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RESEARCH ARTICLE

High blue carbon stock in mangrove forests of Eastern India

Kakoli Banerjee[1] · Chandan Kumar Sahoo[1] · Gobinda Bal[1] · Kapileswar Mallik[1] · Rakesh Paul[1] · Abhijit Mitra[2]

Abstract

Present study focuses on the carbon sequestration potential of five dominant mangrove species (*Avicenia marina*, *Avicenia officinalis*, *Excoecaria agallocha*, *Rhizophora mucronata* and *Xylocarpous granatum*) in Bhitarkanika and Mahanadi mangrove ecosystem. Water and soil parameters were sampled and analyzed for 10 selected stations along with aboveground biomass (AGB) and aboveground C (AGC) values. AGB value in the study area ranged from 15.00 ± 2.12 to 70.09 ± 6.68 tha^{-1} for *A. marina*, 26.13 ± 3.19 tha^{-1} to 616.94 ± 50.15 tha^{-1} for *A. officinalis*, 3.56 ± 0.96 tha^{-1} to 98.66 ± 5.24 tha^{-1} for *E. agallocha*, 7.06 ± 2.21 tha^{-1} to 224.41 ± 21.20 tha^{-1} for *R. mucronata*, and 0.64 ± 0.21 tha^{-1} to 6.25 ± 1.52 tha^{-1} for *X. granatum*, respectively. AGC value ranged from 7.63 ± 1.08 to 35.65 ± 2.63 tha^{-1} for *A. marina*, 1.73 ± 0.01 tha^{-1} to 280.83 ± 21.29 tha^{-1} for *A. officinalis*, 1.64 ± 0.41 tha^{-1} to 44.95 ± 2.53 tha^{-1} for *E. agallocha,* 3.44 ± 1.45 tha^{-1} to 114.05 ± 10.29 tha^{-1} for *R. mucronata* and 0.31 ± 0.10 tha^{-1} to 3.25 ± 0.31 tha^{-1} for *X. granatum*, respectively. The average SOC values in tha^{-1} varied from 3.52 ± 0.12 to 7.71 ± 0.45. The total carbon (AGC + SOC) calculated for the study area varied from 55.20 ± 7.90 to 330.41 ± 111.97 tha^{-1} with a mean total carbon of 124.11 ± 30.14 which is equivalent to 455.47 ± 110.56 tons of CO_2. Considering the total area of Bhitarkanika and Mahanadi mangrove ecosystem ($672 + 141,589$) to be $142,261$ km^2, the mean CO_2e be 455.47 ± 110.56 tones, it is approx. $64,795,617.67 \cong 64.80$ TgC that were absorbed from the atmosphere, thus reducing the amount of carbon dioxide from the atmosphere.

Keywords AGB · AGC · Carbon dioxide equivalent · Carbon sequestration potential · Climate change mitigation · Mangrove ecosystem

Introduction

Mangroves are distributed between latitude 32°20′ in northern hemisphere in Bermuda to 38°59′ in southern hemisphere in New Zealand (Spalding et al. 2010; Giri et al. 2011). Forest cover and its distribution including mangroves in India were monitored by the Forest Survey of India (FSI) from 1987 (FSI 1987). The mangrove patches are distributed in the nine coastal states including three union territories. The total mangrove cover of India was 4921 km^2, which covers 0.15% of India, 3% of world mangrove area, and 8% of Asia (Singh and Odaki 2004; FSI 2017) and all

the mangrove patches experienced an increase in area. The top 10 mangrove dominated states in India are West Bengal (2097 km^2) > Gujarat (1103 km^2) > Andaman and Nicobar Islands (604 km^2) > Andhra Pradesh and Telangana (352 km^2) > Odisha (213 km^2) > Maharashtra (186 km^2) > Tamil Nadu (39 km^2) > Goa (22 km^2) > Kerala (6 km^2) > Karnataka (3 km^2). In the east coast of India mangroves are concentrated in the Sundarbans region of West Bengal, Subarnarekha, Bhitarkanika and Mahanadi delta of Odisha, Godavari and Krishna delta of Andhra Pradesh, Pichavaram estuary and Cauvery estuary of Tamil Nadu (Mitra 2013). Agarwal et al. (2017) reported that in Odisha, the mangroves spread over an area of 214 km^2. Out of the total mangrove area of the state, Mahanadi delta covers an area of 120 km^2. The mangrove area in the Mahanadi delta (20°15′ to 20°70′ N latitude and 87° to 87°40′ E longitude) extends from south eastern boundary of Mahanadi river to river mouth of Hansua (a tributary of Brahmani) in the north, from the north eastern end of Mahanadi river up to Jambu river in

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east. Mahanadi mangrove wetland encompasses eight forest blocks.

Estimation of biomass in mangrove forests typically involves both destructive and non-destructive methods. Destructive method involves cutting down of trees and measuring biomass directly. Although the data are more accurate, but, looking at the conservation aspect, this method is not acceptable. In case of non-destructive method height and DBH, measurements are taken in order to calculate the biomass using mathematical formulae and allometric equations. These results of biomass vary w.r.t the distribution of the species in an area, particularly plantation areas and wild forest (Chave et al. 2005; Komiyama et al. 2005). Mangroves can sequester 3–5 times more atmospheric CO_2 than other terrestrial forest (Lee et al. 2014). Including all the economic services, mangrove forest produces an estimated annual economic value of more than US\$ 900,000 km^{-2} (UNEP-WCMC 2006). All the ecological services of mangrove depend on the productivity of the forest. The higher productivity also contributes significantly to global carbon budget. The average productivity of mangrove biomass ranges between 3.07 and 24.1 tha^{-1} $year^{-1}$ having turn over time period < 30 year (Twilley et al. 1992; Estrada and Soares 2017). The carbon stock of mangroves in 10 countries vary as per the order Indonesia > Mexico > Malaysia > Bangladesh > Thailand > Philippines > Vietnam > Dominican Republic > Micronesia > Palau, respectively. Carbon values ranged between 441.76 ± 120.76 and 1267.00 ± 872.72 $tCha^{-1}$ with global mean of carbon stock is 78.0 ± 64.5 tha^{-1} and carbon sequestration rate of 2.9 ± 2.2 $tCha^{-1}$ $year^{-1}$ (Murdiyarso et al. 2015; Estrada and Soares 2017). Globally carbon stored in mangrove biomass (AGB + BGB) is 4.03 Pg C with an annual storage capacity of 0.18 Pg C $year^{-1}$ (0.16 Pg C $year^{-1}$ by biomass and 0.02 Pg C $year^{-1}$ by sediments) (Twilley et al. 1992). The sediment characteristics of mangroves played a pivotal role in carbon sequestration. Optimum physico-chemical composition and condition of sediment increases the rate and potential of carbon sequestration (Banerjee et al. 2018).

The alternation and change of an ecosystem, extinction of species and habitat is a continuous natural process of earth (IUCN 2019). Due to multifarious human induced problems like global warming, climate change, oceanic acidification, glaciers melting, sea level rise (SLR), pollution (air, water, soil and spectrum), radiation, etc. the mangroves have been affected directly or indirectly. Since Industrial Revolution, the concentration of CO_2 and equivalent gas has increased rapidly in the atmosphere from 280 ppm to > 410 ppm causing global warming (NOAA 2019). The increase in average global temperature to 1.0 ± 0.2 °C from the industrial era is expected to increase by 1.5 °C between 2030 and 2052 (IPCC 2018). CO_2 is the major greenhouse gas in the atmosphere that releases ≥ 80% among all other GHG in a year from all sources with a rate of 11.3 ± 0.9 Pg C $year^{-1}$ in the year 2018 (Le Quere et al. 2018). Hence to mitigate the global problem along with development, sequestration of carbon, increased use of renewable energy and adopting sustainable policies is of utmost importance.

Mangrove forest floor is an important pool of organic matter (OM) and nutrients which are added to the sediment on account of degradation of leaf litter and accumulation of detritus during run-offs hence there is huge amount of nutrient deposition in the mangrove sediment which plays important role in global nutrient cycling. This decomposition rate is basically due to the sulphur reducing bacteria (e.g. *Desuifovibrio* species), which creates an anoxic environment in the substratum. These generate an acidic character of the soil which gives a blackish colour of the soil (Ferreira et al. 2007a, b). However, there are certain areas which contain higher sand particles in comparison to silt and clay particles (Ferreira et al. 2010). These soils are huge sinks of carbon and hence SOC monitoring has become so important. The huge amount of litter and detritus in mangrove forests along with adjacent land run-off contributes to huge quantities of SOC.

Little information is available on estimation of biomass and carbon stock inside and outside the conservation areas particularly Protected Forests (PF). REDD and REDD + programmes have mainly focused on National Parks, Sanctuaries, and Biosphere Reserves for conservation aspects with quantification on carbon storage potential. Very recently the role of mangroves in carbon sequestration has gained mileage as it stores four times more carbon than any tropical forest including rain forests (Donato et al. 2011). An unprecedented increase in atmospheric CO_2 from fossil combustion and land use land cover changes has focused the attention towards mitigation strategies of global warming. The challenges of climate change can be effectively overcome by storage of carbon over long period of time. Carbon storage is a situation where degraded soil is restored through afforestation increased biomass and reduces CO_2 concentration generated due to fossil fuel (Panda and Panda 2015). On this background the present research programme has pointed towards estimation of aboveground biomass (AGB), aboveground C (AGC) and soil organic C (SOC) along with other selected water and soil parameters of Bhitarkanika and Mahanadi mangrove ecosystem.

Materials and methods

Study area

The study area encompasses both Bhitarkanika and Mahanadi mangrove ecosystem of Odisha. These are the two major mangrove chunks of coastal zone of Odisha located in western Bay of Bengal. Geographically the Bhitarkanika mangrove ecosystem is located between the coordinates 20°40′–20°48′ N latitude and 86°45′–87°50′ E longitude bordered and surrounded by river Hansua on the West, Dhamra Port on the North and Bay of Bengal in the eastern and southern side. Politically it is situated in the Rajnagar block of Kendrapara district in the state Odisha

under the supervision of Divisional Forest Office, Rajnagar, Kendrapara. The Bhitarkanika mangrove ecosystem was formed by the mighty river system of Brahmani and Baitarani. They join together near Lalitapatia village and formed Dhamra river and formed various small river, creeks and delta. Rivers Khola, Pathasala, Bhitarkanika, Hansua, Kharasrota, Maipura and Hansina are the distributaries of mighty Brahmani–Baitarani, respectively, which are further criss-crossed by numerous creeks, channels and nallahs thus providing peculiar ecological niche for growth and development of mangrove life forms. The Bausagada river is tidal fed river which originates and ends its mouth in Bay of Bengal near Ekakula and Chinchiri, respectively. Five stations namely Stn.1 Dangmal, Stn.2 Bhitarkanika, Stn.3 Gupti, Stn.4 Habalikhati and Stn.5 Ekakula were selected in
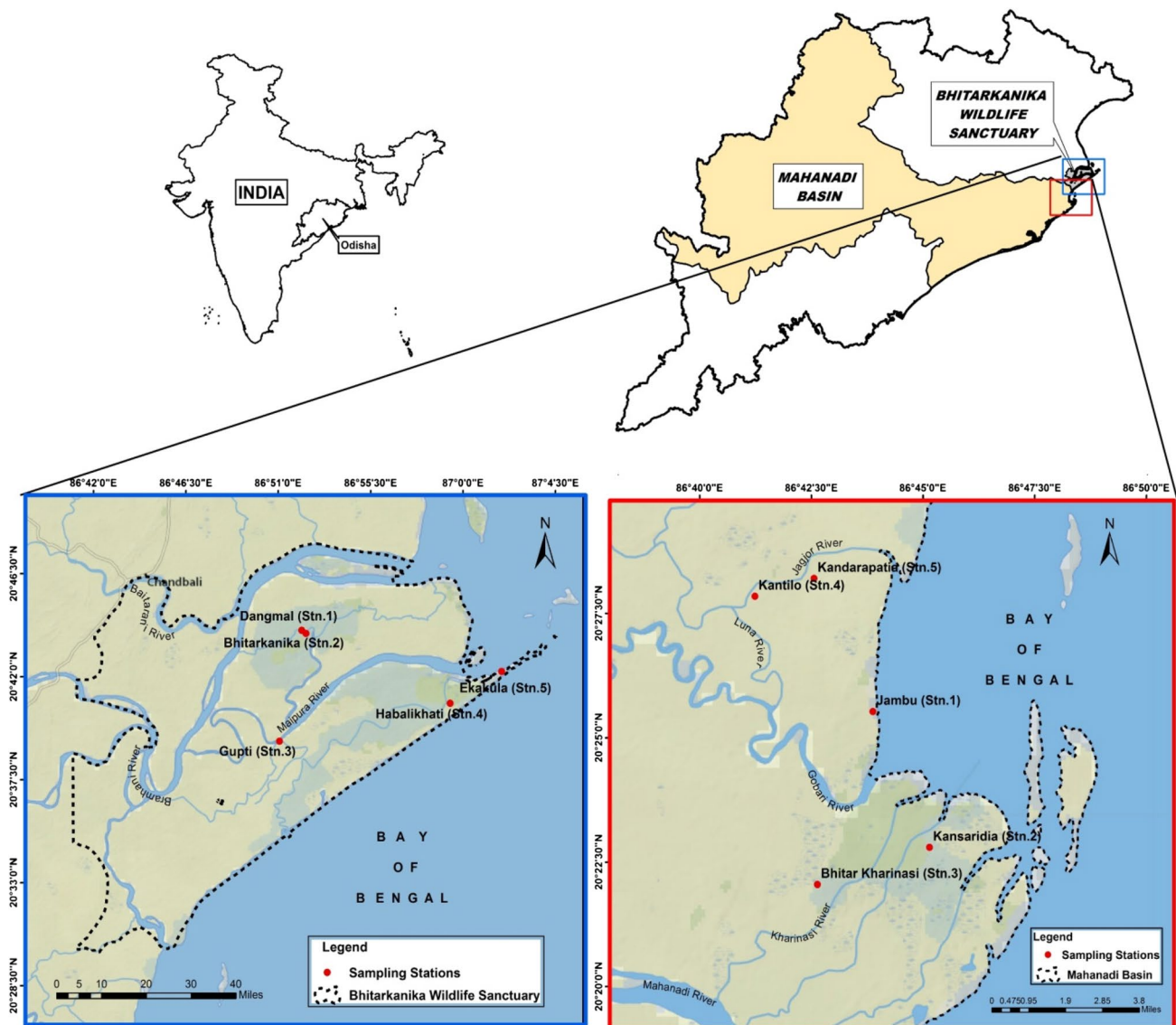

Fig. 1 Study area map for Bhitarkanika and Mahanadi mangrove ecosystems

Bhitarkanika mangrove ecosystem for the present research programme (Fig. 1).

Mahanadi mangrove wetland is located in Kendrapara district between 20°18′ and 20°32′ N latitude and 86°41′–86°48′ E longitudes in Odisha, which is a maritime state in the east coast of Indian sub-continent, being located south of Bhitarkanika Wildlife Sanctuary. The region has dense mangrove, which extend from Hukitola Bay in the north to Mahanadi river mouth near Paradeep port in the south. The ecosystem enjoys tropical monsoon climate. According to the records of Odisha Forest Department, the total mangrove area of the region is about 6651 ha including plantation. Within the Mahanadi mangrove wetland ecosystem, five sites were selected for carrying out the research programme, i.e. Stn.1 Jambu, Stn.2 Kansaridia, Stn.3 Kandarapatia, Stn.4 Kantilo and Stn.5 Bhitar Kharinasi, respectively (Fig. 1).

Estimation of above ground biomass

Simple random sampling method was used to collect the samples. Sample plots were laid along line transects based on tidal variation in the study area. 15 random sampling plots of 10 m × 10 m were selected on the intertidal mudflats. The sampling was carried out during low tide period for continuously 2 years (2017–18 and 2018–19) for three seasons (pre-monsoon, monsoon and post-monsoon) and only the live trees with a diameter at breast height (DBH) ≥ 5 cm were recorded. The DBH was measured at breast height, which is 1.3 m from the ground level of 5 selected mangrove species namely *Avicennia marina, Avicennia officinalis, Excoecaria agallocha, Rhizophora mucronata* and *Xylocarpus granatum*. It was measured by using tree calliper and measuring tape. Trees with multiple stems connected near the ground were counted as single individuals and bole circumference was measured separately. Stem height was recorded by using laser-based height measuring instrument (BOSCH DLE 70 Professional model). The methodology and procedures to estimate the stem biomass of the selected true mangrove tree species were carried out step by step as per the VACCIN project manual of CSIR (Mitra and Sundaresan 2016) considering and measuring parameters like DBH, DBR (Diameter of basal region), height of the stem, density of the stem wood and form factor. The population density of each species was also documented to express the value of biomass in tha^{-1}.

Estimation of above ground carbon

Direct estimation of percent carbon was done by *Vario MACRO elementar* CHN analyzer, after grinding and random mixing the oven dried samples from 15 different sampling plots. The estimation was done separately for each species and mean values were expressed as tha^{-1}. The analyses were done from Institute of Forest Biodiversity, Hyderabad.

Analysis of physico-chemical parameters of the ambient media

The soil and water temperature were measured by using digital thermometer (SIGMA). The soil pH was measured by using digital pH meter (Systronics) and water pH was measured through pocket type digital pH meter (Eco Testr). Water samples are from different rivers, creeks whereas the soil samples near the sampling stations are tested for the salinity. The handy portable Refractometer (Atago, Japan) was used for the salinity test. The handy digital EC meter (Model: Eco Testr) was dipped directly in situ in the soil during field sampling and the reading and mean of several reading was taken as final. Several readings were taken from each station for 2 years (2017–18 and 2018–19) and three seasons (viz. pre-monsoon, monsoon and post-monsoon) and the mean of which taken as final.

Soil samples were collected from different forest blocks for the analysis of carbon content in the soil. The carbon in the soil was determined by wet digestion method of Walkley and Black (1934). Soil samples were collected by the help of a cylindrical still ring of known volume. The Bulk density was calculated by dividing the dry soil weight by soil volume and values were expressed in g cm^{-3}.

Soil samples were brought to laboratory from different sites for determining soil texture i.e. sand, silt and clay according to the particle size. Sieve analysis and hydrometric tests were conducted to find out the percentage of sand, silt and clay in soil. Sieve analyses using various sieves of different mesh opening (0.075–4.75 mm) were used to calculate the percentage of sand. The percentage of soil retained on each sieve is calculated on the basis of the total biomass of the soil sample. In addition, soil fraction finer than 0.075 mm were separated out for further hydrometric test. Hydrometric test was carried out for particle size lesser than 0.075 mm to determine the percentage of silt and clay in soil.

Statistical analyses

All data are expressed as mean ± standard deviation. Inter-relationships were plotted for all the physico-chemical parameters, AGB and AGC for all the selected species in both Bhitarkanika and Mahanadi mangrove ecosystems through correlation analysis. Multivariate analysis of variance (MANOVA) was performed keeping physico-chemical parameters, AGB and AGC (per species) as dependent variables and stations and seasons as fixed factors in order to pinpoint the variation of parameters between stations and

seasons. The analyses were performed using IBM SPSS Statistics-21 software.

Results and discussion

Mangrove forests play an important role in global carbon cycle. Their carbon dynamics are based on long periods of gradual build up of biomass (a sink) altered with short periods of massive biomass loss (source) (Omar et al. 2003). Carbon dioxide is absorbed from the atmosphere by growing trees and other vegetation through a process of photosynthesis. The same CO_2 is emitted by the forest through plant respiration and through process of death and decay. Thus, the balance between the two is the net primary productivity (NPP) of the forest which determines the ecosystem to be a sink or source of carbon (Lal 2007).

Aquatic parameters

In the present study the surface water temperature showed pre-monsoon peaks and post-monsoon troughs which ranged from 20.5 ± 1.50 °C at Stn.1 during post-monsoon 2017–18 to 32.4 ± 2.40 °C at Stn.3 during pre-monsoon 2018–19 at Bhitarkanika and 24.65 ± 0.32 °C at Stn.3 during post-monsoon 2017–18 to 33.80 ± 0.46 °C at Stn.5 during pre-monsoon 2018–19 at Mahanadi mangrove ecosystem. The pH values varied from 7.39 ± 0.24 at Stn.3 during monsoon 2018–19 to 8.22 ± 0.56 at Stn.4 during pre-monsoon 2017–18 at Bhitarkanika mangrove ecosystem and 7.75 ± 0.72 at Stn.3 during monsoon 2018–19 to 8.30 ± 0.64 at Stn.5 during pre-monsoon 2017–18 at Mahanadi mangrove ecosystem respectively. In the present study a bimodal pattern of salinity was observed with maximum in pre-monsoon (34.64 ± 8.32 psu at Stn.5 during 2018–19 at Bhitarkanika and 29.21 ± 0.67 psu at Stn.5 during 2018–19) at Mahanadi and minimum in monsoon (10.12 ± 0.23 psu at Stn.1 during 2017–18 at Bhitarkanika and 9.41 ± 0.21 psu at Stn.3 during monsoon 2017–18) at Mahanadi mangrove ecosystem, respectively.

Soil parameters

The overall pH in the study area showed increasing trend with respect to season. The values ranged from 5.32 ± 0.14 at Stn.2 during monsoon 2018–19 to 6.60 ± 0.23 at Stn.5 during pre-monsoon 2017–18 at Bhitarkanika and 5.02 ± 0.21 at Stn.2 during monsoon 2018–19 to 6.74 ± 0.26 at Stn.5 during pre-monsoon 2017–18 at Mahanadi mangrove ecosystem, respectively. Soil salinity expressed in terms of electrical conductivity is an indicator of the amount of river discharge received in the Sanctuary from the major rivers Brahmani, Baitarani and Bausagada and other small distributaries and anthropogenic outfall. The relatively low EC values were observed at Stn.1 and 2 compared to other stations at Bhitarkanika owing to their proximity to riverine discharge of Brahmani and Baitarani, respectively. Similarly, lower EC values at Stn.3 for Mahanadi is also due to the riverine discharge of river Kharinasi. The seasonal EC values ranged from 3.73 ± 0.28 mScm^{-1} at Stn.2 during monsoon 2017–18 to 10.22 ± 0.24 at Stn.5 during pre-monsoon 2018–19 at Bhitarkanika and 2.15 ± 0.22 mScm^{-1} at Stn.3 during monsoon 2017–18 to 17.21 ± 2.92 mScm^{-1} at Stn.5 during pre-monsoon 2018–19 at Mahanadi mangrove ecosystem, respectively.

In the present study, low bulk density was observed at all the selected stations being mangrove soil, which are characteristics of more percentage of silt and clay in comparison to sand. However, with respect to season, monsoon has shown a lower bulk density than post-monsoon and pre-monsoon in both mangrove ecosystems, respectively. Bulk density values ranged from 0.71 ± 0.10 g cm^{-3} at Stn.2 during monsoon 2017–18 to 1.02 ± 0.10 g cm^{-3} at Stn.5 during pre-monsoon 2018–19 in Bhitarkanika and 0.58 ± 0.05 g cm^{-3} at Stn.3 during monsoon 2017–18 to 1.29 ± 0.08 g cm^{-3} at Stn.1 during pre-monsoon 2018–19 in Mahanadi, respectively. The higher values of bulk density during pre-monsoon and lower value in monsoon may be due to the fact that there is more sand, silt and clay deposition in monsoon because of higher precipitation and huge run-off from adjacent landmasses.

The nature of soil texture in the present study is characterized by silt clayey loamy soil in all the stations and in all the months with no much variation among them. The sand percentage varied from 8.21 ± 1.34 at Stn.1 during monsoon 2017–18 to 23.40 ± 3.86 at Stn.5 during pre-monsoon 2018–19 at Bhitarkanika and 2.64 ± 0.25 at Stn.3 during monsoon 2017–18 to 18.72 ± 1.41 at Stn.5 during pre-monsoon 2018–19 at Mahanadi, respectively. The silt percentage varied from 23.41 ± 5.60 at Stn.5 during monsoon 2017–18 to 45.10 ± 2.24 at Stn.2 during post-monsoon 2018–19 at Bhitarkanika and 10.37 ± 1.07 at Stn.5 during monsoon 2017–18 to 30.29 ± 1.24 at Stn.3 during post-monsoon 2018–19 at Mahanadi, respectively. Clay percentage varied from 35.02 ± 1.81 at Stn.5 during monsoon 2017–18 to 55.60 ± 3.51 at Stn.2 during post-monsoon 2018–19 at Bhitarkanika mangrove ecosystem and 28.72 ± 4.31 at Stn.5 during monsoon 2017–18 to 76.29 ± 1.84 at Stn.3 during post-monsoon 2018–19 at Mahanadi mangrove ecosystem, respectively.

Above ground biomass (AGB)

AGB is an important parameter to estimate carbon accumulation of a forest and its current information is required to study the importance of forest distribution on total biomass (Wijaya et al. 2010). AGB has been estimated for years

together using different data and approaches namely field observation data (Brown and Lugo 1984, 1992), remote sensing (RS) data (Steininger 2000; Foody 2003; Thenkabail et al. 2004) and GIS (Brown and Gaston 1995). Among the various methods field observation approach is known to be the best and most accurate method although it is costly and time consuming as destructive sampling data is required (Lu 2006). The amount of standing biomass stored in mangrove forest is a function of the system productivity, age and organic matter allocation and exportation strategies (Kasawani et al. 2007).

In the present study the total AGB in Bhitarkanika ranged from 15.00 ± 2.12 tha^{-1} during monsoon at Stn.3 to 67.69 ± 6.86 tha^{-1} during pre-monsoon at Stn.5 (2017–18) and 15.17 ± 3.05 tha^{-1} during monsoon at Stn.3 to 70.09 ± 6.89 tha^{-1} during pre-monsoon at Stn.5 (2018–19) for *A. marina*; 3.81 ± 1.19 during monsoon at Stn.5 to 614.51 ± 50.15 tha^{-1} during pre-monsoon at Stn.2 (2017–18) and 3.91 ± 1.21 tha^{-1} during monsoon at Stn.5 to 616.94 ± 50.15 tha^{-1} during pre-monsoon at Stn.2 (2018–19) for *A. officinalis*; 35.26 ± 2.54 tha^{-1} during monsoon at Stn.5 to 95.58 ± 5.16 tha^{-1} during pre-monsoon at
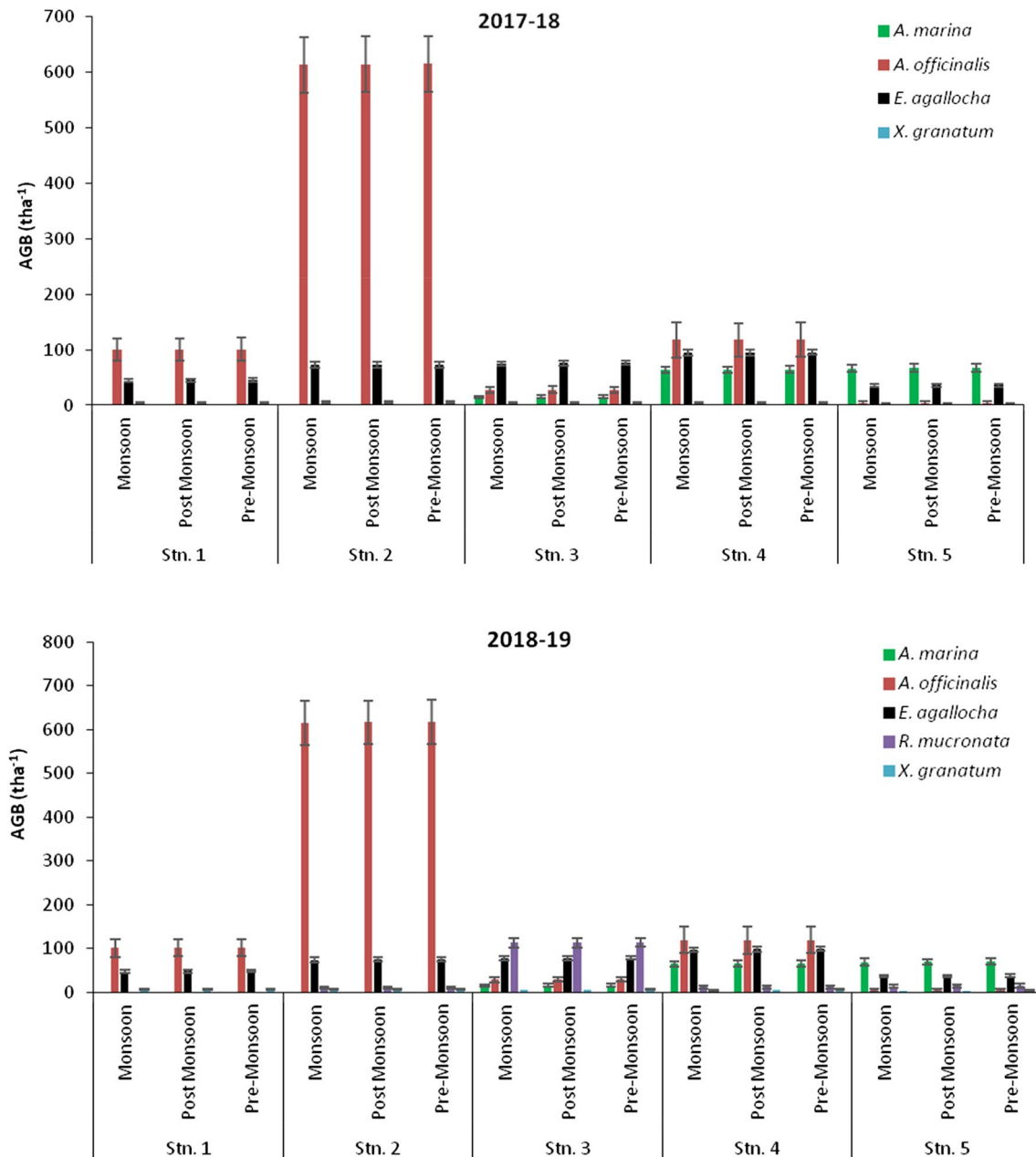

Fig. 2 Seasonal variation in AGB (tha^{-1}) of the selected species and stations at Bhitarkanika

Stn.4 (2017–18) and 36.63 ± 2.55 tha^{-1} during monsoon at Stn.5 to 98.66 ± 5.24 tha^{-1} during pre-monsoon at Stn.4 (2018–19) for *E. agallocha*; 8.87 ± 2.12 tha^{-1} during monsoon at Stn.2 to 111.93 ± 10.79 tha^{-1} during pre-monsoon at Stn.3 (2017–18) and 8.96 ± 2.13 tha^{-1} during monsoon at Stn.2 to 113.43 ± 10.65 tha^{-1} during pre-monsoon at Stn.3 (2018–19) for *R. mucronata*; 2.66 ± 0.42 tha^{-1} during monsoon at Stn.5 to 5.84 ± 1.52 tha^{-1} during pre-monsoon at Stn.2 (2017–18) and 3.06 ± 1.43 tha^{-1} during monsoon

at Stn.5 to 6.25 ± 1.52 tha^{-1} during pre-monsoon at Stn.2 (2018–19) for *X. granatum*, respectively (Fig. 2).

In case of Mahanadi mangrove ecosystem, the total AGB ranged from 20.97 ± 1.39 tha^{-1} during monsoon at station 3 to 41.02 ± 3.19 tha^{-1} during pre-monsoon at Stn.5 (2017–18) and 22.28 ± 1.41 tha^{-1} during monsoon at Stn.3 to 43.65 ± 3.31 tha^{-1} during pre-monsoon at Stn.5 (2018–19) for *A. marina*; 26.13 ± 3.19 tha^{-1} during monsoon at Stn.5 to 122.15 ± 12.12 tha^{-1} during pre-monsoon at Stn.3 (2017–18) and 27.89 ± 3.20 tha^{-1} during monsoon
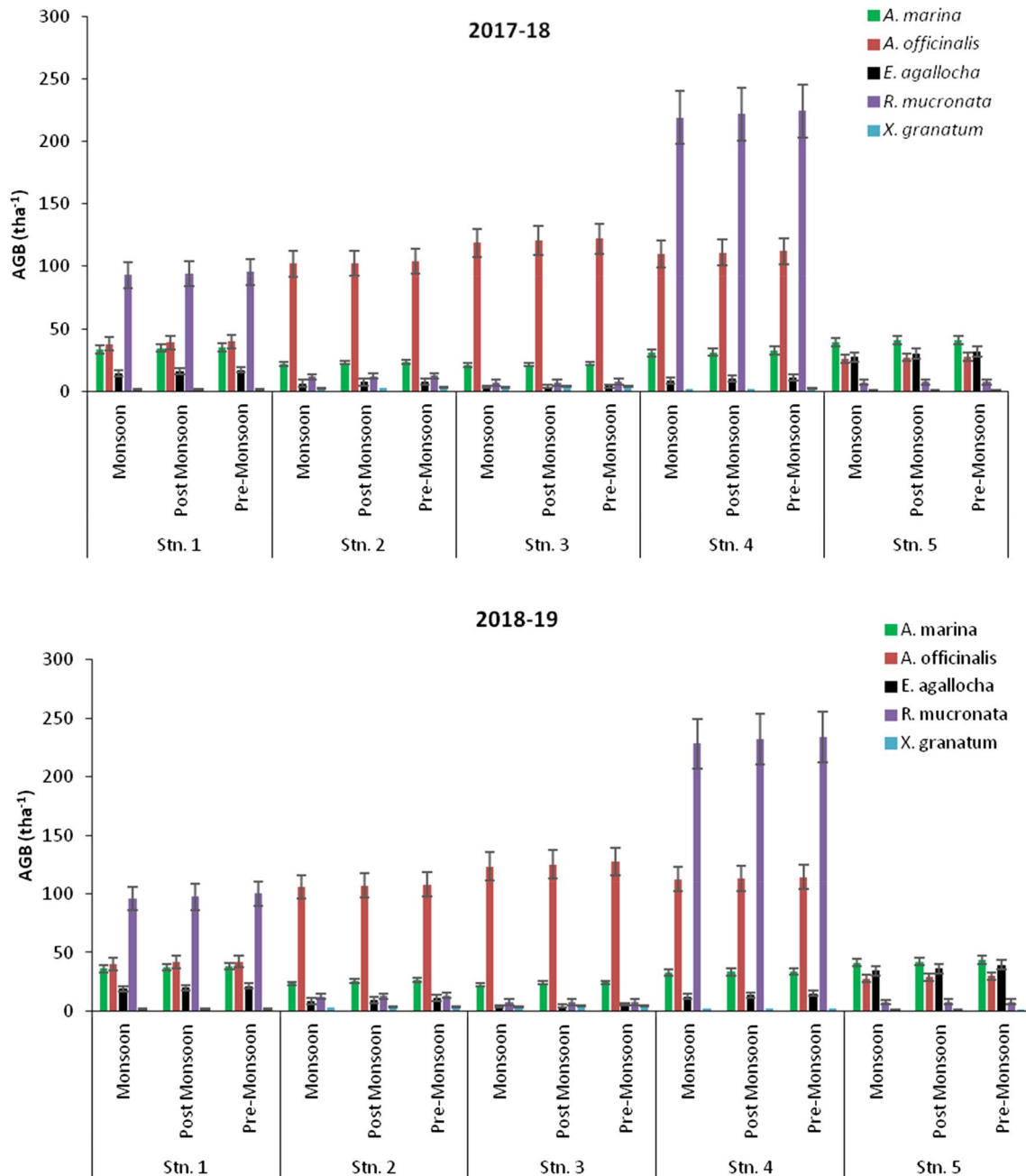

Fig. 3 Seasonal variation in AGB (tha^{-1}) of the selected species and stations at Mahanadi

at Stn.5 to 127.51 ± 12.15 tha^{-1} during pre-monsoon at Stn.3 (2018–19) for *A. officinalis*; 3.56 ± 0.96 tha^{-1} during monsoon at Stn.3 to 31.84 ± 4.10 tha^{-1} during pre-monsoon at Stn.5 (2017–18) and 4.25 ± 0.95 tha^{-1} during monsoon at Stn.3 to 39.35 ± 4.11 tha^{-1} during pre-monsoon at Stn.5 (2018–19) for *E. agallocha*; 7.06 ± 2.21 tha^{-1} during monsoon at Stn.5 to 224.41 ± 21.20 tha^{-1} during pre-monsoon at Stn.4 (2017–18) and 7.49 ± 2.56 tha^{-1} during monsoon at Stn.5 to 233.96 ± 21.35 tha^{-1} during pre-monsoon at Stn.4 (2018–19) for *R. mucronata*; 0.64 ± 0.21 tha^{-1} during monsoon at Stn.5 to 3.61 ± 0.39 tha^{-1} during pre-monsoon at Stn.3 (2017–18) and 0.92 ± 0.22 tha^{-1} during monsoon at Stn.5 to 4.33 ± 0.39 tha^{-1} during pre-monsoon at Stn.3 (2018–19) for *X. granatum*, respectively (Fig. 3).

Station wise variation plotted for five selected species at Bhitarkanika showed maximum AGB of *A. marina* at Stn.5 which is characterized by high saline environment with inland mangroves proving the affinity of *A. marina* to saline environment. On the contrary, *A. officinalis* showed maximum growth at Stn.2 owing to lower salinity and continuous fresh water flow of Brahmani and Baitarani rivers, respectively. *Excoecaria agallocha* and *X. granatum* has shown an almost simi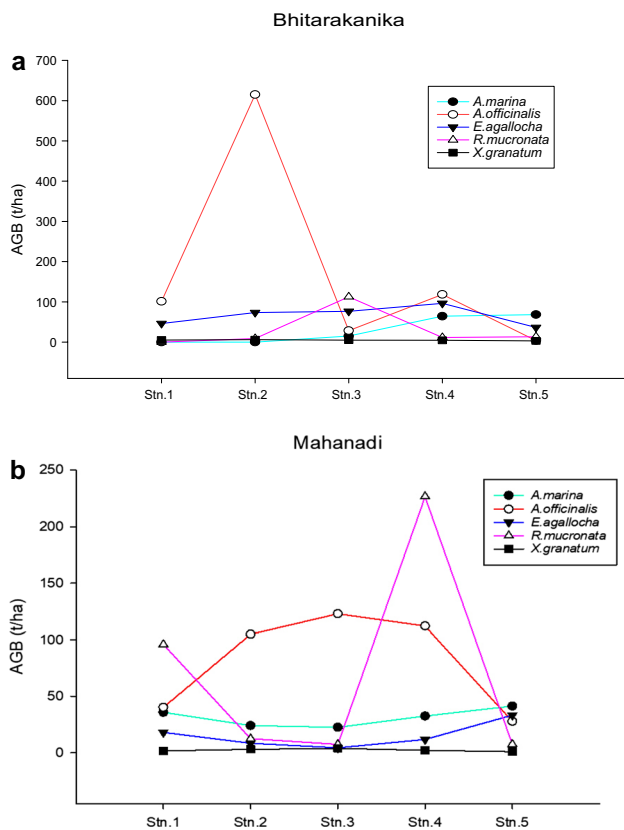lar trend in its growth and distribution in the selected stations proving its acclimatization in thriving in wide range of salinity. *Rhizophora mucronata* showed high growth at Stn.3 in a moderately saline environment, thus proving its adaptability in tide fed river channels with a constant change in salinity in every tidal action (Fig. 4a). Station wise variation plotted for five selected species at Mahanadi showed maximum AGB of *R. mucronata* at Stn.4 which is characterized by moderate saline environment and *A. marina* showed higher AGB at Stn.5 proving the affinity to the saline environment. *Avicenia officinalis* showed maximum growth at Stn.3 followed by Stns.4 and 2 owing to lower salinity and continuous fresh water flow of river Bhitar kharinasi (Fig. 4b). *Avicenia marina*, *E. agallocha* and *X. granatum* showed similar trend in growth and distribution like Bhitarkanika in the selected stations proving its adaptation in thriving in a wide range of salinity. The overall range of AGB in the present study varied from 2.66 ± 0.42 tha^{-1} to 616.94 ± 50.15 tha^{-1} in case of Bhitarkanika and 0.64 ± 0.21 tha^{-1} to 233.96 ± 21.35 tha^{-1} in Mahanadi which is comparable with that in the Sundarbans (Roy Choudhuri 1991; Mitra et al. 2009, 2010, 2011; Banerjee et al. 2013; Joshi and Ghose 2014), Japan (Suzuki and Tagawa 1983), Australia (Woodroffe 1985), Senegal (Doyen 1986), Guade-loupe
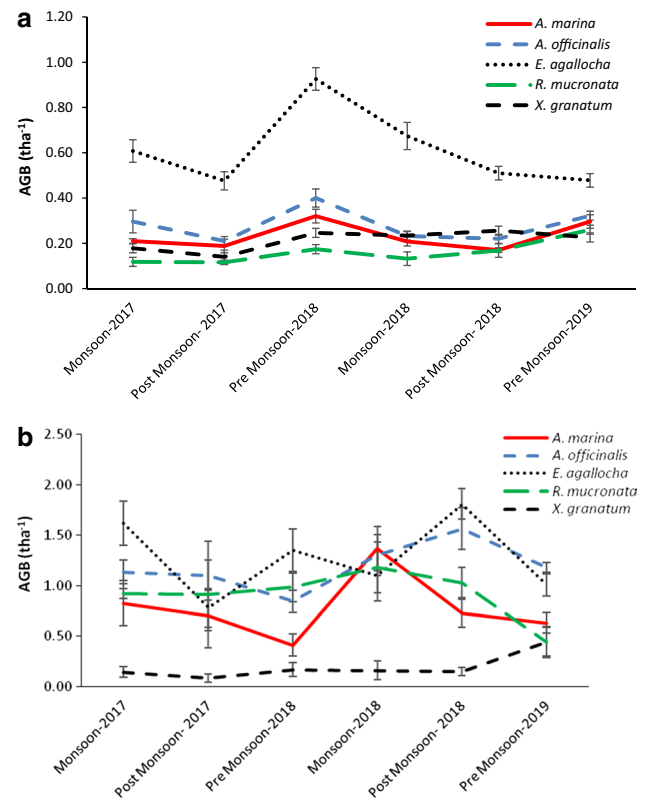

Fig. 4 a Variation of AGB (tha^{-1}) with respect to stations and selected species over a period of 2 years. **b** Variation of AGB (tha^{-1}) with respect to stations and selected species over a period of 2 years

Fig. 5 a Seasonal increase of AGB (tha^{-1}) of the selected species in Bhitarkanika. **b** Seasonal increase of AGB (tha^{-1}) of the selected species in Mahanadi
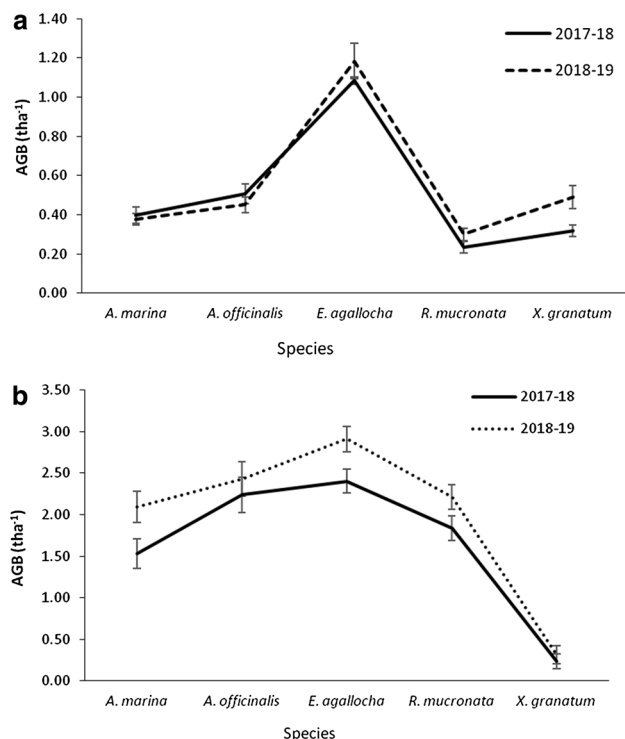
Fig. 6 a Yearly increase of AGB (tha⁻¹) of the selected species in Bhitarkanika. **b** Yearly increase of AGB (tha⁻¹) of the selected species in Mahanadi

(Imbert and Rollet 1989), Puerto Rico (Golley et al. 1962), Thailand (Christensen 1978), Florida (Lugo and Snedaker 1974) and estuarine complex along Indian Bay of Bengal (Kathiresan et al. 2013), Indonesia (Komiyama et al. 1988), Malaysia (Putz and Chan 1986), Sri Lanka (Amarasinghe and

Balasubramaniam 1992), Andaman islands (Mall et al. 1991) and Philippines (Camacho et al. 2011).

In the present study the biomass values showed a wide variation in AGB with respect to season for all the selected species over period of 2 years 2017–18 and 2018–19 (Fig. 5a, b) which is basically due to density and distribution of species in relation to the soil and water parameters particularly water salinity, EC and SOC. In forests with no natural and human disturbances, biomass values can go > 250 tha⁻¹ (Lakyda et al. 2019) as has been observed in Stn.2 in Bhitarkanika mangrove ecosystem and Stn.4 in Mahanadi mangrove ecosystem. Season–wise variation of AGB at Bhitarkanika Wildfile Sanctuary and Mahanadi showed high growth of *E. agallocha* followed by *A. officinalis*, *A. marina*, *R. mucronata* and *X. granatum*, respectively. This may be due to adaptability of *E. agallocha* to wide range of water salinity (9.41 ± 0.21 psu to 34.64 ± 8.32 psu) and soil salinity (2.15 ± 0.22 to 17.21 ± 2.92 mScm⁻¹). Year-wise trend of AGB at Bhitarkanika mangrove ecosystem clearly reveals that there is high growth of *E. agallocha* > *A. officinalis* > *X. granatum* > *A. marina* > *R. mucronata* (Fig. 6a). For Mahanadi year-wise trend showed high growth in *E. agallocha* > *A. officinalis* > *R. mucronata* > *A. marina* > *X. granatum*, respectively (Fig. 6b). Species-wise average increase in biomass for 2 years at Bhitarkanika mangrove ecosystem (2017–18 and 2018–19) was calculated, where *A. marina* showed 1.83 ± 0.56 tha⁻¹, *A. officinalis* showed 1.36 ± 0.31 tha⁻¹, *E. agallocha* showed 3.24 ± 0.54 tha⁻¹, *R. mucronata* showed 0.79 ± 0.22 tha⁻¹ and *X. granatum* showed an increase of 1.05 ± 0.39 tha⁻¹ respectively (Table 1). Species wise average increasing biomass for 2 years at Mahanadi mangrove ecosystem (2017–18 and 2018–19) was calculated where *A. marina* showed 4.04 ± 0.76 tha⁻¹, *A. officinalis*

Table 1 Growth pattern in terms of biomass and carbon (tha⁻¹) of selected species over 2 years (2017–18 and 2018–19) at Bhitarkanika

Sl. no.	Species	Minimum	Maximum	Increase in AGB	Minimum	Maximum	Increase in AGC
1	*Avicennia marina*	15.00 ± 2.41	70.09 ± 7.50	1.83 ± 0.56	7.63 ± 1.08	35.65 ± 3.38	0.93 ± 0.29
2	*Avicennia officinalis*	3.81 ± 0.85	616.94 ± 44.38	1.36 ± 0.31	1.73 ± 0.44	280.83 ± 23.08	0.62 ± 0.18
3	*Excoecaria agallocha*	35.26 ± 2.42	98.66 ± 6.75	3.24 ± 0.54	16.06 ± 1.09	44.95 ± 3.04	1.48 ± 0.28
4	*Rhizophora mucronata*	8.87 ± 1.65	113.43 ± 12.63	0.79 ± 0.22	4.88 ± 0.91	62.39 ± 6.95	0.43 ± 0.13
5	*Xylocarpus granatum*	2.66 ± 0.21	6.25 ± 0.37	1.05 ± 0.39	1.38 ± 0.10	3.25 ± 0.17	0.55 ± 0.21

Table 2 Growth pattern in terms of biomass and carbon (tha⁻¹) of selected species over 2 years (2017–18 and 2018–19) at Mahanadi

Sl. no.	Species	Minimum	Maximum	Increase in AGB	Minimum	Maximum	Increase in AGC
1	*Avicennia marina*	20.97 ± 1.39	43.65 ± 1.45	4.04 ± 0.76	9.14 ± 0.61	18.89 ± 0.63	1.74 ± 0.32
2	*Avicennia officinalis*	26.13 ± 1.29	127.51 ± 3.31	6.16 ± 2.17	11.72 ± 0.57	57.63 ± 1.51	1.13 ± 0.96
3	*Excoecaria agallocha*	3.56 ± 0.42	39.35 ± 4.11	5.99 ± 1.79	1.64 ± 0.18	17.40 ± 1.69	2.50 ± 1.55
4	*Rhizophora mucronata*	7.06 ± 2.21	233.96 ± 19.35	5.03 ± 2.76	3.44 ± 0.12	114.05 ± 10.29	2.45 ± 1.15
5	*Xylocarpus granatum*	0.64 ± 0.18	4.33 ± 0.39	0.71 ± 0.25	0.31 ± 0.08	2.17 ± 0.19	0.34 ± 0.12

Table 3 Interrelationship between physico-chemical parameters, biomass and carbon in Bhitarkanika mangrove ecosystem

	BWtemp	BWpH	BWsalinity	BSpH	BSsalinity	BBdensity	BSOC	BSand	BSilt	BClay	BBAm	BBAo	BBEa	BBRm	BBXg	BCAm	BCAo	BCEa	BCRm	BCXg
BWtemp	1.00																			
BWpH	0.06	1.00																		
BWsalinity	0.25	0.54	1.00																	
BSpH	0.24	0.74	0.74	1.00																
BSsalinity	0.32	0.47	0.87	0.67	1.00															
BBdensity	0.20	0.69	0.85	0.72	0.84	1.00														
BSOC	−0.35	−0.36	−0.54	−0.42	−0.42	−0.45	1.00													
BSand	0.15	0.58	0.77	0.60	0.83	0.77	−0.55	1.00												
BSilt	−0.31	−0.11	−0.25	−0.17	−0.15	−0.18	0.85	−0.28	1.00											
BClay	−0.30	−0.20	−0.36	−0.18	−0.27	−0.29	0.88	−0.48	0.91	1.00										
BBAm	0.07	0.53	0.73	0.52	0.63	0.71	−0.83	0.80	−0.67	−0.77	1.00									
BBAo	−0.10	−0.11	−0.57	−0.36	−0.46	−0.43	0.60	−0.43	0.48	0.49	−0.50	1.00								
BBEa	0.00	−0.15	0.00	−0.21	−0.15	−0.05	0.01	−0.34	−0.06	0.08	0.04	0.27	1.00							
BBRm	0.15	−0.51	0.20	−0.15	0.11	−0.18	0.05	−0.11	0.06	0.08	−0.15	−0.32	0.27	1.00						
BBXg	−0.02	−0.37	−0.53	−0.49	−0.44	−0.40	0.76	−0.69	0.66	0.77	−0.77	0.68	0.45	0.05	1.00					
BCAm	0.07	0.53	0.73	0.52	0.63	0.71	−0.83	0.80	−0.67	−0.77	1.00	−0.50	0.04	−0.15	−0.77	1.00				
BCAo	−0.10	−0.11	−0.57	−0.36	−0.46	−0.43	0.60	−0.43	0.48	0.49	−0.50	1.00	0.27	−0.32	0.68	−0.50	1.00			
BCEa	0.00	−0.15	0.00	−0.21	−0.15	−0.05	0.01	−0.34	−0.06	0.08	0.04	0.26	1.00	0.27	0.45	0.04	0.26	1.00		
BCRm	0.15	−0.51	0.20	−0.15	0.11	−0.18	0.05	−0.11	0.06	0.08	−0.15	−0.32	0.27	1.00	0.05	−0.15	−0.32	0.27	1.00	
BCXg	−0.02	−0.37	−0.53	−0.49	−0.44	−0.40	0.76	−0.68	0.66	0.77	−0.77	0.68	0.45	0.05	1.00	−0.77	0.68	0.45	0.05	1.00

Table 4 Interrelationship between physico-chemical parameters, biomass and carbon in Mahanadi mangrove ecosystem

	MWtemp	MWpH	MWsalinity	MSpH	MSsalinity	MBdensity	MSOC	MSand	MSilt	MClay	MBAm	MBAo	MBEa	MBRm	MBXg	MCAm	MCAo	MCEa	MCRm	MCXg
MWtemp	1.00																			
MWpH	0.16	1.00																		
MWsalinity	0.19	0.79	1.00																	
MSpH	0.37	0.78	0.77	1.00																
MSsalinity	−0.02	0.85	0.92	0.76	1.00															
MBdensity	0.16	0.71	0.88	0.59	0.79	1.00														
MSOC	−0.51	−0.43	−0.28	−0.19	−0.18	−0.48	1.00													
MSand	0.08	0.70	0.82	0.55	0.84	0.78	−0.34	1.00												
MSilt	−0.66	−0.27	−0.10	−0.08	−0.04	−0.17	0.78	−0.31	1.00											
MClay	−0.46	−0.36	−0.28	−0.11	−0.27	−0.32	0.70	−0.59	0.85	1.00										
MBAm	0.14	0.57	0.59	0.29	0.62	0.72	−0.66	0.82	−0.53	−0.73	1.00									
MBAo	−0.14	−0.54	−0.50	−0.16	−0.47	−0.60	0.66	−0.69	0.54	0.73	−0.85	1.00								
MBEa	0.16	0.52	0.59	0.26	0.60	0.63	−0.51	0.87	−0.52	−0.79	0.93	−0.87	1.00							
MBRm	−0.02	0.12	0.02	0.11	0.09	0.22	−0.38	−0.03	−0.13	0.05	0.21	0.19	−0.11	1.00						
MBXg	−0.12	−0.56	−0.40	−0.16	−0.45	−0.52	0.76	−0.69	0.71	0.84	−0.89	0.86	−0.84	−0.18	1.00					
MCAm	0.14	0.57	0.58	0.29	0.61	0.72	−0.66	0.82	−0.53	−0.73	1.00	−0.84	0.93	0.22	−0.89	1.00				
MCAo	−0.14	−0.54	−0.49	−0.15	−0.46	−0.60	0.65	−0.69	0.54	0.73	−0.84	1.00	−0.87	0.19	0.86	−0.84	1.00			
MCEa	0.16	0.52	0.59	0.26	0.60	0.62	−0.50	0.87	−0.52	−0.79	0.92	−0.88	1.00	−0.14	−0.84	0.92	−0.87	1.00		
MCRm	−0.02	0.12	0.02	0.11	0.09	0.22	−0.39	−0.03	−0.13	0.05	0.21	0.18	−0.11	1.00	−0.18	0.22	0.19	−0.14	1.00	
MCXg	−0.13	−0.56	−0.40	−0.16	−0.45	−0.52	0.76	−0.70	0.71	0.84	−0.89	0.87	−0.85	−0.17	1.00	−0.89	0.86	−0.84	−0.17	1.00

showed 6.16 ± 2.17 tha^{-1}, *E. agallocha* showed 5.99 ± 1.79 tha^{-1}, *R. mucronata* showed 5.03 ± 2.76 tha^{-1} and *X. granatum* showed 0.71 ± 0.25 tha^{-1} respectively (Table 2).

Mangrove photosynthesis is usually limited by high midday leaf temperature (Cheeseman 1994) and thus increases in temperature with declining humidity and rainfall would reduce productivity in mangrove forest by accentuating mid-day depression in photosynthesis. For Bhitarkanika and Mahanadi mangrove ecosystem all the selected species did not show any relationship with temperature which proves that the selected sites are geographically not very distinct from each other being a smaller geographical locale (Tables 3, 4).

With respect to water pH, *A. marina* showed significant positive relationship ($P < 0.05$; $P < 0.01$) for both Bhitarkanika and Mahanadi mangrove ecosystem. In case of soil pH, it showed significant relationship ($P < 0.05$) in Bhitarkanika mangrove ecosystem, but insignificant relationship in case of Mahanadi mangrove ecosystem. The relationship of pH with biomass of *A. marina* in Bhitarkanika proves its affinity to low acidic environment. With respect to water pH, *A. officinalis* and *X. granatum* showed significant negative relationship at Mahanadi but insignificant relationship with that of soil pH in both Bhitarkanika and Mahanadi. *Rhizophora mucronata* showed significant negative relationship with respect to water pH and *X. granatum* in case of soil pH at Bhitarkanika mangrove ecosystem. For *E. agallocha* water pH has shown significant positive relationship ($P < 0.05$) at Mahanadi mangrove ecosystem and insignificant relationship in case of Bhitarkanika mangrove ecosystem which proves that excepting *E.agallocha* all other species especially *A. officinalis* and *X. granatum* are more sensitive to the changing pH (Tables 3, 4).

With respect to salinity, *A. marina* has shown significant positive relationship in both the blocks of Bhitarkanika and Mahanadi mangrove ecosystem which is quite similar to that of *E. agallocha* in case of Mahanadi (excepting it has shown insignificant relationship in Bhitarkanika mangrove ecosystem) owing to the affinity of these species to water and soil salinity. In case of *R. mucronata* it has shown insignificant relationship in both the ecosystem proving that this species is not salinity dependent rather we can say its higher adaptability to tidal inundated areas. However, a contrasting feature was located in case of *A. officinalis* and *X. granatum* which has shown significant negative relationship ($P < 0.05$; $P < 0.01$) which proves that they are comparatively more acquainted with low saline environment in both Bhitarkanika and Mahanadi mangrove ecosystem as has also been stated by Kathiresan et al. (1996) (Tables 3, 4). Lower total AGB is observed generally in higher saline areas as has been observed at Stn.5 (128.64 ± 15.81 tha^{-1}) in Bhitarkanika and (120.78 ± 13.14 tha^{-1}) in Mahanadi mangrove ecosystem in contrast to Stn.2 in Bhitarkanika (706.75 ± 68.96 tha^{-1}) and Stn.4 (399.82 ± 37.43

tha^{-1}). This has also been proved by earlier workers (Mitra et al. 2010, 2011; Banerjee et al. 2013).

With respect to soil bulk density significant positive correlation was observed for *A. marina* ($P < 0.01$) and significant negative relationship for *A. officinalis* and *X. granatum* ($P < 0.05$; $P < 0.01$) proving the variation in sediment composition for the growth of the species in Bhitarkanika and Mahanadi mangrove ecosystem. On contrary *E. agallocha* and *R. mucronata* did not show any relationship with bulk density in case of Bhitarkanika mangrove ecosystem but significant positive relationship in case of Mahanadi mangrove ecosystem (only for *E. agallocha*, $P < 0.01$) proving that these species are adapted to more silt and clayey soil with higher bulk density. Such type of studies for effect of BD on mangrove forests has also been studied by Hossain and Nuruddin (2016) (Tables 3, 4).

With respect to soil organic carbon AGB of *A. marina* showed significant negative relationship ($P < 0.01$) and for *A. officinalis* and *X. granatum* it showed significant positive relationship ($P < 0.01$) proving that with increasing carbon load in the soil the growth of *A. marina* decreases and *A. officinalis* and *X. granatum* increases. This is in contrast with soil pH which has been explained earlier. This is true both for Bhitarkanika and Mahanadi mangrove ecosystem. For *E. agallocha* and *R. mucronata* no relationship was observed for SOC in Bhitarkanika and Mahanadi mangrove ecosystem (excepting *E. agallocha* at Mahanadi which has shown significant negative relationship like *A. marina*, $P < 0.05$) during the study period which justifies that the minimum amount of SOC is sufficient for the growth of these two species. This might be the probable cause for a wide spread distribution of these two species in all the stations respectively (Tables 3, 4). Increasing SOC along with biomass growth has also been demonstrated by Ren et al. (2010).

Soil texture relationship has been studied with respect to sand, silt and clay composition respectively. With respect to sand, *A. marina* showed significant positive relationship ($P < 0.01$), with silt and clay, it showed significant negative relationship ($P < 0.05$; $P < 0.01$) both for Bhitarkanika and Mahanadi mangrove ecosystem. The reverse trend has been followed for *A. officinalis* and *X. granatum* in all the selected stations ($P < 0.05$; $P < 0.01$). For *R. mucronata*, there is no relationship with respect to soil texture. However, for *E. agallocha* although there is no relationship in Bhitarkanika but it has shown significant positive relationship with sand ($P < 0.01$) and significant negative relationship ($P < 0.05$; $P < 0.01$) with respect to silt and clay in Mahanadi mangrove ecosystem which is proved by the distribution of both the species almost evenly in Mahanadi mangrove ecosystem (Tables 3, 4). Soil texture in the study area has shown higher percentage of silt and clay compared to sand particles, proving that the present study area has finer clay than sand and have greater ability to trap nutrients (Nguyen et al. 2013).

MANOVA computed for biomass of *A. marina* showed significant variation between stations ($P < 0.05$) both in case of Bhitarkanika and Mahanadi mangrove ecosystem, but insignificant variation between season as well as station vs season respectively. Similar variation has also been observed for *A. officinalis, E. agallocha, R. mucronata* and *X. granatum*, respectively.

Above ground carbon (AGC)

Mangrove forest contributes a significant proportion to global carbon cycle although they comprise 0.7% of the global coastal zone (Kathiresan et al. 2013). Since mangroves play a major role in reducing greenhouse gases and problems of global warming through the process of photosynthesis, they
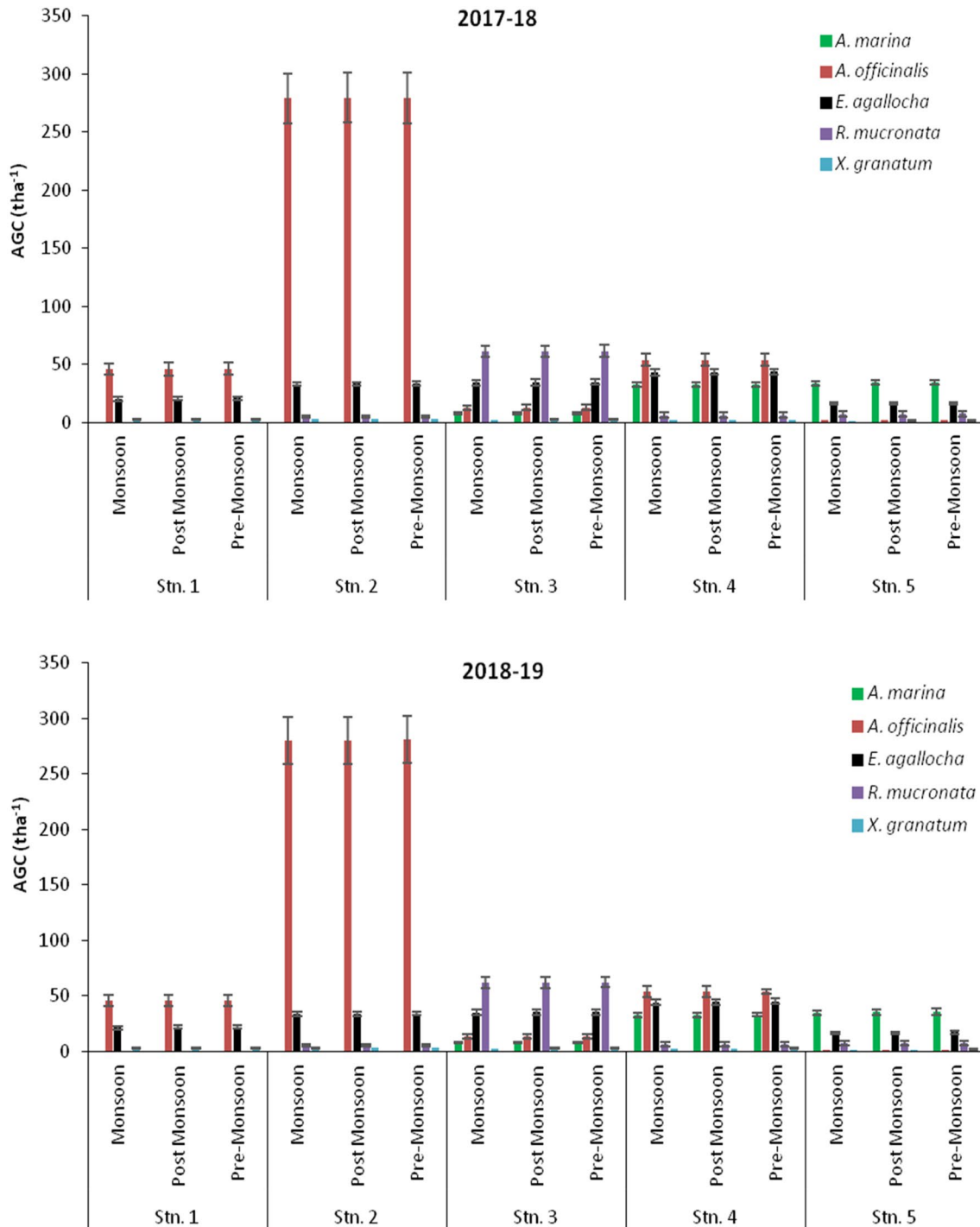

Fig. 7 Seasonal variation in AGC (tha^{-1}) of the selected species and stations at Bhitarkanika

are excellent store house of carbon. Carbon storage in mangroves is a function of the quantity of biomass which varies with respect to age and growth efficiency. In the present study we observed significantly higher stored carbon in above ground structures of species thriving in Stn.2 and Stn.4 in Bhitarkanika and Mahanadi mangrove ecosystem in comparison to other stations. In case of Bhitarkanika mangrove ecosystem for *A. marina* AGC values varied from 7.63 ± 1.08 tha^{-1} during monsoon at Stn.3 to 34.42 ± 2.03 tha^{-1} during

pre-monsoon 2017–18 at Stn.5 and 7.72 ± 0.81 tha^{-1} during monsoon at Stn.3 to 35.65 ± 2.63 tha^{-1} during pre-monsoon 2018–19 at Stn.5; for *A. officinalis* the AGC varied from 1.73 ± 0.01 tha^{-1} during monsoon at Stn.5 to 279.72 ± 22.01 tha^{-1} during pre-monsoon 2017–18 at Stn.2 and 1.78 ± 0.02 tha^{-1} during monsoon at Stn.5 to 280.83 ± 21.29 tha^{-1} during pre-monsoon 2018–19 at Stn.2; for *E. agallocha* AGC varied from 16.06 ± 1.05 tha^{-1} during monsoon at Stn.5 to 43.54 ± 2.89 tha^{-1} during pre-monsoon 2017–18 at Stn.4 and

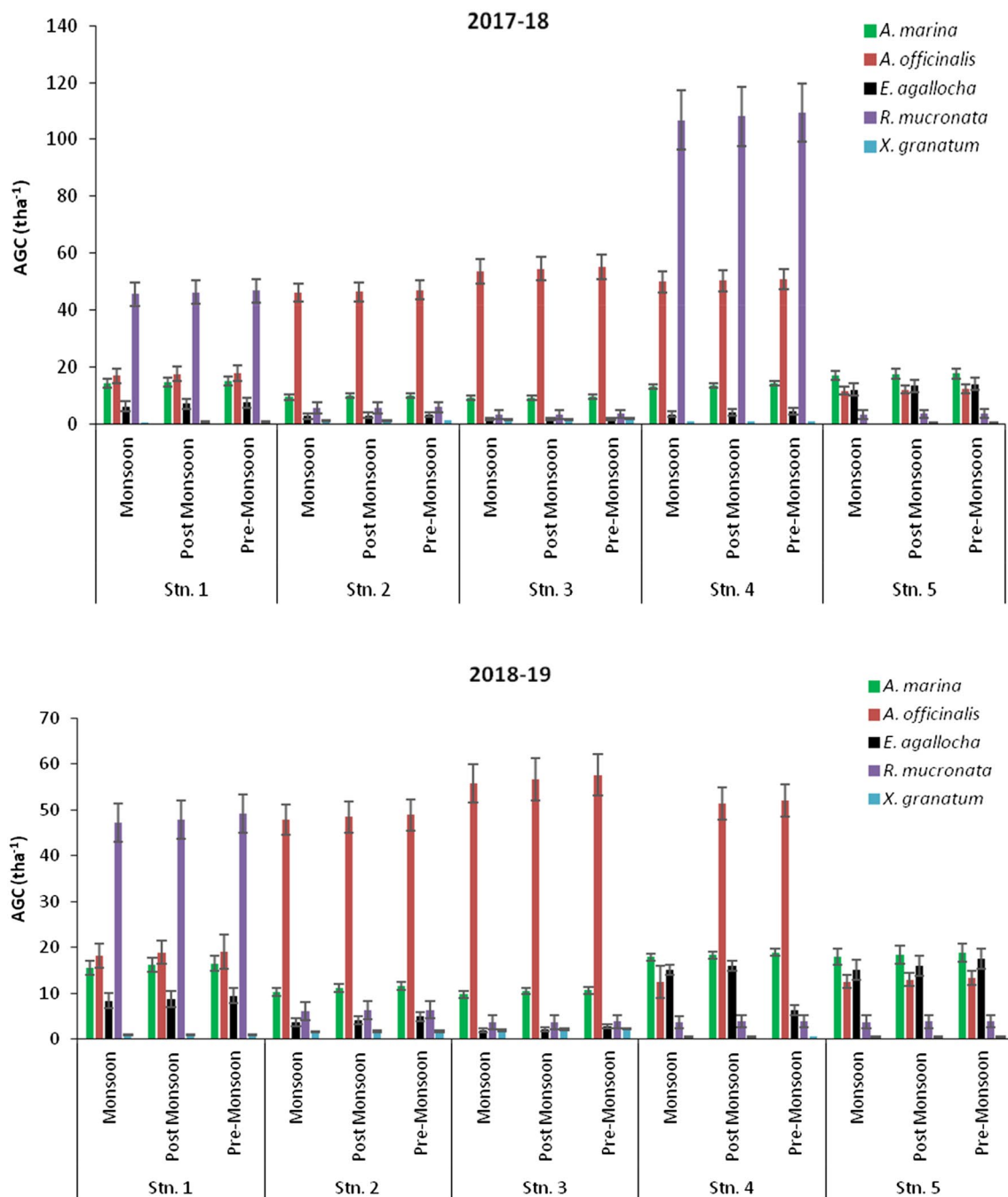**Fig. 8** Seasonal variation in AGC (tha^{-1}) of the selected species and stations at Mahanadi

16.69 ± 1.06 tha^{-1} during monsoon at Stn.5 to 44.95 ± 2.53 tha^{-1} during pre-monsoon 2018–19 at Stn.4; for *R. mucronata* the values ranged from 4.88 ± 1.05 tha^{-1} during monsoon at Stn.2 to 61.56 ± 4.95 tha^{-1} during pre-monsoon at Stn.3 2017–18 and 4.93 ± 1.06 tha^{-1} during monsoon at Stn.2 to 62.39 ± 4.95 during pre-monsoon 2018–19 at Stn.3; For *X. granatum* AGC values ranged from 1.38 ± 0.10 tha^{-1} during monsoon at Stn.5 to 3.04 ± 0.32 tha^{-1} during pre-monsoon at Stn.2 (2017–18) and 1.59 ± 0.11 tha^{-1} during monsoon at Stn.5 to 3.25 ± 0.31 tha^{-1} during pre-monsoon at Stn.2 (2018–19), respectively (Fig. 7). In case of Mahanadi, for *A. marina* AGC values varied from 9.14 ± 0.72 tha^{-1} during monsoon at Stn.3 to 17.76 ± 1.57 tha^{-1} during pre-monsoon at Stn.5 (2017–18) and 9.70 ± 0.69 tha^{-1} during monsoon at Stn.3 to 18.89 ± 1.99 tha^{-1} during pre-monsoon at Stn.5 (2018–19); for *A. officinalis* AGC values varied from 11.72 ± 1.41 tha^{-1} during monsoon at Stn.5 to 55.25 ± 4.26 tha^{-1} during pre-monsoon at Stn.3 and 12.48 ± 1.43 tha^{-1} during monsoon at Stn.5 to 57.63 ± 4.52 tha^{-1} during pre-monsoon at Stn.3 (2018–19); for *E. agallocha* AGC values varied from 1.64 ± 0.41 tha^{-1} during monsoon at Stn.3 to 14.08 ± 2.16 tha^{-1} during pre-monsoon at Stn.5 (2017–18) and 1.94 ± 0.43 tha^{-1} during monsoon at Stn.3 to 17.40 ± 2.21 tha^{-1} during pre-monsoon at Stn.5 (2018–19); for *R. mucronata* the AGC values ranged from 3.44 ± 1.45 tha^{-1} during monsoon (2017–18) at Stn.5 to 109.40 ± 10.25 tha^{-1} during pre-monsoon (2017–18) at Stn.4 and 3.64 ± 1.52 tha^{-1} during monsoon (2018–19) at Stn.5 to 114.05 ± 10.29 tha^{-1} during pre-monsoon (2018–19) at Stn.4 and for *X. granatum* the AGC values ranged from 0.31 ± 0.10 tha^{-1} during monsoon at Stn.5 to 1.82 ± 0.19 tha^{-1} during pre-monsoon (2017–18) at Stn.3 and 0.44 ± 0.11 tha^{-1} during monsoon at Stn.5 to 2.17 ± 0.19 tha^{-1} during pre-monsoon (2018–19) at Stn.3, respectively (Fig. 8).

Station-wise trend of AGC was replicate of AGB with highest value of *A. officinalis* at Stn.2 for Bhitarkanika mangrove ecosystem (Fig. 9) and Stn.3 for Mahanadi
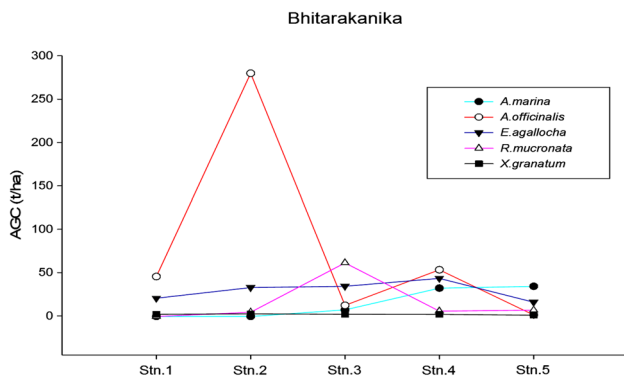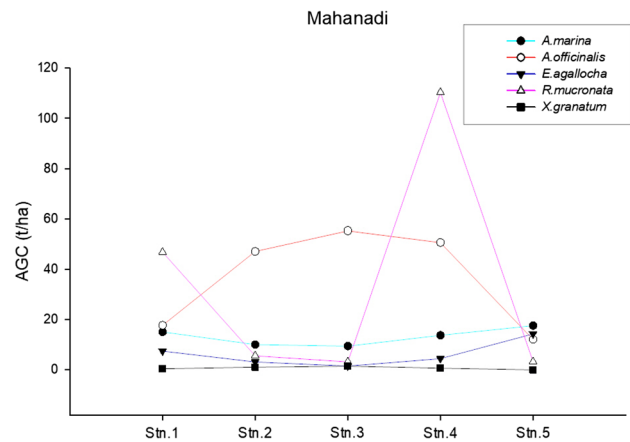

Fig. 10 Variation of AGC (tha^{-1}) with respect to stations and selected species over a period of 2 years

mangrove ecosystem (Fig. 10) owing to lower salinity of these stations due to discharge from Brahmani and Baitarani at Bhitarkanika and river Kharinasi at Mahanadi mangrove ecosystem. Another highest peak was recorded at Stn.4 in Mahanadi for *R. mucronata* which is due to the fact that this area is basically a plantation site of *R. mucronata* by Forest Department in collaboration with M.S. Swaminathan Research Foundation.

Correlation coefficient computed for AGC along with water and soil parameters has shown similar relationship with that of AGB (Tables 3, 4). However significant variation within stations ($P < 0.05$) have proved variation in carbon storage with respect to stations (Tables 3, 4). Species-wise average of carbon (tha^{-1}) in Bhitarkanika mangrove ecosystem was *E. agallocha* $(1.48 \pm 0.28) > A.$ *marina* $(0.93 \pm 0.29) > A.$ *officinalis* $(0.62 \pm 0.18) > X.$ *granatum* $(0.55 \pm 0.21) > R.$ *mucronata* (0.43 ± 0.13) respectively (Tables 5, 6). In case of Mahanadi species-wise average carbon (tha^{-1}) was *E. agallocha* $(2.50 \pm 1.79) > R.$ *mucronata* $(2.45 \pm 1.15) > A.$ *marina* $(1.74 \pm 0.32) > A.$ *officinalis* $(1.13 \pm 0.96) > X.$ *granatum* (0.34 ± 0.12), respectively.

Total carbon (AGC + SOC) calculated for the study area varied from 66.31 ± 13.39 tha^{-1} at Stn.5 to 330.41 ± 111.97 tha^{-1} at Stn.2 in case of Bhitarkanika and 55.20 ± 7.90 tha^{-1} at Stn.5 to 187.89 ± 43.81 tha^{-1} at Stn.4 in Mahanadi, respectively (Tables 5, 6) with a mean total carbon of 149.07 ± 38.32 tha^{-1} at Bhitarkanika mangrove ecosystem and 99.14 ± 21.93 tha^{-1} for Mahanadi mangrove ecosystem, respectively. Carbon dioxide equivalent (CO_2e) calculated station-wise varied from 243.37 ± 49.14 tons at Stn.5 to 1212.59 ± 410.92 tons at Stn.2 for Bhitarkanika mangrove ecosystem with a mean CO_2e of 547.08 ± 140.62 tons for Bhitarkanika mangrove ecosystem. In case of Mahanadi mangrove ecosystem, the CO_2e varied from 202.60 ± 29.00 tons at Stn.5 to 689.55 ± 160.77 tons at Stn.4 with mean CO_2e of 363.85 ± 80.50 tons, respectively (Tables 5, 6).

Fig. 9 Variation of AGC (tha^{-1}) with respect to stations and selected species over a period of 2 years

Table 5 Carbon storage potential (tha^{-1}) of Bhitarkanika mangrove ecosystem (for the selected species)

Stations	AGC (tha^{-1})	SOC (tha^{-1})	Total carbon (tha^{-1}) (AGC + SOC)	CO_2 equivalent (t)
Stn.1	71.17 ± 18.57	6.68 ± 0.47	77.84 ± 19.04	285.69 ± 69.87
Stn.2	322.69 ± 111.52	7.71 ± 0.45	330.41 ± 111.97	1212.59 ± 410.92
Stn.3	121.38 ± 23.69	5.83 ± 0.24	127.20 ± 23.94	466.84 ± 87.85
Stn.4	140.05 ± 23.13	3.52 ± 0.12	143.57 ± 23.25	526.91 ± 85.33
Stn.5	62.77 ± 13.28	3.55 ± 0.11	66.31 ± 13.39	243.37 ± 49.14
Mean ± SD	143.61 ± 38.04	5.46 ± 1.68	149.07 ± 38.32	547.08 ± 140.62

Table 6 Carbon storage potential (tha^{-1}) of Mahanadi mangrove ecosystem (for the selected species)

Stations	AGC (tha^{-1})	SOC (tha^{-1})	Total carbon (tha^{-1}) (AGC + SOC)	CO_2 equivalent (t)
Stn.1	90.67 ± 17.24	3.61 ± 0.30	94.28 ± 17.53	346.00 ± 64.35
Stn.2	69.64 ± 17.92	7.55 ± 0.56	77.19 ± 18.48	283.28 ± 67.83
Stn.3	73.44 ± 21.49	7.71 ± 0.45	81.15 ± 21.94	297.83 ± 80.53
Stn.4	182.53 ± 43.51	5.36 ± 0.29	187.89 ± 43.81	689.55 ± 160.77
Stn.5	49.82 ± 7.66	5.39 ± 0.25	55.20 ± 7.80	202.60 ± 29.00
Mean ± SD	93.22 ± 21.56	5.92 ± 1.54	99.14 ± 21.93	363.85 ± 80.50

The carbon sequestration rate for the selected species was calculated as per the order *A. officinalis* (197.26 tha^{-1} year^{-1}) > *E. agallocha* (74.89 tha^{-1} year^{-1}) > *R. mucronata* (40.10 tha^{-1} year^{-1}) > *A. marina* (37.53 tha^{-1} year^{-1}) > *X. granatum* (6.10 tha^{-1} year^{-1}) > *P. coarctata* (3.14 tha^{-1} year^{-1}) for Bhitarkanika mangrove ecosystem. In case of Mahanadi mangrove ecosystem the carbon sequestration rate varied from *A. officinalis* (92.29 tha^{-1} year^{-1}) > *R. mucronata* (85.43 tha^{-1} year^{-1}) > *A. marina* (33.86 tha^{-1} year^{-1}) > *E. agallocha* (16.55 tha^{-1} year^{-1}) > *X. granatum* (2.85 tha^{-1} year^{-1}) > *P. coarctata* (2.06 tha^{-1} year^{-1}), respectively.

Conclusion

Estimation of C-stocks revealed a very high potential of mangroves in sequestering carbon. Assessment of biomass and carbon stocks in mangroves can increase their perceived conservation value through quantification of carbon storage potential that would attract investment for its protection and/or restoration under international emerging mechanism such as REDD + programme. Hence, financial incentives available for mangrove conservation based on carbon Payments for Ecosystem Services (PES) should be introduced and possible approaches for increasing forest biomass programmes should be undertaken. The present research suggests participatory plantation and restoration of mangrove forests for climate change mitigation measure.

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