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ORIGINAL ARTICLE

Carbon stock in three mangrove forests in north Persian Gulf

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Abstract

Pars Special Economic Energy Zone (PSEEZ) in the north of the Persian Gulf has made major changes to the landscape of the Nayband mangrove forest in Iran, but there have been very few studies on the carbon in mangrove forests of the region. To study the carbon stock of the mangrove forests in Bushehr, and to compare it according to the distance from PSEEZ, some mangrove forests, including 6 stations in Asalouyeh, 2 stations in Basatin (close to PSEEZ), and 1 station in Malegonzeh (far from the PSEEZ) were sampled in November 2018. The carbon of trees was calculated by allometry equations and the carbon of sediment was measured by the Walkley and Black method. The results showed a significant difference between the forests in biomass, carbon of vegetation, and sediments ($P<0.05$). The carbon stock of the mangrove vegetation was 34.92, 12.50, and 27.54 t ha^{-1} in Asalouyeh, Basatin, and Malegonzeh forests, respectively, while the carbon stock of sediments was 867.4, 728.4, and 612.6 t ha^{-1} in the mentioned forest, respectively. The highest total carbon was observed in the Asalouyeh and the lowest was observed in the Malegonzeh. The pattern of carbon was different in the sediment depth profile in the three forests. The rate of the carbon storage was 6.6 t ha^{-1} y^{-1} and 3.33 t ha^{-1} y^{-1} in Asalouyeh and Basatin, respectively. The carbon and CO2 sequestration rate in Basatin was lower than Asalouyeh. According to the results, mangrove forests in the area can act as a carbon sequestration service against the CO_2 emitted by PSEEZ, if their habitats are not destroyed. The rate of the CO_2 sequestration was 22.46 t ha^{-1} y^{-1} in Nayband forest. The carbon stock was 640.14–902.32 t ha^{-1}, which was equal to and greater than the carbon stock of the other mangroves in the world.

Keywords Carbon stock · Carbon sequestration · Mangrove forest · Persian Gulf · Pars special economic zone

Introduction

Among the carbon sequestrate ecosystems, Mangrove forests are one of the highest producers and have the highest carbon sequestration capabilities (Kathiresan 2012). However, as mangroves exist on the margin of water and land, they have the cumulative benefits for carbon accumulation (Barbier et al. 2011). Mangrove can sequester and store large quantities of carbon in vegetation via photosynthesis, and in the sediment by settlement (Murdiyarso 2010; Pendleton et al. 2012; Adame et al. 2013). High carbon deposits in mangroves emerge through high sedimentation rates and anaerobic constant conditions below the surface, which reduces the rate of organic matter decomposition. This causes carbon to precipitate in sediment (Ray et al. 2011). Moreover, the sequestration and storing of the carbon in the mangrove ecosystem is a continuous process and has led to the deposition of large amounts of carbon in the mangrove ecosystem (Bouillon et al. 2008; Matsui et al. 2012).

So far as vastness is concerned, Iran's mangrove forests have the 43rd ranking in the world and the 10th in Asia. Among the countries on the edge of the Persian Gulf, the largest area of mangrove forest is in Iran with 12,000 ha (Namjoo et al. 2012).

In 2005, the area of mangrove forests in Iran was 19,000 ha, while the area of mangrove forests in the neighboring countries such as Bahrain, Kuwait, Oman, the United

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Arab Emirates, and Qatar was 90, 5, 1000, 4100, and 500 ha, respectively (FAO 2007).

The mangrove forests in Nayband National Park, in the Nayband beautiful Bay, are one of the ecological values and mangrove communities of the southern part of Iran. These forests spread along two large bays: Asaloyeh (5,25 km) and Basatin (3,10 km) (Rashvand and Shirzad 2013). The only species of mangroves in this region is *the Avicennia marina*.

Pars Special Economic Energy Zone (PSEEZ) was established in 1998 to exploit the oil and gas resources of the south pars region in the southeast of Bushehr province. It is located at 27° north latitude and 52° east longitude, in Asalouyeh city and close to the Nayband National Park. The activities of oil, gas and petrochemicals of PSEEZ started in 2002. The full development of the region is 24 phases of gas refineries and 44 phases of petrochemical plants. This region is the largest special economic area of oil, gas, and petrochemical industry in the world that is situated on the borderland between Iran and Qatar. The total gas field area is 3788 km^2 and it is divided into 2 areas of ownership, i.e., 1788 km^2 off the coast of Iran and 6888 km^2 in the waters of Qatar. It is one of the main sources of energy in Iran, allocating 38 percent of the country's gas reserves (Malekizadeh 2014). Change in the mangrove area causes a significant reduction in the carbon stocks (Pandey and Pandey, 2013). The rapid land-use change (Khatibi et al. 2018) or rapid mangrove destruction is parallel to the loss of a large number of carbon stockpiles and the discharge of large volumes of carbon into the atmosphere (Kauffma et al. 2011). The PSEEZ is the main reason for the land-use change in Nayband mangroves.

The working of PSEEZ facilities at a distance of 10 km from the mangrove forests, guiding some of their sewage into this area, has destroyed a large part of these forests. Consequently, a large part of the mangrove trees has dried up at the western end of the Asalouyeh bay near the South Pars facility. This is due to the discharge of gas refineries sewage. The construction of the road at the entrance of Basatin bay caused the bay to be emptied before it is filled with water. A large part of the mangrove trees in this area have dried up or completely disappeared. The Basatin bay is connected to the estuary of the Parsian flood river. The closed entrance of the bay prevents the proper discharge of the sediments during the flooding of the river. This made the bay lose its natural system, and consequently result in sediment accumulation in the main channel. As a result, the depth of the channel is reduced and there is limited access to sufficient water. Therefore, mangrove trees are wither and dried up (Davoodi 2014).

Before PSEEZ activities begin, Nayband Bay had undisturbed natural communities, including mangrove forests, mud beaches, wetlands, pastures, agricultural land, and so on. Although not all of the predicted phases are currently active, essential changes have been made to the region's landscape. In this regard, Malekizadeh (2014) carried out a study on the land-use changes in Nayband Bay, focusing on the development of the PSEEZ. The results of the study showed that significant changes have been made in land use from 1998 to 2013. According to the result of that research, 34.11 ha of Mangrove forests have been lost. The highest decrease in the mangrove area occurred in Basatin Bay. The decrease of the mangrove areas in Nayband was mostly caused by the sewage discharge of two refinery phases of PSEEZ in the coastal zone (Malekizadeh 2014). Industrial wastewater and sewage discharge of PSEEZ into the Basatin areas were reported by another researcher too (Zahed 2002). Another factor of mangrove destruction in the Basatin area was the road construction at the mouth of the estuary, which prevents complete flooding of the estuary in the high tide (Shojay Gori 2014; Davoodi et al. 2014).

The Nayband mangrove forest is located close to the PSEEZ and the direction of the dominant wind is northeast to southwest, which is exposed to the CO_2 emitted from the PSEEZ industries. If the forest is protected and recovered, it could be a good option for sequestering and sinking CO_2 emissions from these industries. However, there are no studies on the carbon stock in mangroves in Iran, and the only study on carbon in Nayband (Ghasemi et al. 2016) investigated the carbon in trees but not in the sediment.

To preserve the Mangrove forest in Nayband and determine its carbon sequestration potential, it is necessary to investigate the current carbon stock and determine its sediment characteristics. Therefore, it is required to study the mangrove area of Asalouyeh and Basatin. Malegonzeh forest in Bushehr province coast located geographically far from PSEEZ which has no exposure to PSEEZ and seems to be suitable as a control site.

Materials and methods

Area of the study

Nayband bay is situated in a semi-tropical climate region. The average temperature is 12–16 °C in winter, and 36–42 °C in summer. The average rainfall is 150 mm/year, but in some years, it reaches 495 mm/year (Lar Consulting Engineers 2006). The map of the study area is shown in Fig. 1. The sampling site was in Bushehr Province. Nayband mangrove forest includes Asalouyeh with a total area of 120 ha and Basatin with an area of 37 ha. Another site is Malegonzeh with an area of 10.3 ha.

Asalouyeh forest (Bidkhoon), in Asalouyeh (Bidkhoon) bay with 5250 m long, can be found 1.5 km from Bidkhoon village. The northwestern part of the forest is affected by the gas refinery sewage of PSEEZ. Basatin forest in Basatin bay

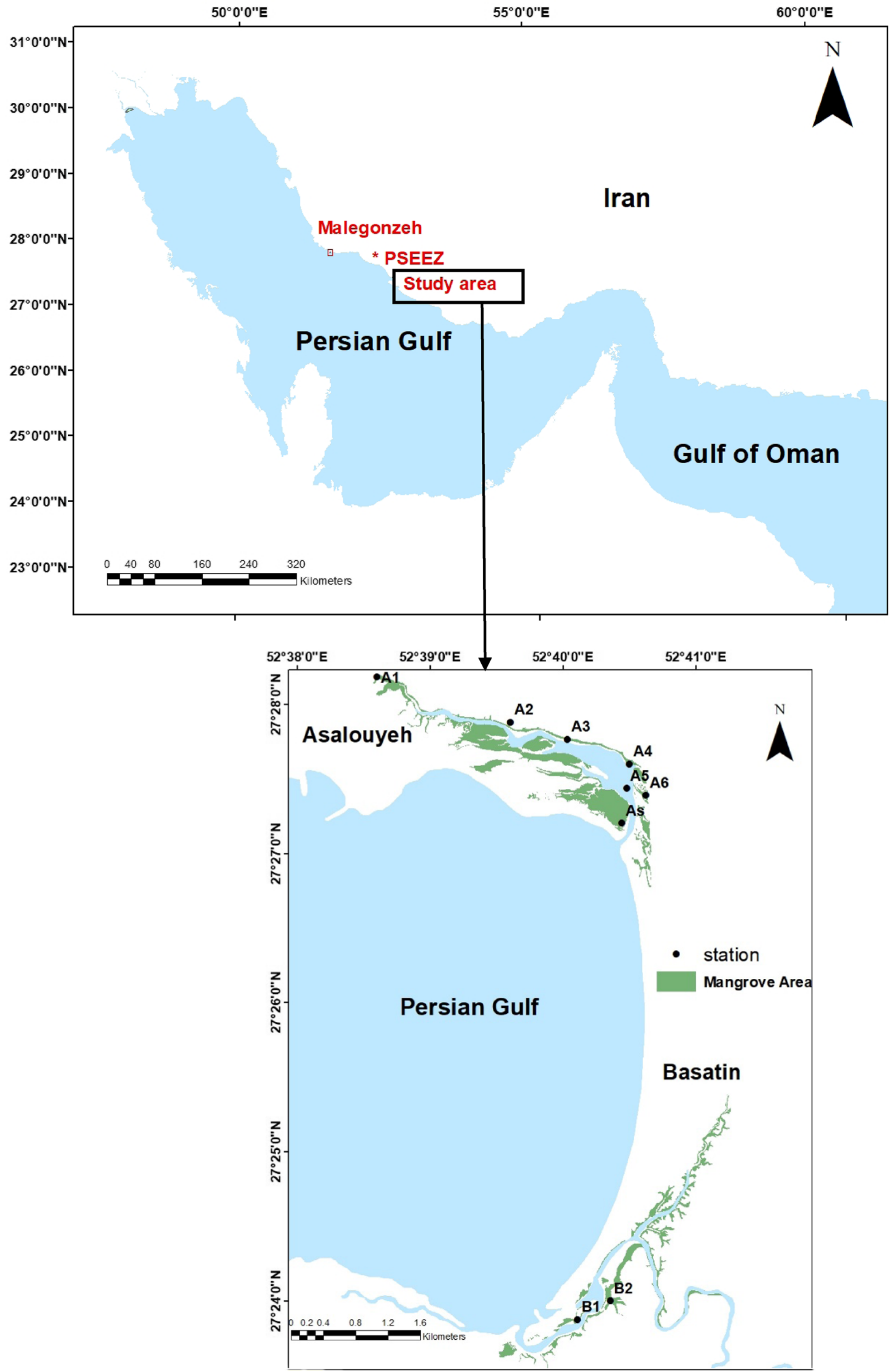


Fig. 1 Study area and stations

with 3100 m long, is 2 km far from Basatin village. Due to the construction of the road, the water intake from the sea in this bay was closed down. The Persian Gulf international airport is 5 km away from this forest. Also, the two-phase sewage of the PSEEZ refinery enters this bay. Simultaneously, with the increase of industrial activities in the region, agricultural activities have also developed. In Persian city, the upstream of Parsian river, which passes through Basatin bay, out-of-season tomato cultivation has spread. The cultivation is associated with the high consumption of chemical fertilizers and toxins that can enter this bay by surface currents. In addition to the above-mentioned points, the oil pollution caused by the transportation of oil ships, and the gas condensate export docks in the vicinity of the region, there are other threatening factors of mangroves in the two forests (Shojay Gori 2014).

Sampling and measurement

The carbon stock was measured at the sampling site following Kauffman and Donato's method (2012). The linear quadratic transects (10^2 m^2), vertical to the coastal line were for sampling the Nayband mangrove at each site. The site was selected according to the NDVI[1] map and field information. NDVI maps were made using the Flash algorithm in Envi 5.3 software and were classified in ArcGis 10.4.1 software. However, since the densities in Nayband mangroves vary, the transects were selected according to the NDVI map for accurate carbon calculating. Six transects were in Asalouyeh bay according to more variation in density and larger area than the two other forests. Two and one transects were considered in Basatin and Malegonzeh, respectively. Each transect consisted of 6 plots of 100 m^2 in Basatin and Asalouyeh. The Malegonzeh transect included 4 plots of 100 m^2. Total 36 plots were sampled and measured in Asalouyeh, 12 plots in Basatin, and 4 plots in Malrgonzeh. In general, 52 plots were analyzed in this study. The trees, shrubs, downed wood, and fallen litter on the floor were measured and counted in all plots.

Due to the softness of the sediments in the area, sampling the sediment core was very difficult. The sediment sample was taken from 0 to 60 cm depth by an iron pipe with a PVC core tube. The sediment core samples were taken from the studied transects in A1, A3, A5, B1, and M stations. Also, to compare carbon content in vegetated and non-vegetated sediment one core sediment sample was taken from the uncovered (non-vegetated) area (station As).

To sampling and carbon measurement, different parts of mangrove forest including trees and shrubs, fallen branches and leaves, tree and shrubs roots, and sediments were sampled, counted, and measured based on Kauffman and Donato 2012. In each plot, the collar diameter of all trees was measured by a caliper and recorded. The diameter of the trees of the studied sites was from 5 to 25 cm. The different factors of all shrubs in plots include collar diameter, crown high, crown diameter, and Diameter at 30 cm high were measured and recorded. Downed wood sampled using the line-intersect method according to Brown 1971. Sample and measurement of downed wood and litter are explained below.

[1] Normalized Differences Vegetation Index.

The biomass and carbon of mangrove forest

The biomass and carbon of trees

Regarding the value of mangrove species, allometry seems to be the best method for the study of biomass. Depending on the species and the ecological conditions, different allometry models have been presented by scientists. Considering the multiple branches of mangrove trees in Nayband and according to the previous study in the area, the diameter at the collar is very likely the best allometric equation. The biomass of trees was measured using an allometric model of *A. marina* in Nayband ($ABG = 9498.05 + e^{0.76d}$) (Ghasemi 2016). In this equation, ABG is the aboveground biomass of trees and d is the collar diameter of trees. The BG (belowground biomass) was 20% of the ABG biomass. According to Ghasemi 2016, in *A. marina* of Nayband forest, the carbon of ABG was 42% of ABG and the carbon of BG was 39% of the BG.

Biomass and carbon of shrubs

According to the existing carbon measurement methods in mangroves, the allometry of trees varies from shrubs (Kauffman and Donato 2012). Therefore, *A. marina* shrubs in different sizes with roots were removed from different stations of the studied area. Then, the shrub's biometric factors were recorded and the samples were weighed on the ground. The sample was transferred to the environmental laboratory at the University of Tehran for biomass and carbon measurement. After that, the root and the leaf were separated from the trunk and each section was weighed. The specimens were reweighed after oven-dried (80 °C for 48 h). 1 g of each specimen sample was burned inside the furnace at 450 °C for 7 h to calculate the carbon (Heiri et al. 2001). Equation 1 was used to calculate the carbon content of the samples. In this equation, LOI is the Loss on Ignition, MBCd is the dry mass before combustion (mg), and MACd is the dry mass after combustion (mg) (Howard et al 2014).

$$\begin{aligned} \%\ \mathrm{Corg} &= 0.415 \times \%\ \mathrm{LOI} + 2.89 (r = 0.59), \\ \%\ \mathrm{LOI} &= (\mathrm{MBCd} - \mathrm{MACd} / \mathrm{MBCd}) \times 100. \end{aligned} \quad (1)$$

The results of the regression analysis are showed in Table 1. It shows that there was no significant correlation between the DBH and biomass. According to the table, the stem diameter at 30 cm height is the best parameter for the allometric model of *A. marina* shrubs in the studied area. Therefore, the diameter at 30 cm height of the shrubs was recorded in plots, and the biomass was calculated using Eq. 2. The biomass of BG was found approximately 24% of the ABG biomass. The amount of carbon in the ABG shrub was calculated as much as 42% of the ABG biomass and the

Table 1 Result of regression between Y (biomass) and X (biometric parameter) of the shrubs

Independent variable	Regression type	R^2 adj	F	Sig	Std. error	Equation
Collar diameter	Linear	0.94	85.65	0.001	73.362	$Y = 151.19x - 218.82$
	Logarithmic	0.91	51.738	0.02	93.041	$Y = 710.912\ln(x) - 556.023$
	Power	0.91	56.991	0.002	0.197	$Y = 39.897x^{1.579}$
	Exponential	0.84	28.271	0.006	0.217	$Y = 91.103e^{0.321x}$
Diameter at 30 cm high	Power	0.98	243.57	0	0.098	$Y = 139.3x^{1.263}$
	Exponential	0.95	115.558	0	0.141	$Y = 99.128e^{0.537x}$
Crown high	Linear	0.98	250.896	0	43.508	$Y = 12.032x - 432.89$
	Logarithmic	0.95	103.505	0.001	66.994	$Y = 938.06\ln(x) - 3540.32$
	Power	0.88	39.71	0.03	0.233	$Y = 57.482e^{0.0256x}$
Crown diameter	Power	0.84	27.163	0.06	0.275	$Y = 90.756e^{0.0152x}$

amount of carbon in the BG shrub was calculated as much as 39% of the BG biomass. According to Table 1, Eq. 2 was selected to calculate the biomass of shrubs. In this equation, ABG is aboveground biomass and d_{30} is the diameter at 30 cm height of the shrubs.

$$ABG = 139.3d_{30}^{1.263}(\text{This study}) \quad (2)$$

The biomass and carbon of the downed wood

The fallen woods were divided into 2 categories based on diameter ($d \geq 7.6$ cm and $2.5 \text{ cm} < d < 7.6$ cm), and they were counted using the line-intersect technique (Brown 1971). All woods with $d \geq 7.6$ were counted in 2–10 m of the transect. Also, all wood with $2.5 \text{ cm} < d < 7.6$ cm were counted in 5–10 m of the transect. In the center of each plot, the first 2 m was not counted.

From each diameter class $d \geq 7.6$ cm and $2.5 \text{ cm} < d < 7.6$ cm), the diameter of 50 samples was randomly measured by caliper. Also, to determine the density of each class of parts, 20–25 samples with weights of 5–50 g were taken and dried in the laboratory at 100° C. By dividing the weight of the dried wood into the volume of non-dried wood, the class density of the desired part was calculated (Eq. 3). The quadratic mean diameter (QMD) for each class diameter, the volume class 2.5 cm < d < 7.6 cm and volume class d ≥ 7.6 cm were calculated by Eqs. 4, 5, 6 (Brown 1971). The final step is to calculate the conversion of parts weight to carbon, using a coefficient of 50% biomass (to calculate the carbon of dry tree parts) (Kauffman and Donato 2012.).

$$\text{Density}_i\left(\text{g cm}^{-3}\right) = W/V, \quad (3)$$

where Density $_i$: Density of the sample piece size class, W: Weight of dried sample piece (g), and V: Volume of the undried sample piece (cm^3)

$$\text{QMD (Cm)} = \sqrt{\left(\Sigma Di^2\right)/n}, \quad (4)$$

where D_i = the diameter of each sampled piece of wood in the size class, and n = the total number of pieces sampled.

$$\text{Volume}\left(m^3h^{-1}\right) = \pi^2 * \left[Ni * QMD_i^2/8 * L\right], \quad (5)$$

where Ni = the count of intersecting woody debris pieces in size class I, QMDi = the quadratic mean diameter of size class i (cm) and, L = transect length (m)

$$\text{Volume}\left(m^3h^{-1}\right) = \pi^2 * \left[d_1^2 + d_2^2 + d_3^2 \ldots + d_n^2/8 * L\right], \quad (6)$$

where d_1, d_2, etc. = diameters of intersecting pieces of large deadwood (cm), and L = the length of the transect line for large size class (m).

The biomass and carbon of the litter

Two subplots (1×1 m^2) were made in each plot and the samples of litter were collected. The samples were dried at 60 °C to calculate a constant weight (biomass). Finally, the carbon was estimated at 45% of the biomass (Kauffman and Donato 2012).

The total Carbon of mangrove vegetation

The total carbon of vegetation was calculated by the sum of the carbon trees, shrubs, downed wood, and litters in each plot and transect. The total carbon was calculated using Eq. 7.

$$\begin{aligned}\text{TOC of vegetation of each transect (ton)} &= \text{C trees ABG} + \text{C trees BG} \\ &+ \text{C shrubs ABG} + \text{C shrubs BG} \\ &+ \text{C downed wood} + \text{C litter.}\end{aligned} \quad (7)$$

The carbon of the sediments

The carbon of the sediments was measured using the modified Walkley and Black method (Walkley and Black 1934). The amount of the corrected dichromate used in carbon oxidation, organic carbon percent, and SOC (Sediment Organic Carbon) were calculated by Eqs. 8, 9, and 10, respectively (Schumacher 2002; Wang et al. 2013; Liu et al. 2013).

$$A = [\text{ml BB} - \text{ml sample}) \times (\text{ml UB} - \text{ml BB})] / \text{ml UB}] + (\text{ml BB} - \text{ml sample}), \quad (8)$$

where A: corrected titrated dichromate value, ml UB: the amount of unboiled blank titer, ml BB: the amount of boiled blank titer, ml sample: the amount of sample titer

$$\%\ \text{Organic C} = [A \times \text{MFe}^{2+} \times (0.3)] / \text{weight of oven} - \text{dried soil (g)}] \times 100, \quad (9)$$

where A: corrected titrated dichromate value, and MFe^{2+}: Iron ammonium sulfate molarity 0.3 equivalent of carbon

$$\text{SOC (kg/h)} = 10000 \times \text{BD} \left(\text{g/cm}^3\right) \times \text{soil depth interval (cm)} \times \%\text{OC}, \quad (10)$$

where: BD: The density of the dry weight of the sediment.

Calculating the uncertainty

The uncertainty of the carbon storage in this study was investigated at two levels: 1—the carbon reservoirs of the study, including the vegetation (trees) and the sediments with 95% confidence interval (Eq. 11), and 2—the total carbon of the study area with 95% confidence interval (Eq. 12).

$$95\%\ \text{CI of each pool} = 2 * \text{SE}, \quad (11)$$

where SE: mean standard error, and CI: Confidence Interval. (Kauffman and Donato 2012)

$$95\%\ \text{CI of pool C stock} = \sqrt{95\%\ \text{ci}^2\text{veg} + 95\%\ \text{ci}^2\text{sedi}}, \quad (12)$$

where Veg: trees, Sedi: Sediments. (Pearson et al. 2005; Kauffman and Donato 2012).

The density and particle size of the sediment

The organism shells and vegetation were discarded from the sediment samples in the laboratory and then the density (g cm^{-3}) of samples was determined. A combination of the sieve and hydrometer method was used to measure the particle size of the sediment samples (Yang et al. 2014). The sample passed through the last mesh was separated for the hydrometric process. After calculating the diameter and percentage of the sediment particles, the data were fed into the Gradistat software. The mean particle size, ϕ index, skewness, kurtosis, sorting, clay, sand, and silt percent were obtained following the corresponding formulas described by folk and ward (1957).

Carbon sequestration rate

Difference between the mean past carbon stock (t ha^{-1}) and mean current carbon stock (t ha^{-1}) in a forest divided on The length of time (reported in t ha^{-1} y^{-1}) display carbon sequestration rate. The carbon stock of the Ghasemi study was used as the initial stock in 2016 and the carbon stock obtained from the present study was used as the second stock in 2019. Considering that the only study on carbon stock in Nayband forests (study area) was the Ghasemi study in 2016, and considering that a similar allometric equation has been used in both studies, as well as the way of transecting and plot size in both studies. The difference between the carbon stock obtained from these two studies was divided into 3 (number of years), for calculating the carbon sequestration rate in t ha^{-1} y^{-1}.

Table 2 Biomass of different parts of mangrove vegetation (t ha^{-1})

Station	ABG. Tree	BG. Tree	ABG. Shrub	BG. Shrub	Downed Wood	Litter	Total	Density
A1	88.38 ± 5.62	17.68 ± 1.12	0.37 ± 0.3	0.09 ± 0.07	0.19 ± 0.09	0.54 ± 0.07	107.23 ± 6.59	High
A2	28.33 ± 7.05	5.67 ± 1.41	0.47 ± 0.22	0.11 ± 0.05	0.07 ± 0.03	0.13 ± 0.02	34.78 ± 8.38	Low
A3	64.50 ± 4.97	12.90 ± 0.99	0.43 ± 0.17	0.10 ± 0.04	0.09 ± 0.02	0.29 ± 0.06	78.30 ± 5.85	Medium
A4	76.05 ± 8.07	15.21 ± 1.61	0.35 ± 0.15	0.08 ± 0.04	0.09 ± 0.01	0.45 ± 0.06	92.23 ± 9.80	High
A5	90.58 ± 27.16	23.52 ± 4.18	0.24 ± 0.00*	0.06 ± 0.00*	0.15 ± 0.03	0.65 ± 0.14	115.20 ± 28.36	Very High
A6	63.50 ± 6.73	12.70 ± 1.35	0.48 ± 0.09	0.12 ± 0.02	0.12 ± 0.02	0.31 ± 0.06	77.22 ± 8.36	Medium
B1	36.19 ± 8.77	7.24 ± 1.75	0.15 ± 0.04	0.04 ± 0.01	0.13 ± 0.02	0.07 ± 0.03	43.81 ± 10.48	Low
B2	13.20 ± 3.54	2.64 ± 0.71	0.37 ± 0.03	0.09 ± 0.01	0.08 ± 0.06	0.05 ± 0.01	16.42 ± 4.19	Low
M	55.40 ± 12.12	11.08 ± 2.42	0.56 ± 0.13	0.13 ± 0.03	0.07 ± 0.04	0.15 ± 0.02	67.37 ± 14.33	-

Table 3 The carbon content of different parts of mangrove vegetation (t ha^{-1})

Station	ABG. Tree	BG. Tree	ABG. Shrub	BG. Shrub	Downed Wood	Litter	Total	Density
A1	37.12 ± 2.36	6.89 ± 0.44	0.15 ± 0.12	0.03 ± 0.01	0.09 ± 0.01	0.24 ± 0.03	44.53 ± 2.71	High
A2	11.90 ± 2.96	2.21 ± 0.55	0.20 ± 0.09	0.04 ± 0.02	0.03 ± 0.01	0.06 ± 0.01	14.44 ± 3.47	Low
A3	27.09 ± 2.09	5.03 ± 0.39	0.18 ± 0.1	0.04 ± 0.02	0.04 ± 0.01	0.13 ± 0.02	32.51 ± 2.43	Medium
A4	31.94 ± 3.39	5.93 ± 0.63	0.15 ± 0.08	0.03 ± 0.02	0.05 ± 0.01	0.20 ± 0.03	38.30 ± 4.09	High
A5	38.04 ± 11.41	9.17 ± 1.63	0.10 ± 0.04	0.02 ± 0.01	0.07 ± 0.01	0.29 ± 0.03	47.71 ± 11.49	Very High
A6	26.67 ± 2.83	4.95 ± 0.52	0.20 ± 0.11	0.04 ± 0.02	0.06 ± 0.02	0.14 ± 0.02	32.06 ± 3.45	Medium
B1	15.20 ± 3.68	2.82 ± 0.68	0.06 ± 0.02	0.01 ± 0.00	0.06 ± 0.01	0.03 ± 0.01	18.19 ± 4.36	Low
B2	5.54 ± 1.49	1.03 ± 0.28	0.15 ± 0.01	0.03 ± 0.00	0.04 ± 0.02	0.02 ± 0.01	6.82 ± 1.75	Low
M	22.94 ± 5.64	4.26 ± 1.05	0.18 ± 0.01	0.05 ± 0.03	0.03 ± 0.1	0.07 ± 0.01	27.54 ± 6.54	-

Statistical analysis

The statistical analysis was conducted using SPSS version 25. Shapiro–Wilk test was used to check the normality of the biomass and carbon at each station. The Curve estimation test was used for the calibration of the biomass allometry model of the shrub. Moreover, ANOVA (One-way analysis of variance) was used to compare the carbon stock of mangroves and sediments in different stations at $P < 0.05$. Finally, the Pearson correlation test was used at $P < 0.05$ to verify the relationship between the carbon in the sediment surface layer and the vegetation cover.

Results and discussion

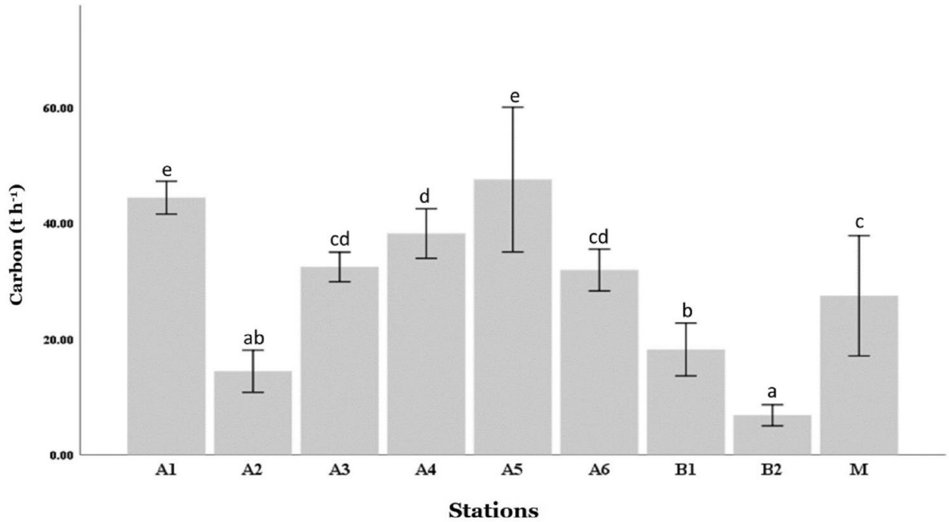
The biomass of the mangrove forest

Biomass in different stations was calculated by the mean and standard deviation of all plots in each station. This value was in kg*100 m^2 that converted into t ha^{-1}. The biomass of the ABG of trees varied from 13.20 to 90.58 t ha^{-1}. The biomass of the BG of trees varied from 2.64 t to 23.52 t ha^{-1}. The biomass of the ABG and the BG of the shrub ranged from 0.15 to 0.56 t ha^{-1} and 0.04 to 0.13 t ha^{-1}, respectively. However, the total biomass in the study area was 16.42 to 115.20 t ha^{-1} (Table 2). The average biomass was 84.16 t ha^{-1} in Asalouyeh, 30.11 t ha^{-1} in Basatin, and 67.37 t ha^{-1} in Malegonzeh. The biomass variation in different sites was consistent with the vegetation density.

The carbon of mangrove vegetation

The total carbon was 6.82–47.71 t ha^{-1} in the studied stations. More carbon content was found in the stations that have denser cover vegetation. The carbon content was 5.54 to 38.4 t ha^{-1} and 1.03 to 9.17 t ha^{-1} in the ABG and the BG of the trees, respectively (Table 3). Moreover, the carbon values were 0.06–0.20 t ha^{-1} and 0.01–0.05 in the ABG and the BG of the shrub. The average carbon in Mangrove vegetation was 34.92, 12.50, and 27.54 t ha^{-1} in the Asalouyeh, Basatin, and Malegonzeh forest. The uncertainty for the total carbon of vegetation in the studied ecosystems was 4.24 t ha^{-1}. Therefore, a significant difference was observed among many stations in the carbon of mangrove vegetation ($P < 0.05$). The highest vegetation carbon content was observed in stations A5 and A1, while the lowest carbon content was observed in stations B2 and A2 (Fig. 2). On

Fig. 2 The average carbon content of mangrove vegetation in the studied stations. Different letters (a–e) indicate significant differences ($P < 0.05$)



the other hand, the more biomass and carbon content is the result of the more coating and density.

Carbon in the ABG of the *A.marina* in the Assaluyeh, Basatin, and Malegonzeh was 34.92, 12.49, and 27.54 t ha^{-1}, respectively. The mean carbon in the ABG of the *A.marina* in the present study was 24.98, which was not much different from the carbon in *A.marina* ABG reported in the Indian Sandarban forest (29.5 t ha^{-1}) (Ray et al. 2011), but it was lower than the carbon in *A.marina* ABG reported in Australia and China (40 t ha^{-1}) (Luo et al. 2010; Alongi et al. 2000) and more than the values reported in Saudi Arabia (4.9 t ha^{-1}) (Abohassan et al. 2012) and Kenya (5.3 t ha^{-1}) (Kairo et al. 2009).

It has been stated that in addition to the species and latitude, local factors such as microclimate, hydrology, physicochemical properties of water (Day et al. 1996; Twilley et al. 1992), age, and density also influence the carbon content of the mangrove trees.

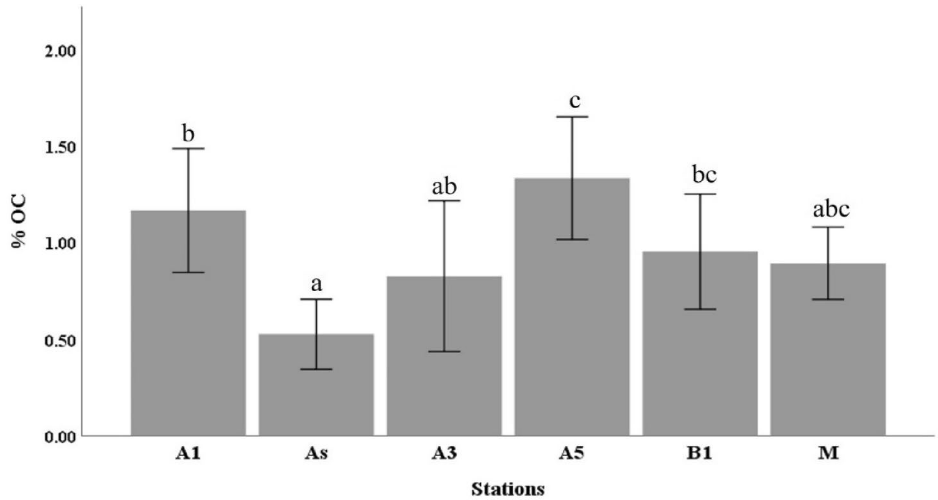
Temperature and precipitation patterns have the potential to change mangrove functions such as leaf formation, photosynthesis rates, and seedling establishment (Feher et al. 2017; Osland et al. 2016). Rapid twenty-first-century sea-level rise (SLR) as a climate-change consequence has been cited as a serious threat to mangroves, which have responded to the past sea-level changes by migrating landward (Schuerch et al. 2018).

Etemadi et al (2020) reported that the area of vegetation of Basatin and Asalouyeh increased in 2002 compared to 1990, while the area of Basatin decreased significantly from 2002 to 2015 after the construction of South Pars facilities. According to the study, mangroves in the study area are not riverine and the most important factors affecting the area and density are rainfall, annual temperature, sea-level rise, salinity, and anthropogenic activities. According to the mentioned study, the average rainfall in the study area has changed significantly, from 1990 to 2003 and since 2003. This means that in the period from 2003 onwards, the average rainfall has decreased significantly. The NDVI and area also increased from 1990 to 2002, indicating the health of mangroves during this period, which may be due to temperature and rainfall increase. But the NDVI and area have declined since 2002 in Basatin. According to this study, the conditions affecting mangroves in the three forests are not very different; an exception is the Basatin forest that has been affected by the PSEEZ industries. According to the mentioned cases, it seems that the reason for the low carbon content in Basatin is due to the destructive effects of PSEEZ.

The carbon of the sediment

The mean carbon of sediment was 931.8, 443.4, 625.2, 1045.2, 728.4 and 612.6 t^{-1} ha in stations A1, As, A3, A5, B1, and M, respectively. The amount of carbon in the sediment varied from 0.53% to 1.33% in the stations. The mean carbon percent were 1.17, 0.83, 1.33, 0.53, 0.95, and 0.89 in stations A1, A3, A5, As, B1, and M, respectively (Fig. 3). In the mangrove forest, there is a physical and chemical interaction between the plant carbon and the sediment carbon. In other words, more vegetation density caused further trapping of the allochthonous carbon (carbon entering the river or tide). Also, part of the carbon source of the sediments is residue and the carcass of the plants which are autochthonous sources (Bouillon et al. 2003; Chen et al. 2012). Furthermore, the ability to grow and maintain mangroves is improved in the carbon-rich sediments. However, in this study, the highest carbon and biomass content was observed in the transects with higher mangrove cover densities such as A1 and A5. Also, the lowest amount of carbon and biomass was observed in transects with lower cover densities such as B1, B2, and A2. The stations with more vegetation

Fig. 3 The average carbon percent of sediments in the studied stations. Different letters (a–c) indicate significant differences ($P < 0.05$)



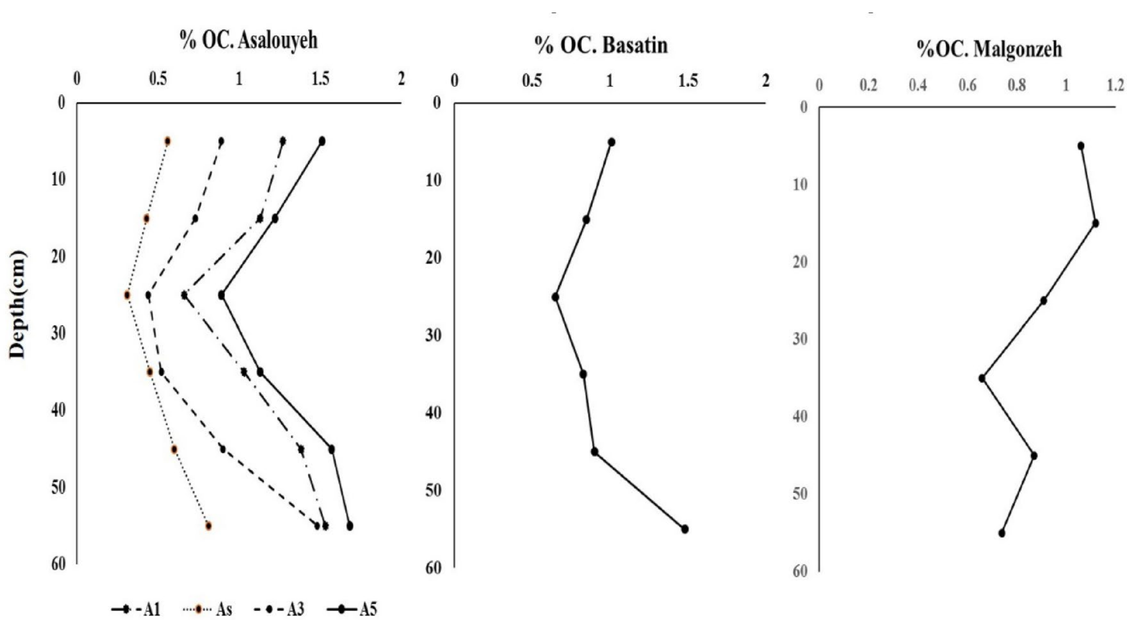


Fig. 4 The average carbon percent of sediment at the depth profile in studied stations

density, such as A1 and A5, had more carbon content in their sediments.

The carbon percent in the sediment in the present study was close to the carbon percentage in the sediments of China (1%) (Alongi et al. 2005) and Thailand (1.1%) (Brunskill et al. 2004). But it was less than carbon reported in sediment from Brazil (5.8%) (Sanders et al. 2010), Indonesia (6.5%) (Brunskill et al. 2004), and Malaysia (7.8%) (Alongi et al. 2004).

Sediment characteristics

The pattern of depths carbon changes in the studied stations is presented in Fig. 4. The pattern of the carbon percent changes was different in the sediment depth profile in three forests. However, the pattern was somewhat similar in Basatin and Asalouyeh. But the pattern of the carbon in-depth profile is slightly different in the control station (M) compared to the stations in Nayband (Basatin and Asalouyeh), which can be due to differences in carbon deposition conditions. Several factors are affecting carbon sedimentation including physical factors such as water depth, hydrodynamic, sedimentation rate, biological factors including vegetation cover productivity and its density, and chemical factors including organic carbon sustainability (Serrano et al. 2016). Many of the mentioned factors are different in Malegonzeh and Nayband. The similar depth carbon pattern observed in Basatin and Asalouyeh concluded that the

Table 4 Sediment characteristics of studied stations

	A1	A3	A5	As	B1	M
OC (g/cm2)	15.53 ± 3.94	10.42 ± 3.74	17.42 ± 3.83	7.39 ± 2.12	12.14 ± 2.89	10.21 ± 1.60
%OC	1.17 ± 0.30	0.83 ± 0.37	1.33 ± 0.30	0.53 ± 0.17	0.95 ± 0.28	0.89 ± 0.18
%Clay	1.75 ± 0.30	1.08 ± 0.35	1.67 ± 0.19	1.48 ± 1.73	1.77 ± 0.41	0.80 ± 0.55
%Clay&Silt	97.93 ± 0.48	94.52 ± 2.42	98.27 ± 0.36	94.90 ± 2.56	97.52 ± 1.02	97.07 ± 0.90
%Silt	96.48 ± 0.39	93.58 ± 2.27	96.60 ± 0.28	94.12 ± 1.74	95.75 ± 1.04	96.28 ± 0.96
%Sand	1.75 ± 0.27	5.33 ± 2.60	1.73 ± 0.33	4.50 ± 2.20	2.48 ± 0.98	2.93 ± 0.90
ϕ	5.70 ± 0.06	5.50 ± 0.08	5.70 ± 0.04	5.56 ± 0.11	5.70 ± 0.04	5.67 ± 0.08
Mz	19.35 ± 0.66	22.17 ± 1.24	19.25 ± 0.55	21.31 ± 1.64	19.41 ± 0.81	19.69 ± 1.09
Sor	1.43 ± 0.04	1.37 ± 0.05	1.42 ± 0.03	1.41 ± 0.07	1.44 ± 0.05	1.35 ± 0.05
Sk	0.22 ± 0.06	0.31 ± 0.04	0.21 ± 0.03	0.30 ± 0.03	0.18 ± 0.02	0.12 ± 0.06
Ku	0.59 ± 0.04	0.59 ± 0.06	0.59 ± 0.02	0.59 ± 0.08	0.58 ± 0.04	0.55 ± 0.03
Sed. D(g/cm3)	1.28 ± 0.11	1.32 ± 0.18	1.31 ± 0.04	1.33 ± 0.03	1.29 ± 0.11	1.16 ± 0.09

Mz Mean size µm, *ϕ* Logarithmic Particle size, *Sor* Sorting, *Sk* Skewness, *Ku* Kurtosis, *Sed.D* Sediment Density

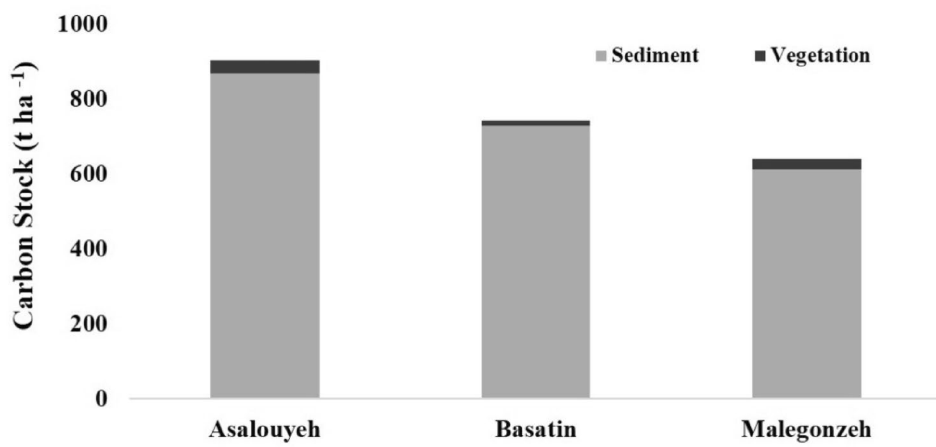


Fig. 5 The total carbon stock of the studied Forest

physical and chemical factors have a greater impact on the carbon depth pattern than the ecological factors in the long term.

The amount of the organic carbon and the factors related to the size of the sediment particles at the studied stations are presented in Table 4. The sediment texture was muddy or silty in all samples. Silt percent was the highest fraction and ranged from 93.58 to 96.60. The clay and sand were low in all sediment samples. The sediment characteristics were not significantly different among the three forests. But carbon stock in the sediment and trees was significantly different among the forests.

The total carbon of the forests

The mean of the carbon stock was 931.8, 625.2, 1045.2, 443, 728.4, and 624.6 t ha^{-1} in stations A1, A3, A5, As, B1 and M, respectively. Also, the carbon stock was 867.4, 728.4, and 612.6 t ha^{-1} in Asalouyeh, Basatin, and Malegonzeh, respectively (Fig. 5). The uncertainty of the sediment carbon was 109.2 t ha^{-1}. The carbon uncertainty of all ecosystems in the present study was 109.3 t ha^{-1}. The lowest value was observed in Malegonzeh and the highest value was observed in Asalouyeh.

According to the results, in terms of biomass and carbon in vegetation Asalouyeh > Malegonzeh > Basatin. However, in terms of the carbon in sediment and the carbon in the total forest Asalouyeh > Basatin > Malegonzeh. In recent years, Basatin bay has been damaged and destroyed due to the construction of the road and discharge of some of the phases of PSEEZ. The bay has been physically destroyed due to the entrance closing and reduced water inflow (Davoodi et al. 2014). It is suggested that the main reason for the reduction of biomass and carbon in Basatin is related to the same issues.

The anthropogenic impact, particularly the land-use change and deforestation, as well as the coastal development, pollution and oil spills, timber, and charcoal production will have a major influence on mangrove loss (Hamilton and Casey 2016; Mafi-Gholami et al. 2020). Within the same line, Davari et al. (2013) reported that the concentration of heavy metals in the sediments and roots of the mangrove plants in Asalouyeh and Bastatin was more than Malegonzeh, and more than the permissible limit for the soil on US EPA standard. They stated that the main reason is the oil and gas activities in PSEEZ. Zare-Maivan 2010 reported the contamination of metals related to petroleum activity (Ni, V, and S) in Nayband sediments. The concentrations of Pb and Cd in Nayband bay sediment were higher than the Persian Gulf standards (Dehghani et al. 2014). The presence of the toxic substrates such as petroleum waste, anoxia, and hydrogen sulfide in the sediment of mangroves limited the pneumatophore functions and subsequently threatened mangrove survival (Snedaker et al. 1981).

Despite the lower carbon content of vegetation in Basatin, the carbon of sediment in Basatin is more than Malegonzeh. This indicates that Basatin is more capable than Malegonzeh. Also, it had more mangrove cover in the past. The results of the total carbon also showed that Basatin had more carbon (740.9 t ha^{-1}) than Malegonzeh (640.14 t ha^{-1}). Given the Basatin susceptibility, it needs to be considered for reconstruction, eliminating the restrictions, expanding the areas of mangroves, and cultivating trees.

Mangrove trees are well known as ponds for trapping and depositing fine particles and carbon in sediments due to their sub-branches upper parts and roots, and their aerial roots. Accordingly, a large portion of the carbon in the mangrove is in the sediment pools, in that mangroves hold more than 90% of their carbon content in their sediment beds (Donato et al. 2011; Kauffman et al. 2012; Stringer et al. 2015). The slow motion of water in the mangroves helps to settle suspended particles, but the terrestrial trees do not have these conditions (Kristensen et al. 2008). In this study, the first sediment layer (0–10 cm) in all stations had a significant carbon content. A significant positive correlation was observed between the carbon of the first layer and the carbon of vegetation ($P<0.05$, $R^2=0.69$), indicating that the current plant coating has a significant effect on the amount of carbon in the surface layer of the sediment. This is likely due to the autochthonous carbon, the decomposed fallen leaves, and the vegetation. On the other hand, the amount of carbon in the sediment of non-cover location was the lowest in this study, concluding that the preservation of mangrove vegetation has an effective role in increasing carbon in sediments.

The high density of mangroves increases nutrients due to more deciduous leaves, and wood and their decomposition. A study by Kumara et al. 2010 showed that the mangrove sediments with different densities of the tree were significantly different in nitrogen content. The study showed that increasing the tree density leads to surface and altitude growth as well as tree survival in areas prone to sea-level rise. It seems that in mangrove development options, increasing the existing forest density will lead to more fertility, growth, and carbon than increasing the area with the current density in a forest. However, although denser and older forests have more carbon stock, the rate of carbon increase (carbon storage potential) is higher in young forests (Walcker et al. 2018).

The mean carbon in this study was 761.2 t ha^{-1}, which was much higher than the carbon in the terrestrial forests of Iran, 14.5 t ha-1 (Rousta et al. 2013), 48.3 t ha^{-1} (Panahian et al. 2014), 258.25 t ha^{-1} (Pato et al. 2017). The carbon ranged from 640.14 to 902.32 t ha^{-1}, which is similar to the total carbon in the mangrove forest of Australia and south China 937 t ha^{-1} (Alongi 2012). But it was greater than the carbon reported from China's mangrove 353.23 t ha^{-1} (Liu et al. 2013), Japan 119.3 t ha^{-1} (Khan et al. 2007), Indonesia 237 t ha^{-1} (Chen et al. 2018), and Malaysia 246.21 t ha^{-1} (Hemati, 2017), and less than the carbon reported from IndenoPasefic 1023 t ha^{-1} (Donato et al. 2011) and Paula 479–1068 1023 t ha^{-1} (Kauffman et al. 2012). The reason for the difference in the carbon among the mangrove forests in countries is due to the effect of the factors on the growth and carbon of the mangrove. This might be because the latitude is a major factor that controls the distribution and growth of the mangroves on a global scale. Other factors related to the importance of and the correlation with the carbon content are annual precipitation, isothermality, water balance, and temperature annual range (Estrada and Soares 2017).

Carbon sequestration rate

The carbon of the mangrove vegetation was 34.92 t ha^{-1} in Asalouyeh in the present study, which shows an increase (8.64 t ha^{-1}) compared to the carbon of the mangrove vegetation in Asalouyeh reported by Ghasemi (2016) (26.28 t ha^{-1}). In other words, the annual rate of the carbon sequestration has been 2.88 t ha^{-1} in the mangrove vegetation of Asalouyeh, while in Basatin, the carbon storage of trees has been reduced compared to 2016 (Ghasemi 2016). This decrease is due to deforestation in this forest that happened for the reasons mentioned previously. According to the CO_2 equivalent of 3.67 (Kouffman and Donato 2012), the CO2 sequestration rate has been 10.56 t ha^{-1} y^{-1} in the mangrove vegetation of Asalouyeh. According to the result, the mean carbon in the surface layer of Asalouyeh sediment was 1.05% and in the surface layer of Basatin, the sediment was 1.01%.

The sedimentation rate in different locations in the Persian Gulf was reported at 0.03–2.5 mm y^{-1}, and the sedimentation rate in the Nayband bay was considered 2.5 mm y^{-1} (AI-Ghadban 1998). However, the approximate rate of the carbon sedimentation has been 3.435 t ha^{-1} y^{-1} in Asalouyeh and 3.030 t ha^{-1} in Basatin based on the sedimentation rate and the carbon surface layer. Considering the CO_2 equivalent of 3.67, 12.60 t ha^{-1} y^{-1} of CO_2 has been stored by the sediments of Asalouyeh, and 11.12 t ha^{-1} y^{-1} has been stored by the sediments of Basatin. Therefore, the total sequestration rate in vegetation and sediment in the two mentioned forests has been 22.46 t ha^{-1} y^{-1}, which is the capacity of Nayband mangrove forest for CO_2 absorption. This capacity can be enhanced by eliminating the limitations of mangrove habitat, and can be used for sequestering carbon dioxide emissions from PSEEZ industries in the area.

Conclusion

There were significant differences between the carbon values at the stations and all the three studied forests. In general, denser coating stations had more carbon in their biomass and sediments. The amount of the carbon in the studied area was moderate to high compared to the carbon reported for other mangroves in the world. The highest total carbon was observed in the Asalouyeh and the lowest was observed in the Malegonzeh. The CO_2 sequestration rate in Basatin was lower than in Asalouyeh. The amount of the carbon in vegetation in Malegonzeh with no influences of PSEEZ, Basatin with the negative influences of PSEEZ, and Asalouyeh with fewer influences showed the impact of the anthropogenic activity relative to PSEEZ on the neighborhood mangrove.

The total CO_2 sequestration capacity of Nayband Mangrove forests has been 22.46 t ha^{-1} y^{-1}. The mangrove in Nayband can be used as an opportunity, by sequestering the CO_2 from PSEEZ. Further studies are suggested on the management and modeling of the Nayband forest to sequestrate the CO_2 emitted from PSEEZ.

Declarations

Conflict of interest The authors declare there are no conflicts of interest regarding the publication of this paper.

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