiculata*	2.23
4	*Rhizophora annamalayana*	1.48
5	*Lumnitzera racemosa*	5.20
6	*Bruguiera cylindrica*	7.42
7	*Xylocarpus mekongensis*	1.48
8	*Ceriops decandra*	0.74
9	*Aegiceras corniculatum*	0.74
10	*Excoecaria agallocha*	3.71

3.2. Principal component analysis

The PCA score plot of the first two principal component axes (PC1 and PC2) expounds the cumulative variances of 33% and 53.8% respectively (Table S4). The PC5 showed the maximum cumulative variance of 84.8% compared to the other axis. Hence, PC5 was considered for the identification of the positive and negative effect of the mangrove's net primary productivity. Among the data set PC5 showed the negative correlation with pH and temperature and high positive correlation with total organic carbon (TOC) of sediment and total carbon in sediment, bulk density, net canopy photosynthesis ($gC/m^2/day$). Accordingly, when PC1 scores are considered, mangrove plots with negative scores represent more productive areas than those with positive PC5 scores (Fig. S3).

4. Discussion

Mangrove forests play an important role in the carbon cycle by sequestering atmospheric CO_2 and storing it as carbon biomass in plant materials and sediments. As about half of mass in trees is carbon, large amounts of carbon are potentially stored in mangrove forests. It is the largest store of carbon in coastal zones. To better understand the dynamic of carbon sequestration in mangroves, it is important to know the productivity of mangrove forests in terms of primary production, biomass, carbon accumulation, and burial (Bravo et al., 2008).

According to Batjes (1995) and Kjerfve et al. (1999), the forests where *Avicennia alba* and *Avicennia marina* were the dominant species showed slightly alkaline sediments. But observations made in the present study showed the pH in the range of 6.74–6.82 (almost neutral). This could be correlated with the higher amount of fresh water in flow in the study plots from the Coleroon river. However, in the natural mangrove plot, pH values were least which could be attributed to the high productivity of sediments and the flooding conditions prevailing in the sampling plots (Ceron-Breton et al., 2011).

Sediment carbon is the fundamental building block and the primary determinant of sediment organic matter and many soil chemical properties including nutrients availability and physical properties including soil structure and water holding capacity (Lal, 1997, 1999), all these soil properties directly influence the soil quality and ecosystem productivity. There was no significant difference in total organic carbon (TOC) between species and age. This reflects the contrasting rates of tree growth in different plots. The maximum TOC was recorded in the natural mangrove plot. A soil carbon measurement is the focus of current and future international negotiations and treaties related to global change.

There is an interrelationship between vegetation and soil carbon dynamics in the ecosystem. The input can be drawn from above ground leaf litter and below ground fine roots (Bloomfield et al., 1996) and their decomposition rates are governed by microbial activities and soil environmental conditions. The chemical composition of vegetation greatly determines the residence time of organic carbon in the terrestrial ecosystem (Rasse et al., 2006). Some plant materials are easily decomposable, while others are highly recalcitrant. Total above and below ground carbon stocks in tropical forests of the world has been reported to be 243 t ha^{-1} (Higuchi et al., 1997). There are various methods for estimating mangrove biomass. Among them, the harvesting method, the mean-tree method and the allometric method are mostly employed. Among these, the allometric method is most popular due to its non-destructive nature and for being less tedious (Kridiborworn et al., 2012). It is used to estimate the whole or partial weight of a tree from measurable tree dimensions such as stem and height of plants, using an allometric equation (Komiyama et al., 2008). The basic concept of an allometric relationship is the growth rate of one part of a tree is proportional to that of another. For example, it is well known the stem diameter of a tree is highly correlated with stem weight. Over the past decades, allometric equations have been developed for various tree species and forest types including mangroves. The main parameter that is usually used for defining the relationship is biomass weight and diameter at breast height (DBH). Since measurements of tree height in the field are quite difficult, especially when canopy and plant density are high, most of allometric relationship derived in the past have used only DBH (Kridiborworn et al., 2012; Ong et al., 2004). However, according to Kridiborworn et al. (2012) the relationship coefficient was higher when height was included than when it was not considered. Therefore, both height and DBH were considered for estimation of biomass calculation in the present study. For more accuracy, it is thus recommended that the height of mangrove should be measured when an allometric relationship is derived to estimate biomass. The present study reports a significant variation in shoot Biomass root Biomass, plant biomass, carbon biomass and CO_2 equivalent with respect to age and species.

In most mangroves, the biomass density appears to be higher than in terrestrial forests (Teas, 1979; Kathiresan et al., 2013). However, AGB values vary with the mangrove forest; 281 t ha^{-1} in *Rhizophora* forest (Tamai et al., 1986), 357 t ha^{-1} in *Sonneratia* forest (Komiyama et al., 1987) and 315 t ha^{-1} in *Avicennia germinans* (Fromard et al., 1998), 94.8 t ha^{-1} in a secondary mangrove forest of *R. mucronata* and *Bruguiera gymnorrhiza* (Suzuki and Tagawa, 1983) and 62.9 t ha^{-1} in a *R. mangle* forest (Golley et al., 1962). AGB are reportedly more than 300 t ha^{-1} in Malaysia (Putz and Chen, 1986), Indonesia (Komiyama et al., 1988) and French Guiana (Fromard et al., 1998). AGB is also reportedly as less than 100 t ha^{-1} in most secondary forests and primary forests of high latitude areas (> 24°23′ N or S) (Mackey, 1993). The lowest AGB is reported as 7.9 t ha^{-1} for a *Rhizophora mangle* forest in Florida, USA (Lugo and Snedaker, 1974).

Generally, mangroves show relatively high root biomass than other forms of forests (Saintilan, 1997a, b; Komiyama et al., 2000). It is noteworthy that the large biomass allocated to the underground roots in the mangroves as revealed by the low ratio in the present study (Table 1). Mangroves are usually coping with the stresses of high water tables, salty soil and less mechanical support due to the soft muddy substrate. Mangroves are unable to mechanically support their aboveground weight without a heavy root system. Therefore, a large allocation of net production into roots is necessary. In addition, soil moisture may cause increased allocation of biomass to the roots with enhanced cambial activity induced by ethylene production under submerged conditions (Yamamoto et al., 1995). Most mangrove species are highly sensitive to variation in nutrient availability (Boto and Wellington, 1988; Koch, 1997; Feller et al., 2007; Lovelock et al., 2005, 2007; Naidoo, 2006). Enhanced allocation to root biomass relative to shoot biomass is a common adaptation to low nutrient availability. Species of Rhizophoraceae are more tolerant to low nutrient conditions than other mangrove species (Komiyama et al., 2000; Krauss et al., 2008).

In the present study, the primary productivity exhibited significant variation largely between mangrove species rather than mangrove plots. This is in accordance with Komiyama et al. (2005) who have suggested that the allometric equations of mangrove species are highly species-specific but less site-specific. For example, the present study registered net canopy photosynthesis in a range of 11.06 ± 0.84 to 21.52 ± 0.72 tC $ha^{-1}year^{-1}$ (Table 1). A similar range of the net canopy photosynthesis has been recorded in other mangrove areas; from 24.5 tC $ha^{-1}year^{-1}$ in 5-year-old forest to 76.6 tC $ha^{-1}year^{-1}$ in 25-year-old forest in Sawi Bay (Alongi and Dixon, 2000). Relatively high primary production of tree biomass is considered to bring about unusual carbon dynamics (Komiyama, 2006). Therefore, mangroves forest is a highly efficient carbon sink in the tropics.

Complexity index (CI) was significant among mangrove species only. The present survey reveals that the age group 2 was structurally more complex (multispecies stand comprising a large number of trees with low or medium size). Net Primary Productivity (t/ha/yr) significantly varied between mangrove species ($p < 0.01$). Maximum primary productivity of 30.80 ± 2.13 t/ha/yr was beheld in a youngest plot with age group 2, and the minimum was observed in natural mangrove plot (17.04 ± 1.43 t/ha/yr) (Table 1). Mature mangrove systems are thought to be carbon neutral, but some studies show higher gross primary production/respiration ratios in older mangroves (Alongi, 2011). Recently, Estrada and Soares (2017) also reported that the carbon stock in the aboveground biomass tends to increase and sequestration tends to decrease linearly with age.

Species dominance was calculated based on the importance value index (IVI). Among the ten species encountered in the sampling plots, *Avicennia marina*, a pan-tropical mangrove species was found to occur under a wide range of edaphic conditions, dominates Pichavaram mangroves. A similar observation has been made recently by Kathiresan et al. (2013). Hence, from the results of species composition and IVI values, it is obvious that the family Avicenniaceae is the single largest family followed by Rhizophoraceae. Similar observations were made by

Nabi et al. (2012) from the Machilipatnam coast, Andhra Pradesh. Similar trends have been discerned for the mangrove stands in Puttalam lagoon and Dutch bay of Sri Lanka (Amarasinghe and Balasubramaniam, 1992). Structural complexities of mangroves also have shown a statistically significant positive relationship with habitat availability in the mangroves, measured in terms of shrimp abundance (Jayasundera et al., 1999).

Principal Component Analysis score of the first two principal component axes such as PC1 and PC2 showed the cumulative variances of 33% and 53.8% respectively while PC3 explains 84.8% of the cumulative variance among the dataset. Hence, when PC1 scores are considered, mangrove plots with negative scores represent more productive areas than those with positive PC1 scores. Net primary productivity was found to vary with the age groups. Interestingly, the plot 5 with age 2 years showed the maximum primary productivity (26.25 ± 4.23 t/ha/yr) whereas, the plot 4 i.e. the natural population showed minimum primary productivity (17.04 ± 1.43 t/ha/yr). This could be attributed to the fact that as trees reach maturity, the sequestration rate declines because respiration begins to equal or exceed primary production (Baral and Guha, 2004). But, in the case of young plants it just the opposite, where the rate of primary production is more than the rate of respiration.

Direct carbon sequestration by trees has been proposed as an emergency stop-gap measure to stop or reverse the increase in atmospheric CO_2, while allowing time to develop and implement clean energy technologies. In contrast, the use of tree biomass for fossil fuel substitution can be a longer-term measure because harvesting and replanting in a given piece of land can be carried out in perpetuity. Additionally, the use of biomass for energy production helps rural economies to grow and enhances energy security. Soils are the largest carbon reservoirs of the terrestrial carbon cycle. Sediments contain about three times more carbon than vegetation and twice as much as that present in the atmosphere. Sediments contain much more C (1500 Pg of C to 1 m depth and 2500 Pg of C to 2 m; 1 Pg = 1 × 1015 g) than is contained in vegetation (650 Pg of C) and twice as much C as the atmosphere (750 Pg of C) (USEPA, 1995). Carbon in the form of organic matter is a key element to healthy soil. It is estimated that each tonne of soil organic matter releases 3.667 tonnes of CO_2, which is lost into the atmosphere. In Pichavaram mangrove forest the carbon sequestration potential differed from each other significantly among study plot (age groups). The maximum carbon sequestration potential was observed in a natural mangrove plot. This could be attributed to high biomass and litter fall production (Kathiresan et al., 2013). Soils in the mangrove forest have a distinct advantage over those in many other environments in the sequestration of organic carbon (Brevik and Homburg, 2004; Alongi et al., 2001). Thus, coastal wetlands and mangrove have the potential to accumulate carbon with high rates over long time periods because they continuously accumulate organic-rich sediment. Moreover, the global warming may hit the efficiency of carbon sequestration by mangroves, because there is a negative correlation between carbon sequestration and soil temperature (Kathiresan et al., 2013).

5. Conclusion

Mangrove ecosystems are a significant carbon sink in terms of forest biomass as well as organic sediment accumulation. The mangroves are known to remove CO_2 from the atmosphere through photosynthesis and fix greater amounts of CO_2 per unit area, than what the phytoplankton do in the tropical Oceans. In this study, we undertook an interesting assessment of net primary productivity, vegetative characteristic and carbon sequestration potential in relation to various age group and species of mangrove plants. We found that net canopy photosynthesis is directly proportional to the age of the forest, while the Net primary productivity decreases with the increase in the age of the forest. We also found that *Xylocarpus mekongensis* shows the maximum carbon sequestration potential compared to all the studied 12 species. Therefore, the physicochemical, vegetative and carbon sequestration data obtained from the present extensive survey imply the greater contribution of mangroves, as sources of energy for aquatic food webs and a potential source of carbon sink, which could be achieved through enhancing plant species diversity in the mangrove forest. Coastal marsh and mangrove are a fragile ecosystem which is declining at an alarming rate of 0.66% per year. It is necessary to protect and restore these ecosystems for carbon sequestration as well as other valuable ecosystem services.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bcab.2019.101235.

Conflicts of interest

Authors declare that they have no conflict of interest.

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