Regional Studies in Marine Science 66 (2023) 103142

Contents lists available at ScienceDirect

Regional Studies in Marine Science

journal homepage: www.elsevier.com/locate/rsma

Estimating blue carbon storage in the mangrove forest of Gaz-Harra wetland, Strait of Hormoz

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ARTICLE INFO

Article history:
Received 9 April 2023
Received in revised form 26 June 2023
Accepted 31 July 2023
Available online 5 August 2023

Keywords:
C stock
Climate change
Azini Creek
Sirik
Harra
Chandal

ABSTRACT

Mangrove forests efficiently absorb and fix carbon ecosystems, playing an influential role in reducing greenhouse gases. In this study, we measured the whole and top 1 m soil carbon (C) stock and the carbon stored in the above- and belowground parts of mangroves in 10 stations within the Gaz-Hara Wetland (GHW). GIS-based satellite image processing indicated that the total area of the GHW mangrove forest is 1038 ha, and *Rizophora mucronata*, mixed, high-density *Avicennia marina,* and low-density *A. marina* habitats comprise 12.5, 30, 35.5 and 22% of the forest area, respectively. Soil organic C content ranged from 0.45–3.01%, with *A. marina* habitats having a higher content than the *R. mucronata* habitats. The average top 1 m soil C stock of mangrove is 108 MgC ha^{-1}, with high-density *A. marina* habitat accounting for 37% of it. This amount is within the global average range of mangroves in dry subtropical areas. The total amount of soil C stock in the area is 220,867 MgC. Furthermore, 361,000 MgC has been sequestered in the mangrove trees of GHW, 69% of which is accumulated in the aboveground and the rest in the belowground portions. The soil and trees of the GHW habitats have stored 537 Gg C, equivalent to 1.97 Tg CO_2, of which 220 and 317 Gg C have been accumulated in the soil and the biomass of mangrove trees, respectively. Deforestation of GHW mangroves would result in a potential CO_2 emission of 1.33 Tg CO_2 (1.16 Tg CO_2 by trees and 0.17 Tg CO_2 by the top 1 m of soil).

1. Introduction

Mangrove forests are among the most fertile coastal ecosystems, with valuable functions such as protecting the coast against wave erosion, creating a habitat for aquatic and terrestrial animals, and exchanging nutrients with the surrounding coastal environments (Lee et al., 2019). One of the essential services that mangrove forests provide is the absorption and stabilization of atmospheric carbon (C), which has attracted the attention of scientists in the last two decades due to increasing concern about global warming. Studies show mangroves can store two to three times more organic carbon per unit area than most terrestrial forests (Tue et al., 2012). Tropical–subtropical mangrove forests can store about 550 and 900 MgC ha^{-1}, respectively (Sanders et al., 2016). Moreover, these forests can store C up to several meters deep in their soil. Due to being saturated with water and creating an anoxic environment in the bed, their ability to preserve C is ten times more than the terrestrial forests of temperate or tropical regions (Alongi et al., 2016; Smoak et al., 2013). Therefore, evaluating the environmental importance of these forests due to their protection is an essential tool to reduce man-made greenhouse gases.

Compared to dense mangrove forests in humid tropical areas, few studies have been conducted on mangrove habitats in subtropical dry regions characterized by high temperature, low and short-term rainfall, and high salinity (Atwood et al., 2017). However, due to the hot and dry climate and very sparse coastal vegetation, the mangrove forests of these areas have particular importance for the local economy and environment. These forests are also more vulnerable to climate change and global warming (Schile et al., 2017). In recent years, increasing studies have been conducted on the amount of C sequestration in mangrove forests of subtropical dry areas, including the Bay of California (Ezcurra et al., 2016), Saudi Arabia (Eid et al., 2019; Shaltout et al., 2020), Qatar (Chatting et al., 2020), United Arab Emirates (Schile et al., 2017) and Egypt (Eid and Shaltout, 2016). Similar studies in the Iranian mangrove environments have a concise history and are all limited to the last few years. These include the evaluating C stock in the Khuran area (Hamzeh and Alizadeh, 2022), Bushehr (Hamzeh, 2023; Mahmoudi et al., 2022) and Govatr (Hamzeh et al., 2023). Askari et al. (2021) have conducted the only blue carbon investigation in the study area. However, as this study

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https://doi.org/10.1016/j.rsma.2023.103142
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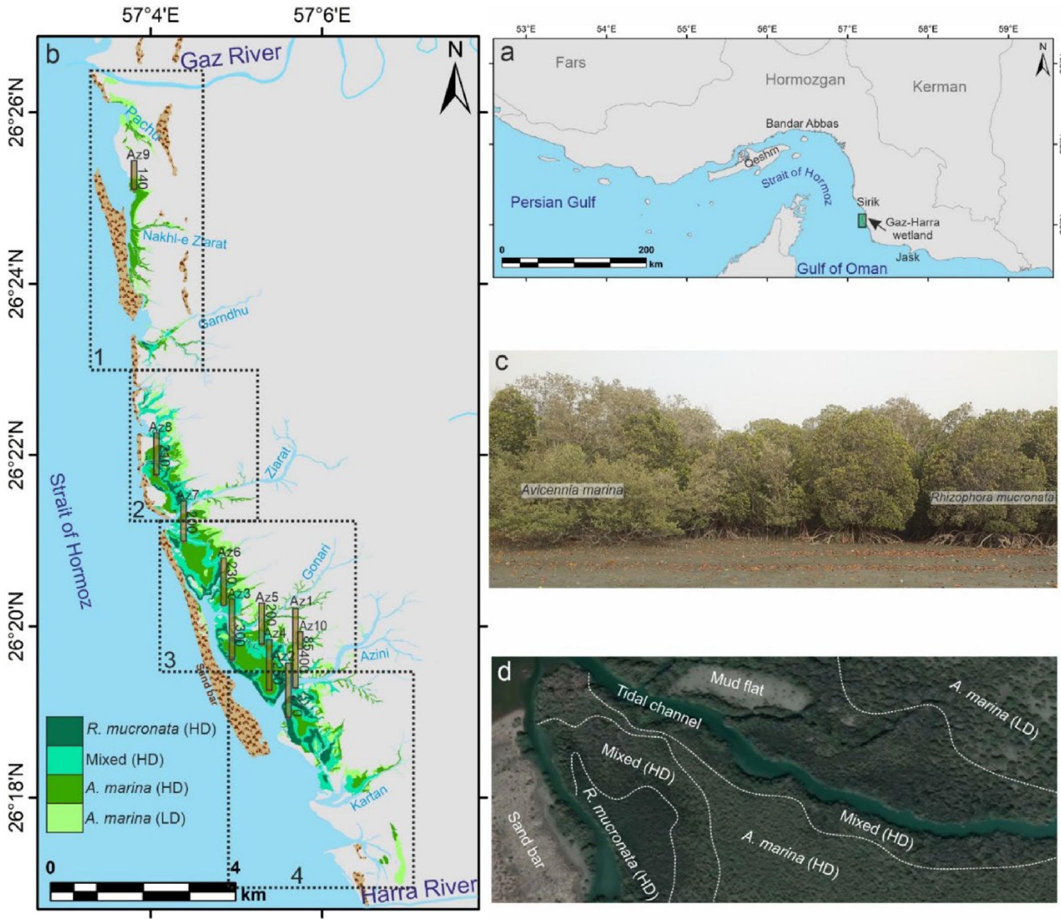

Fig. 1. General map of GHW mangrove forests (a) and the investigated area and sampling points (b). The length of the cores is given in the sampling points. (c) Photo of *A. marina* (Harra) and *R. mucronata* (Chandal) tree species; (d) Satellite image showing *R. mucronata*, mixed and high density (HD) and low density (LD) *A. marina* forests.

is done on the top 50 cm of mangrove soil with limited stations, it cannot provide detailed information on C stock in the whole ecosystem of the Sirik (Gaz-Harra) mangrove area and its potential to contribute to the CO_2 release into the atmosphere.

The Gaz-Harra Wetland (GHW) mangrove is the second largest mangrove in Iran and the only mangrove forest in Iran with two species of mangrove trees. Therefore, it can be considered a unique habitat for mangrove communities in Hormozgan province and the country. This study investigates C stock in the mangroves of estuaries between Gaz and Harra seasonal Rivers (GHW), the most crucial mangrove forest between two different marine environments, the Sea of Oman and the Persian Gulf.

2. Study area

The study area is located in the Gaz-Hara International Wetland, situated along the coasts of the entrance to the Strait of Hormoz, between the Gaz and Hara (Hivi) rivers (Fig. 1a). This wetland has been formed in Pachur, Nakhle Ziarat, Garndho, Ziarat, Gonari, Azini and Kartan creeks, which are 27 km away from Sirik Port (Fig. 1b) (Taghizade et al., 2009). This wetland, with an area of 16,914 ha, was designated as a protected area under the name of the Gaz River Mangrove Protected Area. This international wetland includes a set of tidal mudflats, mangrove forests (900 ha), tidal channels (creeks), several permanent and seasonal islands (sand bars) and sandy beaches (Hamzeh et al., 2023). The mangrove habitat of this area is the only Iranian mangrove environment hosting two species, including *Avicennia marina* (Harra) and *Rhizophora mucronata* (Chandal). Except for the first two estuaries (Pachur and Nakhle Ziarat), *A. marina* and *R. mucronata* communities can be observed together (Danehkar et al., 2010).

These forests, which are also known as Sirik mangrove forests (due to being located close to the Sirik port), are grown in the margins of several small and large creeks behind a barrier beach (sand bar). The presence of two mangrove tree species has created three types of forest stands. The pure *R. mucronata* habitat is often along the margins of the main creeks; the pure *A. marina* habitats evolved at the end of the habitat, in part facing the dry upper limit of high tides and sometimes on the margin of the subsidiary creeks and finally the mixed habitats between them (Danehkar et al., 2010). The study of the distribution of mangrove communities in this habitat shows that from the north to the south of the GHW, and by getting closer to the main creeks, *R. mucronata* becomes more abundant. Based on the processing of satellite images by Taghizade et al. (2009), the area of *A. marina*, *R. mucronata,* and mixed habitats is 272.6, 43.9 and 326.7 ha, respectively.

The GHW has a hot and dry climate with low rainfall (100 to 300 mm year^{-1}) and a high average annual temperature. The maximum air temperature exceeds 40 °C on most summer days. The region's coasts have diurnal tides (Taghizade et al., 2009). In terms of geology, the studied area is located between two distinct geological zones, coastal Makran (Makran subduction zone) and coastal Zagros (Arabian subduction zone beneath Iran), which are separated by the Minab-Zindan fault system (Regard et al., 2006).

The geological facies upstream of the study area include gypsiferous shales, conglomerate, sandstone, foothill conglomerate and melange. The composition of the soil is generally sandy silt (sand: 22%, silt: 58% and clay: 20%) (Parvaresh et al., 2011). Due to the flooding regime of rivers in a sparsely vegetated catchment area, the amount of sediment brought by the inflowing seasonal rivers in the region is relatively high. The Gaz River originates from Siba Mountain, and after traveling for about 80 km and passing through the Gaz Village, it enters the GHW. Harra River (Hivi) is about 65 kilometers long and originates from 100 km southeast of Minab and enters this international wetland after passing through the valley of Puste Kuh and Mount Sikuei. Every year, 5350 tons km^{-2} of sediment enters the mangroves through the Gaz River, which is trapped by mangroves, especially *A. marina* (Parvaresh et al., 2011; Askari et al., 2021).

3. Methods

3.1. Spatial analyses

For investigating the vegetative conditions of mangrove forests, high-resolution geo-referenced Google Earth satellite images were downloaded and processed by geographic information system software(so that the crown of the trees can be seen in the images; Fig. 1d). The distribution map of *A. marina*, *R. mucronata*, and mixed habitats was done by combining satellite images, field survey, and previous studies. The density map of mangroves was compiled by combining studies and field and remote sensing studies, and the area of each density class was determined with high accuracy using ArcMap analyses. This classification is based on tree canopy cover (percentage of forest area covered by trees) and tree height (Elijah et al., 1996; Heumann, 2011). Since the density of *R. mucronata* and mixed forests is very high (over 70%) everywhere, only the names of *R. mucronata* and mixed forests were used. On the other hand, the areas dominated by *A. marina* were divided into two categories: high-density (HD; canopy cover above 50%) and low-density (LD; canopy cover below 50%) areas.

3.2. Field measurement and analyses

The field studies include studying and measuring the size and density of both mangrove species and sampling the sediment core. This survey conducted field studies in 10 stations (4 HD *A. marina* stations, one LD *A. marina* station, 2 *R. mucronata* stations and three mixed stations). In each sampling station, a 7 m radius circle was considered. In the center of each circle, the sediment core was retrieved by an auger corer to a maximum depth of the mangrove forest soil (reaching the light-colored sandy sediments). Then sub-samples were taken from the depths of 0–15, 15–30, 30–50, 50–70, and 70–100 for the upper one meter. In areas with deeper cores, the distance between sub-samples was considered 50 cm (Kauffman and Donato, 2012). Furthermore, the vegetative characteristics of all trees, including tree height and diameter of the main trunk at the height of 130 cm (diameter at breast height (dbh_{130}); Komiyama et al., 2005, were measured inside the circle. Since *A. marina* generally branches from the ground's surface, the dbh $_{130}$ of all branches was measured (Howard et al., 2014).

3.3. C stock analysis and measurement

3.3.1. Vegetative C stock

To calculate the biomass of mangroves, we applied 0.69 and 0.83 gr cm^{-3} as the wood densities of *A. marina* (Ghasemi et al., 2016) and *R. mucronata* (Askari et al., 2021), respectively.

Aboveground carbon (AGC): The amount of aboveground biomass (AGB) of each tree was calculated by Eqs. (1) and (2) (Komiyama et al., 2005; Kauffman et al., 2011):

$$AGB_{A.marina} = 0.0509 \times \rho \times D_2 \times H \tag{1}$$

$$AGB_{R.mucronata} = 0.251 \times \rho \times D^{2.46} \tag{2}$$

Where AGB is the aboveground biomass (kg) of mangrove trees, ρ is the wood density (gr cm^{-3}), D is the diameter at breast height (dbh_{130}) (cm), and H is the tree height (meters) (Komiyama et al., 2005). For calculating the amount of carbon in each tree, the calculated biomass was multiplied by the conversion factor (0.5) (Kauffman et al., 2011).

Belowground carbon (BGC): The amount of belowground biomass (BGB) of *R. mucronata* was calculated by Eq. (3) (Komiyama et al., 2005):

$$BGB_{R.mucronata} = 0.199 \times \rho^{0.899} \times D^{2.22} \tag{3}$$

BGB is the belowground biomass of R. mucronata (kg), and the other parameters are similar. To calculate the belowground tree biomass of *A. marina*, the $AGB_{A.marina}$ was multiplied by a factor of 0.724 (Wang et al., 2014). Also, to calculate the amount of BGC, the amount of BGB was multiplied by the carbon conversion factor (0.39) (Kauffman et al., 2011).

Finally, the total amount of AGC and BGC calculated in all the trees within a circle (0.0154 ha: the area of the 7 m radius circle) was converted to AGC and BGC in one ha.

3.3.2. Soil C stock

In the laboratory, 10 cm^2 of sediment was sampled by a syringe whose head was cut off and placed in an oven at 60 °C for 48 h to reach a constant weight. Hence, the dry density of the dry sediment (gr cm^{-3}) was obtained by Eq. (4) (Howard et al., 2014):

$$DBD_{soil} = W_{dry\ soil}/V_{wet\ soil} \tag{4}$$

Where DBD $_{soil}$ is the dry bulk density of mangrove soil (gr cm^{-3}), $W_{drysoil}$ is the weight of oven-dried sediment (gr), and $V_{wetsoil}$ is the volume of wet sediment (cm^3). Then, the oven-dried sediment was combusted in an electric furnace (450 °C for 4 h) to obtain loss of ignition (LOI) as follows (Eq. (5); (Heiri et al., 2001)):

$$LOI_{soil} = W_{combusted\ soil}/W_{dry\ soil} \times 100 \tag{5}$$

Where LOI_{soil} is the loss of ignition of soil, $W_{combusted\ soil}$ is the weight of combusted soil (gr), and $W_{drysoil}$ is the weight of oven-dried soil. In this study, the conversion formula of Ouyang and Lee (2020) was used to evaluate the percentage of organic carbon (% C_{org}). In the mentioned new research, they proposed an equation for the conversion of LOI into organic carbon by examining more than 1,500 mangrove forest soil samples (Eq. (6)):

$$\%C_{org} = 0.21 \times \%LOI^{1.12} (r^2 = 0.86) \tag{6}$$

Where % C_{org} is the percentage of organic carbon in mangrove soils, and the LOI_{soil} is the loss of ignition of soil. For each interval of the core sample, the organic carbon density of the soil was calculated by multiplying % Corg/100 by DBD $_{soil}$. Then, the amount of carbon in the various sections of the core was calculated by multiplying each soil carbon density value by the thickness of the sample interval (cm). We Summed the amount of carbon in core sections over the sampling depth (1 m for the top 1 m soil C stock and the entire depth for the whole soil C stock). Finally, the total core carbon was converted into the mega gram C per hectare (MgC ha^{-1}) by multiplying the summation of the amount of carbon in each core (top 1 m and whole core) by 100. The average of these values in each habitat was multiplied by the area of each habitat to obtain the soil C stock in different areas. These values were calculated for the soil's total thickness and its top 1 meter.

In previous studies, the area of Iranian mangrove forests was calculated using Landsat images with a spatial resolution of 15

Table 1
Area of mangrove forests and soil depth in each part of GHW mangrove.

Zone (Soil depth (cm))	Habitat	Area (ha)	Top 1 m soil volume (m^3)	Whole soil volume (m^3)
1(140)	HD *A. marina*	66.0	660,320	924,448
	R. mucronata	1.7	16,854	23,596
	Mixed	6.4	64,060	89,684
2(210)	HD *A. marina*	53.7	536,870	1,127,427
	R. mucronata	23.4	233,980	491,358
	Mixed	72.6	795,953	1,524,501
3(232)	HD *A. marina*	188.1	1,881,210	4,373,813
	R. mucronata	45.4	454,370	1,056,410
	Mixed	145.0	1,450,000	3,371,250
4(307)	HD *A. marina*	61.7	617,320	1,893,145
	R. mucronata	59.2	592,380	1,816,632
	Mixed	86.1	861,440	2,641,749
LD *A. marina*		230.2	2,302,920	1,957,482
Total		1,038	10,397,678	21,291,496

to 30 m. However, this method does not allow for the accurate separation of different mangrove habitats and densities. This study used high-resolution Google Earth images with a spatial resolution of less than 1 m to measure the mangrove area using GIS processing. The forests were divided into four zones based on the average length of the cores taken in each zone, and an estimate of the soil depth of each area was calculated (Fig. 1, Table 1). The amount of area and soil volume of each habitat in these areas were calculated using ArcMap. The total amount of carbon storage in the mangrove forest soil was obtained using each region's average soil density. The sand and mud content of soil samples were separated by wet sieving using a 63 μm sieve.

4. Results

Based on satellite image processing, the total area of mangrove forest in GHW is estimated to be 1038 ha. Of this, 35% (370 ha) is HD *A. marina*, 30% is mixed (310 ha), and 12% is *R. mucronata* (129 ha). These three habitats cover a total area of 808 ha. LD *A. marina*, which in many parts has a density of less than 10% with an area of 230 ha, occupy 22% of the region's forest area. Table 1 shows forest area, soil depth, soil volume, and as a result, the C stock in the soil of *A. marina*, *R. mucronata*, and mixed habitats in each section. According to the table, the area and percentage of *R. mucronata* habitat increase from north to south. *R. mucronata* and mixed habitats in Garndhu Creek comprise about 10% of mangrove forests. Around Ziarat Creek, these habitats cover more than 60% of forests (*R. mucronata*: 15%, mixed: 48%). The most participation of *R. mucronata* forests is observed between Azini and Kertan creeks (28%). In these areas, the amount of mixed habitats is about 40%. The mangroves are generally scattered along the edges of numerous tidal channels (creeks) in the area. *R. mucronata* trees are generally located at the border of main creeks (fringing mangroves), and the amount of *A. marina* trees increases landward (Danehkar et al., 2010). LD *A. marina* forests are at the extreme limit of forests. Danehkar et al. (2010) showed that R. mucronanta seedlings are replacing the older A. marina trees along the major creeks. They suggest that due to the lower salinity tolerance of *R. mucronata* compared to *A. marina*, they tend to grow along the major creeks with a higher ability of water exchange with the open water. Instead, the pneumatophore system of *A. marina* enables them to survive in more saline environments (Zahed et al., 2010). Therefore, they are dominated landward and along minor shallow creeks with higher evaporation rates. Numerous sand bars, which result from alongshore currents, play a vital role in reducing the effect of waves and creating a relatively calm condition, especially in the mouth of estuaries (Fig. 1).

Az1 (400 cm long; around Azini Creek) is the longest core in the area. The length of the cores decreases from the south to the north, reaching 140 cm at the Az9 station. However, the landward decreasing trend of the core length should not be overlooked. Hence, the length of the core in the LD *A. marina* forests (Az10) is only 85 cm. There are no significant spatial changes in the DBD and average soil $\%C_{org}$ in the area, but in general, the average amount of soil $\%C_{org}$ in *R. mucronata* (1.39%) and mixed (0.83%) habitats is 78% and 5% more than that of *A. marina* (0.79%), respectively. DBD variation in these habitats shows a reverse trend. The DBD and %Corg amount fluctuate between 0.6–1.6 gr cm^{-3} and 0.45–3.01 percent, respectively. The average DBD of the soil in the *A. marina* habitat is 1.3 gr cm^{-3}, which is 18% more than the *R. mucronata* habitat. On the contrary, the soil $\%C_{org}$ in the *R. mucronata* habitat is 1.39%, which is 75% more than the *A. marina* habitat (0.79%) (Fig. 2). The remarkable point is the negative correlation between soil DBD and the soil $\%C_{org}$ in soil cores (Fig. 2). The downward changes of the soil $\%C_{org}$ indicate a slight decrease in the carbon content from the surface to the depth, especially in the *R. mucronata* habitats (Az2 and Az3). The sand content of the soils oscillates between 26 and 41% (average: 33 ± 5.5).

4.1. Soil C stock

The total volume of mangrove soil in the GHW is about 21 million m^3, of which HD *A. marina* and *R. mucronata* habitats comprise 39% (8,318,834 m^3) and 16% (3,387,996 m^3), respectively. This amount for mixed mangroves is slightly less than the HD *A. marina* habitat (36%, equivalent to 7,627,185 m^3). About 9% of the volume of mangrove soils in the wetland also belongs to LD *A. marina* forests (1,957,482 m^3). The mean top 1 m soil C stock in the *R. mucronata* habitat is 150 MgC ha^{-1}. With a slight difference, mixed habitat (112 MgC ha^{-1}) and HD *A. marina* (108 MgC ha^{-1}) are placed in the second and third order. Nevertheless, the LD *A. marina* (60 MgC ha^{-1}) is in the last order by far. From the view of the C stock in the whole soil, the *R. mucronata* habitat contains the highest 312 MgC ha^{-1}(. After that, mixed habitat, HD *A. marina* and LD *A. marina* with 286, 212 and 60 MgC ha^{-1} are in the following orders (Table 2).

4.1.1. Top 1 m soil C stock

The top 1 m soil C stock of mangrove is 108,000 Mg, of which HD *A. marina* account for 37%. After that, mixed habitat, LD *A. marina,* and *R. mucronata* are in the following orders with 32, 18 and 13%, respectively. These changes are due to changes in the area of forests. As a general trend, C stock shows a significant decrease from the southern creeks close to the Harra River towards the

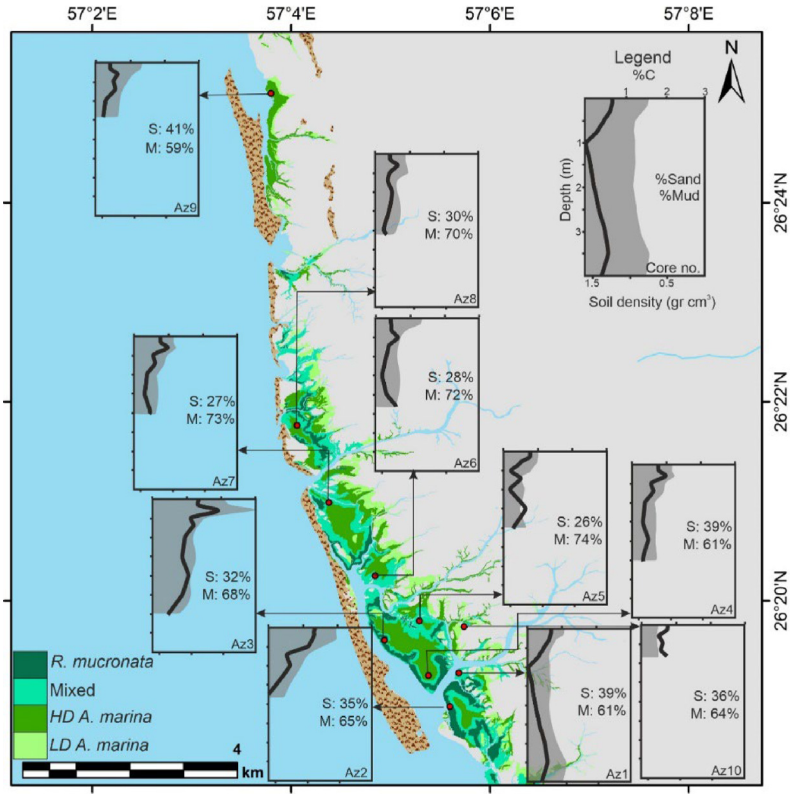

Fig. 2. Graph of changes in $\%C_{org}$ (the gray area) and soil DBD (solid line) along the soil cores of GHW mangrove forest. The average sand and mud content of cores is also included. The same range has been considered in all graphs to compare the changes along the core and the range of changes in soil %Corg and DBD. For showing the negative correlation between soil $\%C_{org}$ and DBD, the increasing direction of DBD is drawn reversely.

Table 2
The area of mangrove forests and soil depth and the C stock in the mangrove soil in GHW habitats (average ± SD).

Habitat	Area (ha)	Average soil thickness (cm)	Soil volume (m^3)	Average top 1 m soil C stock (MgC ha^{-1})	Average whole soil C stock (MgC ha^{-1})	Total top 1 m soil C stock (MgC)	Total whole soil C stock (MgC)	No. of stations
HD *A. marina*	369	215	8,318,800	107.7 ± 8.2	211.5 ± 35.9	39,702 ± 3,023	77,995 ± 13,237	4
R. mucronata	129	285	3,388,000	150.4 ± 0.2	311.8 ± 128.9	19,471 ± 26	40,365 ± 16,687	2
Mix	310	257	7,627,200	112.1 ± 7.6	286.3 ± 157.8	34,716 ± 2,354	88,682 ± 48,880	3
LD *A. marina*	230	85	1,957,500	60.0	60.0	13,824	13,824	1
Total	1,038	228	21,291,496	108.2 ± 26	281.4 ± 116.7	107,713 ± 26,993	220,867 ± 121,161	10

northern ones. For example, C stock in Az2 (*R. mucronata*) station is 150 MgC ha $^{-1}$ while C stock in Az8 (HD *A. marina*) station is 101 MgC ha^{-1}. However, exceptionally, this amount increases again in the Az9 station and reaches 121 MgC ha^{-1} (Fig. 3).

4.1.2. Whole soil C stock

The highest whole soil C storage is observed in mixed habitats (40%). After that, HD *A. marina* contains 35% of the whole soil C stock. More than 18% of the whole soil C is stored in the *R. mucronata* habitat, and the rest (about 6%) in the LD *A. marina*. The variation trend in C stock of the total depth of the soil is almost similar to its upper one meter and increases from the south to the north, with the difference that there is no further increase in the northernmost station due to the low soil thickness.

4.2. Vegetative C stock

Vegetative parameters highly vary in different habitats. For example, due to the smaller diameter of the crown, the number of trees in *R. mucronata* habitats (average 7,800 ± 755 trees per ha) is 17th times more than that of HD *A. marina* (450 ± 175 trees per ha). Because about 90% of the trees in mixed habitats are *A. marina*, the average number of trees in these habitats is close to the HD *A. marina* habitat (1,100 ± 230 trees ha^{-1}). On the other hand, the height of *A. marina* trees mainly varies between 4.5–5 m, which is about 2 m more than the *R. mucronata*. The trunk diameter of the *A. marina* trees is more than three times that of the *R. mucronata* (see Table 3).

The average AGC stock of *R. mucronata* habitats (381 MgC ha^{-1}) is about 26% more than that of HD *A. marina* (301 MgC ha^{-1}). AGC in LD *A. marina* is negligible (5 MgC ha^{-1}). The amount of BGC stock of the three dense habitats (*A. marina*, *R. mucronata* and mixed habitat) is almost similar. Due to the difference in the areas of the habitats, HD *A. marina* comprises about 45% of the total vegetative C stock in the area. After that, the mixed habitat (AGC: 34% and BGC: 39%) and *R. mucronata* (AGC: 20% and BGC: 15%) are in the following orders (see Table 4).

The highest vegetative C stock is observed in the area between Azini and Gonari creeks, as well as the northern part of Ziarat Creek (Fig. 4). As the vegetative C storage is independent of the depth of the soil, the trend of reducing the amount of carbon from the south to the north is less intense. However, the highest C stock in the trees can be seen in the Azini and Gonari creeks.

As shown in Fig. 5, in most stations, the amount of vegetative C stock is more than that of soil. The highest difference is observed in station Az5 (HD *A. marina*), where the carbon content of trees

Table 3
Area of mangrove forests and biometry of mangrove trees. The numbers separated by a hyphen indicate the minimum and maximum, and the numbers in parentheses indicate the average ± SD.

Habitat	Area (ha)	Tree height (m)	No. of trunks per ha	Trunk diameter (cm)
HD *A. marina*	369	0.5–6.5 (5.1 ± 1.3)	190–900 (450 ± 175)	8–85 (39 ± 23)
R. mucronata	129	0.7–6.8 (2.9 ± 0.95)	5500–9100 (7800 ± 755)	2–27 (12 ± 7)
Mixed	310	0.4–6.1 (3.9 ± 1.7)	580–1430 (1100 ± 230)	2–77 (27 ± 22)
LD *A. marina*	230	3.5	190	12–25 (18)
Total	1038	0.5–6.8 (4.3 ± 1.4)	190–9100 (2100 ± 700)	2–85 (31 ± 19.5)

Table 4
Vegetative C stock in different habitats of GHW mangrove (average ± SD).

Habitat	Average AGC ($MgC\ ha^{-1}$) *A. marina*	Average AGC ($MgC\ ha^{-1}$) *R. mucronata*	Average BGC ($MgC\ ha^{-1}$) *A. marina*	Average ($MgC\ ha^{-1}$) *R. mucronata*	Total AGC (MgC) *A. marina*	Total AGC (MgC) *R. mucronata*	Total BGC (MgC) *A. marina*	Total BGC (MgC) *R. mucronata*
HD *A. marina*	301 ± 45	0	137 ± 81	0	111,283 ± 16,637	0	50,689 ± 30,075	0
R. mucronata	23	381 ± 108	13	119 ± 48	2,991	49,326 ± 13,982	1,690	15,489
Mixed	224 ± 159	47 ± 43	127 ± 90	15 ± 13	69,484 ± 49,321	14,449 ± 13,219	39,239 ± 27,807	4,742 ± 4,109
LD *A. marina*	5	0	3	0	1,075	0	607	0
Total					184,834 ± 49,712	63,776 ± 22,798	92,225 ± 28,655	20,230 ± 7,700

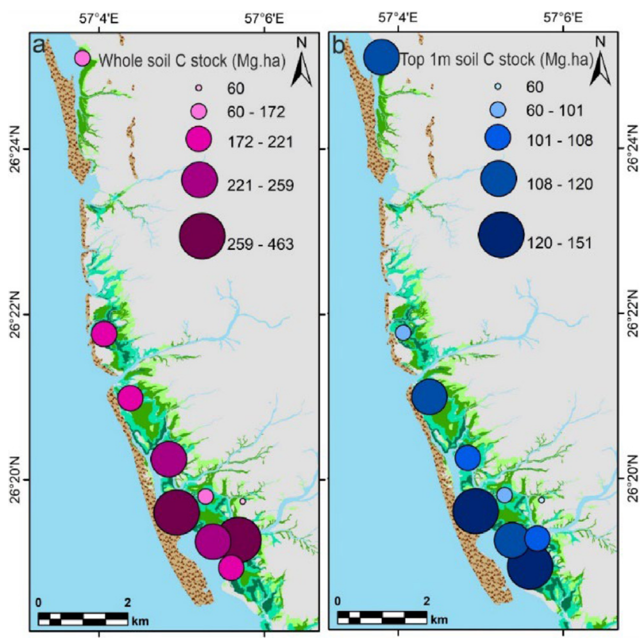

Fig. 3. Variations in whole soil C stock (a) and top 1 m C stock (b) of soil in Gaz-Hara mangrove.

is about three times more than soil C storage. Az8, Az6, Az2, Az3, Az1, and Az7 stations are in the following orders. Only in the Az9 station these two values are equal, and in the HD *A. marina* station, the amount of soil carbon storage is higher. The highest vegetative C stock is observed in the *R. mucronata* habitat (Az3). As seen in Fig. 5, in mixed habitats, vegetative C stock is much higher than that of *R. mucronata* trees due to the more significant number of branches of these trees and the small size of *R. mucronata* trees.

5. Discussion

Previous studies estimated that the total area of mangrove forests in the Gaz-Harra Wetland is 643 ha, with *R. mucronata* (44 ha), mixed (327 ha), and *A. marina* (273 ha) habitats accounting for 7%, 51%, and 42%, respectively (Taghizade et al., 2009). However, our GIS-based detailed measurement of the forest area in this survey showed that the area of the forests in the region (regardless of the LD *A. marina*) is 809 ha, which is 25% more than the former estimate. Also, the percentage of *R. mucronata*, mixed, and *A. marina* habitats is 16, 38, and 46 percent, respectively (*R. mucronata*: 129 ha, mixed: 310 ha and *A. marina*: 369 ha). It means that the percentage of *A. marina* habitat cover in the two surveys is almost the same, but the portion of mixed forests has been reduced and replaced by *R. mucronata*. This event is precisely similar to their suggestion that R. mucronata is superior in competition with A. marina, pushing aside them in mixed areas and dominating them (Danehkar et al., 2010). Nonetheless, it must be considered that Taghizade et al. (2009) used medium-resolution Landsat images (the spatial resolution: 30 m for the panchromatic band), while our area estimations are based on high-resolution (< 1 m) Google Earth images (Fig. 1d).

Mangrove habitats, especially *A. marina* species, have a significant effect in trapping suspended particles of sediment and organic matter due to the complex system of aerial roots (pneumatophore) and thus increasing the sedimentation rate (Dalrymple and Choi, 2007). Suspended sediments that enter the forest floor as a result of the rising phase of the tide (flood) are trapped in the network of roots while returning flow of the tide (ebb) cannot efficiently return them to the sea (Alongi, 2012; Ferreira et al., 2022). Trapped muddy sediment particles have a high surface area and absorbability due to relatively high organic matter content (Kristensen et al., 2008). However, compared to typical mangrove environments such as the Khuran mangrove (west of Hormoz Strait) with low energy vast intertidal mudflats (sand content: mostly <15% (Hamzeh and Alizadeh, 2022)), GHW is located in high energy (especially during the summer monsoon) straight S–N directed coast and is covered by sandy silt sediments (sand content: 27%–41%; mean 33.5%) which have low ability to absorb and store organic matter. Moreover, as most of the fringing mangroves of the area are *R. mucronata* which have no pneumatophore, the habitat cannot efficiently trap muddy sediments, which causes the enrichment of coarse grains and, in turn, declines organic carbon content.

The comparison of C stock in different mangrove habitats in Iran reveals that the Khuran mangrove (area: 8830 ha) constitutes around 85% of the country's mangrove area and holds more than 90% of Iran's blue carbon reserves (Hamzeh et al., 2023). Following the Khuran mangrove, the GHW mangrove has the subsequent highest C storage with 7% (0.65 TgC). However, with an upper 1 m soil sequestration of 113 $MgC\ ha^{-1}$, the GHW mangrove falls in the lower order of Iranian mangroves. In the study of mangrove habitat, vegetative C stock is approximately 65% more than the soil C stock. Compared to mangroves in humid tropical areas, mangroves in hot and dry sub-tropical areas have less biomass and biological productivity. The trees in these areas

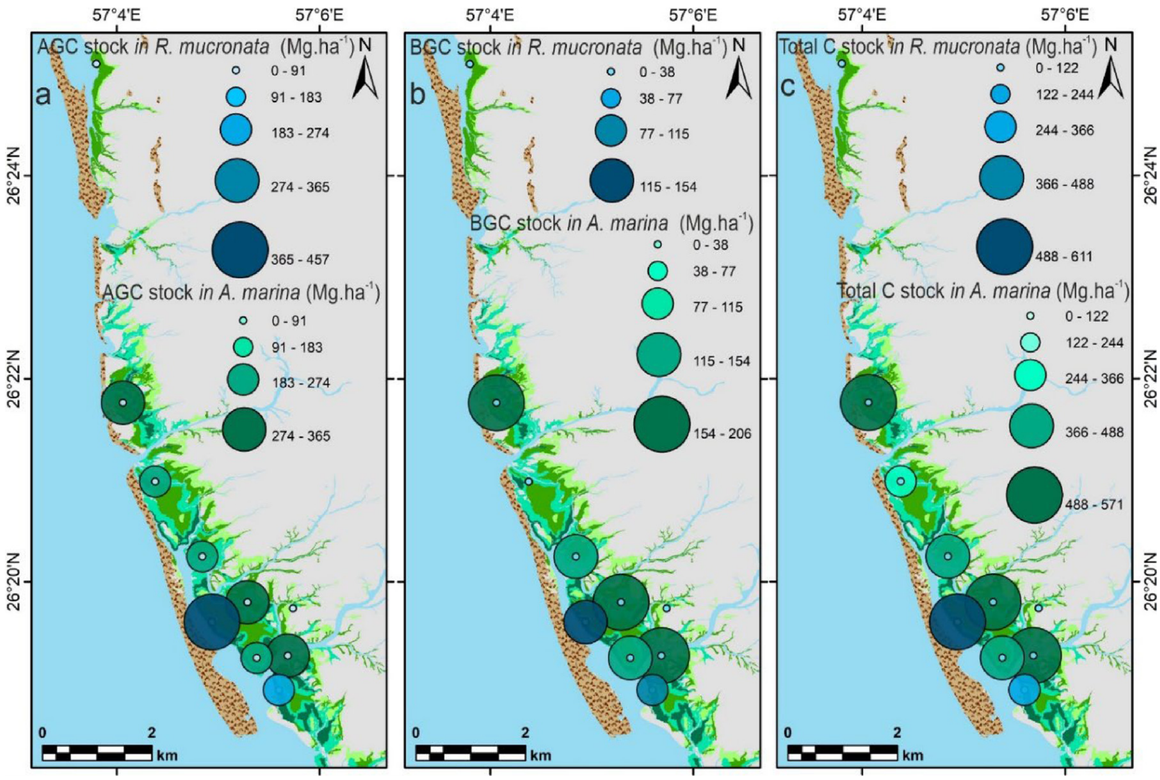

Fig. 4. Variation in AGC (a), BGC (b) and total vegetative C stock (c) in GHW mangrove.

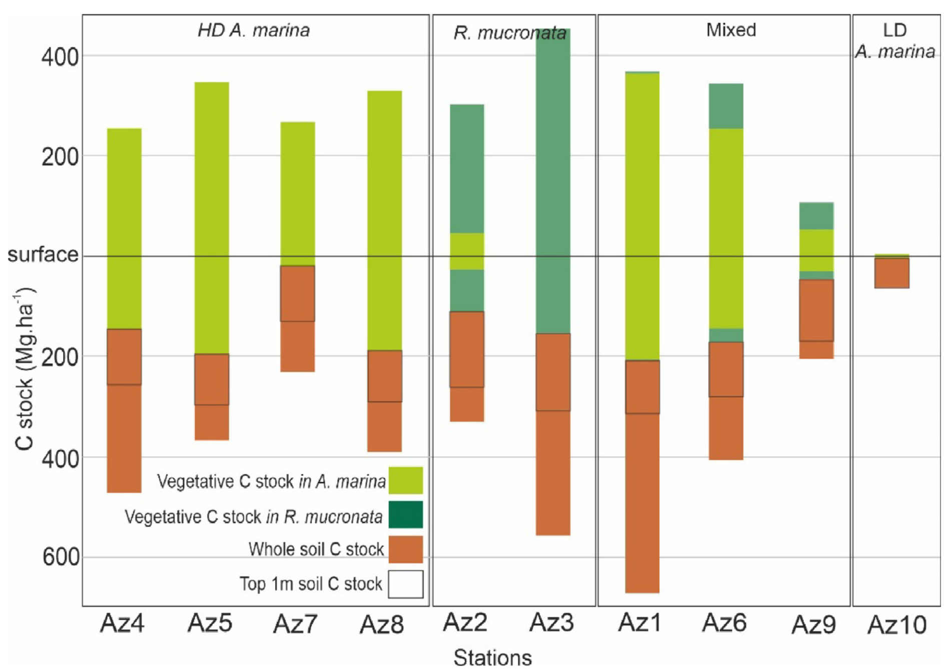

Fig. 5. Variation in soil and vegetative C stock (AGC and BGC) in different sampling areas in GHW mangrove.

have high density, but they are often smaller than in tropical areas, and the sediments of the forest floor are generally coarser (Alongi, 2012). The range and median of %C_{org} in mangrove GHW soil are 0.45–3.01 and 0.8, respectively, which is at the lower limit of the global average range (<0.1%–>40%) with a median of 2.2% (Kristensen et al., 2008). The average top 1 m soil C stock in the mangroves of Saudi Arabia is 72 MgC ha^{-1} (the lowest in the world) (Atwood et al., 2017), which is 50% less than this amount in the study area (113 MgC ha^{-1}) (Fig. 6). Atwood et al. (2017) demonstrated that mangroves at latitudes between 20–30° *N* have the lowest amount of carbon per unit area (222 ± 151 MgC ha^{-1}). However, the top 1 m soil C stock of GHW is 113 MgC ha^{-1}, which is in the lower part of the global average range.

The Iranian mangroves represent the upper limit of temperature tolerance at the northernmost boundary of growable areas (30° N) (Schile et al., 2017). Hence, these habitats are more sensitive to climate change and have much lower biological production and biomass than mangroves in humid tropical areas

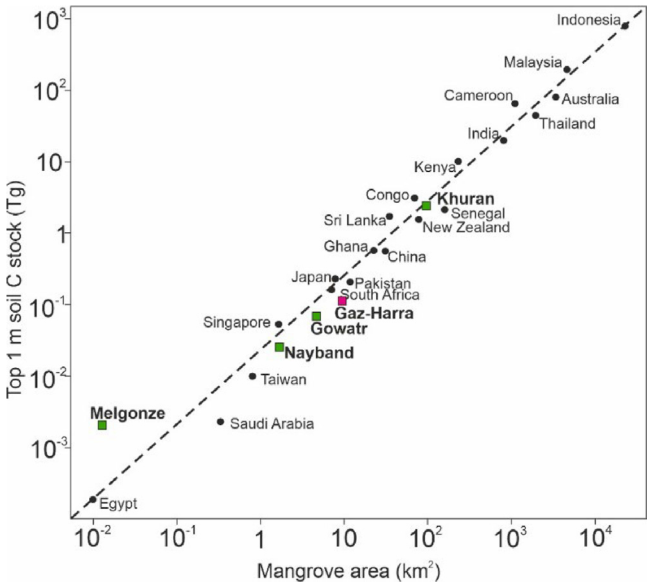

Fig. 6. The relationship between the top 1 m soil C stock and the area of mangrove forests in different countries (Atwood et al., 2017). The recent data from Iranian mangroves (including Khuran mangroves Hamzeh and Alizadeh, 2022, Gowatr Hamzeh et al., 2023, Nayband and Melgonze Hamzeh, 2023) are also included.

(Etemadi et al., 2018; Adame et al., 2021). As Ghyoumi et al. (2022) suggest, the annual temperature range is the most critical determinant of the Iranian mangrove distribution. During the last four decades, the mean temperature in southern Iran has increased by 3.14 °C (Etemadi et al., 2015). Although, the increasing trend of the Iranian mangrove area during the last decades is documented in several investigations (increasing rate: 21.6, 14.7, 3.2, 1.43 and 0.4 ha yr^{-1} in Minab, Qeshm, Govatr, GHW and Jask mangroves, respectively) (Danehkar et al., 2012; Safa-Eisini et al., 2006; Sadeghi, 2005); however, as Danehkar et al. (2010) indicated, in recent years, the expansion rate of mangrove forests has been stopped, and even, their area started to decrease in some habitats. Based on the predictions, the synergistic impacts of salinity and aridity, freshwater shortage and frequent exposure to the critical temperature threshold will decline the area of mangrove forests in the Persian Gulf in 2070, so that the GHW mangroves will disappear, and only two habitat patches will remain in the middle of the coasts of the Persian Gulf and the Oman Sea (Ghyoumi et al., 2022). Our calculations indicate that the soil and trees of the region's habitats have stored 537 Gg C, equivalent to 1.97 Tg CO_2, of which 220 Gg C have been accumulated in the soil and the rest (320 Gg C) in the biomass of mangrove trees. According to the calculations of Atwood et al. (2017), as a result of the of mangrove habitats destruction, about 43% of the carbon from the top 1 m of the soil returns to the atmosphere in the form of carbon dioxide. Accordingly, with the deforestation of GHW mangroves, about 1.33 Tg CO_2(1.16 Tg CO_2 by trees including foliage and roots and 0.17 Tg CO_2 by the top 1 m of soil) enters the atmosphere.

Declaration of competing interest

This paper is financially supported by the Iran National Environment Fund (IRNEF) and the Iranian National Institute for Oceanography and Atmospheric Sciences (INIOAS). The paper is prepared by one author (Mohammad Ali Hamzeh) and has no conflict of interest to declare.

Data availability

Data will be made available on request.

Acknowledgments

The present study is evolved from a joint research project by the Iran National Environment Fund (INEF) and the Iranian National Institute for Oceanography and Atmospheric Sciences (INIOAS), entitled "Assessment of the health of the mangrove forests of the Persian Gulf and the Sea of Oman"; no: 9310/1020571. The authors thank Mr M. Karimpour and B. Parasteh for their assistance in retrieving sedimentary cores and measuring tree biometrics.

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