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Carbon sequestration and annual increase of carbon stock in a mangrove forest

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ABSTRACT

Here we show carbon stock is lower in the tropical mangrove forest than in the terrestrial tropical forest and their annual increase exhibits faster turn over than the tropical forest. Variable for above ground biomass are in decreasing order of importance, breast height diameter (d), height (H) and wood density (ρ). The above ground biomass (AGB) and live below ground biomass (LBGB) held different biomass (39.93 ± 14.05 t C ha^{-1} versus 9.61 ± 3.37 t C ha^{-1}). Carbon accrual to live biomass (4.71–6.54 Mg C ha^{-1} a^{-1}) is more than offset by losses from litter fall (4.85 Mg C ha^{-1} a^{-1}), and carbon sequestration differs significantly between live biomass (1.69 Mg C ha^{-1} a^{-1}) and sediment (0.012 Mg C ha^{-1} a^{-1}). Growth specific analyses of taxon density suggest that changes in resource availability and environmental constrains could be the cause of the annual increase in carbon stocks in the Sundarbans mangrove forest in contrast to the disturbance – recovery hypotheses.

1. Introduction

The increase of atmospheric CO_2 is unavoidable but sinks for this carbon are not well understood. During 2000–2009, combination of fossil fuel and land use change lead to an emission of 8.8 ± 0.86 Gt C per year with coefficient of variance (C.V) 9.77%, whereas the atmospheric growth and the uptake by land and ocean together could account 8.8 ± 1.12 Gt C a^{-1} with C.V 12.75% (Global Carbon Project, 2009). Two large reservoirs: the terrestrial biosphere and the ocean uptake CO_2 approximately in equal proportion. Greater coefficient of variance for the uptake by land and ocean indicates considerable annual variability in the estimation of CO_2 storage by the ocean and land. This could be due to the weakening of sink strength of the ocean and increasing capacity of forest uptake in response to atmospheric CO_2 increase (Spiecker et al., 1996; Lewis et al., 2004; Ciais et al., 2008). These CO_2 'sinks' are not stable, in fact, they are highly variable and respond to elevated atmospheric CO_2 levels and climatic change. Therefore, it is of interest to know the size of the land and ocean CO_2 sinks and their evolution with time.

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 C is sequestered in the forests, and about 70% of this C is stored in the soil (Dixon et al., 1994; Schimel, 1995) with slow turnover rate (Guggenberg 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 region to produce different spatial and temporal pattern of carbon uptake by trees (Muller-Landau, 2009). Mangrove forest accounts for about 2.4% of tropical forest (www.fao.org/forestry/mangroves; Spaulding et al., 1997) and to improve accuracy of global carbon sink quantification of carbon dynamics is essential in the mangrove swamps (Chmura et al., 2003).

The Indian Sundarbans mangrove forest in the estuarine portion of the River Ganges covers an area of 9630 km^2 out of which 4264 km^2 is law protected forest. It is the largest delta on the globe (world's heritage site, www.unesco.org/en/list/452) and covers about 2.84% of the global mangrove area (15×10^4 km^2).

Attempts are made to quantify biomass and characterize carbon dynamics in tropical rainforest, yet uncertainty remains, specifically with respect to the mangrove forest (Ometto et al., 2005; Pyle et al., 2008; Lewis et al., 2009; Miller et al., 2004). The objective of this study is to quantify carbon sequestration and to examine the

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controlling factors for annual increase of carbon stock in the tropical mangrove forest.

2. Material and methods

2.1. Study area, geology, soil and climate

The study sites are located in the Sundarbans (21°32′ and 22°40′ N; 88°05′ and 89°E), a natural mangrove forest, which is part of the estuary associated with the river Ganges, on the northeast coast of the Bay of Bengal, covering a total area of 9630 km^2 out of which 4264 km^2 comprising intertidal habitat. The area is covered with thick mangroves, which can be treated as forest and aquatic sub ecosystems (1781 km^2). In 1985, the Indian Sundarban was included in UNESCO's list of world heritage site and in 1989, India designated 9360 km^2 of Sundarban as a law protected forest. In 1985, the area of Sundarban forest was about 20,000 km^2 but now is only 9630 km^2, out of which about 4200 km^2 is mangrove forest. It is the last frontier of Bengal flood plains, sprawling archipelago of 102 islands out of which 54 are impacted.

The tidal Islands at the central positions show elevations of the order of 3–8 m from mean sea level. The Ganges drain much of the southern slopes of the Himalaya and delivers an enormous amount of sediment (324×10^6 t annually) to the Bengal fan. The Hooghly estuary, a tributary of the river Ganges, is a main artery of the Sundarban mangrove ecosystem and is dominated by fresh water discharge from Farrakka dam, which is located 285 km upstream from the mouth of the river. Tide in the study area is semidiurnal with tidal amplitude, i.e., 2.5–7 m. Mean current velocities ranges between 117 and 108 cm s^{-1} during low tide and high tide, respectively (Mukhopadhyay et al., 2006).

Climate in the region is characterized by the southwest monsoon (June–September), north east monsoon or post-monsoon (October to January) and pre-monsoon (February–May); 70–80% of annual rain fall occurs during the summer monsoon (South west monsoon), resulting in high river discharge (2952 and 11, 897 $m^3 s^{-1}$), which gradually diminish to 900–1500 $m^3 s^{-1}$ during non −monsoonal months (Mukhopadhyay et al., 2006).

Out of the several approaches (Whittaker and Marks, 1975) both allometric technique for above ground biomass increase and micrometeorological approaches for whole community CO_2 gas exchange were applied for the measurement of primary productivity in the Sundarban mangrove forest.

2.1.1. Measurement of the above and below ground biomass

For allometric studies more than 100 trees covering all species, total weight, wood specific gravity (oven dry weight over green volume), height (H) and tree circumference at breast height (cbh) at 1.3 m height were measured. Trees of each species were felled (three trees per cbh class) and after collection of above ground biomass (AGB) tree roots were dug up as complete as possible for the measurement of below ground biomass (BGB). Based on field measurements, different cbh classes of trees were recognized: ≤10, 10–20, 20–30, 30–40, 40–50, 50–60, >60 cm. Trees of each of the species were considered (three trees per cbh class) in the forest. Quadrates (10 m × 10 m) were selected randomly in west Sundarbans: Lothian Island North (Stn.1, four quadrates), Lothian Island South, Ecocamp (Stn.2, four quadrates), Prentice Island (Stn.3, two quadrates), and in east Sundarbans: Bonnie camp (Stn. 4, two quadrates) and Halliday Island (Stn.5, four quadrates) for cbh measurements of mangrove trees (Fig. 1). About 25 m observatory towers constructed by ministry of forest, Govt. of WB, over the

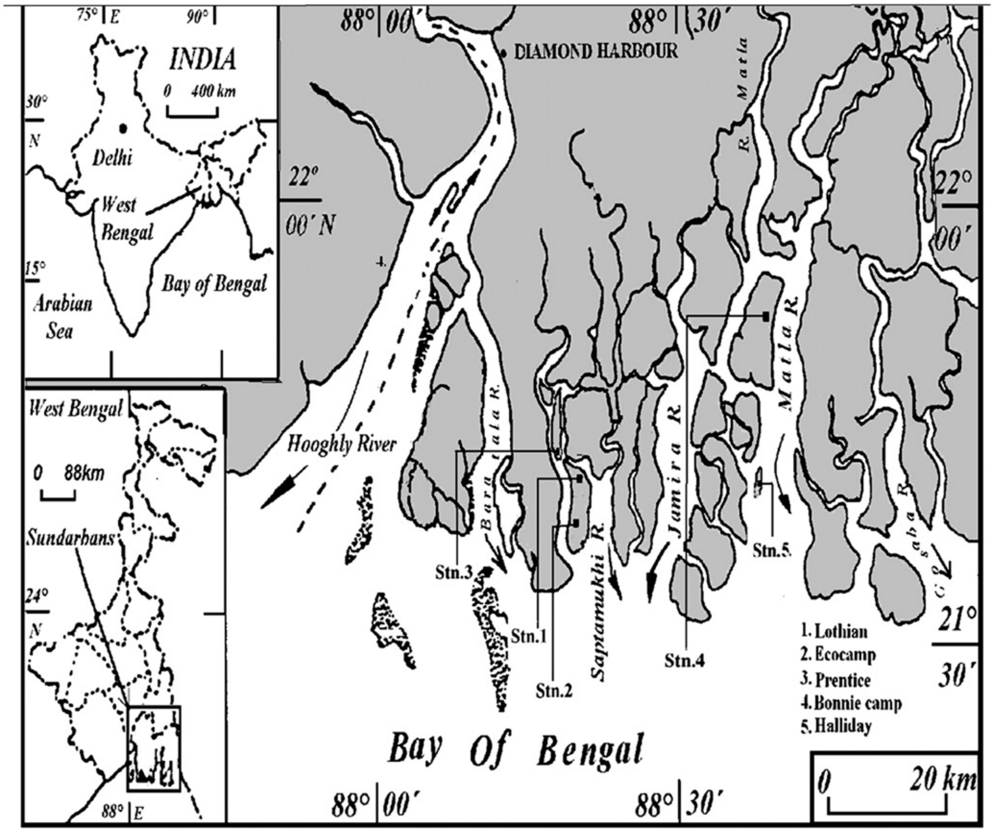

Fig. 1. Map showing site location.

mangrove forest stands at Stns 1, 2 and 4 were used for micrometeorological observation. Considering the number of mangrove species in a quadrate and their density, height and diameter, above ground biomass (AGB) was obtained from allometric equations separately and the AGB for each individual species was then summed to calculate the total AGB. Data were used to extrapolate over the entire mangrove forest. The below ground biomass (BGB) of live root material was collected from the soil core ($1 \times 1 \times 0.45$ m) from each quadrate. The soil samples were washed with a fine jet of water.

Five quadrates of 10×10 m size in the foot print of the observatory tower selected randomly along a transect covering a plot (54 ± 21 trees in 0.01 ha quadrate) of 1 ha. Different mangrove species were marked and measured for cbh increment at one year interval (September, 2009, 2010) at Stns 1, 2 and 4. Annual increment of above ground biomass was estimated from increased diameter (dbh) using allometric equations. Litter fall was collected from a trap (3×3 m) made of nylon screen and suspended below the canopy from branches of the trees at height sufficiently above the ground to avoid tidal inundation. Litter were collected monthly using 10 such type of traps placed randomly inside the deep forest during the period between September, 2009 and September, 2010. All samples of AGB, BGB and litter were oven dried at 60 °C for the determination of their dry weight. Density (ρ) of blocks ($2 \times 2 \times 4$ cm) cut from wood discs was determined dividing sample oven dry weight by the wet sample volume (Haygreen and Bowyer, 1996) and density was represented in g cm^{-3} in this study. Carbon was estimated in different components of dried plant material using CHN Analyzer (2400 series-11, Perkin–Elmer).

2.2. physico-chemical properties of soil

Core samples were collected by using a corer made of stainless steel (5.5 cm i.d.) during three seasons at different depths up to 30 cm from surface to estimate soil organic carbon.

Sediment was placed in a screw capped centrifuge tube with septum and pore water was separated avoiding air contact by means of centrifugation (30 min, 5000 rpm). For total inorganic nitrogen, 30 g of soil was extracted in 75 mL of 2 M potassium chloride (KCl). The mixture was shaken for 24 h and total inorganic nitrogen (TIN = ammonia–nitrogen (NH_4^+–N), nitrate and nitrite-nitrogen (NO_3–N)), and soluble and total extractable phosphorus (TEP) were determined by spectrophotometric method (Riley et al., 1995; Grasshoff, 1983; APHA, 1995; Chang and Jackson, 1957). A relative error of accuracy was ±2% for phosphate; ±3% for nitrate. Salinity (S) of the pore water samples were determined by Mohr–Knudsen titration. Air dried sediment samples were used for the grain size analysis following pipette method (Piper, 1950), for organic carbon using modified Walkley–Black method (Shrawat, 1982). Glucose was used as a standard for labile organic matter in the sediment and 97.6% accuracy and 3.14% coefficient of variation were achieved for the determination. 0.5 g of dried sediment was extracted with 0.1 (N) KOH by constant shaking for 24 h and concentration of humic (HA) and fulvic (FA) acid in the centrifugate were estimated by Fluorescence method using LS-50 Luminescence spectrophotometer. FA (Excitation 313 and Emission 425 nm) and HA (Excitation 392 and Emission 484 nm) procured from Aldrich. Co. was used as standard (Ghatak et al., 2002; Leifer, 1988; Silva et al., 1994). pH and Eh (Redox potential) were measured by gently lowering the electrodes into the sediment (Vischer et al., 1991).

2.3. Community exchange of CO_2

Micrometeorological parameters were measured using weather monitoring stations (Model-Davis 440) and CO_2 by gas chromatography at Stns 1, 2 and 4. Air samples were collected monthly from 10 to 20 m height with the help of a portable air sampler (Tecnovation air sampler, Model AS2) at a rate of 2 L min^{-1} and drawn into pre-evacuated glass sampling bulbs. The pCO_2 in marine air was measured with gas chromatography (Varian CP 3800 GC) connected to methanizer (Nickel catalyst system) for catalytic reduction of CO_2 followed by its subsequent determination with flame ionisation detector (FID). A chromapack capillary column ($12.5 \text{ m} \times 0.53$ mm) and FID at 50 °C and 150 °C were used. Calibration gas supplied by Chemtron Science Laboratory Pvt. Ltd. had mixing ratios of 300 and 400ppmv. The relative uncertainty of pCO_2 measurements was found to be ±0.063.

The rate of exchange of atmospheric CO_2 was calculated considering aerodynamic (r_a) and surface layer (r_s) resistance, and from the concentration (χ_i) difference between 10 and 20 m: $\Delta\chi = \chi_{10} - \chi_{20}$. With exchange velocity, V_C, defined as $1/(r_a + r_s)$, net flux, F, was calculated using the relation (Barrett, 1998):

$$F = V_C \Delta\chi$$

Negative F indicates net transfer from the atmosphere to the biosphere and positive F, for emission. The aerodynamic resistance was evaluated from the relation (Wesely and Hicks, 1977):

$$r_a = \frac{\ln(Z/Z_0) - \Psi_c}{ku}$$

where Z_0 is roughness height and Ψ_c is a correction function for atmospheric stability. Equations used for the correction functions are (Wesely and Hicks, 1977):

$$\Psi_c = -5Z/L \text{ for } 0 < Z/L < 1 (\text{stable condition}) \text{and}$$

$$\Psi_c = \exp\left[0.0598 + 0.39\ln(-Z/L) - 0.09\{\ln(Z/L)\}^2\right]$$

$$\text{for } 0 > Z/L > -1 (\text{unstable condition})$$

The correction functions are expressed in terms of a stability parameter Z/L, in which Z is the height and L is the Obukhov Scale length. The friction velocity, u^* was estimated from the wind velocity at 10 and 20 m in the following manner:

$$u^* = k(u_{10} - u_{20})/\ln(Z_{20} - Z_{10})$$

where k is the Von Karman constant. Z_0 was determined from the intercept ($\ln Z_0$) of the straight line obtained by plotting $\ln Z$ versus u. 80% of the average height (10 m) of the mangrove plants was considered to calculate displacement length, d (Panofsky and Dutton, 1984). Gradients of wind velocity and temperature observed over the canopy at 10 and 20 m for computing aerodynamic resistance were found well with in the limit of sensitivity (±0.01 °C and ±0.01 m s^{-1}) of the used sensors.

Considering the stability classes of Pasquill: A–F (Pruppacher and Klett, 1997) the scale length, L, was evaluated using the following relation:

$$1/L = a + b \log Z_0,$$

where 'a' ranges between 0.035 and −0.096 and 'b' ranges between 0.029 and −0.036 (Golder, 1972).

Pasquill stability classes in terms of wind speed, insolation and state of sky were as follows, D–F (stable) for post-monsoon, B–D (unstable) for pre-monsoon and E, F for monsoon in the nighttime and A–C (unstable) for post-monsoon, E, F (unstable) for pre-monsoon and B (unstable or occasionally stable) were observed in the daytime. For surface layer resistance (r_s), following relations

Table 1
Seasonal variation of micrometeorological parameters and atmospheric CO_2.

Parameters		Pre-monsoon	Monsoon	Post-monsoon
Temperature (°C)	10 m	29.06 ± 2.16	28.34 ± 2.25	21.2 ± 2.15
	20 m	28.84 ± 2.03	27.9 ± 2.21	20.53 ± 2.22
Wind speed (m s^{-1})	10 m	4.28 ± 2.47	3.35 ± 1.94	1.18 ± 1.12
	20 m	5.12 ± 2.88	3.98 ± 2.43	1.65 ± 1.08
Pressure (mm)	10 m	757 ± 1.36	754.1 ± 3.1	763.4 ± 1.76
Humidity (%)		77.91 ± 1.49	86.63 ± 7.61	73.54 ± 5.98
CO_2 (ppmv)	10 m	370.2 ± 5.5	374.3 ± 4.5	366.8 ± 8.9
	20 m	376 ± 10.34	369 ± 6.56	371 ± 5.61

with surface transfer function, B^{-1} (Wesely and Hicks, 1977) and u^* were used:

$$kB^{-1} = 2(K/D_c)^{2/3} \text{ and } r_s = B^{-1}/u^*(\text{for forest cover}),$$

where k is the Von Karman constant; K is the thermal diffusivity of air and D_c is the molecular diffusivity:

$D_c = 0.115\ (T_2/273)^{1.5}$, where T_2 is the temperature at 20 m height.

In the mangrove sediment, the long term rate of accumulation of soil organic carbon/humic material is calculated from bulk density ($\rho = 2.5$ g cm^{-3}) and the percentage of organic carbon/humic material at each depth in the sediment profile of depth 0–30 cm.

$$\text{Organic C or Humic material}\left(\text{g cm}^{-2}\right) = \sum_{D=0}^{30} 100.D.p(D).P(D)$$

where $p(D)$ and $P(D)$ are the bulk density in g cm^{-3} and the percentage of humic organic material at the depth D (cm). The long term average rate of accumulation is obtained by dividing the humic carbon content (50%) by radio carbon data of humic materials which is frequently 1000 yrs (Schlesinger, 1990).

3. Results

Annual movement of the Inter-tropical Convergence Zone in this part of the world produces significant changes in micrometeorological parameters throughout the year because of differential temperature and pressure in different seasons (Table 1). Mean temperature and humidity are 28.12 ± 1.67 °C and 80.36 ± 9.74%, respectively with annual rain fall 1750 mm. Geologically the area is the result of extensive fluvio-marine deposits of the river Ganges and Bay of Bengal and the character of the sediment of the study site is silty clay (Table 2, sand 9.23%, silt 79.6%, clay 11.2%). Salinity, noted during the pre-monsoon is highest ca 30.0 ± 1.29 and lowest during – monsoonal run off coming down to 18.31 ± 3.86 .The sediments are nutrient poor (nitrogen 2.5 ± 0.41 μg g^{-1}, phosphorus 0.57 ± 0.64 μg g^{-1}) with mean organic carbon 0.61 ± 0.061% and pH 8.07 ± 0.29. The large tidal range and extremely gentle shelves (1.2–4.0°) with muddy substrate make water current and tidal action quite appropriate for extensive mangrove occurrence. *Avicennia* is the pioneering mangrove followed by other mangrove species like *Ceriops* sp., *Excoecaria* sp. etc.

Table 2
Seasonal variation physico-chemical properties of mangrove sediment and pore water.

Soil parameters	Pre-monsoon	Monsoon	Post-monsoon
Soil T (°C)	30.7 ± 1.04	28.63 ± 0.90	25.04 ± 0.96
S (pore water)	30.0 ± 1.29	18.31 ± 3.86	21.05 ± 4.67
Soil pH	8.23 ± 0.01	7.78 ± 0.29	8.21 ± 0.06
Org.C (%)	0.514 ± 0.029	0.649 ± 0.032	0.654 ± 0.04
Total inorganic N (TIN) (μg g^{-1})	2.3 ± 0.43	2.4 ± 0.35	2.9 ± 0.4
Extractable PO_4–P (TEP) (μg g^{-1})	0.5 ± 0.4	0.3 ± 0.4	0.9 ± 0.3
HA (μg g^{-1})	216.3 ± 65.2	454 ± 136.8	457.8 ± 138
FA (μg g^{-1})	629.9 ± 113.1	1298 ± 232.3	1308 ± 234.8
Eh (mV)	37.16 ± 92.13	−99.14 ± 48.53	−129.48 ± 93.32
Sediment texture			
Sand (%)	6.24 ± 0.57	5.33 ± 1.43	16.12 ± 4.11
Silt (%)	79.76 ± 5.34	87.00 ± 4.29	72.00 ± 5.11
Clay (%)	13.99 ± 1.12	7.66 ± 1.27	11.88 ± 3.45

3.1. Tree allometry and estimation of biomass

Biomass-diameter-height regression models are developed using data given in Table 3 between the above ground biomass (AGB) and most important predictive variable: Diameter of breast height (dbh, cm) calculated from cbh, height ($4 \le H \le 10.55$ m) and density (ρ, g cm^{-3}).

The best fit regression equations are:

Equation (1): with density factor:

$$\text{AGB} = 1.0471(d)^{0.864}(H)^{0.635}(\rho)^{-1.37} \quad \left(R^2 = 99.2,\ p < 0.001,\ n = 100\right), \tag{1}$$

Equation (2): without density factor:

$$\text{AGB} = 1.3799(H)^{0.687}(d)^{0.955} \quad \left(R^2 = 98.1,\ p < 0.001,\ n = 100\right), \tag{2}$$

Equation (3): Above ground biomass (AGB) and live below ground biomass (LBGB) regression model:

$$\text{LBGB} = (\text{AGB})^{1.63} - 30.29 \quad \left(R^2 = 97.4,\ p < 0.001,\ n = 100\right), \tag{3}$$

Equation (4): For smaller trees and shrubs of mangrove (above ground height <4 m) not reaching breast height diameter of trunks below 0.5 m above the surface of the sediment (Saintilan, 1997):

$$\text{AGB} = 0.162\,(H)^{1.81}(d)^{1.24} \quad \left(R^2 = 95.4,\ p < 0.001,\ n = 40\right), \tag{4}$$

3.2. Variation of above ground biomass

Total above ground biomass in the Indian mangrove forest ranges from 65.4 to 171.8 t dry wt. ha^{-1} (Avg. 93.72 ± 32.98 t dry wt ha^{-1} or 49.54 ± 17.42 t C ha^{-1}) (Table 4) and living below ground biomass varies between 15.3 and 39.6 t dry wt. ha^{-1} (Avg. 21.69 ± 7.61 t dry wt ha^{-1} or 9.61 ± 3.37 t C ha^{-1}). Major mangrove species contributing to AGB distribution are found different and *Avicennia marina* (4.12–96.96%), *Avicennia alba* (1.61–82.3 7%), *Avicennia officinalis* (1.17–26.93%), *Excoecaria agallocha* (19.3–22.4%) and *Ceriops decandra* (9.24–21.4%) are predominant in the western part of Sundarbans,

Table 3
Structural parameters of mangrove tree of different size class used for allometry.

Range of cbh (cm)	No of trees	dbh (cm)	Height (m)	Density (g cm^{-3})[a]	Biomass (Wet wt. in kg)
≤10	14	1.56 ± 1.43	4.26 ± 3.76	0.79 ± 0.04	4.33 ± 4.08
10–20	29	5.52 ± 0.48	4.96 ± 0.75	0.72 ± 0.01	19.77 ± 3.4
20–30	12	6.83 ± 0.38	5.15 ± 0.77	0.69 ± 0.01	27.42 ± 3.95
30–40	10	10.63 ± 0.87	8.66 ± 1.44	0.7 ± 0.04	51.05 ± 12.69
40–50	14	14.09 ± 2.88	8.71 ± 2.56	0.63 ± 0.04	78.69 ± 18.43
50–60	14	18.38 ± 3.97	8.90 ± 2.57	0.62 ± 0.05	157.47 ± 31.95
>60	7	24.5 ± 2.78	10.55 ± 0.9	0.59 ± 0.02	271.57 ± 46.06
Total	100				

[a] Density = Dry wt./wet volume.

Table 4
Species wise spatial variation of above ground and below ground biomass along with their structural parameters and contribution to carbon storage.

Name of species	Total no of trees in the quadrate	Circumference range (cm)	Height range (m)	Average density (g cm^{-3})	Stem (wet wt., t ha^{-1})	Leaf + Branch (wet wt., t ha^{-1})	Total AGB (dry wt., t ha^{-1})	Total BGB (dry wt., t ha^{-1})	Total C (t C ha^{-1})	% Contribution to total AGB
Lothian-1										
A. marina	34	4–42	4.07–7.42	0.69	53.6	327	61.6	14.19	32.55	89.8
A. alba	3	3–24	3.98–5.83	0.67	0.8	3.5	1.1	0.25	0.5	1.6
A. officinalis	2	27–48	6.1–7.95	0.67	4.9	32.5	5.8	1.39	3.1	8.6
Total	39				59.7	363.0	68.6	15.84	36.23	
Lothian-2										
A. marina	50	4–30	4.16–6.45	0.69	52.5	319.9	60.4	13.90	31.88	78.6
A. alba	10	4–21	4.07–5.13	0.71	7.8	49.9	9.1	2.10	4.82	11.9
A. officinalis	8	4–26	4.07–6.01	0.72	6.1	39.9	7.2	1.72	3.84	9.5
Total	68				66.8	406.0	76.7	17.73	40.54	
Lothian-3										
A. marina	14	9.8–30.5	4.58–6.5	0.73	17.0	105.7	19.7	4.54	10.42	25.0
A. alba	32	8–34.6	4.42–6.77	0.69	44.9	273.9	51.7	11.90	27.28	65.5
A. officinalis	4	10.6–3.8	4.65–4.93	0.69	3.0	21.0	3.7	0.87	1.94	4.6
Ceriops sp.	3	11.3–9.9	4.71–5.47	0.67	3.1	21.7	3.8	0.91	2.01	4.8
Total	53						78.8	18.22	41.65	
Lothian-4										
A. alba	10	8–23.6	4.42–5.80	0.77	1.6	12.8	2.1	0.48	1.1	3.1
A. marina	44	4–78	4.53–10.68	0.73	57.8	351.4	66.4	14.77	34.82	96.9
Total	54				59.4		68.5	15.25	35.92	
Eco camp-1										
Excoecaria agallocha	10	2.13–8.78	4.31–6.15	0.77	14.4	89.9	16.7	3.85	8.83	23.1
A. marina	16	1.65–9.7	4.17–6.41	0.73	14.3	89.0	16.6	3.95	8.80	23.0
A. officinalis	31	5.8–30.5	4.25–6.41	0.69	33.7	206.5	38.9	9.32	20.68	54.0
Total					62.4	381.8	72.1	17.12	38.31	
Eco camp-2										
A. marina	30	8–25.9	4.50–6.00	0.69	28.1	172.3	32.4	7.47	17.1	32.9
Ceriops sp.	15	6.5–29.9	4.29–6.36	0.67	18.2	112.5	21.0	5.21	11.25	21.7
E. agallocha	17	6.8–30.1	2.16–9.57	0.67	16.5	102.3	19.1	4.40	10.07	19.4
A. officinalis	14	8–51.5	4.42–8.26	0.71	22.3	137.2	25.7	5.73	13.48	26.0
Total							98.1	22.80	51.91	
Prentice Island-1										
A. marina	33	6.5–40	4.39–7.03	0.69	46.1	280.8	53.0	12.22	27.97	80.8
A. alba	13	6.1–18.8	4.23–5.38	0.73	10.6	67.0	12.4	3.07	6.64	19.2
Total							65.3	15.29	34.61	
Prentice Island-2										
A. marina	36	6.4–64.8	4.28–9.44	0.69	63.7	387.0	73.1	16.87	38.63	80.9
A. alba	11	8–38.3	4.42–7.10	0.73	13.8	85.9	16.0	3.96	8.56	17.9
A. officinalis	2	6.5–7.6	4.29–4.39	0.77	0.7	7.4	1.1	0.24	0.56	1.2
Total							90.2	21.07	47.74	
Halliday-1										
Agialitis rotundifolia	60	9.5–45.2	4.55–7.53	0.65	90.4	548.0	103.7	23.92	54.77	78.6
A. marina	6	11–13.5	4.69–4.91	0.71	4.6	30.5	5.4	1.35	2.92	4.2
Ceriops sp.	15	9.5–38	4.55–5.41	0.72	17.0	105.5	19.7	4.54	10.40	14.9
A. alba	3	10.2–14	4.62–4.95	0.79	2.5	18.0	3.1	0.71	1.63	2.3
Total							131.9	30.52	69.71	
Halliday-2										
Agialitis rotundifolia	109	9–37.5	4.51–7.32	0.59	105.7	640.4	121.2	27.96	64.03	70.6
A. marina	23	10–14	4.82–6.5	0.74	19.7	122.0	22.8	5.26	12.05	13.3
Ceriops sp.	16	12–14	4.5–5.5	0.71	13.7	85.4	15.9	3.66	8.38	9.2
A. alba	12	7–15	4.0–6.5	0.78	10.2	64.5	11.9	2.75	6.29	6.9
Total							171.8	39.64	90.76	
Bonnie Camp										
A. marina	11	11–33.5	4.69–6.67	0.73	16.6	10.3	19.2	4.44	10.16	17.6
A. alba	44	5–44.5	4.16–7.65	0.69	78.3	475.0	89.8	20.72	47.45	82.4
Total							109.1	25.16	57.60	

and *Aegialitis rotundifolia* (70.55–78.61%), *A. alba* (2.33–82.37%), in the eastern part. The contribution of the stem to AGB is greater by 24% than leaf and branches.

To find how much of the variation in our measurements of AGB, LBGB, cbh, height and number of trees/quadrate is due to between sample differences and how much to random variability within the samples ANOVA test is applied. Observed value of F is 0.23 versus the critical value of F 2.13 with (10, 33) degrees of freedom at $p = 0.05$, indicating that difference of observed parameters at different sites are insignificant.

Table 5
Total Annual growth of mangroves in five quadrates (500 m^2).

cbh range (cm)	No. of trees	Mean cbh (cm)	Ava H (m)	Density (g cm^{-3})	Total AGB (Initial) Dry Wt. (Kg)	Mean increase cbh (cm a^{-1})	Mean increase in H (m a^{-1})	Total AGB (increase) Dry wt. (Kg a^{-1})
0–10	82	6.4	4.5	0.79	424.2	0.65	0.47	179.8
10–20	133	14.9	5.0	0.72	1732.7	0.86	0.36	167.6
20–30	72	24.3	5.9	0.69	1686.4	0.76	0.31	102.2
30–40	50	33.8	6.7	0.7	1660.6	0.63	0.26	67.3
40–50	26	46.3	7.8	0.63	1440.6	0.43	0.14	27.7
50–60	18	53.9	8.1	0.62	1186.9	0.32	0.04	9.3
>60	8	71.8	10.1	0.59	832.6	0.12	0.01	1.8
Total	389				8964.2			555.7

3.3. *Carbon storage as ABG and BGB*

Carbon concentrations are found to be 43.0–45.1% to roots, 42.4–43.05% to stems, 42.09–42.5% to leaves. The net accumulation of the carbon in the above ground biomass obtained from the annual increment of cbh (circumference at breast height) is estimated to be 2.0 Tg C a^{-1} or 4.71 Mg C ha^{-1} a^{-1} (Table 5). Total storage of carbon in the above and below ground biomass (live) in the Sundarban mangrove forest is estimated to be 21.13 Tg C. The East and the West Sundarbans hold comparable above ground biomass (50.78 ± 13.57 Mg C ha^{-1} versus 29.19 ± 4.36 Mg C ha^{-1}, respectively), but live below ground biomass are about 4 times lower (7.94 ± 1.22 Mg C ha^{-1} at West Sundarbans, versus 14.1 ± 8.24 Mg C ha^{-1} at East Sundarbans) than above ground biomass. East and West Sundarbans exhibit spatial variability of biomass (27% and 58% coefficient of variance for AGB and LBGB, respectively at East Sundarbans versus 15% coefficient of variance for AGB and LBGB at west Sundarbans).

3.4. *Whole community CO_2 gas exchange*

There is clear day and night change in CO_2 flux above the canopy (Fig. 2) and CO_2 flux shows net uptake during day time (negative flux) and efflux in the night (positive flux). Mean up take and emission rate of CO_2 are found to be 1.00 ± 0.66 and 0.92 ± 0.44 mg CO_2 m^{-2} s^{-1}, respectively.

3.5. *Litter fall*

Monthly variation of mean litter fall (Fig. 3) ranges between 56.1 ± 35.81 g dry wt. m^{-2} $month^{-1}$ in December–January with coefficient of variance 15.9–47.9%. Annual litter fall of this riverine mangrove is estimated to be 1173.85 g dry wt. m^{-2} a^{-1} being greater than that of fringe mangroves (900 g m^{-2}) and shrub mangroves (186 g m^{-2}) in southwest Florida (Twilley et al., 1986).

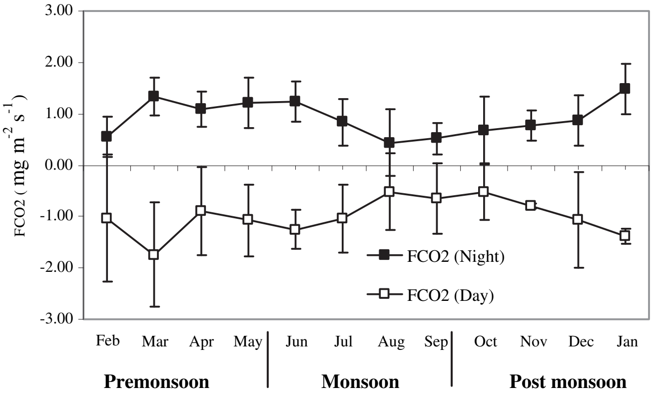

Fig. 2. Monthly variation of biosphere-atmosphere CO_2 exchange flux.

Carbon concentration in litter varies between 34.6 and 42.1%. Annual litter fall is estimated to be 485.85 g C m^{-2} a^{-1} or 2.07 Tg C a^{-1}or 4.85 Mg C ha^{-1} a^{-1}

3.6. *Soil carbon sequestration*

Soil organic carbon (30 cm depth) showed greater concentration of 0.65% in the post-monsoon than in the pre-monsoon (0.51%) (Table 2). Total carbon storage in the sediment was estimated to be 5.49 Tg C with an addition rate of 2.07 Tg C a^{-1} in terms of litter fall.

3.7. *Low Carbon storage potential of soils*

Amount of carbon stored in soil organic matter and humic material are 2598 g C m^{-2}/5.49 Tg and 1125 g C m^{-2}, respectively. Total storage of humic material implies an annual rate of production 1.12 g C m^{-2} a^{-1}, which is 0.23% of the total litter addition rate of 485.85 g C m^{-2} a^{-1}. This pool of soil carbon is large and plays a dynamic part in the geochemical carbon cycle.

4. Discussion

Soares and Schaeffer-Novelli (2005) analyzed the above ground biomass of *Rhizophora mangle* and *Laguncularia racemosa* in southeast Brazil and recommended the use of models related to structural development such as dbh (diameter of breast height) and height and stressed the need to obtain specific data for each geographical area. Chave et al., 2005 deduced a mixed species tree biomass regression model for converting plot census data into estimates of AGB across a broad range of tropical forest. He argued that as many as 300 different species could exist in 1 ha of tropical forest, for which the use of species-specific allometric regression model could be the large sources of uncertainty in estimates of carbon stocks. Lewis et al., 2009 showed that estimates of change in above ground carbon stocks in intact African tropical forests using single mixed species allometric equation were unlikely to be biased. Because, 4264 km^2 Sundarbans mangrove forest shelter

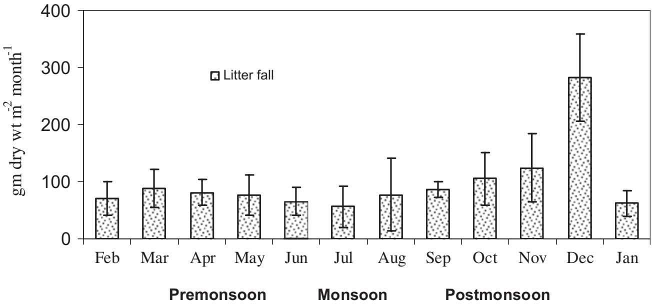

Fig. 3. Monthly variation of litter fall in the mangrove forest.

different mangrove species, instead of using species-specific regression models mixed species trees biomass regression model was deduced and used for the estimation of AGB per quadrate which provided much better fit for extrapolation over the entire forest area.

The variable in Equation (1) for the estimation of above ground biomass (dry weight) of a mangrove tree are, in decreasing order of importance, dbh 96.9%, H 1.2% and ρ 1.1%. Several studies that used regression model to investigate AGB of mangrove species are found dbh either alone or associated with the height as the important predictive variable and rarely, with diameter of the crown (Fromard et al., 1998; Komiyama et al., 2002; Soares and Schaeffer-Novelli, 2005).

Woodroffe (1985) reported 6.8 t dry wt. ha^{-1} of AGB for *A. marina* in Tuffcrater, Newzeland. In the western Australia, *A. marina* showed lower range of AGB (45.8–147.6 t dry wt. ha^{-1}) and LBGB (11.5–21.2 t dry wt. ha^{-1}) relative to Rhizophora stylosa (AGB = 207.9–282.8 t dry wt. ha^{-1}, LBGB = 36.3–55.8 t dry wt. ha^{-1}). In the present study, the mean AGB 93.74 ± 32.98 t dry wt ha^{-1} or 39.93 ± 14.05 t C ha^{-1} with 35.0% coefficient of variance (C.V) is found lower than that of terrestrial tropical forest (246 t dry wt. ha^{-1}, Alongi, 2009) and African tropical forest (201.5–298 t C ha^{-1}; Lewis et al., 2009). Rana et al. (1989) reported even greater AGB (385.9 ± 176.4 t dry wt. ha^{-1}, C.V. 45.7%) in the upland forest (central Himalaya, dominated by Sal, Chirpine, Bangoak, Rianj, Tilonj etc.). Sundarbans mangrove has difference in the allocation of live below- and above ground biomass and the observed ratio (LBGB/AGB% = 24) is comparable with the average value reported for world mangroves (19%, Alongi, 2009).

In ecological analyses, limitation for the use of stepwise multiple regression analysis is due mainly to bias in parameter estimation (Whittingham et al., 2006). The observed variability in the physico-chemical parameters and AGB were used in VARIMAX -rotated factor analysis and the results are given in Table 6. It showed the communality of the factor analysis that expressed the percentage of elements variability explained by the factor model and gave the variance explained by each retained factor. Factor loading larger than approximately 0.3 were considered statistically significant (Chatterjee et al., 2006). The five factor model could explain 99.4% of the data variance. The first factor had high loading and could account 44.9% of total variance. Association of AGB with salinity (S), pH, Organic Carbon (OC), total inorganic nitrogen (TIN) and total extractable phosphorus (TEP) in the factor 1 justified their use in multiple regression analysis as independent parameters. However, OC, TIN, TEP in association with S showed positive loading in factor 2, 3 and 4 respectively indicates that the role of salinity on their variation. The significance of the response of the AGB was tested by multiple regression analysis (Table 7). The dependent variable is AGB and the independent variables are salinity (S), pH, Organic Carbon (OC), Total inorganic nitrogen (TIN) and total extractable phosphorus (TEP). Statistical analysis reveals significant correlation of AGB with independent variable tested (AGB = −13085 + 81 S + 1420 pH + 1014 °C−161 TIN + 1639 TE P, R^2 = 89.3%, $p = 0.022$, $n = 12$) and explained variability of AGB is found to be 26.2% for salinity, 35.2% for pH and 15.2% for nutrients (TIN and TEP). High salinity result to physiological responses, as highly saline soil has low osmotic potential that constrain water relation of mangroves (Ball, 1996). Saintilan (1997) also found substratum salinity as a major controlling factor for the variation of above ground biomass of *A. marina* and *Aegiceras corniculatum*. Sherman et al. (2003) suggested that the relationship between pore water salinity and forest biomass was not robust because of co-variation of salinity with other potentially stressful factors in the soil environment such as H_2S, pH and anoxic condition, flooding frequency etc. In the present study, p values in the Table 7 indicates pH rather than salinity could be considered the leading factor. In oxic condition variation of soil pH could be attributable to oxidation of organic matter and sulfide promoted by the release of oxygen from roots especially in the surface as well as by production and release of organic acids from mangrove roots and metabolic by products of microbial decomposition of organic matter (Marchand et al., 2003), in contrast to the anoxic environment where anaerobic decomposers operate at slower rate resulting low rate of organic matter decomposition, and exposure to anaerobic conditions reduces tolerance of most mangrove to increase in salinity (Ball, 1996).

Table 6
VARIMAX -rotated factor loading matrix for AGB with soil parameters.

Variable	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Community
AGB	0.939	0.181	0.200	−0.135	0.131	0.990
S	−0.292	−0.262	−0.37	0.84	0.019	0.997
pH	0.871	0.128	0.217	−0.094	−0.409	0.999
OC	0.163	0.951	−0.187	−0.178	−0.017	0.998
TIN	−0.225	0.248	−0.89	0.303	0.035	0.997
TEP	0.944	0.048	0.067	−0.271	−0.003	0.983
Variance	2.6947	1.0861	1.0553	0.941	0.1863	5.9634
%Var	44.9	18.1	15.7	15.7	3.1	99.4

Table 7
Multiple regression[a] analysis with a stepwise variable selection. Dependent variable (AGB, kg m^{-2}), independent variable Salinity, (psu, S), pH, Organic carbon (%, OC), Total inorganic nitrogen (μg g^{-1} dry wt of sediment, TIN), Total extractable phosphate–phosphorus (μg g^{-1} dry wt of sediment, TEP).

Predator	R^2 (Stepwise)	p	F	n
S	26.2	0.017	5.2	12
pH	73.8	0.005	11.25	12
OC	74.1	0.013	6.96	12
TIN	75.6	0.047	4.66	12
TEP	89.3	0.022	7.60	12

[a] AGB = −13085 + 81S + 1420 pH + 1014 °C-161TIN + 1639 TEP.

Evapotranspiration rates of 5.54 mm d^{-1} in monsoon, 4.7 mm d^{-1} in the post-monsoon and 5.85 mm d^{-1} in the pre-monsoon (Ganguly et al., 2008) in the Sundarbans mangrove forest were found different relative to water limited ecosystem such as Savana (3.1–3.6 mm d^{-1}). Therefore, the mangrove forest has shown no sign for water limitation in forest carbon flux or canopy carbon uptake. Absence of dry season carbon up take or evapotranspiration reduction due to water stress was attributed to deep roots accessing deep water during dry season in the Tapajos National Forest, Para (Pyle et al., 2008). Extrapolating net ecosystem productivity (0.021 Mg C m^{-2} s^{-1}) to the entire Sundarbans gives an overall annual uptake rate 2.79 Tg C a^{-1}or 6.54 Mg C ha^{-1} a^{-1}.

Carbon accrual to live biomass is greater by 35–48% in the Sundarban mangrove forest than in the Amazonia forest (2.59–3.24 Mg C ha^{-1} a^{-1}; Pyle et al., 2008).

Live biomass is about 4 times lower in the Sundarbans than in the two sites of Amazonia forest (167 ± 7.1 Mg C ha^{-1} and 149 ± 6.0 Mg C ha^{-1}, Pyle et al., 2008), but by contrast it shows relatively rapid carbon accrual in live biomass at Sundarbans than at Amazon. This rapid carbon accrual in the Sundarbans results turn over much faster (10 years) than Amazon forest (~50 years), indicating the advantage of mangroves over terrestrial forests for rapid carbon sequestration.

Litter fall plays a pivotal role in mangrove ecosystem carbon dynamics and leads to a significant shift in the observed net carbon balance. The data show small net uptake (production − litter fall) of ~1.69 Mg C ha^{-1} a^{-1} leading to the conclusion that rate of accumulation carbon in Tropical mangrove forest is greater than the global mean of 0.49 Mg C ha^{-1} a^{-1} in tropical forests (Phillips et al., 1998; Lewis et al., 2009).

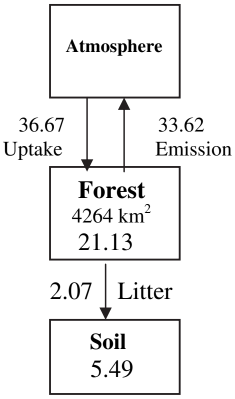

Fig. 4. Schematic diagram of organic stocks (Tg C in large boxes) and fluxes (Tg C a^{-1} soild straight arrow) at the Sundarbans during the study period.

The net biosphere-atmosphere exchange of CO_2 (2.79 Tg C a^{-1}) is consistent with the rate obtained by cbh measurement (2.0 Tg C a^{-1}). The overall carbon storage in the Sundarbans mangrove forest reservoir is estimated to be 21.13 Tg C and in the soil reservoir (30 cm) 5.49 Tg C. It stores 0.41% of the total carbon storage in the Indian forest (6621 Tg C) and uptakes (2.79 Tg C a^{-1}) 0.55% of the annual fossil fuel emission (504.6 Tg C a^{-1}) from India (Kishwan et al., 2009). Fulvic acid is believed to be the precursors of humic acids in the humification process. Its concentration exceeds by a factor 3 of the amount occurred as humic acid, indicating the allochthonous source of this organic matter and its transformation in the sediment (Sardessai, 1995; Table 2). Organic matter associated with humic materials is found to be 16–27%. Sardessai (1995) observed that 28–30% organic matter was bound to humic material in the sediment collected from offshore region of the Arabian Sea.

Production of 0.005 Tg C a^{-1} refractory humic substances in the Sundarbans is equivalent to 0.2% of the net ecosystem production. Schlesinger (1990) showed low carbon storage potential of soil from chronosequence studies and production of refractory humic substances in soils sequesters only 400 Tg C a^{-1} from the atmosphere, accounting for just 0.7% of terrestrial net primary production over mass of the earth land surface. World mangrove and salt marshes account for 11.1% (44.6 Tg C a^{-1}) of global soil sequestration and net effect of the increase in biomass production due to CO_2 increase and increase in decomposition of soil organic matter in response to temperature rise could further reduce carbon sequestration in the wetland ecosystem (Chmura et al., 2003). Increases in temperature and CO_2 concentration could differently affect growths of different mangrove species (Luo et al., 2010). Under favorable conditions of low vapour pressure deficit and low salinity (<15 psu) Avicennia assimilates CO_2 (12.5–20.1 μ mol m^{-2} s^{-1}) by photosynthesis at higher rate than many other mangrove species (Alongi, 2009). Since it is one the predominant species in the Sundarbans mangrove forest, it could be more sensitive to increasing temperature and CO_2 during the course of climate change. A final plot giving a summary representation of stocks and fluxes for the mangrove ecosystem under study is given in Fig. 4. It clearly shows that the carbon sink in term of live biomass is about 3.87 fold greater than that of the sediment in the Sundarbans mangrove ecosystem.

The change in the carbon stock in mangroves in terms of dbh increase exhibits negative relation with its density ($\rho = 0.84 - 0.0233$ dbh, $R^2 = 0.71$, $F = 33.69$, $n = 25$, $p < 0.001$). This indicates that lighter-wooded species dominate over heavier-wooded species in the Sundarbans mangrove forest. Mangrove species with greater density (*A. marina*, 0.71 ± 0.02; *A. alba*, 0.734 ± 0.04; *A. officinalis*, 0.708 ± 0.035) predominates in the west Sundarbans sites (Lothian, Ecocamp, Prentice) than in the east Sundarbans sites (Halliday 1–2). Shifting of species composition of mangrove is observed in the Halliday island where lighter-wooded species (*Agialitis rotundifolia*, $\rho = 0.62 \pm 0.042$; *Ceriops*, $\rho = 0.693 \pm 0.026$) is more abundant over heavier-wooded species, indicating the role of resource availability (CO_2, nutrients etc.) and stress (salinity, pH). This suggests that the overall annual increase in mean carbon stock across the Sundarbans mangrove forest could be due to, at least in part, by an increase in resource availability favoring lighter-wooded mangrove species rather than recovery from past disturbance (Malhi et al., 2004).

5. Conclusion

1) Regression models developed in this study involving breast height diameter, height and density can be used to estimate the living above ground and below ground biomass of mangroves.
2) Application of the model allows estimating the spatial variation of above ground biomass and sequestration of anthropogenic carbon dioxide in relation to the resource availability and environmental constrain.
3) Estimated carbon stock is lower than in the terrestrial tropical forest and their annual increase exhibits faster turn over than the tropical forest.
4) Humification of organic carbon for long term sequestration in the sediment is a slow process.
5) Negative relationship between the change in the carbon stocks and wood density suggests resource availability and constraining could make lighter-wooded species to dominate over heavier-wooded species.

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