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Carbon Cycling in Mangrove Ecosystem of Western Bay of Bengal (India)

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Abstract: Carbon cycling in the mangrove ecosystem is one of the important processes determining the potential of coastal vegetation (mangroves), sediment, and adjoining waters to carbon absorption. This paper investigates the carbon storage capacity of five dominant mangrove species (*Avicenia marina*, *Avicenia officinalis*, *Excoecaria agallocha*, *Rhizophora mucronata*, and *Xylocarpous granatum*) on the east coast of the Indian mangrove along with the role they play in the carbon cycling phenomenon. Soil and water parameters were analyzed simultaneously with Above Ground Biomass (AGB) and Above Ground Carbon (AGC) values for 10 selected stations along. The total carbon (TC) calculated from the study area varied from 51.35 ± 6.77 to 322.47 ± 110.79 tons per hectare with a mean total carbon of 117.89 ± 28.90 and 432.64 ± 106.05 tons of carbon dioxide equivalent (CO_2e). The alarm of the Intergovernmental Panel on Climate Change for reducing carbon emissions has been addressed by calculating the amount of carbon stored in biotic (mangroves) and abiotic (soil and water) compartments. This paper focuses on the technical investigations on the factors that control the carbon cycling process in mangroves. This blue carbon will help policymakers to develop a sustainable relationship between marine resource management and coastal inhabitants so that carbon trading markets can be developed, and the ecosystem is balanced.

Keywords: carbon cycling; above ground carbon; dissolved inorganic carbon; sediment carbon; mangroves; conservation policy

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1. Introduction

Mangrove forests make a versatile depository for low-cost climate mitigation scenarios owing to their special adaptation [1]. Mangroves are unique halophytic vegetation (tree or shrub) that grows in tropical and subtropical regions, >1 m in elevation above MSL [2]. Considering the world's forest status, mangroves constitute about 0.7% and 0.1% of tropical forest and total forest area respectively [3] with America 11%, Africa 20%, and Asia 42%, respectively. In the case of tropical mangroves Sundarbans, Mekong Delta, Madagascar, Papua New Guinea, and the Philippines occupy the biggest patches. The maximum number of the true mangrove species are confined to the Southeast Asian region [4,5]. Previous studies have reported globally for the potential carbon sequestration property of mangroves to be 1.8×10^8 $tCyr^{-1}$ and that of soil carbon to be 1.023×10^9 tCm^{-2} [3], considering the depth of 3 m for SE Asia.

India is a sub-continental country of south Asia, with a total coastline of 7516.6 km, with the Bay of Bengal, Indian Ocean, and the Arabian Sea respectively on three sides of the country including Andaman-Nicobar and Lakshadweep islands. The mangroves are distributed in the nine major States including two union territories Puducherry, Daman and Diu, and Andaman–Nicobar Islands of India [6,7]. The mangrove forest of Bhitarkanika

Wildlife Sanctuary, regarded as the second largest coastal dense forest after Sunderbans, has an area of 197 km^2 out of 4921 km^2 of the total mangrove forests in India [7]. Studies on biomass and carbon in Mahanadi Delta of Odisha has documented overall mean carbon stock of 147.0 ± 8.1 tCha^{-1} (vegetation 89.4 ± 7.6 and soil 57.6 ± 3.2 tCha^{-1} up to a depth of 30 cm), in which there is a natural stand of 143.4 ± 8.2 tCha^{-1} (vegetation 89 ± 8.9 and soil 54.3 ± 3 tCha^{-1}) and plantation of 151.5 ± 7.9 tCha^{-1} (vegetation 90.6 ± 16.2 and 60.9 ± 5.6 tCha^{-1}) [8]. Banerjee et al. [9] reported the various physical, biological and anthropogenic factors influencing the soil organic carbon. Sahoo and Dhal [10] reported the organic carbon in the sediment was found to be 1.7, 10.16, and 19.20 mg·g^{-1} in the Bhitarkanika mangrove ecosystem respectively.

Carbon cycling refers to the absorption of carbon dioxide from the atmosphere and conversion to carbohydrates by salt marshes, mangroves, seagrasses, phytoplankton, algae, micro-organisms, and organisms with calcium carbonate covering. During outwelling, this carbon is washed off to the sea and through transformation, carbon fluxes are established (Figure 1). Mangroves and their associated vegetation help in trapping the upwelled waters adding nutrients to the sediment and to the adjoining waters [11]. Coastal sediments in the mangrove ecosystem account for 50% of carbon storage thereby playing a major role in carbon biogeochemical cycling [12].

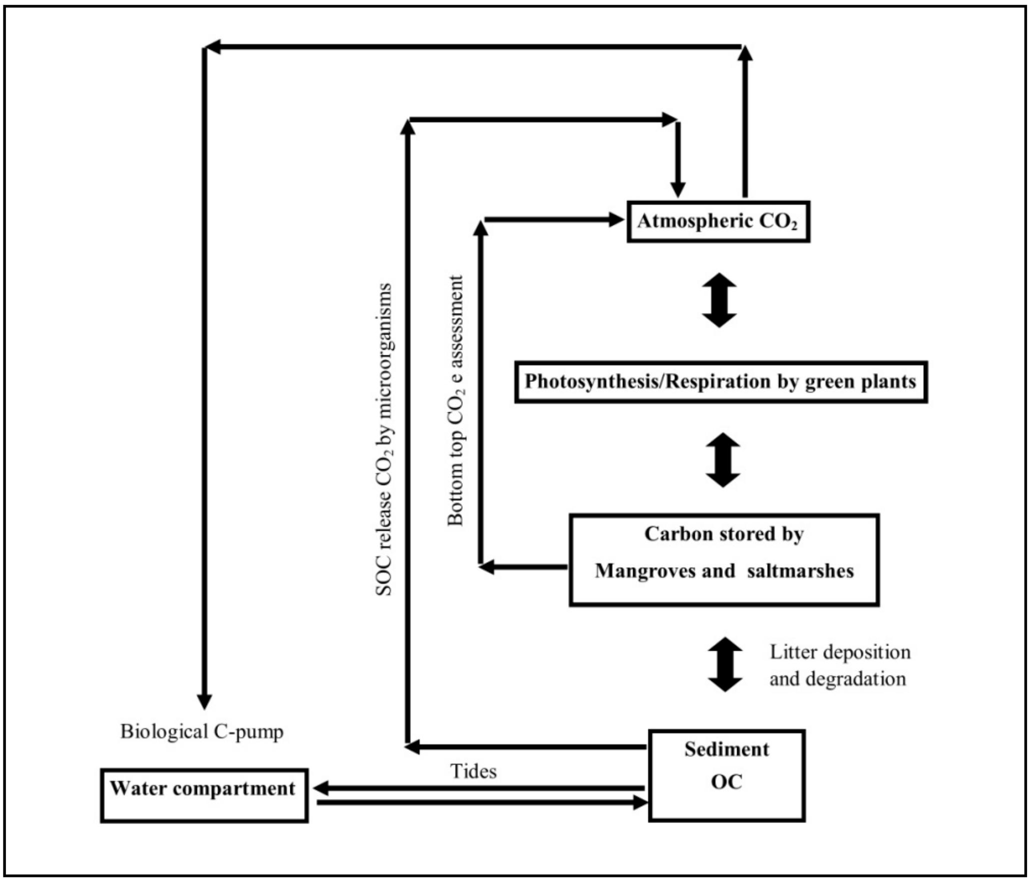


Figure 1. Schematic representation of carbon cycling in the western Bay of Bengal.

In recent years, blue carbon (which encompasses the carbon stored in mangroves, salt marsh grasses, seagrasses, coastal sediments, and the adjoining water bodies) research has gained momentum internationally partially in science and partially in policy. International organizations like Conservation International (CI), International Union for Conservation of Nature (IUCN), Intergovernmental Oceanographic Commission (IOC), and United Nations

Educational Scientific and Cultural Organization (UNESCO) have also come up with various projects on quantification of blue carbon in different coastal ecosystems.

Mangrove carbon cycling is linked to soil carbon, stored carbon in biomass, atmosphere, and the adjacent mangrove waters which are large surface pools of dissolved inorganic matter (DIC). The present paper focuses on the carbon cycling in the bottom-top approach from sediment to seawater, mangroves, and then to the atmosphere by calculating the amount of carbon dioxide being absorbed and stored by the mangroves along with its sediment and adjoining seawater in the western Bay of Bengal. The study also suggests the use of Payment for Ecosystem Services (PES) policies not only for mangrove biomass but also for sediment carbon.

2. Materials and Methods

2.1. Study Area

The western Bay of Bengal comprises two major mangrove chunks *viz*. Bhitarkanika Wildlife Sanctuary and the southern part of it, the Mahanadi mangroves. The two mangrove chunks are noted for their own characteristics, the former being a reserve forest area with dense mangroves and the other an anthropogenically disturbed zone with moderately dense vegetation. Both the areas are located in the Kendrapara district of Odisha and form the estuarine complex of River Mahanadi with the Bay of Bengal. The Bhitarkanika Wildlife Sanctuary located between the coordinates 20°40′ to 20°48′ N latitude and 86°45′ to 87°50′ E longitude covers an area of 0.0672 ha where 5 sampling sites (Stns. 1–5) namely Dangmal, Bhitarkanika, Gupti, Habalikhati, and Ekakula were selected. The Mahanadi estuarine complex covering 6651 ha is located between 20°18′ to 20°32′ N latitude and 86°41′ to 86°48′ E longitudes in Odisha where 5 stations (Stns. 1–5) were selected in the tidal creeks namely Jambu, Kansaridia, Kandarapatia, Kantilo, and Bhitar Kharnasi, respectively. The region experiences a hot and humid climate and is regularly flooded with tidal waters from the Bay of Bengal (Table 1 and Figure 2).

Table 1. (**a**) Station description of Bhitarkanika mangrove ecosystem. (**b**) Station description of Mahanadi mangrove ecosystem.

Stations	Coordinates		Site Description
	Latitude (N)	Longitude (E)	
		(a)	
Stn.1	20°44′21.37′′	86°52′00.00′′	It is a protected mixed natural mangrove forest dominated by *H. fomes*, *E. agallocha*, and *A. officinalis*. The vegetation has a mean stand density of 60 trees per 100 m^2, mean DBH is 0.50 m, and mean height of 12 m. The area is a tourist site that receives a freshwater discharge from rivers like Bramhani, Baitarani, and the distributaries of Bhitarkanika river and different creeks, channels, etc. Eighty percent of crocodile nesting occurs here and it has huge reptile diversity like snakes, turtles, monitor lizards, etc. Owing to dense mangrove vegetation, the sediment is often black in color.
Stn.2	20°42′56.85′′	86°51′48.40′′	This site is similar to Dangmal in all conditions (climatic, vegetation, and river-fed) but it is more pristine and undisturbed w.r.t mangrove habitat. This site is famous for crocodile nesting and bird watching sites, Baga–gahana. The biomass of the *A. officinalis* is very high in comparison to all other study sites. The vegetation has a mean stand density of 80 trees per 100 m^2, mean DBH is 0.60 m, and mean height of 12 m. The soil is also very rich in organic matter derived from mangrove litter.

Table 1. *Cont.*

Stations	Coordinates		Site Description
	Latitude (N)	Longitude (E)	
Stn.3	20°38′38.81″	86°52′20.29″	This site is an anthropogenically stressed area in comparison to other stations. The area is mostly surrounded by villages and agriculture and aquaculture are the main occupations of the residents. Other activities include ecotourism, transportation, fishing, and household pollution. This is the gateway for BWLS. The distributions of mangrove species are unequal and are found in patches due to cutting and plantation. The dominant species include *P. paludosa*, *E. agallocha* and *R. mucronata.* The vegetation has a mean stand density of 70 trees per 100 m^2, mean DBH is 0.40 m, and mean height of 8 m. This site also comes under subtropical and humid climatic zones. The area receives a lot of anthropogenic wastes from adjoining villages, agriculture, and aquaculture discharges.
Stn.4	20°41′08.12″	86°59′16.03″	The site is near the sea mouth. One side is open to the Bay of Bengal and the other side is on the bank of river Bausagada. Both the ends of this river are open to the sea, hence it is always tide fed and maintains higher salinity than other study stations. This site also faces anthropogenic pressures like cutting of forest trees, fishing, ecotourism, and other anthropogenic effects. Plastic pollution is very high on this site, mostly on the oceanic coast. The area was dominated by *E. agallocha*, *A. marina*, *L. racemosa* and *C. decandra.* The vegetation has a mean stand density of 180 trees per 100 m^2, mean DBH is 0.30 m, and mean height 6 m. Owing to the position of the station, the station is very dynamic with fresh water on one side and marine water on the other. Organic matter load is comparatively higher.
Stn.5	20°42′16.91″	86°01′56.34″	The site is called Ekakula, which means one mouth is open to the rivers Bausagada and Patsala. Both sides are open to the Bay of Bengal, hence it always maintains the highest salinity. The site is dominated by high salt-tolerant species like *A. marina*, *E. agallocha*, *A. corniculatum*, *A. rotundifolia*, *A. alba*, *R. mucronata,* and *S. alba.* The vegetation has a mean stand density of 120 trees per 100 m^2, the mean DBH is 0.15 m, and the average height of the tree is below 7 m but the density of the species is more. The soil is usually loose, sandy in character, but due to the high density of mangroves has rich litterfall.
		(b)	
Stn.1	20°25′50.05″	86°43′50.21″	It is a Proposed Forest (PF) block with an area of 369.75 ha and surrounded by the Gobari river in the south and Chataka in the east, Kandarapatia PRF block in the north, and Gobari river with Jambu village in the west. The waterway plays an important role by inundating the forest block diversity. The dominant species are *Avicennia marina Ceriops decandra*, *Excocecaria agallocha*, *Acanthus ilicifolius* and *Avicennia officinalis. Aegiceras corniculatum*, *Avicennia alba,* and *Rhizophora mucronata* are also found in small numbers. *Xylocarpus granatum* is rare in this site. *Dalbergia spinosa*, *Sonneratia apetala*, *Tamarix troupii*, *Aegialitis rotundifolia* and *Phoenix paludosa* are found in this forest block. One of the non-mangrove species *Casuarina* species forest patches is also found in this region. The vegetation has a mean stand density of 55 trees per 100 m^2, mean DBH is 0.60 m, and mean height 10 m. The forest block is degraded by agricultural runoff, anthropogenic activity, shrimp culture, and grazing.

Table 1. *Cont.*

Stations	Coordinates		Site Description
	Latitude (N)	Longitude (E)	
Stn.2	20°22′48.89″	86°45′09.31″	This forest block is the highest area among the selected study sites which comprises about 1394.744 ha. This study site comes under Proposed Reserved Forest (PRF) block. Distributaries of the Gobari river play a crucial role in mangrove growth and regeneration. Kharnasi River separates Kansaridia and Bhitara Kharnasi forest block in the west and one of the creek formations called Kalpana Jore, in the northern part nearer to the Bay of Bengal called as the Chataka and extending to the east. In the southern part, Hetamundia forest and Kajalapatia village are present. *Excoecaria agallocha* is the dominant species on this site. *Rhizophora mucronata*, *Ceriops decandra,* and *Brownlowia tersa* are mostly dominant in the area. *Xylocarpus granatum*, *Rhizophora apiculata*, *Avicennia officinalis*, *Avicennia marina* and *Dalbergia spinosa* are moderately distributed. Apart from that other species present are *Agiceras corniculatum*, *Acanthus ilicifolius*, *Sonneratia apetala*, *Avicennia alba*, *Kandelia candel*, *Bruguiera cylindrical* and *Bruguiera gymnorrhiza.* The vegetation has a mean stand density of 50 trees per 100 m^2, mean DBH is 0.35 m, and mean height of 7 m. The forest block exhibits rich species diversity but it is in a degraded state due to anthropogenic activity and overexploitation.
Stn.3	20°22′03.197″	86°43′13.18″	Kharnasi forest block is classified as Bhitara Kharnasi Reserved Forest (RF-A) and Bahara Kharinasi Reserved Forest (RF-B). Our study site is the Bhitara Kharnasi (RF-A), which has a total area of 577.072 ha. It is surrounded by the distributaries of Kharnasi river and Gobari river which meet the Bay of Bengal. Kharnasi River separates the Bhitara Kharnasi and Bahara Kharnasi in the western part. In the north, the name of the water body is called Chataka which connects with the Bay of Bengal. Kansaridia and Sanatubi forest blocks are present in the east and south respectively. Distributaries play an important role by flushing fresh water inside the region and making it a dense forest. *Excocecaria agallocha* is a dominant species in this region followed by *Avicennia officinalis*, *Heritiera fomes*, *Brownlowia tersa*, *Ceriops decandra*, *Rhizophora mucronata*, *Avicennia marina* and *Xylocarpus granatum* are small in number along with *Sonneratia apetala*, *Avicennia alba*, *Bruguiera gymnorrhiza* and *Phoenix paludosa*. The vegetation has a mean stand density of 80 trees per 100 m^2, mean DBH is 0.45 m, and mean height of 9 m. Anthropogenic activities, shrimp culture, and polluted agricultural flushing by the waterways are the main reasons for the diminishing of mangrove growth.
Stn.4	20°27′53.61″	86°41′15.41″	This forest block comes under the Reserve Forest (RF) block with an area of about 137.784 ha. This forest patch is a mixture of natural and plantation forests. The plantation program was done by MSSRF with the help of local villagers and the Forest department of Odisha. The forest block is surrounded by the Gobari river in the south, the Chataka and distributaries of the Jagjore river in the east and north respectively, and Kantilo village with Luna nai which falls in the Gobari river in the western part of the forest block. To get a sufficient tidal inundation, canals have been excavated in the Kantilo forest block. The dominant species at this site is *Rhizophora mucronata*. *Avicennia marina, Avicennia officinalis, Excocecaria agallocha* are also found in numbers. *Xylocarpus granatum* is rare and *Ceriops decandra*, *Agiceras corniculatum*, *Acanthus ilicifolius*, *Sonneratia apetala*, *Avicennia alba*, *Kandelia candel*, *Tamarix troupii*, *Phoenix paludosa*, *Bruguiera parviflora* and *Sonneratia alba* are also found in the region. The vegetation has a mean stand density of 150 trees per 100 m^2, mean DBH is 0.30 m, and mean height of 8 m. The main causes of mangrove destruction are anthropogenic activities, agricultural runoff, grazing, shrimp culture and plastics, polythene, etc., inside the forest area.

Table 1. *Cont.*

Stations	Coordinates		Site Description
	Latitude (N)	Longitude (E)	
Stn.5	20°26′52.77′′	86°43′32.83′′	This forest block comes under the Proposed Reserve Forest (PRF), which has represented an area of about 105.668 ha. It is surrounded by Jambu forest block in the south, the Bay of Bengal in the east (Chataka), the Jagajhore river at Jagajhore in the north, and Kandarapatia village with a non-mangrove land patch in the west. The forest block is inundated during high tide which is favorable for the distribution of species composition. *Excoecaria agallocha* is dominant in the study area followed by *Avicennia marina* and *Avicennia officinalis* along with *Ceriops decandra*. A very small number of *Rhizophora mucronata* is found near the saline embankment of the site. *Xylocarpus granatum* is rare in this region. Other species found are *Aegiceras corniculatum*, *Avicennia alba*, *Bruguiera cylindrica*, *Tamarix troupii*, *Aegialitis rotundifolia*, *Phoenix paludosa* and *Pongamia pinnata.* The vegetation has a mean stand density of 70 trees per 100 m^2, a mean DBH is 0.30 m, and a mean height of 7 m. Runoff from agricultural land, polluted water from shrimp culture, grazing, and anthropogenic activities are the main cause for the destruction of this dense mangrove patch.

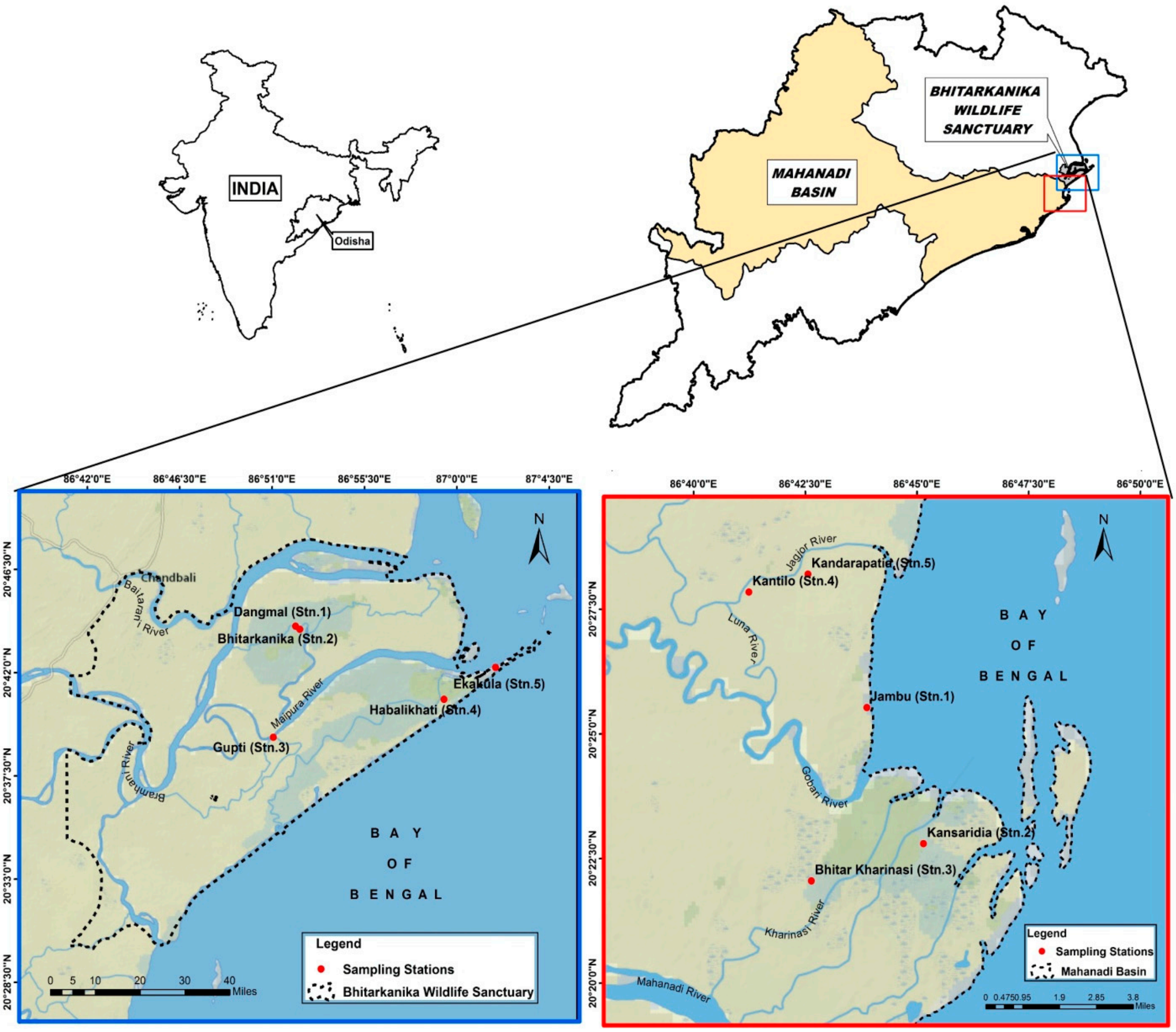


Figure 2. Western Bay of Bengal map showing Bhitarkanika WLS and Mahanadi estuarine complex.

2.2. Estimation of above Ground Biomass and above Ground Carbon

Around 15 sampling plots in each sampling station with 10 m × 10 m quadrats were laid seasonally and only live trees with a diameter at breast height (DBH) ≥ 5 cm were recorded for examining biomass and carbon in mixed stands focusing on the dominant species *viz. Avicennia marina, Avicennia officinalis, Excoecaria agallocha, Rhizophora mucronata* and *Xylocarpus granatum* as per standard formulae [13]. The plots were selected in such a way that all species were presented enough. Seasonal sampling (premonsoon, monsoon, and postmonsoon) during low tide has been carried out over a period of 2 years. Bosch Range Finder (DLE 40 professional) was used to determine the total height of the tree. The stem volume was calculated as: $V = \pi r^2 H$, where, V = volume of the plant, $\pi = 3.14$, r = radius of the plant H = height of the plant. Wood density (g/cm^3) of dry wood was estimated by taking a stem core of 1 cm^3 which was further converted into stem biomass as per the expression: $B = WD \times V$, where, B = Biomass, WD = Wood density, and V = Volume of the stem. Branch groups were selected by branch diameter and then branch biomass was estimated using the equation:

$$B_{db} = n_1 bw_1 + n_2 bw_2 + n_3 bw_3 = \sum nibwi \quad (1)$$

where B_{db} is the dry branch biomass per tree, n_i the number of branches in the *i*th branch group, bw_i the average weight of branches in the ith group, and i = 1, 2, 3, n are the branch groups. The leaf biomass per tree was calculated by multiplying the average biomass of the leaves per branch with the total number of branches in that tree. Finally, the dry leaf biomass of the selected mangrove species (for each plot) was recorded as per the expression:

$$Ldb = n_1 Lw_1 N_1 + n_2 Lw_2 N_2 + \ldots n_i Lw_i N_i \quad (2)$$

where Ldb is the dry leaf biomass of selected mangrove species per stations, n_1 ... n_i are the number of branches of each tree of three dominant species, Lw_1 ... Lw_i are the average dry weight of leaves removed from the branches, and N_1 ... N_i are the number of trees per species in the stations.

Carbon was analyzed by a *Vario MACRO elementar* CHN analyzer. CO_2 equivalent was calculated for each species by multiplying factor 3.67 (ratio of molar masses) with AGC to express the value in tons of CO_2. Carbon sequestration rate (CSR) is calculated by dividing the total carbon accumulated over the specific time period (at the beginning and at the end of our study period). Carbon fluxes were calculated between annual mean storages in both the study sites taking the ratio between carbon storage between atmosphere to ocean and atmosphere to land.

2.3. Analysis of Soil Organic Carbon (SOC)

The Walkley and Black [14] protocol was used to determine SOC. Soil samples (15 in number at each sampling station) were collected from 1 to 5 cm depth. These samples were cleaned leaving the underground roots, twigs, and barks. These soils along with blanks were titrated with Mohr salt solution and the volume of $K_2Cr_2O_7$ consumed to oxidize organic carbon was calculated from the difference. Percentage of carbon was expressed as C (%) = 3.951/g (1-S/B), where g = weight in grams of sample, S = volume of Mohr's salt solution concentration made by sample, B = volume of Mohr's salt solution concentration consumed by a blank.

2.4. Analysis of Dissolved Inorganic Carbon (DIC)

DIC was analyzed in water samples through potentiometric titration as per the method outlined by Edmond [15] with an accuracy level of ±0.3 μmol/L. Total dissolved inorganic carbon (DIC) was measured on board by using a technique based on the potentiometric method with a closed-cell described by Goyet et al. [16]. The calculation of the equivalent point is estimated using a non-linear regression method of DOE [17]. During the estimation, we used the Certified Referenced Material (CRM, Batch#28). Based on CRM analyses and replicates, the analysis of surface water samples, the precision of DIC was estimated to be around 2 µmol/L, which is the precision achieved during most of the analyses.

2.5. Statistical Analyses

About 15 samples of soil and 50 samples for mangrove species were collected from each sampling station to maintain homogeneity of observations. After collection, species-wise segregations were done, processed, and then subsequently analyzed for biomass and carbon. Mean and standard deviations were calculated for the data. In order to understand the spatial and temporal variation of the selected parameters, MANOVA was computed using IBM SPSS Statistics-21 software, keeping physico-chemical parameters, AGB and AGC (per species) as dependent variables and stations and seasons as fixed factors.

3. Results and Discussion

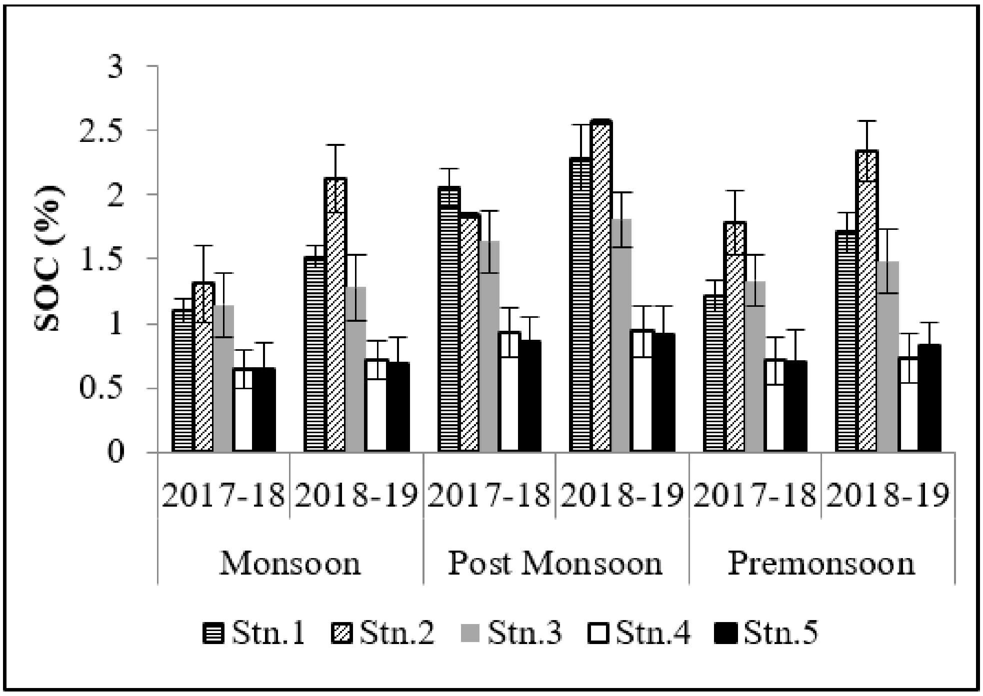
The present research has tried to document the carbon storage capacity of adjacent seawater, soil, and selected mangroves in the study area and, in turn, calculating carbon dioxide equivalent (CO_2e) for understanding the amount of CO_2 that is being absorbed from the atmosphere, thereby trying to establish the carbon cycle.

3.1. Soil Organic Carbon (SOC)

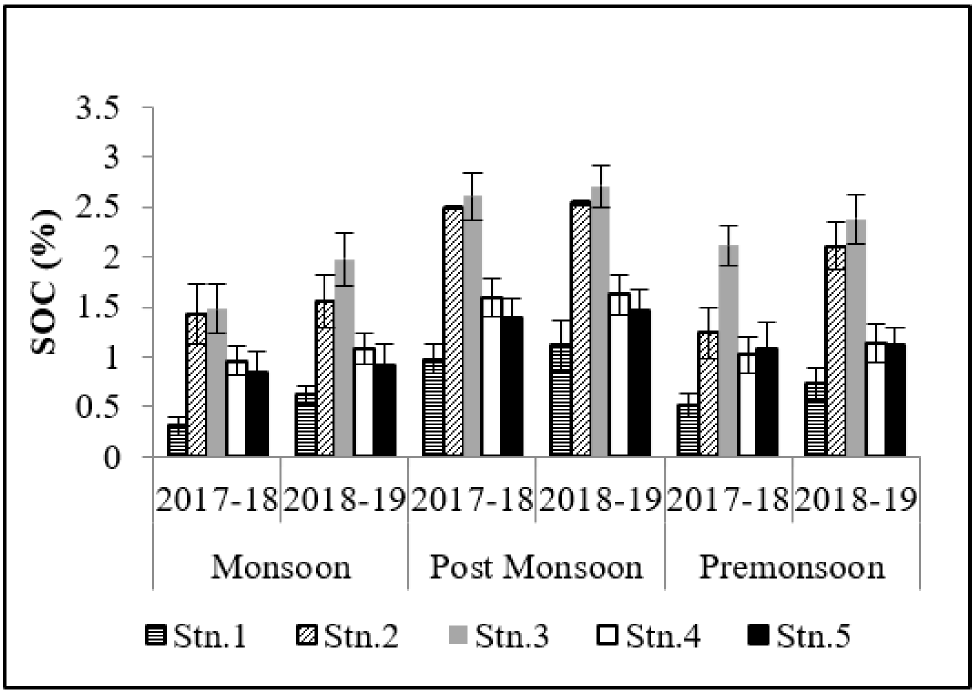
SOC contributes significantly to the carbon cycle as it plays a major role in the mineralization of hydrogen and carbon through microbes and also enriches the adjoining waters during outwelling. Hence, the density of vegetation and climate of the area both have significant roles to play [18]. The highest values of SOC in post-monsoon (2.71 ± 0.03%) is a reflection of the stored carbon after the monsoon precipitation (0.31 ± 0.04%) from the adjoining landmass (Figure 3). Over the last two years (2017–2018 and 2018–2019), it has been observed that SOC values are comparatively higher at Stns.1, 2, and 3 at Bhitarkanika and Stn.2 and 3 at Mahanadi mangrove ecosystem owing to the fact that these stations are areas with dense mangrove patches. ANOVA results have shown significant spatial and temporal variations that have also been reported by Reddy and Hariharan [19]. SOC values were lower in monsoon and higher in post-monsoon which may be attributed to the more microbial degradation (owing to the moist condition) of accumulated inorganic matter, which favors high organic matter in sediments [20]. The present study has indicated that high saline soils have a low potential for carbon storage which may be due to the poor growth of mangroves [21]. The dependence of carbon storage potential on soil quality has also been stated by Canadell et al. [22].

3.2. Carbon Storage in Mangroves (Species Wise)

Above Ground Biomass values ranged from 0.64 ± 0.21 tha^{-1} for *X. granatum* to 616.94 ± 50.15 tha^{-1} for *A. officinalis* in the study area. Similarly, the Above Ground Carbon values also varied from 0.31 ± 0.10 tha^{-1} for *X. granatum* to 280.83 ± 21.29 tha^{-1} for *A. offficinalis* (Figures 4–8). Spatial variation between the five species that were selected showed the highest value of AGB for *A. officinalis* at Bhitarkanika and *R. mucronata* at Mahanadi, while *E. agallocha* showed almost a uniform growth pattern. Comparing all the species and all the stations, the biomass per hectare of *E. agallocha* was the highest owing to its high adaptability. This has been proved by significant MANOVA values between stations ($p < 0.05$) although the variation was insignificant between seasons. Biomass contribution by stem varied from 42.51 ± 21.22% to 89.53 ± 4.30% branch from 9.91 ± 3.67% to 39.97 ± 20.69% and leaf contribution to 0.90 ± 0.47% to 7.65 ± 3.76% and stilt root contributed 29.52 ± 1.11% to 34.14 ± 16.10% (Tables 2 and 3), respectively.



(**a**)



(**b**)

Figure 3. Graph showing variation in soil OC (%) in (**a**) Bhitarkanika and (**b**) Mahanadi estuarine complex.

Table 2. Percentage sharing of floral components of AGB and AGC at Bhitarkanika WLS.

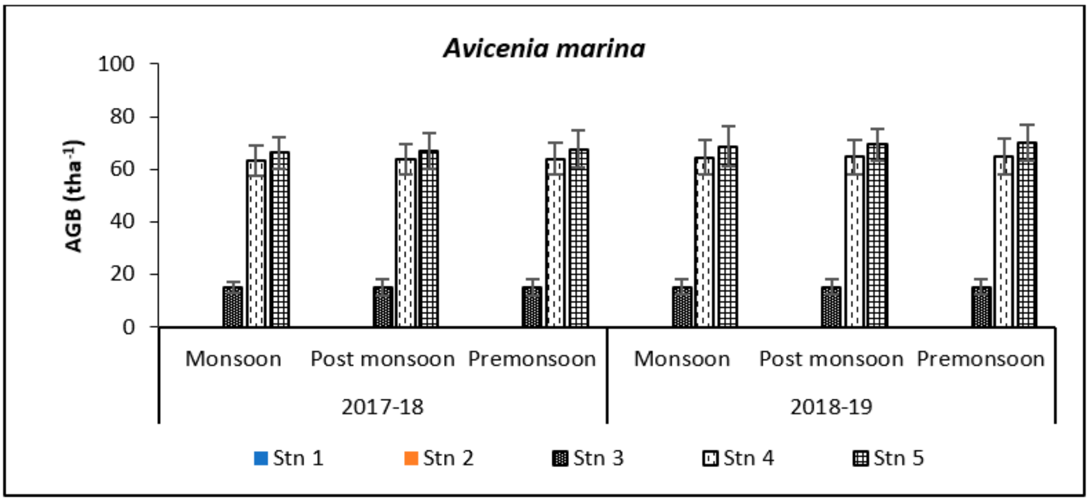
Species	Biomass Contribution by Different Floral Components towards AGB (in %)				Carbon Contribution by Different Floral Components towards AGC (in %)			
	Stem	Branch	Leaf	Stilt Roots	Stem	Branch	Leaf	Stilt Roots
A. marina	63.01 ± 19.16 (46 ± 0.4) *	34.45 ± 17.92 (44 ± 0.3) *	2.54 ± 1.38 (42 ± 0.4) *	–	28.98 ± 8.81	15.16 ± 7.88	1.07 ± 0.58	–
A. officinalis	77.58 ± 12.39 (53 ± 0.3) *	20.81 ± 11.50 (47 ± 0.2) *	1.61 ± 0.90 (50 ± 0.8) *	–	41.12 ± 6.57	9.78 ± 5.40	0.80 ± 0.45	–
E. agallocha	57.81 ± 21.69 (46 ± 0.4) *	39.97 ± 20.69 (45 ± 0.2) *	2.22 ± 1.25 (44 ± 0.3) *	–	26.59 ± 9.98	17.99 ± 9.31	0.98 ± 0.55	–
R. mucronata	42.51 ± 21.22 (56 ± 0.4) *	19.69 ± 8.48 (54 ± 0.2) *	3.65 ± 1.73 (49 ± 0.4) *	34.14 ± 16.10 (55 ± 0.6) *	23.81 ± 11.88	10.63 ± 4.58	1.79 ± 0.85	18.78 ± 8.85
X. granatum	71.22 ± 13.92 (51.93 ± 0.4) *	21.28 ± 10.30 (48.2 ± 0.2) *	7.50 ± 3.70 (45.2 ± 0.4) *		36.98 ± 7.23	10.26 ± 4.96	3.39 ± 1.67	

* Data represents percentage of carbon (Mean ± SD of 5 stations, 3 seasons, and 2 years).

Table 3. Percentage sharing of floral components of AGB and AGC at Mahanadi estuarine complex.

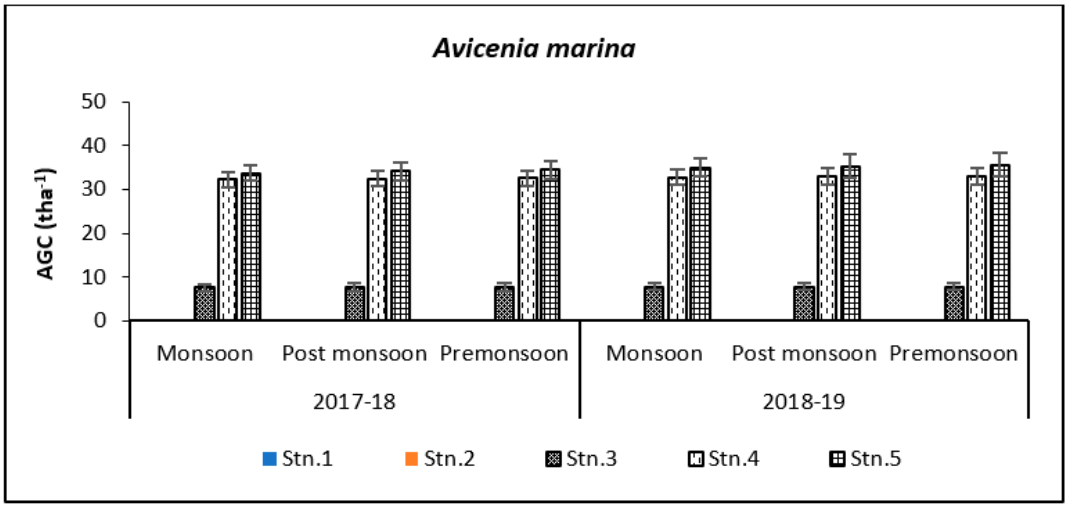
Species	Biomass Contribution by Different Floral Components towards AGB (in %)				Carbon Contribution by Different Floral Components towards AGC (in %)			
	Stem	Branch	Leaf	Stilt Roots	Stem	Branch	Leaf	Stilt Roots
A. marina	79.03 ± 7.43 (43.8 ± 0.5) *	20.07 ± 7.10 (41.8 ± 0.2) *	0.90 ± 0.47 (41.4 ± 0.3) *	–	34.62 ± 9.31	8.39 ± 6.38	0.37 ± 0.18	–
A. officinalis	89.53 ± 4.30 (45.7 ± 0.3) *	9.91 ± 3.67 (39.3 ± 0.2) *	1.28 ± 0.68 (47.3 ± 0.6) *	–	40.92 ± 5.17	3.89 ± 2.49	0.61 ± 0.25	–
E. agallocha	56.89 ± 19.43 (47 ± 0.5) *	37.37 ± 16.96 (33 ± 0.3) *	5.75 ± 2.64 (47.2 ± 0.4) *	–	26.74 ± 8.48	12.33 ± 5.31	2.71 ± 0.95	–
R. mucronata	44.90 ± 4.41 (52 ± 0.2) *	22.54 ± 3.10 (34.8 ± 0.4) *	3.04 ± 0.42 (40.3 ± 0.3) *	29.52 ± 1.11 (47.5 ± 0.5) *	23.35 ± 10.28	7.84 ± 3.28	1.23 ± 0.66	14.02 ± 5.84
X. granatum	71.93 ± 13.88	20.43 ± 10.19	7.65 ± 3.76		36.68 ± 6.48	9.34 ± 4.41	3.37 ± 1.32	–

* Data represents percentage of carbon (Mean ± SD of 5 stations, 3 seasons, and 2 years.

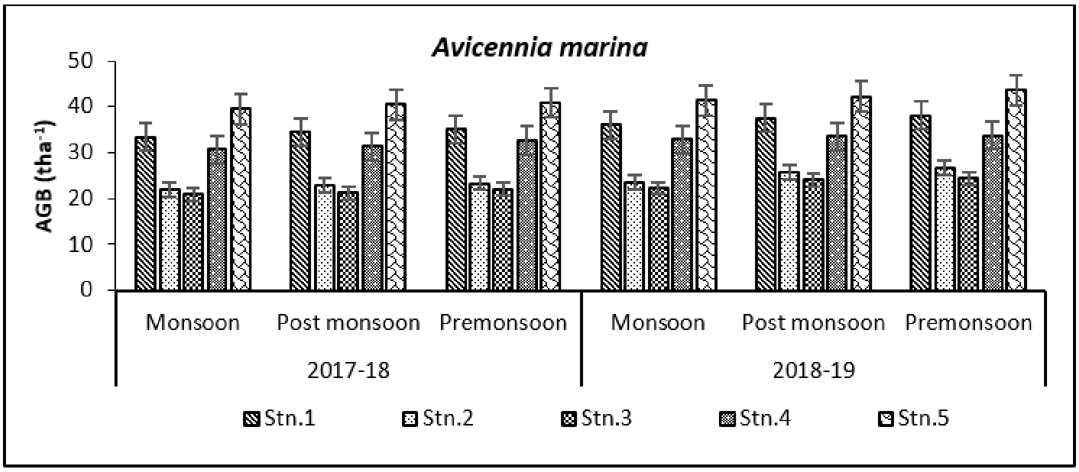


(a)

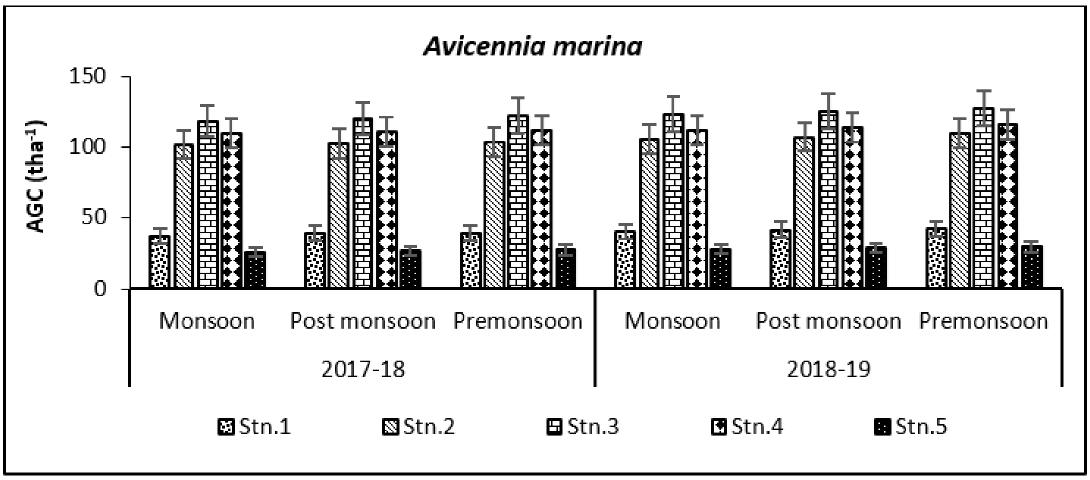
Figure 4. *Cont.*



(**b**)

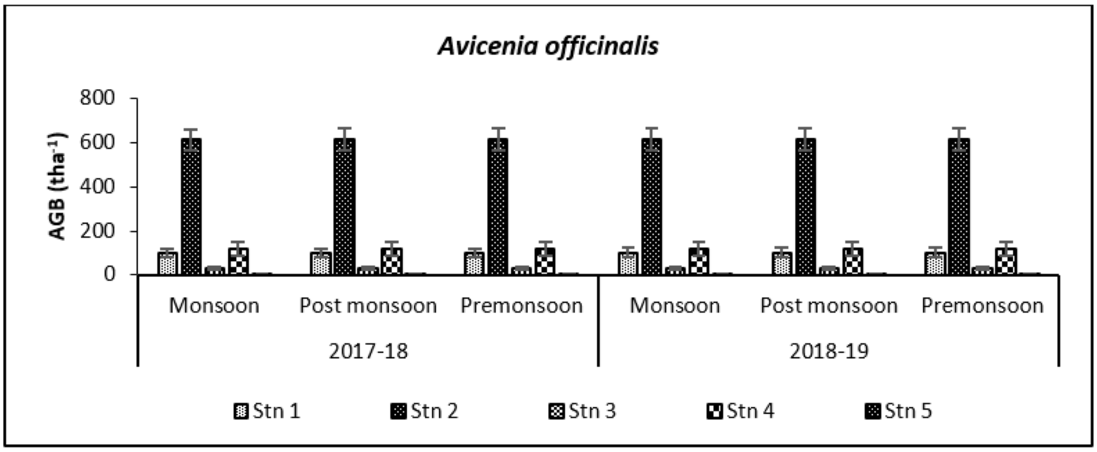


(**c**)

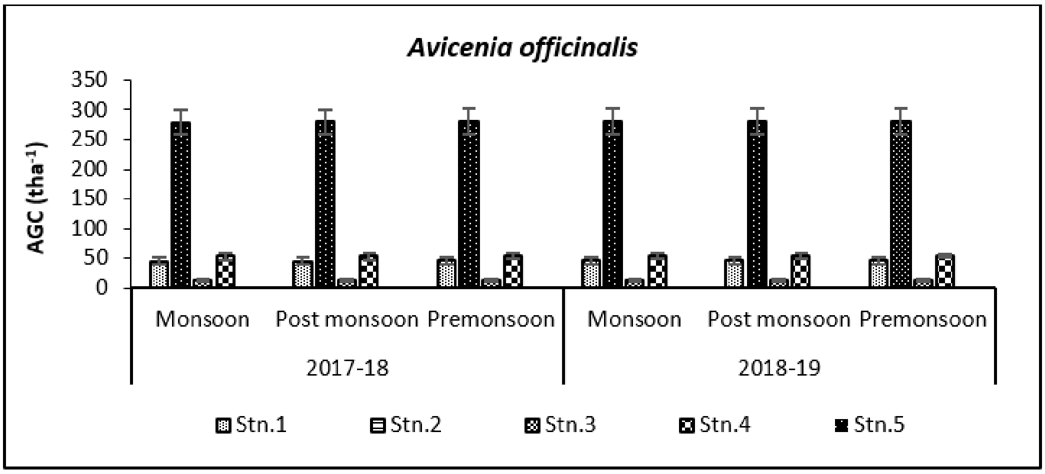


(**d**)

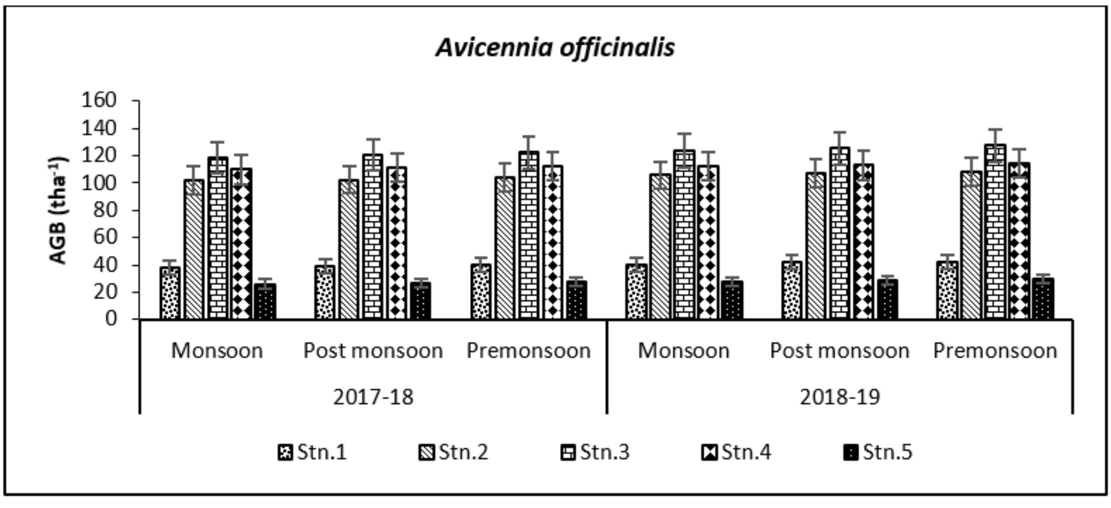
Figure 4. Graph showing biomass (tha^{-1}) (**a**) and carbon (tha^{-1}) (**b**) in Bhitarkanika WLS. Graph showing biomass (tha^{-1}) (**c**) and carbon (tha^{-1}) (**d**) in Mahanadi estuarine complex.



(**a**)

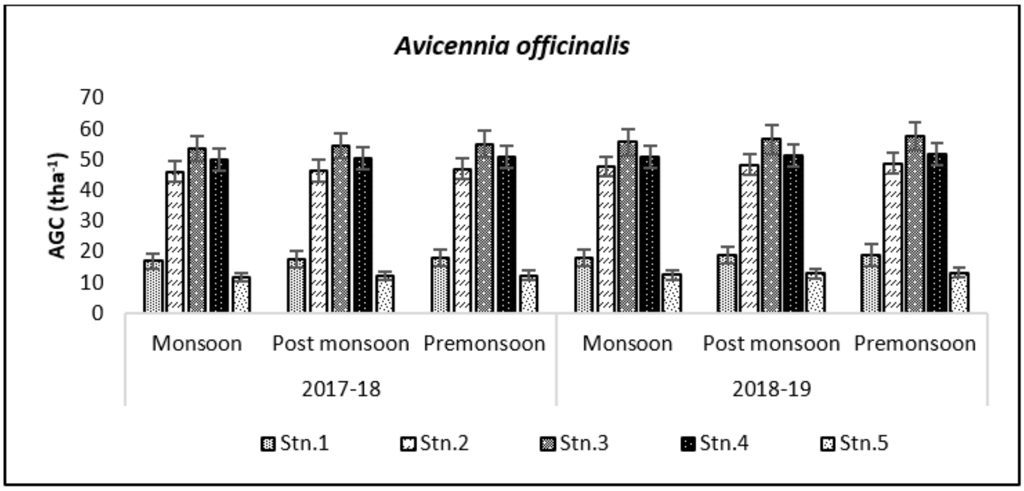


(**b**)



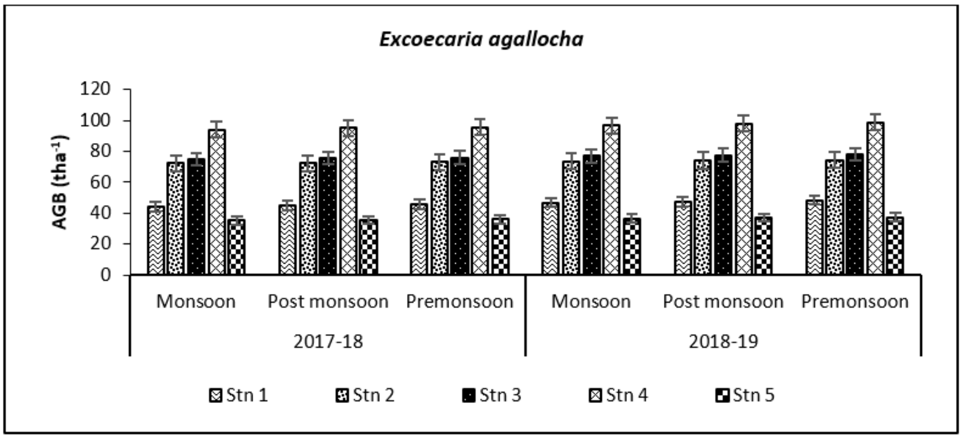
(**c**)

Figure 5. *Cont.*

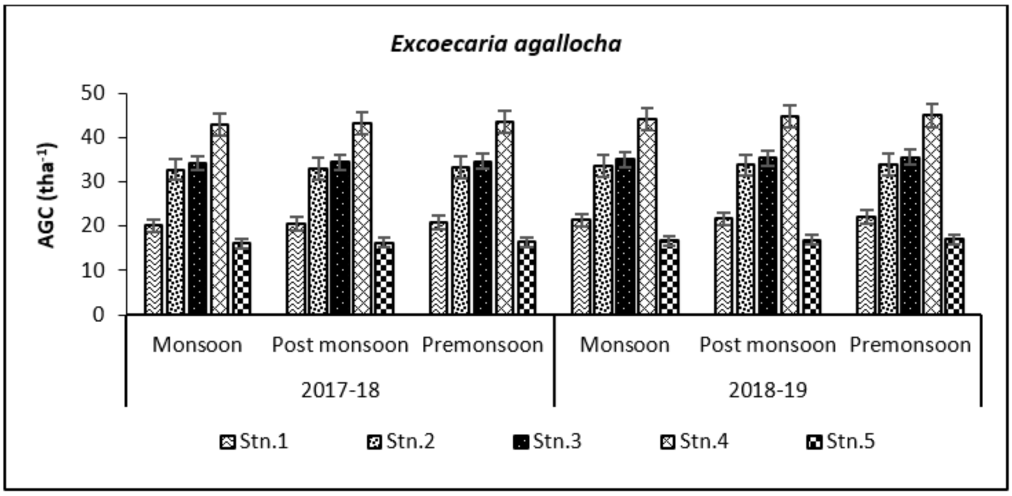


(**d**)

Figure 5. Graph showing biomass (tha^{-1}) (**a**) and carbon (tha^{-1}) (**b**) in Bhitarkanika WLS. Graph showing biomass (tha^{-1}) (**c**) and carbon (tha^{-1}) (**d**) in Mahanadi estuarine complex.

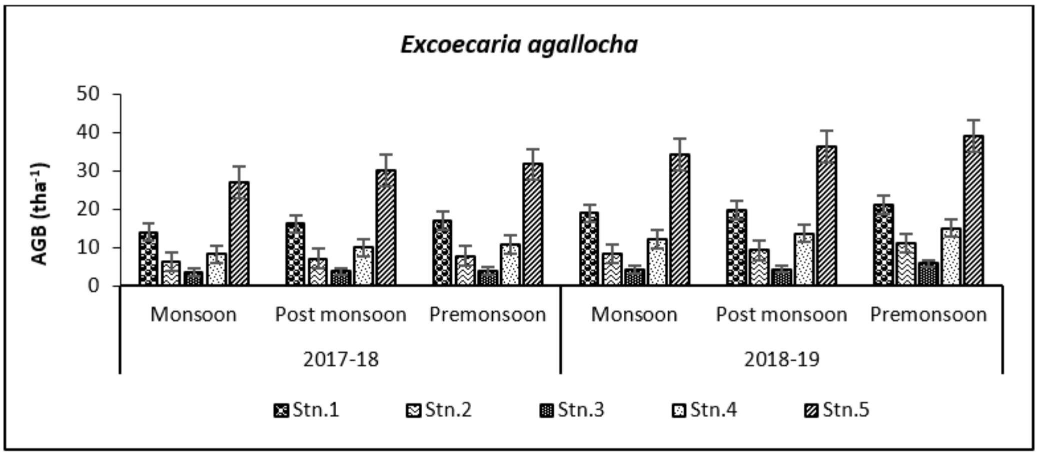


(**a**)

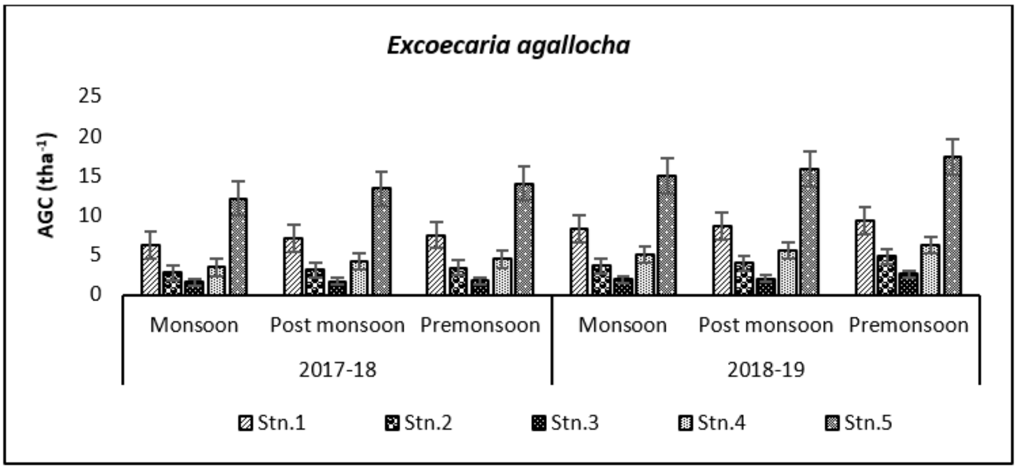


(**b**)

Figure 6. *Cont.*

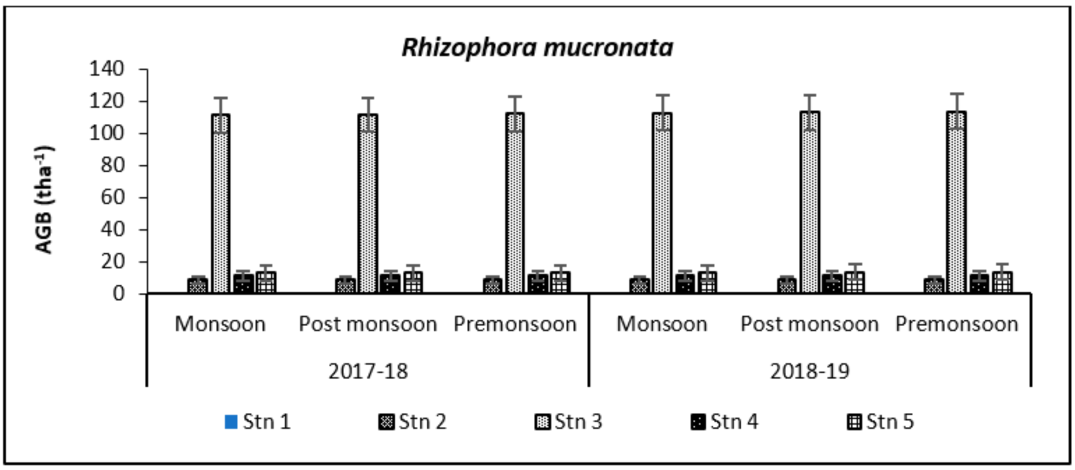


(**c**)



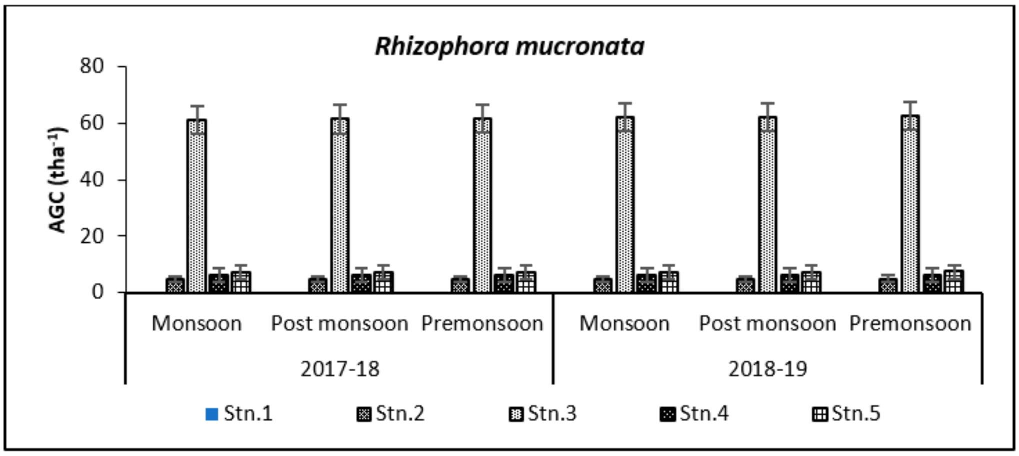
(**d**)

Figure 6. Graph showing biomass (tha^{-1}) (**a**) and carbon (tha^{-1}) (**b**) in Bhitarkanika WLS. Graph showing biomass (tha^{-1}) (**c**) and carbon (tha^{-1}) (**d**) in Mahanadi estuarine complex.

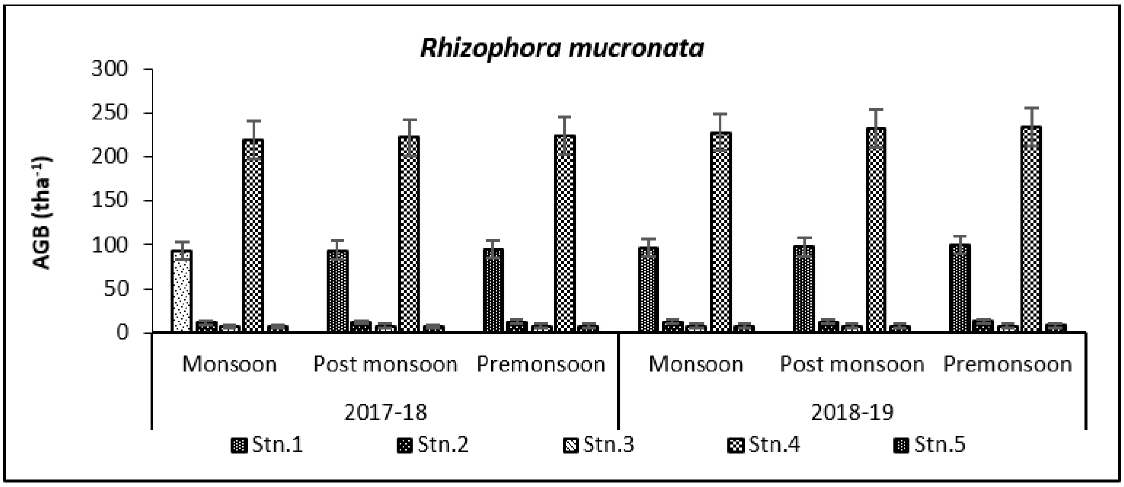


(**a**)

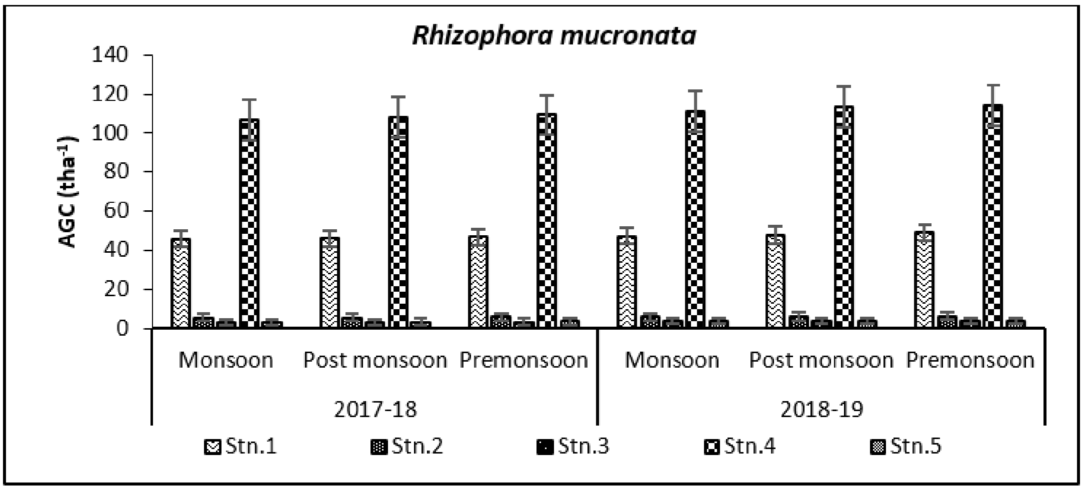
Figure 7. *Cont*.



(**b**)

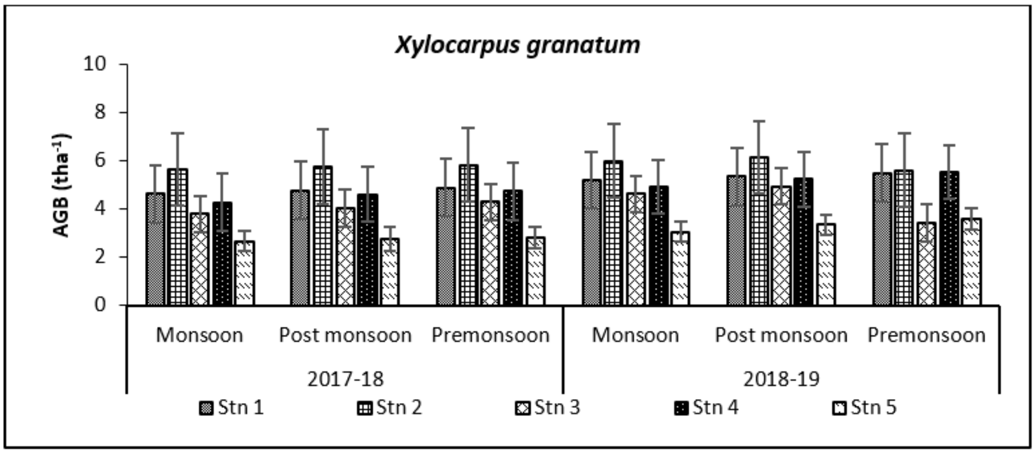


(**c**)

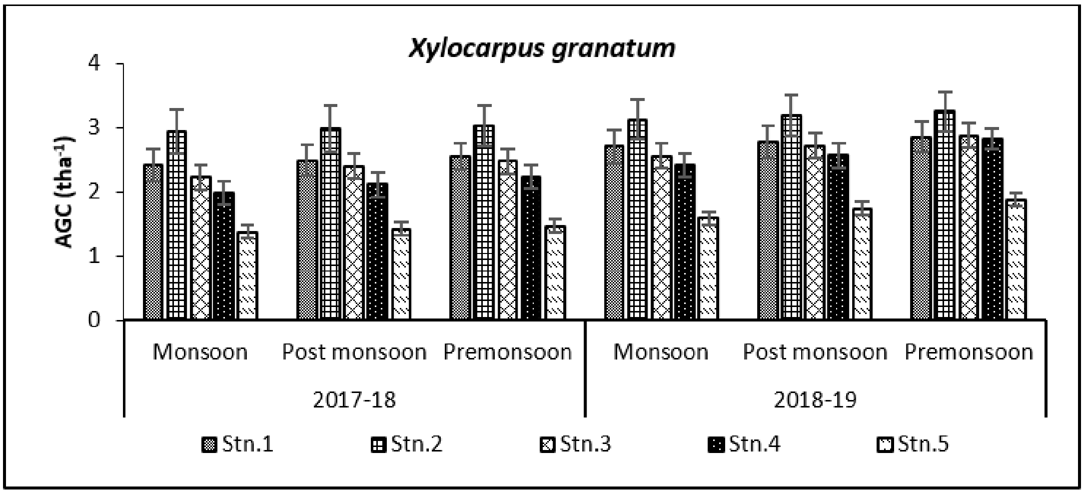


(**d**)

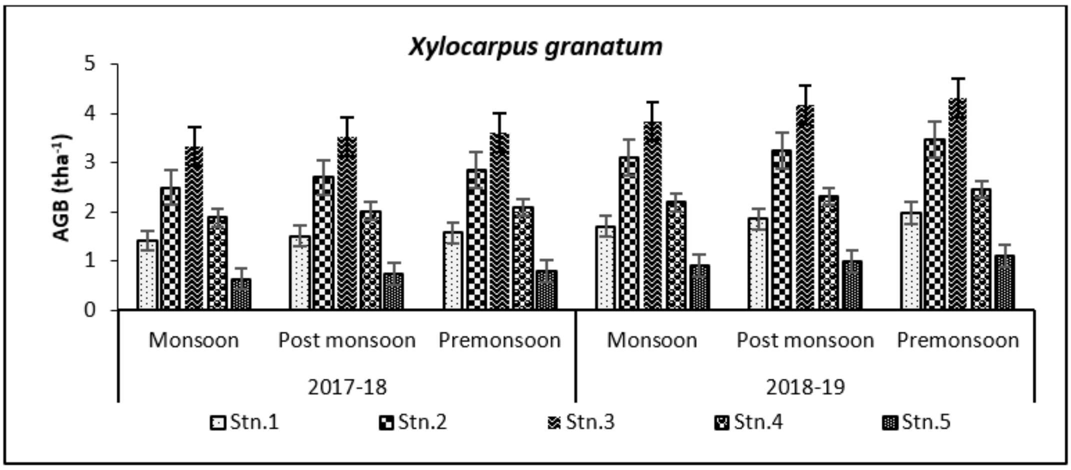
Figure 7. Graph showing biomass (tha^{-1}) (**a**) and carbon (tha^{-1}) (**b**) in Bhitarkanika WLS. Graph showing biomass (tha^{-1}) (**c**) and carbon (tha^{-1}) (**d**) in Mahanadi estuarine complex.



(**a**)

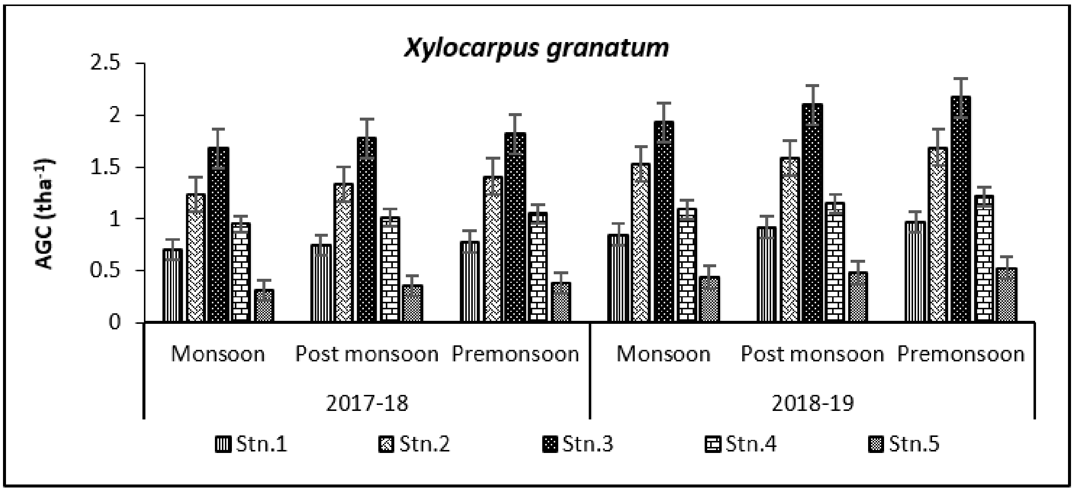


(**b**)



(**c**)

Figure 8. *Cont.*



(**d**)

Figure 8. Graph showing biomass (tha^{-1}) (**a**) and carbon (tha^{-1}) (**b**) in Bhitarkanika WLS. Graph showing biomass (tha^{-1}) (**c**) and carbon (tha^{-1}) (**d**) in Mahanadi estuarine complex.

Species-wise, the average carbon storage over two years (2017–2018 and 2018–2019) were of the order *E. agallocha* > *R. mucronata* > *A. marina* > *A. officinalis* > *X. granatum* respectively (Figures 4–8). MANOVA results showed significant variation of AGC in context to stations for all species in the selected study area which is at par with the AGB values (Table 4). The percentage of carbon in the floral components in the Bhitarkanika mangrove ecosystem for the different species is given in Table 1, where stem carbon varied from 23.81 ± 11.88% to 41.12 ± 6.57%, branch carbon varies from 9.78 ± 5.40% to 17.99 ± 9.31% and leaf carbon varied from 0.80 ± 0.45% to 3.39 ± 1.67% and stilt root comprised of 18.78 ± 8.85% carbon, respectively. In the case of Mahanadi, the percentage of carbon in floral components is given in Table 3, where stem carbon varied from 23.35 ± 10.28% to 40.92 ± 5.17%, branch carbon varied from 3.89 ± 2.49% to 12.33 ± 5.31%, and leaf carbon varied from 0.37 ± 0.18% to 3.37 ± 1.32% and stilt root comprised of 14.02 ± 5.84% carbon, respectively.

Table 4. Carbon storage prospects of Bhitarkanika WLS (B) and Mahanadi (M) estuarine complex.

Stations	AGC (tha^{-1})	SOC (tha^{-1})	TC (tha^{-1})	CO_2 Equivalent (t)
Stn.1 (B)	62.43 ± 16.96	6.68 ± 0.47	69.11 ± 17.43	253.63 ± 63.97
(M)	83.39 ± 15.74	3.61 ± 0.30	87.00 ± 16.04	319.29 ± 58.87
Stn.2 (B)	314.76 ± 110.34	7.71 ± 0.45	322.47 ± 110.79	1183.46 ± 406.60
(M)	65.85 ± 16.90	7.55 ± 0.56	73.40 ± 17.46	269.38 ± 64.08
Stn.3 (B)	111.59 ± 21.97	5.83 ± 0.24	117.42 ± 22.21	430.93 ± 81.51
(M)	70.02 ± 20.77	7.71 ± 0.45	77.73 ± 21.22	285.27 ± 77.88
Stn.4 (B)	133.96 ± 22.12	3.52 ± 0.12	137.48 ± 22.24	504.55 ± 81.62
(M)	176.19 ± 42.13	5.36 ± 0.29	181.55 ± 42.42	666.29 ± 155.68
Stn.5 (B)	57.78 ± 12.27	3.55 ± 0.11	61.33 ± 12.38	225.08 ± 45.43
(M)	45.96 ± 6.52	5.39 ± 0.25	51.35 ± 6.77	188.45 ± 24.85
Mean ± SD (B)	136.10 ± 36.73	5.46 ± 1.68	141.56 ± 38.41	519.53 ± 140.96
(M)	93.22 ± 21.56	5.92 ± 1.54	99.14 ± 23.07	345.75 ± 84.66

It has been reported that biomass values can be even more than 250 tha^{-1} [23] in forests with no anthropogenic interferences. Our results are comparable with that in the Sundarbans [24,25], Japan [26], Australia [27], Senegal [28], Guade–loupe [29], Puerto Rico [30], Thailand [31], Florida [32], the Indian Bay of Bengal [33], Indonesia [34], Malaysia [35], Sri Lanka [36], Andaman Islands [37], and Philippines [38]. In the present study, the diurnal inundation of tides was dominated by *A. marina*, *R. mucronata*, and *E. agallocha* because all the three species dominated in high saline areas of the selected stations.

Spatial dependence of AGB with SOC in this western Bay of Bengal mangrove ecosystem is displayed by significant negative relationship ($p < 0.01$) of AGB with SOC in case of *A. marina* and positive relationship in context to AGB with SOC at 1% level of significance for *A. officinalis* and *X. granatum* respectively. *R. mucronata* being a more adaptive species with respect to acidity or alkalinity of the soil, showed no relationship for AGB with SOC, with the exception of *E. agallocha* at a mangrove patch near Mahanadi, which showed a significant negative relationship like *A. marina* at 5% level of significance. Ren et al. [39] also supported this view for the widespread distribution of the species to changes in SOC composition.

Biomass and carbon in mangroves are a directly proportional relationship, although the percentage of carbon in biomass differs (23.35% to 41.12%) with the age and growth type of the species. More salinity leads to less carbon due to less biomass. The global carbon cycle is very much dependent on this blue carbon, out of which mangroves contribute only a mere 0.7% of tropical forests of the world. These forests have the potential to store up to 20 billion tons of carbon, which is much higher than the carbon stock in tropical upland, temperate, and boreal forests [33]. Mangrove forests contribute a significant proportion to the global carbon cycle as they play a major role in reducing greenhouse gases (*viz*. CO_2) through the process of photosynthesis.

3.3. Carbon Storage in Aquatic Medium

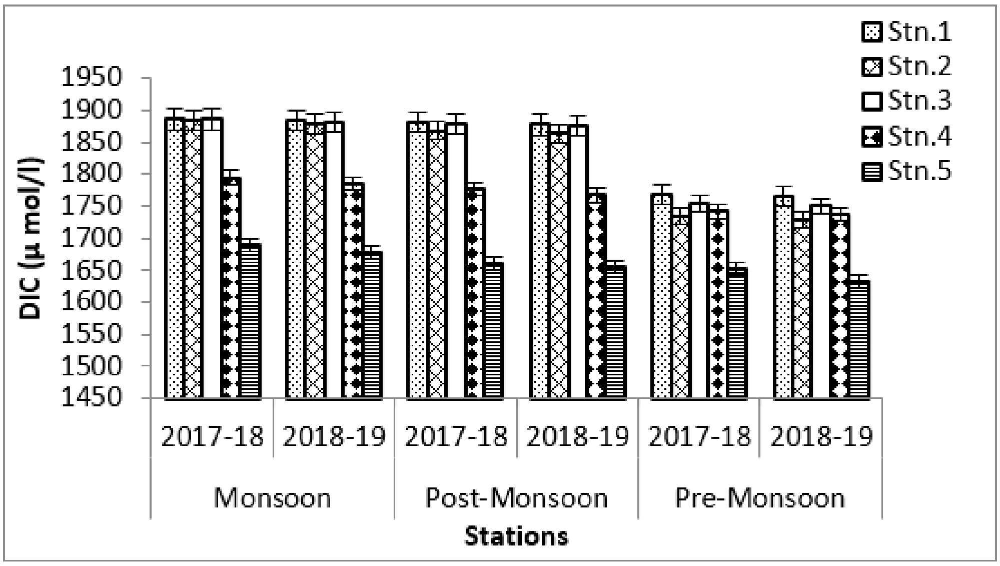
Dissolved Inorganic Carbon (DIC) was monitored in the adjacent waters which are also the sink of carbon dioxide. The amount of carbon in the inorganic state in ambient media is also the contribution of the physico-chemical and microbial interactions (mineral complex) that occur in mangrove sediment [40,41]. The microbial biomass utilizes this newly added carbon in water leading to various metabolic byproducts [42]. These processes help in stabilizing soil organic carbon fraction and nutrient acquisition [43]. Several previous studies have also shown that there is a loss of organic carbon to adjacent saline water [44].

The present study shows that DIC values vary from 1632 $\pm$ 9.37 during premonsoon 2018–2019 at Stn.5 to 1887 $\pm$ 16.82 µmol/Lduring monsoon 2017–2018 at Stn.1 at Bhitarkanika and from 1549 $\pm$ 8.88 during premonsoon 2018–2019 at Stn.1 to 1632 $\pm$ 9.56 µmol/L during 2017–2018 at Stn.5 at Mahanadi (Figure 9). The data shows that increase in DIC is inversely proportional to the pH of seawater and positively proportional to SOC because of its dependency on seawater buffer capacity (Figure 10). The other facts on the change are due to the mixing and air-sea interaction through diffusion [45].

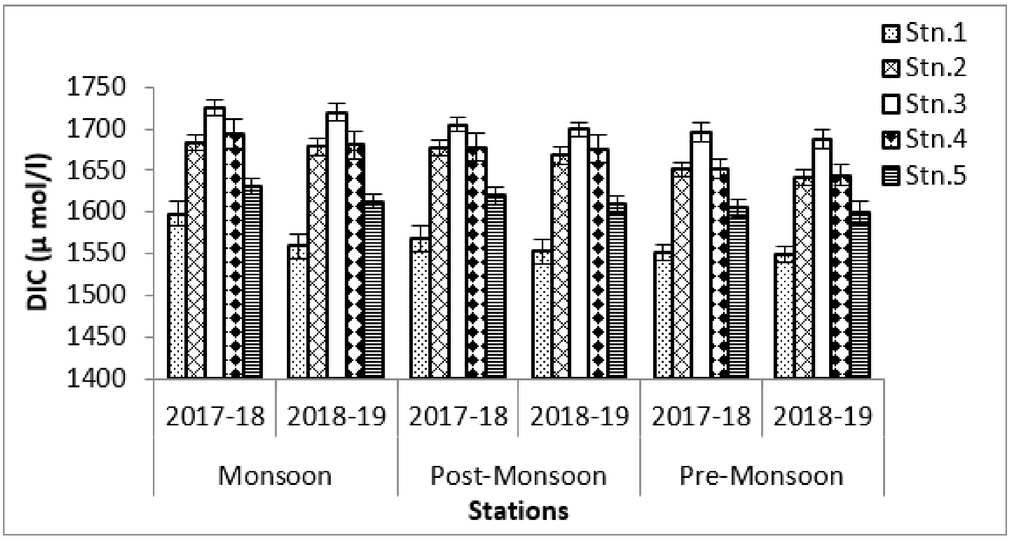
3.4. Prospects in Carbon Storage (Whole Ecosystem)

The ability of carbon storage in the mangrove patches in the western Bay of Bengal accounts for the highest (314.76 $\pm$ 110.34 tha^{-1}) at Bhitarkanika WLS and lowest (45.96 $\pm$ 6.52 tha^{-1}) at Mahanadi estuarine complex, with mean SOC (in tha^{-1}) of 5.69 $\pm$ 1.61.

Total carbon (TC) amounts 51.35 $\pm$ 6.77 tha^{-1} to 322.47 $\pm$ 110.79 tha^{-1} with an average quantity of 141.56 $\pm$ 37.01 tha^{-1} at Bhitarkanika and 94.21 $\pm$ 20.78 tha^{-1} for Mahanadi mangrove ecosystem, respectively. Spatial CO_2e varied from 225.08 $\pm$ 45.43 tons to 1183.46 $\pm$ 406.60 tons with a mean CO_2e of 519.53 $\pm$ 135.83 tons for Bhitarkanika and from 188.45 $\pm$ 24.85 tons to 666.29 $\pm$ 155.68 tons with mean CO_2e of 345.75 $\pm$ 76.26 tons at Mahanadi respectively (Table 3). Species-wise CSR (carbon sequestration rate) calculated in the study area were *A. officinalis* (197.26 tha^{-1}year^{-1}), *R. mucronata* (85.43 tha^{-1}year^{-1}), *E. agallocha* (74.89 tha^{-1}year^{-1}), *A. marina* (37.53 tha^{-1}year^{-1}), and *X. granatum* (6.10 tha^{-1}year^{-1}) respectively. Considering the fact that the amount of carbon in the atmosphere is 750 GT and the total flux out (105 Gt to ocean + 110 Gt to life on land) (http://newmaeweb.ucsd.edu accessed on 4 June 2021), the residence time of carbon is 6.81 years on land and 7.14 years on the ocean. Similarly, in the present study, in the Bhitarkanika and Mahanadi mangrove ecosystems separately, the residence time for carbon on land is 3.67 and 3.48 years respectively, whereas it is 45.09 × 10^5 and 32.64 × 10^5 years in the ocean, respectively. This proves that the mangrove wetlands play a significant role in governing the carbon cycle.



(**a**)



(**b**)

Figure 9. Graph showing DIC values (µmol/L) (**a**) at Bhitarkanika WLS and (**b**) at Mahanadi estuarine complex.

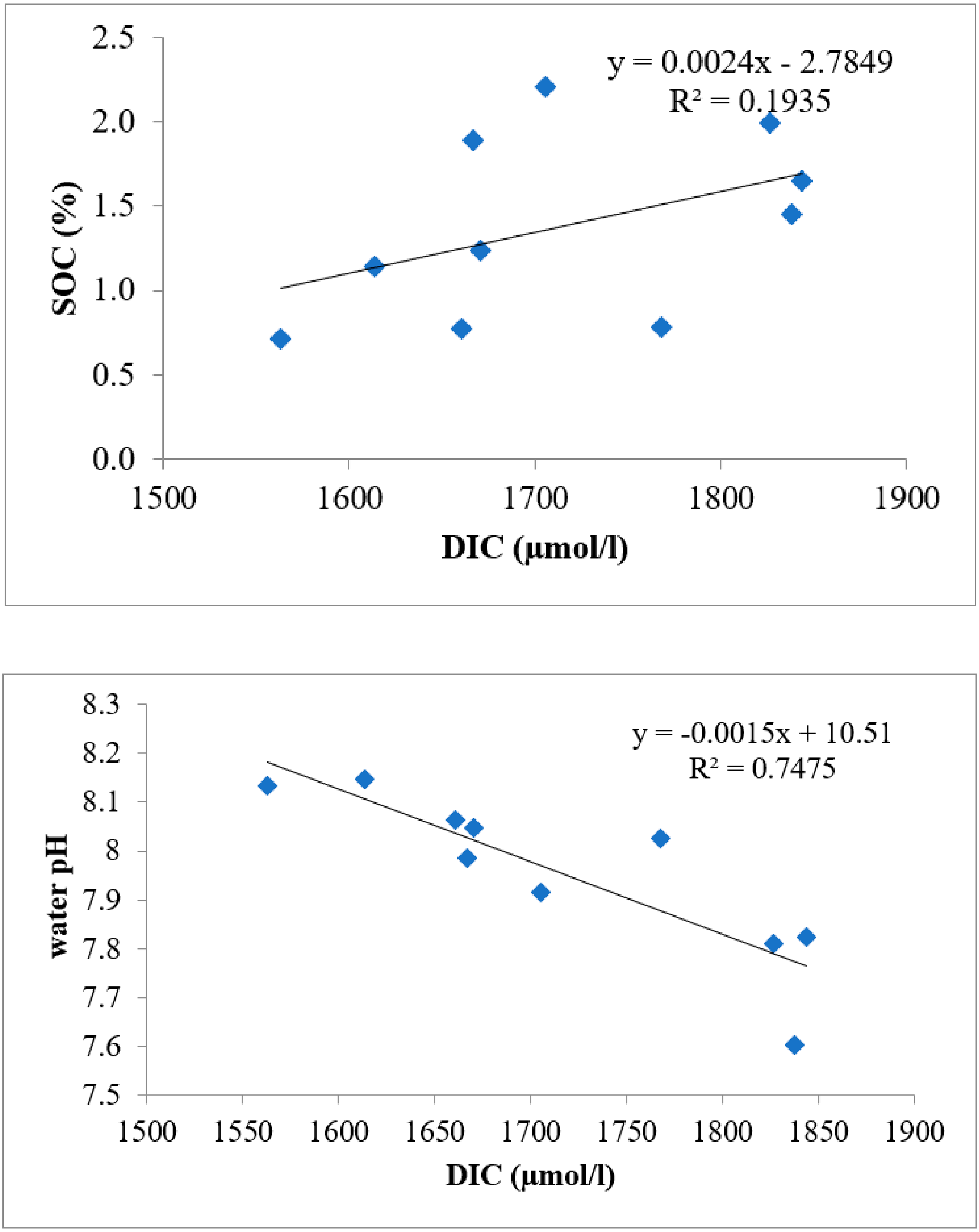


Figure 10. Relationship of DIC with SOC and water pH at the study site.

4. Conclusions

A large proportion of mangrove carbon is unaccounted for in global budgets in climate regulation projects. This present paper has accounted for the amount of carbon that is cycled in mangroves, their adjacent waters, and sediment. The challenge in blue carbon initiatives is to reconcile realistic time frames for its development. The amount of carbon storage in this mangrove ecosystem has been calculated to be 17,655,301.41 ha^{-1}, which will amount to $192.442, considering the carbon price to be $10.90 per ton. The study has tried to highlight the potentiality of the carbon market and the benefits which can be shared among the beneficiaries during plantation projects. The entire study will definitely see the light of implementation if it can be linked with the Clean Development Mechanism (CDM) through the conveyor belt of policy. To achieve the goal of the Paris Climate Agreement through massive plantation, efforts will be required to make a major shift in global priority on the plantation of species with high carbon-storing potential.

Author Contributions: The work has been conceptualized by K.B. and A.M.; methodology, K.B.; software, K.B.; validation, K.B., A.M. and S.V.; formal analysis, K.B.; investigation, K.B.; resources, K.B.; data curation, K.B.; writing—original draft preparation, K.B.; writing—review and editing, A.M. and S.V.; visualization, K.B.; supervision, A.M.; project administration, K.B.; funding acquisition, K.B. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare that there is no conflict of interest.

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