Iranian Journal of Fisheries Sciences 19(4) 1657-1680 2020
DOI: 10.22092/ijfs.2020.121484

Estimation of biomass, carbon stocks and soil sequestration of Gowatr mangrove forests, Gulf of Oman

Savari A.[1]; Khaleghi M.[2*]; Safahieh A.R.[1]; Hamidian Pour M.[3]; Ghaemmaghami S.[1]

Received: January 2020 Accepted: March 2020

Abstract

The mangrove forest ecosystem is known to possess a variety of ecosystem services, including high rates of carbon sequestration, storage and mitigating climate change through reduced deforestation. This study was carried out in the mangrove forests of Gowatr Bay, Gulf of Oman during 2017-18 to quantify biomass and carbon stocks of all components of this forest, including live and dead trees, soil, pneumatophores, herbaceous and litter in three stations during post-monsoon and pre-monsoon. We examined that biomass, carbon stocks and soil carbon varied significantly with spatial locations ($p<0.05$) abut not with seasons ($p>0.05$). The mean of biomass and carbon stock were estimated 125.54±19.31 and 129.21±19.64 Mg ha^{-1}, and 48.48±7.51 and 49.9±7.5 Mg ha^{-1}, in post-monsoon and pre-monsoon, respectively. Also, Soil carbon was determined 227.1±11.86 and 227.3±11.71 Mg ha^{-1} in post-monsoon and pre-monsoon, respectively. A positive correlation was found between the vegetation biomass and soil organic carbon in post-monsoon (r=0.905) and pre-monsoon (r=0.914), indicating the role of vegetation in building soil organic carbon. The mean carbon stock value for the total area of mangroves in post-monsoon and pre-monsoon was extrapolated as 43.9 and 44.2 Kt of C, equivalent to 161.13 and 162.102 Kt of CO2, respectively. This data reveals that Gowatr mangroves store a substantial amount of atmospheric carbon, and therefore need to be conserved and sustainably managed to maintain as well as to increase carbon storage.

Keywords: *Avicennia marina*, Mangrove ecosystem, Sistan and Baluchestan province, Spatial and temporal variation.

1-Faculty of Marine Science and Oceanography, khorramshahr university of Marine Science and Technology Khorramshahr, Iran

2-Faculty of Marine Biology, Chabahar University of Maritime and Marine Sciences, Chabahar, Iran

3-Faculty of Geography and Environmental Planning, University of Sistan and Baluchestan, Zahedan, Iran

*Corresponding author's Email: matinkhaleghi@yahoo.com

Introduction

Mangrove forests are among the most carbon-rich habitats on the planet, and the protection of them for mitigation of greenhouse gases in the atmosphere as well as for multifaceted sustainable growth of ecosystem is of great scientific concern (Bindu *et al*., 2020). Although they occupy only a small fraction of the global coastal area, they are highly productive, with a net primary production rate of 92–280 Tg C/yr and they contribute up to 15% of the total carbon accumulation in marine sediments (Kusumaningtyasa *et al*., 2019). However, climate change and anthropogenic disturbances such as growing trend towards the need to use the land to meet human needs such as the rapid expansion of shrimp cultivation can strongly impair the ecosystem service of sequestering and storing carbon (Grellier *et al*., 2017; Jennerjahn *et al*., 2017; Pérez *et al*., 2017). So, this can cause rapid release of the greenhouse gas carbon dioxide into the earth’s atmosphere, intensifying negative impacts of global climate change (Hoelzer, 2014). The impacts are not only the loss of biodiversity and coastal protection but also the loss of the carbon sink function (Kusumaningtyasa *et al*., 2019). Mangrove ecosystem should be preserved in order to achieve sustainable ecological functions (Khairuddin *et al*., 2016). However, accurate, reliable, and timely information about the distribution and dynamics of mangrove forests of the world is not readily available (Giri, 2016).

Monitoring of biomass changes over time is essential in environmental and economic terms (Zhao *et al*., 2009). The change of biomass density is wholly related to natural sequences, forestry activities, harvesting and destruction and also severe natural effects of fire and climatic changes, so biomass density is significant as a useful tool in evaluation and monitoring of changes in the structure of each forest and is expressed the production power in the unit of surface or time and the number of available carbon stocks (Husch *et al*., 2003). Biomass and carbon stock are essential properties of the trees and play a vital role in the physiological and biological processes of plants. Estimation of biomass is useful in the evaluation and fluctuations of some biochemical elements and the amount of primary energy of forest (Navar, 2010). Recent findings suggest that mangroves annually sequester two to four times more carbon compared to mature tropical forests, and store three to four times more carbon per equivalent area than tropic forests (Giri, 2016). However, little is known regarding the carbon storages of these ecosystems, especially below-ground, so quantifying carbon stocks of live and dead trees and the soil is essential (Sitoe *et al*., 2014).

Studying on biomass and carbon stock in mangrove forests is done in other countries of the world, valuable studies have been conducted about them, especially in recent years.

Mitra *et al*. (2011) evaluated standing biomass and carbon storage of above-ground structures in dominant mangrove trees in the Indian Sundarbans. Camacho *et al*. (2011) investigated tree biomass and carbon stock of a community-managed mangrove forest in Bohol, Philippines. Adame *et al*. (2013) studied carbon stocks of tropical coastal wetlands within the karstic landscape of the Mexican Caribbean. Abino *et al.* (2014) assessed biomass and carbon stock of a natural mangrove forest in Palawan, Philippines. Sitoe *et al.* (2014) measured biomass and carbon stocks of Sofala Bay mangrove forests. Kauffman *et al.* (2014) estimated carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. Patil *et al.* (2014) estimated carbon stocks in *Avicennia marina* stand in the Thane creek of Mumbai city, which lies along the west coast of India using allometry, CHN analysis, and GIS Methods. Joshi and Ghose (2014) investigated Community structure, species diversity and above-ground biomass of Sundarban mangrove swamps. Adame *et al*. (2015) examined carbon stocks and soil sequestration rates of tropical riverine wetlands, the Encrucijada Biosphere Reserve (LEBR) is located in Chiapas, in the south Pacific coast of Mexico. Sahu *et al*. (2016) measured carbon stocks in natural and planted mangrove forests of Mahanadi mangrove Wetland, East Coast of India.

Quantitative changes in mangrove carbon pools and alterations in forest composition are important measures for monitoring health of mangroves, as well as to analyze trends of global climate change and consequences for human population (Hoelzer, 2014). As most countries do not have sufficient information to include mangroves in their national reporting to the United Nations, it is important to generate country- or region-specific data on carbon stocks and emission factors from various land-use activities in mangroves (Murdiyarso *et al*., 2015).

We evaluated biomass and carbon stock in the study area for the first time. The accurate assessment of biomass is essential for sustainable management of forests and understanding the role of forests as a source of carbon excretion.
The study area has significant importance due to intact, unknown and valuable ecologic condition (one of the most sensitive marine areas and part of the Gando protected area- under management supervision of Department of Environment: DoE). On the other hand, part of the area is influenced by shrimp culture site, which should be determined its impact on the biomass and carbon stocks of mangroves forests. Developing Makran coasts is one of the region's future challenges. This region will soon be faced with environmental problems such as greenhouse gases emissions. Therefore awareness of the role of mangroves forests in excretion and reduction of CO_2 and planning for the development and expansion of these forests by sowing and prevention of their destruction is more important than before.

The first aim of this study, is to quantify biomass and carbon stock of all components of Gowatr mangrove forests, including live and dead trees, pneumatophores, herbaceous, litter and soil in three stations during post-monsoon and pre-monsoon, to investigate effect of spatial and temporal variations. The second purpose of this study is to introduce this area as an important ecosystem for carbon sink and diminish of destructive effects of climate change and emission of greenhouse gases.

Materials and methods

Study area

The present investigation was accomplished in mangrove forests of Gowatr Creek-Bay located at Chabahar port of Sistan and Baluchestan Province, southeast of Iran (Pakistan border). Gowatr bay (25°01'- 25°12'N and 61°25'- 61°46' E) is one of the most valuable habitats rich in aquatic organisms. The flow of two important rivers (Bahu Kalat in Iran and Nahr Dasht in Pakistan) to this bay and the entrance of Dashtiari Region's flood streams have prepared a habitat for different kinds of aquatic organisms, birds and vegetation of plants. This bay has two parts consisting of Gowatr and Hur-e-Bahu (Moradi *et al*., 2019). The Gowatr mangroves are 159.33 hectares (Erfani *et al*., 2012). Mangroves communities in the studied area are purified from the tree and shrub species of *Avicennia marina*.

Study design

Sampling was carried out twice, pre-monsoon and post-monsoon (2017-2018) during high tide. In the study area, three stations were selected as intensive monitoring: station 1 in the high intertidal zone, near to the shrimp culture farms; the station 2 in the middle intertidal zone, far from of human activities; and the station 3 in the low intertidal zone, close to the sea and fishing wharf. Each station consists of three transects, and there are three circular plots in each transect (9 transects and 27 plots) (Figure 1).

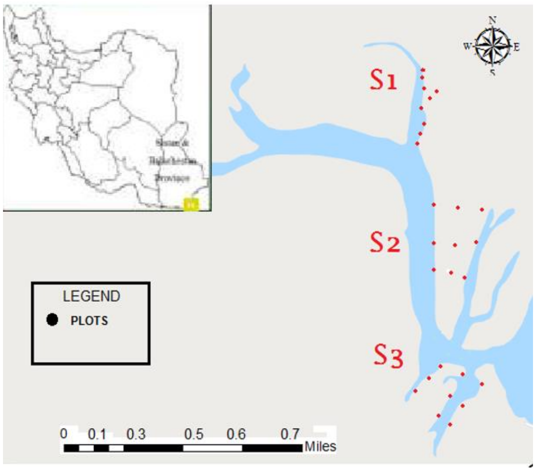

Figure 1: Location of the study site and sampling stations in the Gowatr mangrove forests.

ArcView GIS 10.5 was used to map the study area, a total of 27 sampling points were generated and their geographical coordinates registered (Table 1). In the field, the sampling plots were located using the Global Positioning System (GPS) Model Garmin VISTA HCX. Within each plot, we estimated the whole-ecosystem carbon stocks based on methodologies recommended by other studies (Donato *et al*., 2011; Kauffman and Donato, 2012; Kauffman *et al*., 2014; Sitoe *et al*., 2014; Adame *et al*., 2015). The nested plots are designed in such a way that the trees (live and dead) are measured in the 7 m radius circular plots. Pneumatophores, herbaceous and litter samples are collected by quadrat 0.5×0.5 m per subplot. Soil samples of depth, bulk density and carbon concentration were collected at prescribed depths near the center of each subplot.

Table 1: Geographical coordinates of the study site and sampling stations in the Gowatr mangrove forests.

Stations	X	Y	Z
S1 T1 P1	347991.641881427	2786496.63596227	4
S1 T1 P2	348024.167462304	2786600.88751323	4
S1 T1 P3	348059.323073503	2786690.03263636	3
S1 T2 P1	348037.207845480	2786340.43210176	3
S1 T2 P2	348112.448294821	2786408.82050980	4
S1 T2 P3	348193.339491597	2786456.83824301	3
S1 T3 P1	348003.418872764	2786048.50127178	2
S1 T3 P2	348050.374195791	2786166.12974093	2
S1 T3 P3	348102.683955061	2786236.92888543	4
S2 T1 P1	348051.645903692	2785754.72864807	2
S2 T1 P2	348206.164794141	2785751.46047324	5
S2 T1 P3	348383.964741012	2785751.93388230	4
S2 T2 P1	348059.694287993	2785498.32954504	3
S2 T2 P2	348188.155538896	2785493.19931181	6
S2 T2 P3	348331.461600000	2785488.51974208	4
S2 T3 P1	348051.120065750	2785282.73224016	3
S2 T3 P2	348152.167304480	2785279.75495679	6
S2 T3 P3	348235.655795409	2785284.05174461	5
S3 T1 P1	347852.003123231	2784255.41992702	6
S3 T1 P2	347934.395480942	2784361.26639348	6
S3 T1 P3	348029.221498606	2784427.28163534	6
S3 T2 P1	348166.817898333	2784361.74169831	6
S3 T2 P2	348087.264	2784209.093	6
S3 T2 P3	348029.151016070	2784120.81984827	6
S3 T3 P1	348138.430168526	2784051.90452892	6
S3 T3 P2	348195.005888776	2784178.04134893	6
S3 T3 P3	348284.905425105	2784254.26731928	6

Live tree biomass estimation

The total live tree biomass was estimated by adding above-ground biomass and below-ground biomass or root (Kauffman and Donato, 2012).

Above ground biomass estimation

The above-ground biomass was estimated by adding stem, branch and leaf biomass (Kauffman and Donato, 2012).

The stem volume of the tree was estimated using Newton’s formula (Patil *et al*., 2014). Specific gravity (G) of the wood was estimated taking the stem cores, by boring 7.5cm deep with mechanized corer. Then, was oven-dried at 70°C overnight in hot air oven in order to remove moisture content and was calculated specific gravity by divided mass to volume (Mitra and Zaman, 2014). This was converted into stem biomass (BS) as per the expression (Mitra and Zaman, 2014; Patil *et al*., 2014):

$BS=G.V$

The total number of branches irrespective of size was counted on each of the sample trees. These branches were categorized based on basal diameter into three groups, viz. <6cm, 6–10cm and >10cm. The branches were cut using a handsaw, and the leaves on the branches were removed by hand. The branches were oven-dried at 70°C overnight in hot air oven to remove moisture content if any present in the branches. The dry weight of two branches from each size group was recorded separately using the equation of Chidumaya (1990) as per the expression (Mitra and Zaman, 2014; Sitoe *et al*., 2014):

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

where B_{db} is the dry branch biomass per tree, n_i the number of branches in the ith branch group, b_{wi} the average weight of branches in the ith group and i =1, 2, 3, ..., n are the branch groups. The branch biomass of individual tree was finally multiplied with the number of trees of the species in all the plots for each station.

All leaves from cropped branches (three of each size group) of each individual tree were removed and oven-dried at 70°, and dry weight was estimated. The leaf biomass of each tree was then calculated by multiplying the average biomass of the leaves per branch with the number of branches in that tree using the below expression (Mitra and Zaman, 2014):

$L_{db} = n_1 \times Lw_1 + n_2 \times Lw_2 + \cdot\cdot\cdot + n_i \times Lw_i$

Where L_{db} is the dry leaf biomass, n is the number of branches of each tree in the ith branch group, Lw is the average dry weight of leaves removed from the branches.

Root biomass estimation

Since there is no possibility of taking the ground root due to limits of the protected area, we estimated root biomass using the allometric equation spread by Dharmawan and Siregar (2008) for *A. marina* species. Since the species are the same, the use of this equation is so much safe.

$W_r = 0/1682 \times (DBH)^{1/7939}$

Where W_r is the biomass of below-ground or root (Kg), DBH is the diameter at breast height (cm).

Dead tree biomass estimation

Each dead tree was assigned to one of three decay status (Adame *et al*., 2015): Status 1, dead trees without leaves; Status 2, dead trees without secondary branches; and Status 3, dead trees without primary or secondary branches. In this study, the dead trees were from the first class. For dead trees of Status 1, biomass was calculated as the total dry biomass minus the biomass of leaves (Adame *et al*., 2015).

Pneumatophores biomass estimation

Aerial roots (pneumatophores) of *A. marina* were sampled by counting the numbers in the square 50×50 cm micro-plots. After counting all pneumatophores in the micro-plot, a sample was taken for oven-dry weight determination. The mean amount of oven-dried mass of the collected samples is multiplied by the number of pneumatophores and must be scaled to a per-hectare estimate (Kauffman and Donato, 2012; Sitoe *et al.*, 2014).

Herbaceous and litter biomass estimation

Herbaceous and litter samples were taken in square 50×50 cm micro-plots located 2 m apart from the main plot center (Murdiyarso *et al.*, 2009; Sitoe *et al.*, 2014). In each micro-plot, all above-ground herbaceous vegetation was collected and weighted fresh, and samples for each component were taken for the oven-dry weight estimation in the laboratory (Kauffman and Donato, 2012; Sitoe *et al.*, 2014). The total oven-dry mass of the subplot area (50×50 cm) must be scaled to a per-hectare estimate (Kauffman and Donato, 2012; Sitoe *et al.*, 2014).

Carbon estimation

Direct estimation of carbon percent in the all of the components were done by Vario MACRO CHN element analyzer, after grinding and random mixing the oven-dried stems, branches and leaves (Adame *et al.*, 2015).

Soil carbon pools estimation

Soil sampling

Sediments were collected with a 1m long semi-cylindrical auger. The sediment corer was inserted vertically into the sediment, twisted several times to cut through any fine roots, and then gently pulled out. Sediments were sampled only down to 1m depth. After the sediment was successfully extracted, it was sampled in 0–30, 30–60 and 60–100 cm intervals collected into plastic bags and then preserved in a cool box before the samples were transferred to the laboratory. Undisturbed samples for bulk density estimation and disturbed samples for carbon content estimation were collected from each of the three depths. Bulk density for undisturbed soil samples was determined by dividing oven-dried samples (at 70 °C for 48 h or until constant weight) by the volume of the augur ($\pi r^2 h$).

$$soil\ bulk\ density\ \left(\frac{g}{cm^3}\right) = \frac{oven-dry\ sample\ mass(g)}{sample\ volum\ (cm^3)}$$

Soil carbon content was estimated in the laboratory using the Walkley-Black method (Sahu *et al.*, 2016). The soil carbon (Mg ha^{-1}) per sampled depth interval was calculated using following equation as suggested by several authors (Sahu *et al.*, 2016).

Soil Carbon (Mg ha^{-1})=bulk density (g cm^{-3})×soil depth interval (cm)× %Carbon

Soil carbon pools

The total soil carbon pool is then determined by summing the carbon mass of each of the sampled soil depths (Kauffman and Donato, 2012).

Total ecosystem carbon pool and carbon dioxide sequestration

The total carbon stock or pool was estimated by adding all of the component pools. First, each component pool was averaged across all plots (e.g. trees, soil, etc.). These average values were then summed to obtain the total (Kauffman *et al*., 2014; Sahu *et al*., 2016).

$$\text{Total carbon of project area } (Mg) = \text{Total carbon} \left(\frac{Mg}{ha}\right) * \text{Area } (ha)$$

The total carbon stock can be converted to CO_2 by multiplying carbon stock by 3.67 (Kauffman and Donato, 2012; Sahu *et al*., 2016).

Physicochemical parameters of sediment

Soil samples were analysed for available nitrogen and available phosphorus. Available nitrogen and available phosphorus were estimated by Kjeldahl and Olsen methods, respectively (Sahu *et al*., 2016).

Statistical analysis

Normality was assessed using Shapiro–Wilk tests. Data on biomass and carbon stock in pre-monsoon and post-monsoon (T-Test) and in different stations (One-Way ANOVA) were statistically analysed. Differences in soil C concentrations by depth and stations in pre-monsoon and post-monsoon were tested with Kruskal-Wallis. A Pearson's correlation study was carried out between vegetation biomass and different physico-chemical. Analyses were performed using software SPSS 23.0 and excel 2016.

Results

Live tree biomass estimation

The live tree biomass varied significantly with spatial locations ($p<0.05$) but not with seasons ($p>0.05$). Mangrove ecosystem had a mean of total live tree biomass of 92.66±1 Mg ha^{-1} in post-monsoon and a mean of total live tree biomass of 95.2±17.4 Mg ha^{-1} in pre-monsoon. The highest biomass in post-monsoon and pre-monsoon can be attributed to station 2 (213.25±7.34 Mg/ha and 217.19±8.37 Mg ha^{-1}, respectively), followed by station 3 (37.87±7.05 Mg ha^{-1} and 39.43±7.17 Mg ha^{-1}, respectively) and station 1 (26.85±5.55 Mg ha^{-1} and 28.97±5.89 Mg ha^{-1}, respectively).

Fig. 2 provides the summary of total live tree biomass of 9 sampling transects in the Gowatr mangrove forests in post-monsoon and pre-monsoon.

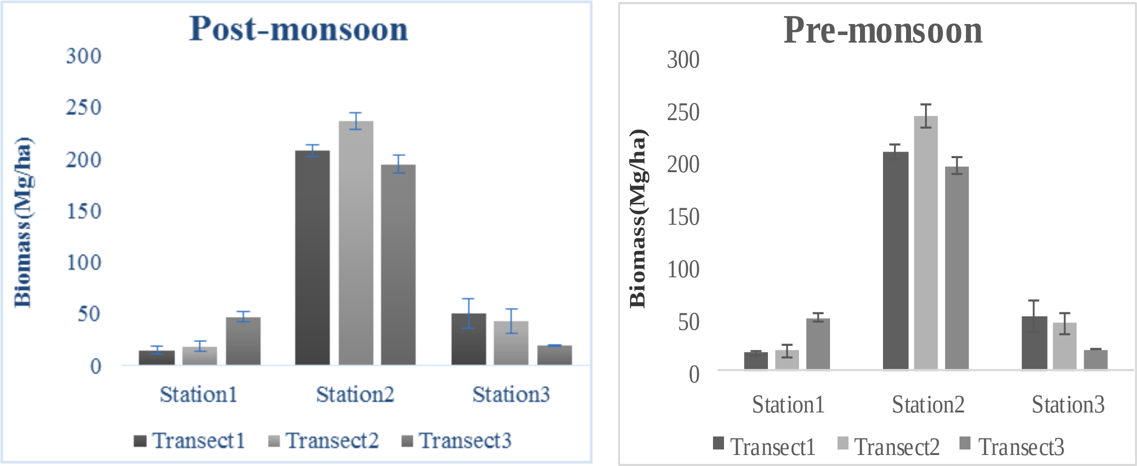

Figure 2: Total live tree biomass of *A.marina* in the Gowatr mangrove forests during post-monsoon and pre-monsoon.

Above-ground biomass estimation

Mangrove ecosystem had a mean of AGB biomass of 28.09±4.52 Mg ha^{-1} in post-monsoon and a mean of total live tree biomass of 28.51±4.49 Mg ha^{-1} in pre-monsoon. The highest biomass in post-monsoon and pre-monsoon can be attributed to station 2 (59.66±1.91 Mg ha^{-1} and 59.89±1.87 Mg ha^{-1}, respectively), followed by station 3 (14.37±2.16 Mg ha^{-1} and 14.73±2.17 Mg ha^{-1}, respectively) and station 1 (10.25±1.61 Mg ha^{-1} and 10.92±1.74 Mg ha^{-1}, respectively).

Root biomass estimation

Mangrove ecosystem had a mean of root biomass of 64.57±12.65 Mg ha^{-1} in post-monsoon and a mean of total live tree biomass of 66.69±12.93 Mg ha^{-1} in pre-monsoon. The highest biomass in post-monsoon and pre-monsoon can be attributed to station 2 (153.6±5.52 Mg ha^{-1} and 157.3±6.63 Mg ha^{-1}, respectively), followed by station 3 (23.51±4.89 Mg ha^{-1} and 24.71±5.01 Mg ha^{-1}, respectively) and station 1 (16.6±4.05 and 18.04±0.26 Mg ha^{-1}, respectively).

The above-ground and below-ground biomass ratio (T/R ratio) for the present study was an average of 0.43 in post-monsoon and pre-monsoon (Fig. 3).

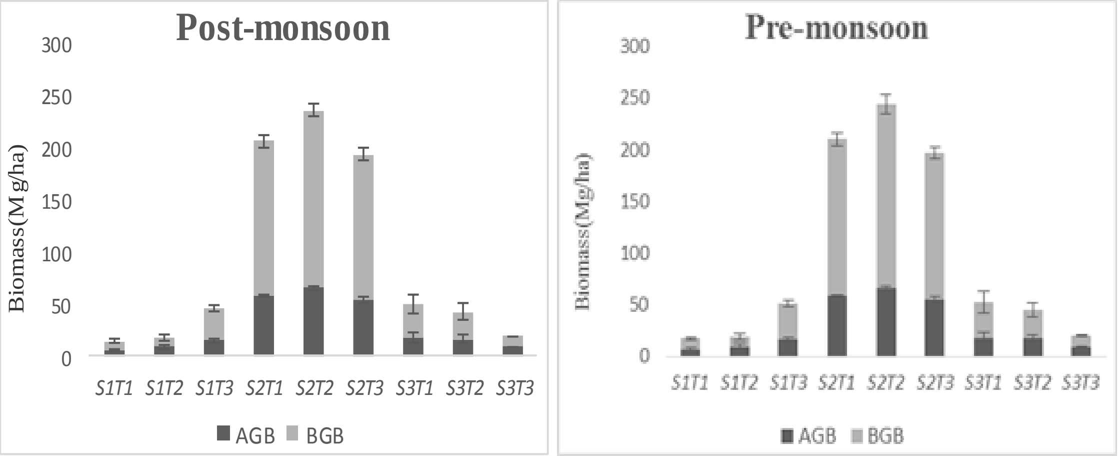

Figure 3: AGB and BGB of *A.marina* in the Gowatr mangrove forests during post-monsoon and pre-monsoon.

Dead tree biomass estimation

Standing dead trees were so less included in the tree carbon stocks estimations. The dead trees observed in 2 transect of stations 1 and 3. The total dead tree biomass was also estimated by adding above-ground biomass and below-ground biomass. Mangrove ecosystem had a mean of total dead tree biomass of 3.24 ± 0.97 Mg ha^{-1} in post-monsoon and pre-monsoon. The overall mean AGB of a dead tree was 1.06±0.3 Mg ha^{-1}, and the overall mean BGB of a dead tree was 2.17±0.68 Mg ha^{-1} in post-monsoon and pre-monsoon.

Pneumatophores biomass estimation

Mangrove ecosystem had a mean of pneumatophore biomass of 17.78±2.4 Mg ha^{-1} in post-monsoon and a mean of pneumatophore biomass of 17.82±2.41 Mg ha^{-1} in pre-monsoon. The highest biomass in post-monsoon and pre-monsoon can be attributed to station 2 (31.53±1.93±5.52 Mg ha^{-1} and 31.62±1.95 Mg ha^{-1}, respectively), followed by station 3 (11.16±3.28 Mg ha^{-1} and 11.14±3.29 Mg ha^{-1}, respectively) and station 1 (10.65±2.49 Mg ha^{-1} and 10.7±1.08 Mg ha^{-1}, respectively). Fig. 4 provides the summary of pneumatophore biomass of 9 sampling transects in the Gowatr mangrove forests in post-monsoon and pre-monsoon.

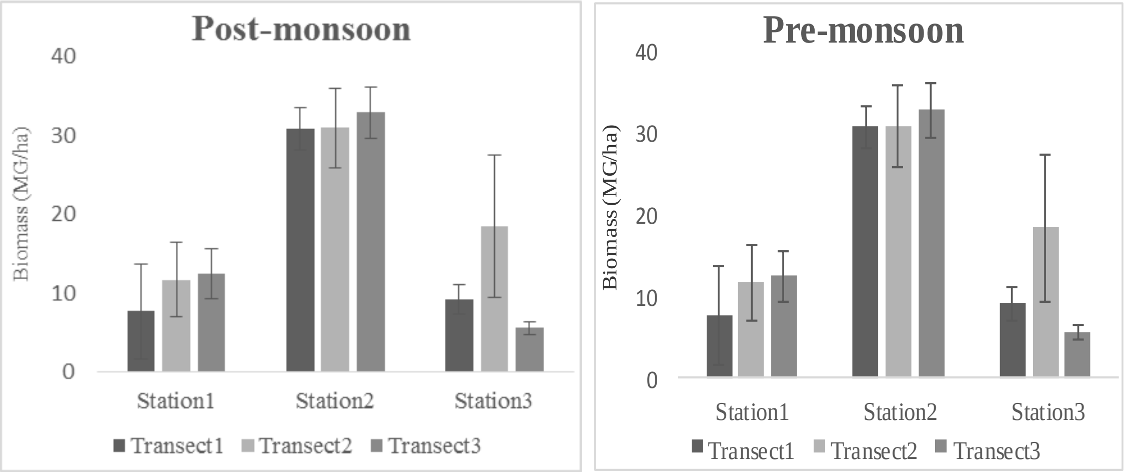

Figure 4: Pneumatophore biomass of *A.marina* in the Gowatr mangrove forests during post-monsoon and pre-monsoon.

Herbaceous and litter biomass estimation

Mangrove ecosystem had a mean of herbaceous and litter biomass of 12±0.92 Mg ha^{-1} in post-monsoon and a mean of herbaceous and litter biomass of 12.96±0.92 Mg ha^{-1} in pre-monsoon. The highest biomass in post-monsoon and pre-monsoon can be attributed to station 2 (17.58±0.26 Mg ha^{-1} and 18.22±0.18 Mg ha^{-1}, respectively), followed by station 3 (11.07±1.001 Mg ha^{-1} and 12.04±1.1 Mg ha^{-1}, respectively) and station 1 (7.34±1.34 Mg ha^{-1} and 8.61±1.08 Mg ha^{-1}, respectively). Figure 5 provides the summary of pneumatophore biomass of 9 sampling transects in the Gowatr mangrove forests in post-monsoon and pre-monsoon.

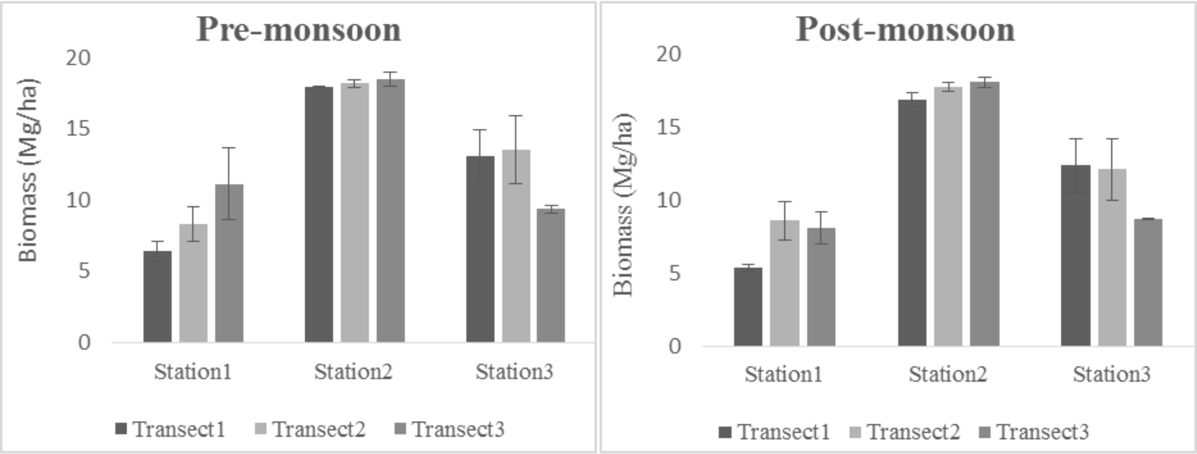

Figure 5: Herbaceous and litter biomass of *A.marina* in the Gowatr mangrove forests during post-monsoon and pre-monsoon.

Carbon stock estimation

Vegetation carbon stocks were significantly different among three stations of mangroves ($p<0.05$), while were not significantly different during post-monsoon and pre-monsoon ($p>0.05$). Mangrove ecosystem had a total mean plant carbon stock of

48.48±7.51 Mg ha^{-1} in post-monsoon and total mean carbon stock of 49.9±7.5 Mg ha^{-1} in pre-monsoon. The highest plant carbon stock can be attributed to dense stem density of station 2 (101.39±2.79 Mg ha^{-1} and 102.52±3.12 Mg ha^{-1}), followed by station 3 (25.14±3.08 Mg ha^{-1} and 27.05±3.12 Mg ha^{-1}) and station 1 (18.92±2.24 Mg ha^{-1} and 20.18±2.69 Mg ha^{-1}) during post-monsoon and pre-monsoon, respectively. Figure 6 shows the summary of carbon stocks of a different component in the Gowatr mangrove forests during post-monsoon and pre-monsoon.

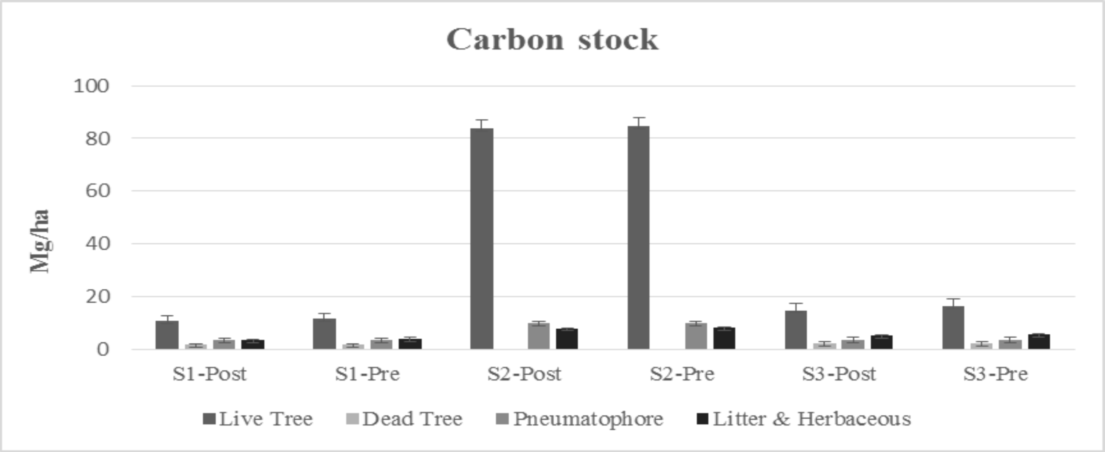

Figure 6: Seasonal and spatial variation in carbon stock (Mg ha^{-1}) of *A.marina* in the Gowatr mangrove forests during post-monsoon and pre-monsoon.

Soil carbon pools estimation

The soil carbon (C-soil) varied significantly with spatial locations ($p<0.05$) but not with seasons ($p>0.05$). The highest C-soil in post-monsoon and pre-monsoon can be attributed to station 2 (296.36±6.7 Mg ha^{-1} and 295.73±7.5 Mg ha^{-1}, respectively), followed by station 3 (218.8±15.51 Mg ha^{-1} and 219.82±14.87 Mg ha^{-1}, respectively) and station 1 (166.06±3.63 Mg ha^{-1} and 166.45±3 Mg ha^{-1}, respectively) (Fig. 7).

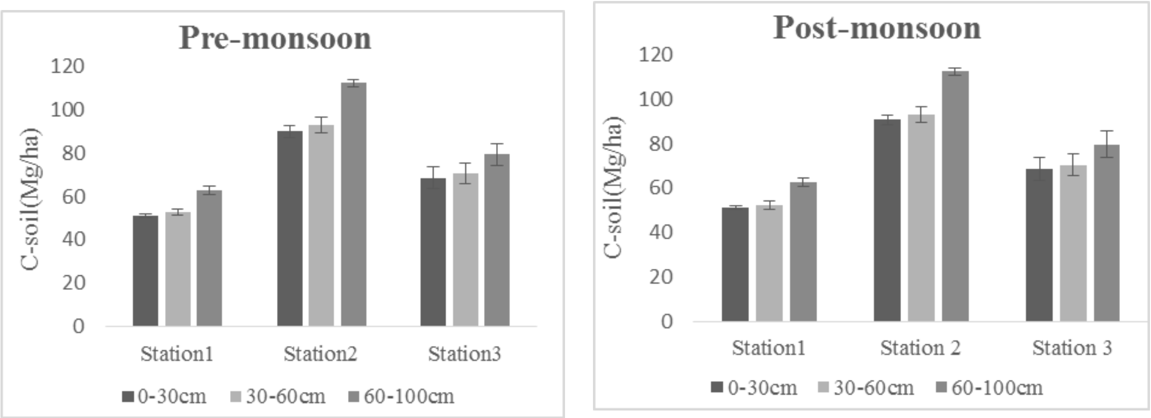

Figure 7: Soil carbon content in the various depths of different stations during post-monsoon and pre-monsoon in the Gowatr mangrove forests.

C-soil stocks were also significantly different among depths ($p<0.05$). The highest C-soil in post-monsoon and pre-monsoon can be attributed to 60-100 cm (84.88±4.56 Mg ha^{-1} and 84.98±4.4 Mg ha^{-1}, respectively), followed by 30-60 cm (72±3.85 Mg ha^{-1} and 72.34±3.81 Mg ha^{-1}, respectively) and 0-30 cm (70.204±3.68 Mg ha^{-1} and 69.97±3.66 Mg ha^{-1}, respectively). Figure 8 presents the overview of C-soil in 9 sampling transects in the Gowatr mangrove forests in post-monsoon and pre-monsoon.

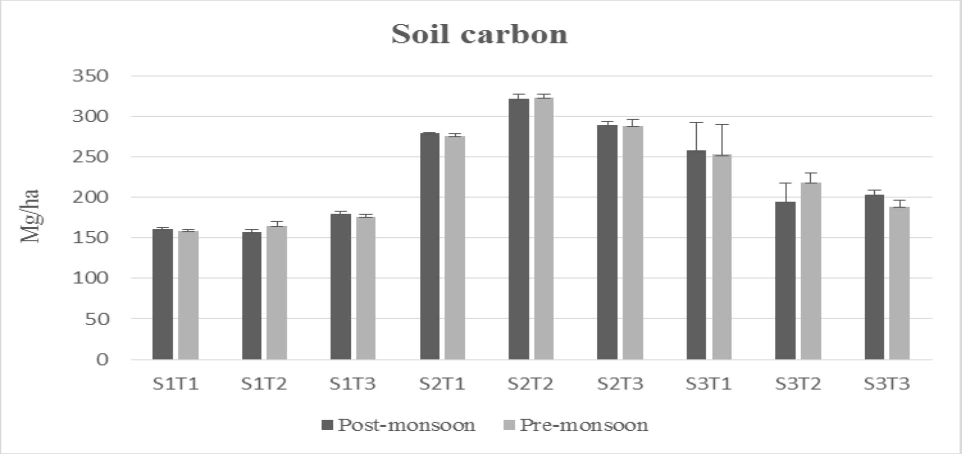

Figure 8: Soil carbon content in the different stations during post-monsoon and pre-monsoon in the Gowatr mangrove forests.

The estimated mean soil C-stock in post-monsoon and pre-monsoon was 227.1±11.86 Mg-C ha^{-1} and 227.3±11.71 Mg-C ha^{-1}, respectively and was not significantly different during post-monsoon and pre-monsoon ($P>0.05$).

Total ecosystem carbon pool and carbon dioxide sequestration

The total carbon stock of the Gowatr mangrove forests was estimated to be 275.557 Mg ha^{-1} and 277.22 Mg ha^{-1} in post-monsoon and pre-monsoon, respectively, around 82% of which was stored in the soil.

The total mean carbon stock in station 2 (397.75 Mg ha^{-1} and 398.25 Mg ha^{-1}) was higher than station 3 (243.94 Mg ha^{-1} and 246.87 Mg ha^{-1}) and station 1 (184.98 Mg ha^{-1} and 186.62 Mg ha^{-1}) in post-monsoon and pre-monsoon, respectively.

The total area of mangrove forest cover in Gowatr was 159.33 hectares (Erfani *et al*., 2012). We extrapolated the mean carbon stock value for the entire area of mangroves and estimated a substantial sink of 43.9 Kt and 44.2 Kt of C, which was equivalent to 161.13 and 162.102 Kt of CO_2 in post-monsoon and pre-monsoon, respectively.

Physico-chemical parameters of sediment

A Pearson's correlation study was carried out between vegetation biomass and physico-chemical parameters to determine the sensitivity of C-Soil response to the change of vegetation biomass. As shown in Table 2, a significant positive correlation was found between C-soil with total plant biomass and available P, both in the post-monsoon and pre-monsoon. There was a significant positive correlation between total plant biomass with available N and available P in the post-monsoon and pre-monsoon. There was also a significant positive correlation between available P with available N in the post-monsoon and pre-monsoon.

Table 2: Pearson's correlation between different physico-chemical parameters and plant biomass in the Gowatr mangrove forests during post-monsoon and pre-monsoon.

Post-monsoon / Pre-monsoon	Available N	Available P	Total Plant Biomass	Soil carbon
Available N	1.00	0.717*	0.847*	0.801**
Available P	0.948**	1.00	0.971**	0.894*
Total plant biomass	0.918**	0.94**	1.00	0.905**
Soil carbon	0.554	0.909**	0.914**	1.00

*Correlation is significant at 0.05 level (two-tailed). **Correlation is significant at 0.01.

Discussion

Biomass

The biomass varied significantly with spatial locations but not with seasons. Variation may be attributed to different environmental conditions to which these areas are exposed to such higher siltation and salinity in a different location. The highest biomass can be attributed to dense stem density of station 2, followed by station 3 and station 1 in post-monsoon and pre-monsoon.

Station 1 had the lowest amount of biomass. Shrimp farms in western Gowatr bay are one of the threatening factors in the station, due to input water channel of shrimp farm that dams water supply of forests and causing drought of this part of the forest. The significant growth of *A. marina* against the environmental stresses will undoubtedly improve their CO_2 sequestration ability. The aboveground biomass and carbon storage is directly related to environmental stress, viz., hypersalinity, due to lack of freshwater inflow (Prasanna *et al*., 2017).

Station 3 had the lower biomass than station 2, which could be due to close proximity to the fishing wharf and related human activities that are considered to be major factors structuring and modifying mangrove communities. These disturbances include pollution, harvesting and cutting of trees to feed the trap, charcoal and wood products, etc.

In this study, the total mean biomass is almost comparable to medium trees of Dominican Republic mangroves (Kauffman *et al*., 2014).

The overall mean AGB in of live tree was not significantly different as Mitra *et al*. (2011) in Sandrabans mangroves. The figures of biomass in this study were in the range estimated by Sitoe *et al*. (2014) in Sofala Bay and Murdiyarso *et al*. (2009) in Indonesia who found that the aerial part of the trees and the roots represented the significant proportion of the plant carbon in forests. We found in this study that biomass of dead tree, herbaceous vegetation, and litter was typically less than 12% of the plant carbon content as Sitoe *et al*. (2014) and Raffli *et al*. (2007) in Aceh, Indonesia. AGB in this study was lower than those for Mahanadi Mangrove Wetland in India (Sahu *et al*., 2016), Sundarbans (Joshi and Ghose, 2014), Java in Indonesia (Dharmawan and Siregar, 2008) and China (Liao *et al*., 2004) and was more than those for *A. marina* forest at the Chishui River Estuary, Tainan County, Taiwan (Kuei, 2008), Karankadu mangrove swamp and Palk Bay, southeast coast of India (Prasanna *et al*., 2017) and plantation of *A. marina* in the Kalisthan area of Henry Island in Indian Sundarbans (Manna *et al*., 2014). Biomass varied along latitude and was also determined by various factors such as density, tree height, species composition and diversity, community structure, growth forms, age of the plant community and geographical location and ecology (Sahu *et al*., 2016). Also, differences in biomass content in different research sites, being influenced by its management model and climatic factors such as temperature, solar radiation intensity and precipitation level of the location. In addition, conversion of mangrove forests into fish ponds had a huge impact on biomass (Istomo *et al*., 2017).

The values of mean BGB in the present study showed comparatively higher than mangrove forests in Java in Indonesia (Dharmawan and Siregar, 2008), Northern Vietnam (Nguyen *et al*. 2009), Tamil Nadu in India (Camacho *et al*., 2011) and southern China (Chen *et al*., 2012). But, in the present study BGB value was comparable to Sofala Bay mangrove forests (Sitoe *et al*., 2014) and lower than tall mangrove trees in Dominican Republic (Kauffman *et al*., 2014). In terms of biomass allocation in this study, AGB of the live tree represented 30% and 70% of the total and root accounts in post-monsoon and pre-monsoon. In this study, we found a significant correlation between above-ground and below-ground tree biomass in post-monsoon and pre-monsoon (Pearson's r=0.997 and Pearson's r=0.995, respectively), this showed that nutrient uptake by roots plays an essential role in plant growth.

Carbon stock

Estimation of carbon is hardly possible, hence in many studies, scientist assumed the range of carbon value to be 50% of dry biomass (Prasanna *et al*., 2017), but in this study, estimation of carbon was based on CHN analysis.

Vegetation C stocks were significantly different among three stations of mangroves ($p<0.05$), while they were not significantly different during post-monsoon and pre-monsoon ($p>0.05$).

The carbon stock measured in the three study sites were still higher when compared to mangrove biomass found in Northern Vietnam (Nguyen *et al*. 2009), southern China (Chen *et al*., 2012) and Tamil Nadu in India (Camacho *et al*., 2011) and Karankadu mangrove swamp and Palk Bay, southeast coast of India (Prasanna *et al*., 2017). But, carbon stock value was much lower than that in mangrove forests in Palawan in Philippines (Abino *et al*., 2014), Quanzhou Bay Estuarine Wetland in China (Fu and Wu, 2011) and Bohol in Philippines (Camacho *et al*., 2011), Sundarbans in Indian (Mitra *et al*., 2011), Yap (Kauffman *et al*., 2011) and Purwakarta, West Java in Indonesia.

The overall mean AGCS of a live tree was varied with the higher biomass observed in stations with a high density of adult trees of *A. marina* to lower biomass in stations with fewer trees.

The highest proportion of carbon was found in the below-ground carbon stock of live tree (%69 of the plant biomass). So, carbon is more concentrated in live trees. Studies including all plant components are scarce, as most have limited their focus to above-ground live tree biomass, not including roots, dead trees, and litter. This study showed that these neglected components could comprise more than half of the plant component biomass and carbon in mangrove ecosystems.

The above-ground and below-ground biomass ratio (T/R ratio) for the present study were an average of 0.43 in post-monsoon and pre-monsoon. It is a general feature of mangrove forests to have lower T/R ratio than upland forests for better adaptation to stand upright in wet and soft mud conditions.

In the present study, we found a significant correlation between above-ground and below-ground tree carbon in post-monsoon and pre-monsoon (Pearson's r=0.997 and 0.993, respectively), that also showed the effective role of the root in nutrient uptake and plant growth.

Soil carbon

A variation of soil carbon (C-soil) in different stations were observed in this study ($p<0.05$), where the majority of carbon stock was stored in the sediment, which is in accordance with other studies (Donato *et al*., 2011; Kauffman *et al*., 2011; Adame *et al*., 2013; Murdiyarso *et al*., 2015; Kusumaningtyasa *et al*., 2019).

Higher C-soil in station 2 is due to higher biomass. Previous studies (Wang *et al*., 2013; Patil *et al*., 2014) suggested organic carbon content and density in the upper layers (down to 100cm) increasing along with biomass growth, as primary production increased and input of leaf litter and dead roots also increased. High vegetation density also can prevent resuspension by water motion and trap particles in the forest floor. On the other hand, mangroves in the upper estuary have been grown in a relatively stable environment that permitted carbon to be buried and forests to develop into a mature state. Besides, station 2 received high sediment inputs from the sea, with a large portion of mineral sediment diluting the organic carbon content.

Lower C-soil in station 3 rather than station 2 was probably grown in the low intertidal zone that was frequently flushed by tides and is exposed to frequent changes in hydrology, sedimentology and were directly struck by tropical storms, which inhibited the accumulation of autochthonous organic matter. As a result, mangroves in the lower estuary are a mosaic of young and old forests, some of them with productivities and C-soil similar to those in the upper estuary, but others with low productivity and C-soil, and thus carbon stocks (Adame *et al*., 2015).

Lowest C-soil in station 1 reflected the dilution with a mineral matter which was generally high in riverine suspended matter and soils (Kusumaningtyasa *et al*., 2019; Yuwono *et al*., 2007). Moreover, wood density was a major predictor of stored carbon in wood biomass and could explain the low values of carbon buried in the soil (Flores and Coomes, 2011; Adame *et al*., 2015), and thus, the low carbon stocks in station 1. So, the low sediment carbon in the station 1 was probably the result (i) of a lower tree density and low primary production, (ii) of a dilution with allochthonous mineral sediment input from the Bahu-Kalat River, and (iii) due to the lower carbon wood content that was buried in the soil. This was mainly because the estuarine mangroves receive large allochthonous inputs from river discharge, which was, to a large extent mineral sediment diluting the carbon content. However, depending on the proportion of mineral sediment, this dilution may also result in lower carbon stocks (Kusumaningtyasa *et al*., 2019). Excess sediment input can reduce seedling numbers and bury aerial roots, thus preventing mangrove growth (Sidik *et al*., 2016), and being aggravated with deforestation practices, these disturbances can inhibit mangrove forests from reaching a mature state.

C-soil stocks were also significantly different among depths ($p<0.05$). The estimated mean soil carbon stock was comparable to C-soil in 1 m sediment depth in Segara Anakan Lagoon in Indonesia (Kusumaningtyasa *et al*., 2019). However, C-soil value in the present study was more in comparison to that reported at 30 cm depth in India (Sahu *et al*., 2016) and at 1m depth of Chiapas, in the south Pacific coast of Mexico (Adame *et al*., 2015) and Kongsi Island of Indonesia (Kusumaningtyasa *et al*., 2019), but, it' s much less than C-soil value in the Dominican Republic (Kauffman *et al*., 2014). Figs. 2 and 3 show C-soil stored in the sediment as estimated in this study.

According to Sitoe *et al*. (2014), the reduction of carbon concentration with depth was more common in terrestrial forests due to high concentrations of biological activity, particularly litter deposition and decomposition near the soil surface, while deposition of sediments from the river stream constitutes an important source of organic matter in mangrove soils. The carbon soil of mangroves generally changes much more slowly with depth than in the upland forest (Sitoe *et al*., 2014). Variation of organic carbon in the sediment is the result of changes in deposition from multiple sources and the decomposition of organic matter by microbes (Bouillon *et al*., 2008; Kusumaningtyasa *et al*., 2019). The increase of C-soil with depth indicates the predominance of autochthonous mangrove organic matter in the sediments. The lower concentrations at the surface might be caused by an admixture of allochthonous sediment input by the river. Local factors such as tidal amplitude, elevation, landform and wave action are the important factors controlling organic carbon distribution and deposition in the intertidal mangroves. The restricted accumulation of organic carbon can be partly related to rapid water circulation that washes off autochthonous organic matter, high input from the ocean such as coral rubble that dilutes the organic matter, and a low residence time of water that increases exposure time to oxygen and promotes decomposition (Bouillon *et al*., 2008; Ranjan *et al*., 2011).

Total ecosystem carbon pool

The total carbon stock of the Gowatr mangrove forests was not significantly different during seasons (p>0.05) but varied significantly with spatial locations (p<0.05).

The total mean carbon stock in station 2 was higher than station 3 than station 1, due to high tree density, with less access. Another reason due to the slope, topography and position in station 2 might be tidal water was going on regularly to each tree. So, the nutrient cycling in station 2 stands was good, favouring visual growth.

The mean carbon stock value for the entire area of mangroves estimated a substantial sink of 43.9 Kt and 44.2 Kt of carbon in post-monsoon and pre-monsoon, respectively. These estimates suggest high carbon storage and carbon sequestration potential of Gowatr mangrove forests, besides providing an array of other ecosystem services, such as fuelwood, fishing, non-timber forest products, soil conservation, cleaning and protecting coastal areas from cyclones and storms and providing livelihoods to local people.

Our results are supported by the findings of Kauffman *et al*. (2011), who also found similar fractions of carbon stock in mangrove soils of some Federated States of Micronesia. In other studies, soil carbon accounted for 72%–99% (Murdiyarso *et al*., 2009; Donato *et al*., 2011) and 40%–98% (Donato *et al*., 2011) of the total mangrove ecosystem carbon. These values show the role of mangrove soil as an essential carbon pool. However, our findings show that the whole carbon storage in the mangrove forest is lower compared to those reported by other authors, e.g. Kauffman *et al*. (2014) who recorded an average of 853 Mg/ha of total carbon in Dominican Republic and Murdiyarso *et al*. (2009), who recorded an average of 986 Mg ha^{-1} of total carbon in Indonesia whereas Bosire *et al*. (2012) recorded an average of 534 Mg ha^{-1} of total carbon in Zambezi Delta, in central Mozambique. These differences may be as carbon soiliated to variations of tree species composition and forest structure, the density of trees, forest conservation status, soil depth, carbon concentration, and soil water content in each region. For instance, the structure of mangrove trees of the Zambezi Delta, dominated by *Sonneratia alba* (Sm.) with higher and ticker trees is clearly different from our study site dominated by relatively small trees of *A. marina*. Fatoyinbo *et al*. (2008) also suggest that mangrove productivity, as expressed by tree biomass, would vary with the quality of the upstream sediment; therefore, taller mangrove trees are found in nutrient-rich sediments of the Zambezi Delta and Limpopo estuary. Kairo *et al.* (2008) stated that biomass accumulation rate is mainly influenced by tree age, species, management regime, as well as the climate, while Fatoyinbo *et al.* (2008) consider the nutrient sediment and proximity to the water stream as additional factors of mangrove productivity. In central Kalimantan, Indonesia, Murdiyarso *et al.* (2009) reported around 1220 Mg ha^{-1} carbon stock, which was higher than present study, due to the presence of both deeper soils and larger trees. In contrast, the same authors found relatively low carbon stocks (586 Mg ha^{-1}) in Segara Anakan, Central Java mainly due to the smaller size of trees and lower soil carbon concentration. Other authors, such as Kauffman *et al.* (2011) infer that the relative high above-ground biomass coupled with carbon-rich soils result in high carbon stocks in mangrove forests compared to other tropical forests.

Physico-chemical parameters of sediment

Many mangrove soils have meager nutrient availability (Hossain and Nuruddin, 2016). Mangroves are generally not limited by the relatively large quantities of sulfur, boron, potassium, magnesium, and sodium in seawater but are frequently limited by nitrogen and phosphorus (Alongi *et al.*, 2018). In this study, C-soil had a significantly positive correlation with total plant biomass, which may be attributed to the larger vegetation biomass and increased net primary production, which resulted in higher input of dead roots over time, as well as the higher rate of litterfall (Ren *et al.*, 2010). Increase in C-soil density along with biomass growth has been demonstrated in a study at the Leizhou Bay mangrove forest of South China (Ren *et al.*, 2010) and mangrove forests of Mahanadi mangrove Wetland in East Coast of India (Sahu *et al.*, 2016).

A positive correlation was found between vegetation biomass and soil organic carbon in post-monsoon (r=0.905) and pre-monsoon (r=0.914), indicating the role of vegetation in building soil organic carbon. Sahu *et al.* (2016) concluded that C-soil had significantly positive correlation with total plant biomass (r=0.87).

The average carbon stock in the mangrove forest was 227.1±11.86 and 227.3±11.71 Mg ha^{-1} in post-monsoon and pre-monsoon, respectively, around 82% of which was stored in the soil, supporting the findings of other studies that the soil of mangrove forests contains about 72%–99% of the total carbon of these types of forests. These proportions of soil carbon to the total ecosystem carbon suggest that mangrove soils are the most carbon-rich when compared to the upland ecosystem in the same region. This study demonstrates that the biomass and carbon storage capacity of mangrove species varied significantly with spatial locations ($p<0.05$). The variation may be attributed to different geomorphic conditions of the sites, with tall mangroves being on the water edge and likely younger and subject to greater disturbances by storm surges, siltation and shrimp culture farms. Among the three stations, station 2 showed the maximum carbon storage, followed by station 3 and station 1 during post-monsoon and pre-monsoon, respectively. Effective soil management, tidal interactions (through artificial canalization), enough flow of freshwater into a mangrove ecosystem and avoiding of over-harvesting are important mediators of biomass production of mangrove system. The carbon stocks and biomass varied significantly not with seasons (p>0.05) due to the same environmental and geomorphic conditions of times. Estimation of carbon stock in Gowatr mangroves revealed the high potential of mangroves for sequestering carbon. The mangroves of Gowatr sequestrate about 161.13 and 162.102 Kt of CO_2 in post-monsoon and pre-monsoon, respectively. In conclusion, degradation and deforestation of mangrove forests due to hydrological modifications, fires and illegal harvesting results in the decomposition of organic matter and the release of CO_2, hence a sink for atmospheric CO_2 is ultimately turned into a source and threaten the potential carbon storage. So, sustainable management of mangroves and protection of these valuable ecotones is essential.

Acknowledgments

The authors are grateful to the Department of Environmental (DoE) office - Chabahar for providing all infrastructural facilities and using the laboratory. We are also honored to thank our colleagues for assisting in collecting data.

References

Abino, A.C., Castillo, J.A.A. and Lee, Y.J., 2014. Species diversity, biomass and carbon stock assessment of a natural mangrove forest in Palawan, Philippines. *Pakistan Journal of Botany*, 46(**6**), 1955–1962.

Adame, M.K.J.B., Medina, I., Gamboa, J.N. and Torres, O., 2013. Carbon stocks of tropical coastal wetlands within the karstic landscape of the Mexican Caribbean. *PLoS One*, 8(**2**), e56569. DOI: 10.1371/journal.pone.0056569

Adame, M.F., Santini, N.S., Tovilla, C., Vázquez-Lule, A., Castro, L. and Guevara, M., 2015. Carbon stocks and soil sequestration rates of tropical riverine wetlands. *Biogeosciences*, 12, 3805–3818.

Alongi, D.M., 2018. Impact of global change on nutrient dynamics in mangrove forests. *Forests*, 9, 596-609. DOI:10.3390/f9100596.

Bindu, G., Rajan, P., Jishnu, E.S. and Ajith Joseph, A., 2020. Carbon stock assessment of mangroves using remote sensing and geographic information system. *The Egyptian Journal of Remote Sensing and Space Sciences*, 23(**1**), 1-9.

Bosire, J., Bandeira, S.O. and Rafael, J., 2012. Coastal climate change mitigation and adaptation through REDD+ carbon programs in mangroves in mozambique: Pilot in the Zambezi Delta. Component: Determination of Carbon Stocks through Localized Allometric Equations; Eduardo Mondlane University: Maputo, Mozambique. 27 P.

Bouillon, S., Borges, A.V., Castañeda-Moya, E., Diele, K., Dittmar, T., Duke, N.C., Kristensen, E., Lee, S.Y., Marchand, C., Middelburg, J.J., Rivera-Monroy, V.H., Smith, T.J. and Twilley, R.R., 2008. Mangrove production and carbon sinks: A revision of global budget estimates. *Global Biogeochemical Cycles*, 22, 1–12.

Camacho, L.D., Gevaña, D.T., Carandang, A.P., Camacho, S.C., Combalicer, E.A., Rebugio, L.L. and Youn, Y.C., 2011. Tree biomass and carbon stock of a community managed mangrove forest in Bohol, Philippines. *Forest Science and Technology*, 7, 161–167

Chen, L., Zeng, X., Tam, N.F.Y., Lu, W., Luo, Z., Du, X. and Wang, J., 2012. Comparing carbon sequestration and stand structure of monoculture and mixed mangrove plantations of Sonneratia caseolaris and S. apetala in southern China. *Forest Ecology and Management*. 284, 222–229.

Dharmawan, I.W.S. and Siregar, C.A., 2008. Soil carbon and carbon estimation of *Avicennia marina* (Forsk) Vierh in Ciasem, Purwakarta. *Journal Penelitian Hutan dan Konservasi Alam*, 5(**4**), 317-328.

Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M. and Kanninen, M., 2011. Mangroves among the most carbon-rich forests in the tropics. *Nature Geosciences*, 4, 293-297.

Erfani, M., Nouri, Gh.R., Danekar, A., Marvi Mohajer, M.R. and Ardakani, T., 2012. Detection of mangrove vegetation area changes at Gowatr Creek in Sistan and Baluchestan province. *Iranian Journal of Forest*, 4(**3**), 197-207.

Fatoyinbo, T.S.M., Washington-Allen, R.A. and Shugart, H.H., 2008. Landscape-scale extent, height, biomass, and carbon estimation of Mozambique's mangrove forests with Landsat ETM+ and Shuttle Radar Topography Mission elevation data. *Journal of Geophysical Research*, 113, 13 P. DOI:10.1029/2007JG000551.

Flores, O. and Comes, D.A., 2011. Estimating the wood density of species for carbon stock assessments. *Methods in Ecology and Evolution*, 2, 214–220.

Fu, W. and Wu, Y., 2011. Estimation of aboveground biomass of different mangrove trees based on canopy diameter and tree height. *Procedia Environmental Sciences*, 10, 2189 – 2194.

Giri, C., 2016. Observation and monitoring of mangrove forests Using Remote Sensing: opportunities and challenges. *Remote Sensing*. 783, 8 P.

Grellier, S., Janeau, J., Nhon, D.H., Cuc, N.T.K., Quynh, L.T.P., Thao, P.T.T., Nhu-Trang, T.T. and Marchand, C., 2017. Changes in soil characteristics and C dynamics after mangrove clearing (Vietnam). *Science of the Total Environment*. 593, 654-663.

Hoelzer, V., 2014. Strategies and tools of mangrove health monitoring - an approach for the Bay Island Roatán, Honduras. International Studies of Aquatic Tropical Ecology (ISATEC) 3rd semester 2014. Mentor: Prof. Dr. Christian Wild, Leibniz Centre for Tropical Marine Ecology (ZMT) and University of Bremen. 42 P.

Hossain, M.D. and Nuruddin, A.A., 2016. Soil and mangrove: A review. *Journal of Environmental Science and Technology*, 9(**2**), 198-207.

Husch, B., Beers, T.W. and Kershaw, J.A., 2003. Forest measuration. 4th Edition, John Wiley and Sons Inc. 443 P.

Istomo, Kusmana, C. and Naibaho, B.D., 2017. Biomass potential on several mangrove planting models in Java Island, Indonesia. *AACL Bioflux*, 10(**4**), 754-767.

Jennerjahn, T.C., Gilman, E., Krauss, K.W., Lacerda, L.D., Nordhaus, I. and Wolanski, E., 2017. Chapter 7: mangrove ecosystems under climate change. In: Rivera-Monroy, V., Lee, S.Y., Kristensen, E., Twilley, R.R. (Eds.), Mangrove Ecosystems: A Global Biogeographic Perspective – Structure, Function and Services. Springer Publishing Company, New York. pp. 211–244.

Joshi, H.G. and Ghose, M., 2014. Community structure, species diversity and above ground biomass of Sundarban mangrove swamps. *Tropical Ecology*, 55(**3**), 283–303.

Kairo, J.L., Lang'at, J.K.S., Dahdouh-Guebas, F., Bosire, J. and Karachi, M., 2008. Structural development and productivity of replanted mangrove plantations in Kenya. *Forest Ecology and Management*, 255, 2670–2677.

Kauffman, J.B., Heider, C., Cole, T., Dwire, K.A. and Donato, D.C., 2011. Ecosystem C pools of Micronesian mangrove forests: Implications of land use and climate change. *Wetlands*, 31, 343- 352.

Kauffman, J.B. and Donato, D.C., 2012. Protocols for the measurement, monitoring and reporting of structure, biomass and carbon stocks in mangrove forests. Working Paper 86. Center for International Forest Research (CIFOR): Bogor, Indonesia. 40 P.

Kauffman, J.B., Heider, C., Norfolk, J. and Payton, F., 2014. Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. *Ecological Applications*, 24(**3**), 518–527.

Khairuddin, B., Yulianda, F., Kusmanab, C. and Yonvitner, 2016. Degradation mangrove by using Landsat 5 TM and Landsat 8 OLI image in Mempawah Regency, West Kalimantan Province year 1989 –2014. The 2nd International Symposium on LAPAN-IPB Satellite for Food Security and Environmental Monitoring 2015, LISAT-FSEM 2015. *Procedia*

Environmental Sciences, 33, 460–464.

Kuei, C.F., 2008. Population structure, allometry and above-ground biomass of *Avicennia marina* forest at the Chishui River Estuary, Tainan County, Taiwan. *Journal of Forest Research*, 30(**2**), 1–16.

Kusumaningtyasa, M.A., Hutahaeanc, A.A., Fischerd, H.W., Pérez-Mayo, M., Ransby, D. and Jennerjahn, T.C., 2019. Variability in the organic carbon stocks, sources, and accumulation rates of Indonesian mangrove ecosystems. *Estuarine, Coastal and Shelf Science*, 218, 310-323.

Liao, W.B., Lan, C.Y., Zan, Q.J., Wong, Y.S. and Tam, N.F.Y., 2004. Growth dynamics and self-thinning of the dominant populations in the mangrove community. *Acta Botanica Sinica*, 46(**5**), 522–532.

Manna, S., Nandy, S., Chanda, A., Akhand, A., Hazra, S. and Dadhwalc, V.K., 2014. Estimating aboveground biomass in *Avicennia marina* plantation in Indian Sundarbans using high-resolution satellite data. *Journal of Applied Remote Sensing*, 8, 14 P. DOI: 10.1117/1.JRS.8.083638.

Moradi, S., Danehkar, A., Erfani, M. and Ardakani, T., 2019. Gastropods diversity in mangrove forests of Govater Gulf in Sistan and Baluchestan. *Journal of Wildlife and Biodiversity*, 3(**3**), 36-43. DOI: 10.22120/jwb.2019.108517.1069

Mitra, A., Kasturi, S. and Kakoli, B., 2011. Standing biomass and carbon storage of above-ground structures in dominant mangrove trees in the Sundarbans. *Forest Ecology and Management*, 261, 1325–1335.

Mitra, A. and Zaman, S., 2014. Carbon Sequestration by Coastal Floral Community. New Delhi, The Energy and Resource Institute Press. 300 P.

Murdiyarso, D., Donato, D., Kauffman, J.B., Stidham, M. and Kanninen, M., 2009. Carbon storage in mangrove and peatland ecosystems: A preliminary account from plots in Indonesia; working paper 48; Center for International Forest Research (CIFOR): Bogor, Indonesia. 37 P.

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

Navar, J., 2010. Measurement and assessment methods of forest aboveground biomass: A literature review and the challenges ahead. In: Momba, M. and Bux, F. (eds.), Biomass, Sciyo, Croatia. 202 P.

Nguyen, T.K.C., Ikuo, N., Nguyen, T.L., Nguyen, H.T., Mai, S.T. and Phan, N.H., 2009. Belowground carbon accumulation in young Kandelia candel (L.) Blanco plantations in Thai Binh River Mouth, Northern Vietnam. *International Journal of Ecology and Development*, 12, 107–117.

Patil, V., Singh, A., Naik, N. and Unnikrishnan, S., 2014. Estimation of carbon stocks in *Avicennia marina* stand using allometry, CHN analysis, and GIS methods. *Wetlands*, 34, 379–391.

Pérez, A., Machado, W., Gutierrez, D., Stokes, D., Sanders, L., Smoak, J.M., Santos, I. and Sanders, C.J., 2017. Changes in organic carbon accumulation driven by mangrove expansion and deforestation in a New Zealand estuary. *Estuarine Coastal and Shelf Science*, 192, 108–116.

Prasanna, J., Anand, M., Vijayasekaran, D. and Kumaraguru, A.K., 2017. Allometric model for estimating above ground biomass and carbon storage in Karankadu mangrove swamp and Palk Bay, southeast coast of India. *Indian Journal of Geo Marine Sciences*, 46(**8**), 1682-1692.

Raffli, T.P., Usher, G. and Niles, J.O., 2007. Reducing carbon emission from deforestation in the Ulu Masen ecosystem, Aceh, Indonesia; Provincial Government of Nanggroe Aceh Darussalam: Aceh, Indonesia. 67 P.

Ranjan, R.K., Routh, J., Ramanathan, A.L. and Klump, J.V., 2011. Elemental and stable isotope records of organic matter input and its fate in the Pichavaram mangrove-estuarine sediments (Tamil Nadu, India). *Marine Chemistry*, 126, 163–172.

Ren, H., Chen, H., Li, Z.A. and Han, W., 2010. Biomass accumulation and carbon storage of four different aged *Sonneratia apetala* plantations in southern China. *Plant Soil*, 327: 279–291.

Sahu, S.C., Kumar, M. and Ravindranath, N.H., 2016. Carbon stocks in natural and planted mangrove forests of Mahanadi Mangrove Wetland, East Coast of India. *Current Science*, 110(**12**), 2253-2260.

Sidik, F., Neil, D. and Lovelock, C.E., 2016. Effect of high sedimentation rates on surface sediment dynamics and mangrove growth in the Porong River, Indonesia. *Marine Pollution Bulletin*, 107, 355–363.

Sitoe, A.A., Mandlate, L.G.C. and Guedes, B.S., 2014. Biomass and carbon stocks of Sofala Bay mangrove forests. *Forests*, 5, 1967-1981.

Wang, G., Guan, D., Peart, M.R., Chen, Y. and Peng, Y., 2013. Ecosystem carbon stocks of mangrove forest in Yingluo Bay, Guangdong Province of south China. *Forest Ecology and Management*, 310, 539–546.

Yuwono, E., Jennerjahn, T.C., Nordhaus, I., Riyanto, E.A., Sastranegara, M.H. and Pribadi, R., 2007. Ecological status of Segara Anakan, Indonesia: A mangrove-fringed lagoon affected by human activities. *Asian Journal of Water, Environment and Pollution*, 4, 61–70.

Zhao, K., Popescu, S. and Nelson, R., 2009. Lidar remote sensing of forest biomass: A scale invariant estimation approach using. *Remote Sensing of Environment*, 113, 182-196.