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Role of Mangrove Rehabilitation and Protection Plans on Carbon Storage in Yanbu Industrial City, Saudi Arabia: A Case Study

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Abstract: Mangroves are one of the main considerations that might be used to mitigate the effects of climate change in coastal areas. Mangrove populations can be affected by industrial and civil activities on coasts. According to the Kyoto Protocol, protection and rehabilitation programs may play a pivotal role in conserving mangroves in industrial areas. Therefore, this study was designed to examine and evaluate the possible impact of conservation plans, implemented by the Royal Commission of Yanbu, in preserving mangrove trees' ability to store carbon in the soil. Soil and plant samples were collected from three distinct locations, including a mangrove conservation site in Yanbu and natural unprotected sites in Umluj and Ar-Rayis. Organic-carbon (OC) stock, in both soil and plants, was calculated. Our results showed that at different depths, soil bulk density (SBD) in Yanbu ranged between 0.32–0.94 g cm^{-3}. In Ar-Rayis and Umluj, SBD ranged between 1.43 to 1.99 and 0.90 to 1.57g cm^{-3}, respectively. The average SBD values in Yanbu, Umluj, and Ar-Rayis were 0.68, 1.71, and 1.20 g cm^{-3}, respectively. Similarly, the average soil OC density in Yanbu, Umluj, and Ar-Rayis was 165.19, 30.82, and 18.90 g C cm^{-3}, respectively. Generally, the conserved mangrove tress grown in Yanbu industrial city showed higher ($P \leq 0.001$) soil OC stock (0.39 t C ha^{-1}) compared to the unprotected trees grown in Umluj (0.12 t C ha^{-1}) and Ar-Rayis (0.11 t C ha^{-1}) cities. Similarly, the highest ($P \leq 0.001$) plant OC stocks (13.93 t C ha^{-1}) were observed in protected mangroves of Yanbu, compared to the plant OC stocks observed in Umluj (8.06 t C ha^{-1}) and Ar-Rayis (8.80 t C ha^{-1}) cities. The results of the current study showed that the protected mangrove trees grown in Yanbu industrial city store more carbon in their sediments than those grown in the Umluj and Ar-Rayis sites without conservation or rehabilitation. These findings may provide evidence for the beneficial role of protecting mangrove forests in mitigating the effects of climate change.

Keywords: Ar-Rayis; Umluj; bulk density; mangrove forests; organic-carbon storage

1. Introduction

Carbon sequestration and storage is defined as the physical, chemical, and/or biological fixation of atmospheric CO_2 into carbon reservoirs such as oceans, soil, and vegetation (especially forests, including mangroves). The main causes of rising atmospheric carbon levels are changes in land use, such as deforestation and consumption of fossil fuels [1]. Therefore, in response to such increases, scientific and public concerns were raised. The Kyoto Protocol was held in an attempt to regulate the atmospheric carbon levels by reducing greenhouse gases (GHG) in the atmosphere, by improving terrestrial carbon sinks (soil and plants) and reducing GHG emissions [2].

Soil, among other terrestrial ecosystem components, is considered to be the largest organic-carbon reservoir [3]. The most important factor affecting soil fertility, and other environmental aspects, is the soil organic carbon (SOC). This might be ascribed primarily to soil's high carbon storage potential. As the largest terrestrial carbon pool, SOC plays a pivotal role in the global carbon cycle [4]. SOC significantly affects soil fertility by altering the physical and chemical properties of the soil and releasing nutrients in plant-available form through mineralization [5]. To a depth of one meter, the soil carbon pool is estimated to be three times that of the atmosphere, and 3.8 times that of the vegetation pool [4]. Therefore, slight changes in the soil carbon pool might have a significant impact on the global carbon balance.

Mangrove coastal forests, considered to be among the most varied ecosystems in the world, perform a pivotal role in marine ecosystem balance and provide a variety of important ecosystem services [2,6,7]. One of the most significant ecological services provided by mangrove forests is their role as carbon sinks [8,9]. Mangrove trees absorb atmospheric carbon (CO_2), store it in their vegetation, and eventually bury it in their sediments; this is referred to as "blue carbon". Compared to a non-vegetated bare flat, mangrove rehabilitation and cultivation led to a significant increase in the ecosystem's organic carbon [10]. The annual carbon sequestration into mangrove soils and woody biomass in Brazil is estimated to be greater than 0.16 Tg C [11]. In Mexico, organic-carbon sequestration in highly preserved mangrove roots reached 2792 Mg C ha^{-1} [12]. Nevertheless, mangrove coastal ecosystems are threatened by deforestation, fragmentation, pollution, rising sea levels, and land use changes caused by human activities such as aquaculture ponds, urbanization, and/or agriculture or infrastructure development [6,13]. According to a 2017 United Nations Environmental Program (UNEP) report, "more than one-fifth (approximately 35,500 km^2) of the world's mangroves have been lost since 1980". This mangrove deforestation contributes about 0.12 Gt of annual CO_2 emissions, around 0.3% of total anthropogenic CO_2 emissions, resulting in significant adverse impacts that exacerbate global climate change. One of the UNEP coastal and marine ecosystems experts, Gabriel Grimsditch, stated that "Mangrove forests are highly productive ecosystems, and their conservation should be the top priority, but where mangroves have disappeared, restoration has also proved possible". Furthermore, according to the Kyoto Protocol (1992), protection and rehabilitation plans may play a pivotal role in the conservation of mangrove around industrial areas. Therefore, this study was designed to examine and evaluate the possible impact of protection plans implemented by the Royal Commission of Yanbu in conserving mangrove trees' ability to store carbon in their soils. This objective was achieved via comparing the soil and plant organic-carbon stocks in protected mangrove trees grown in Yanbu industrial city, with those grown naturally without conservation or rehabilitation in Umluj and Ar-Rayis cities.

2. Materials and Methods

2.1. Study Site Characteristics

Samples were collected from three separate stands in each of the three sites along Saudi Arabia's Red Sea coast: two natural (Umluj and Ar-Rayis) and one conserved (Yanbu) monospecific *Avicennia marina* sites. Yanbu industrial city is a city in Al Madinah Province of western Saudi Arabia that is governed by the Royal Commission of Yanbu (RCU). In general, Yanbu has a hot climate all year-round, with an average temperature of 27 °C and humidity ranging from 54 to 62%. The studied mangrove communities in Yanbu industrial city were the oldest among all the studied communities, with high vegetative growth (Figure 1a,b). Mangrove tress grown in Yanbu industrial city have been subject to a conservation and rehabilitation program since 1975, which was implemented by the Naval Program Department, RCU. This department, in association with other private sector partners, e.g., the Saudi Arabian Oil Company (Saudi Aramco) and the Saudi Basic Industries Corporation (SABIC), plants more than 1000 mangrove seedlings annually, and provides strict conservation measurements for them.

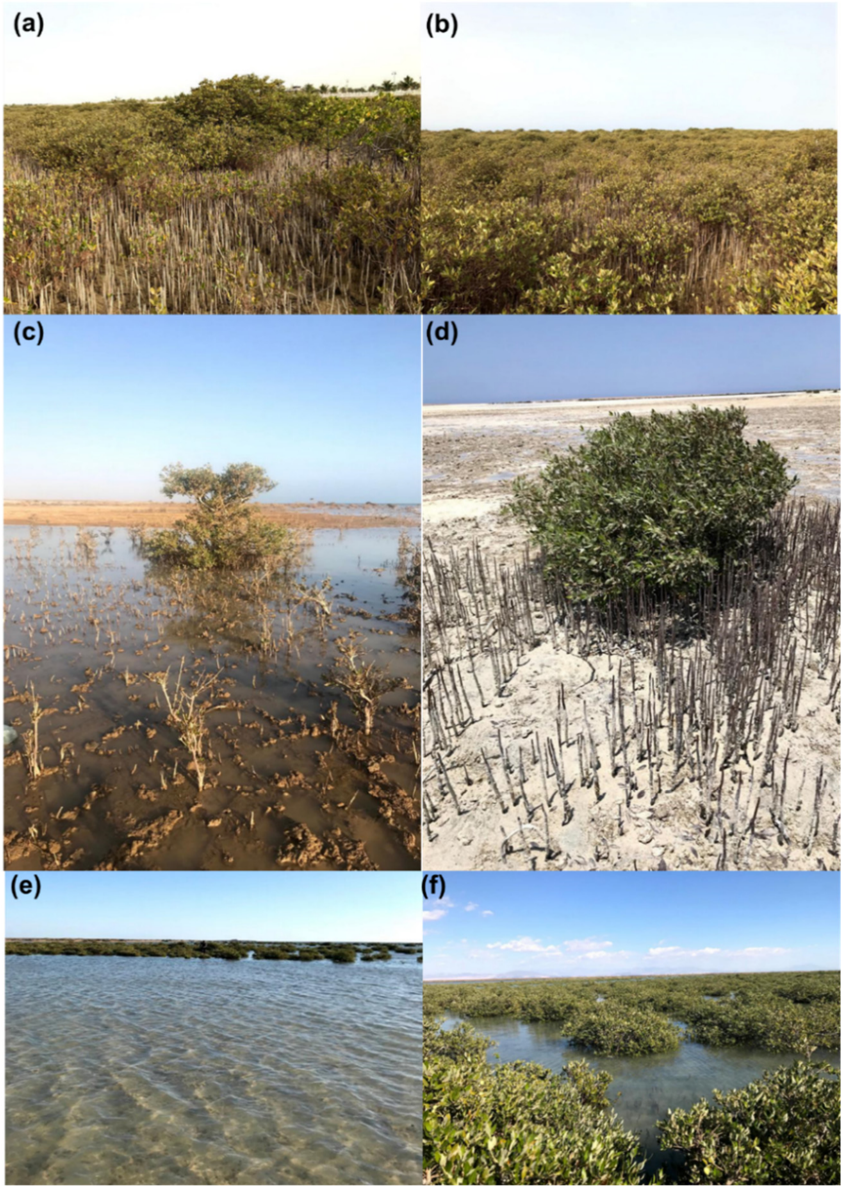

Figure 1. Mangrove communities in the different studied locations. (**a**,**b**) Yanbu industrial city; (**c**,**d**) Umluj; and (**e**,**f**) Ar-Rayis.

Umluj is one of the governorates of Saudi Arabia's Tabuk region, located in the northwestern part of the country. It has a hot and arid environment, with temperatures ranging from 28 to 42 °C, and a maximum monthly precipitation rate of 4 mm. Ar-Rayis is a small coastal town in Al Madinah Province, in western Saudi Arabia. During the last 30 years, the maximum recoded monthly precipitation was 7 mm. The monthly average temperature ranges between 28 and 42 °C. The mangrove communities in both Umluj (Figure 1c,d) and Ar-Rayis (Figure 1e,f) are characterized by lower vegetation compared to the Yanbu communities. Furthermore, no conservation measurements or rehabilitation plans have been implemented on mangrove trees grown in Umluj and Ar-Rayis.

2.2. Sample Collection

The sampling areas were selected randomly (three areas per each site); the size of each area was 50 m × 50 m, and their coordinates were recorded (Table 1 and Figure 2). Three soil cores (spaced in a triangle pattern with 15m between each core) were taken from each of the sampling sites. The soil samples were collected using a 5 cm diameter hand soil corer, which provided a core without distortion, compaction, or disturbance [7,14]. The soil corer was driven to a depth of 40 cm into the soil. After pulling out the corer, the whole of the soil sample was divided into five parts, at 8 cm intervals, to a depth of 40 cm from the core top (i.e., 0–8, 9–16, 17–24, 25–32, and 33–40), and packed in plastic containers. The sample containers were sealed with parafilm and stored on ice until the analysis, to avoid volatilization losses and limit microbial activity [15].

Table 1. The coordinates of the nine stands sampled in the current study.

Stand No.	Area	Latitude	Longitude
1	Yanbu	24°0′7.20″ N	38°9′18.00″ E
2	Yanbu	24°0′0.00″ N	38°9′36.00″ E
3	Yanbu	23°58′48.00″ N	38°11′52.80″ E
4	Umluj	24°47′38.40″ N	37°13′40.80″ E
5	Umluj	25°18′25.20″ N	37°6′57.60″ E
6	Umluj	25°36′10.80″ N	36°57′57.60″ E
7	Ar-Rayis	23°35′52.80″ N	38°32′20.40″ E
8	Ar-Rayis	23°35′52.80″ N	38°32′27.60″ E
9	Ar-Rayis	23°35′52.80″ N	38°32′2.40″ E

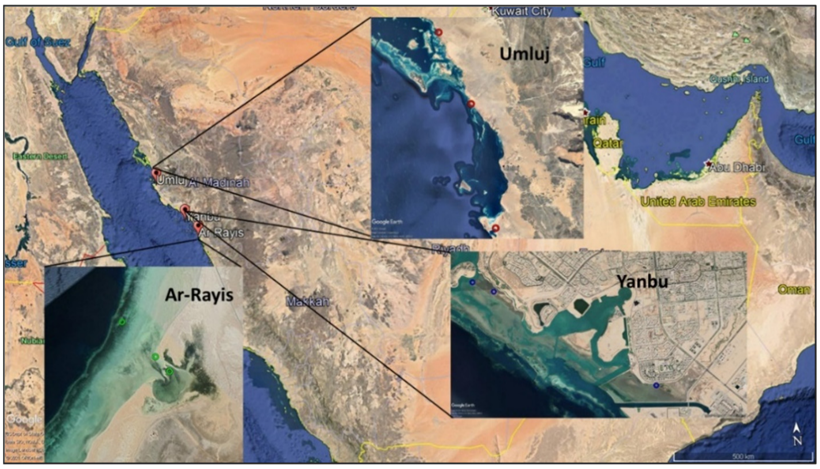

Figure 2. A map showing the location of the sampled stands (expanded images) on the Saudi Arabian Red Sea coast.

Standing-crop biomass of the above ground portions of mangrove was collected from three random quadrats of 0.5 × 0.5 m, in the three areas per each site, using clippers. The fresh weight and dry weight (dried for 48 h at 80 °C) of the plant samples were measured [16].

2.3. Sample Analysis

Each soil sample was dried in an oven at 105 °C for three days, allowed to cool to room temperature in a desiccator, and weighed to determine the SBD (g cm^{-3}) [17], using the following equation:

$$\rho_i = m_i / v_i \tag{1}$$

where ρ_i, m_i, and v_i are SBD, soil mass, and soil volume of the ith layer, respectively.

Air-dried soil samples were analyzed for SOC content by measuring the soil organic matter (SOM) using the loss-on-ignition method at 550 °C for 2 h [18]. SOM was recalculated to SOC using the following equation, developed especially for SOC calculation based on SOM in mangrove forests [19]:

$$SOC = 0.21 \times SOM^{1.12} \tag{2}$$

SOC stock (t C ha^{-1}), expressed as mass per unit surface area to a fixed depth of a profile, was calculated [20] using the following equation:

$$SOC_s = \frac{\sum_{i=1}^{k} \rho_i \times SOC_i \times T_i}{\sum_{i=1}^{k} T_i} \times D_r \times 10 \quad (3)$$

where SOC_s is the SOC stock in mangrove soils (t C ha^{-1}), ρ_i, SOC_i, and T_i are SBD, SOC content, and thickness of the *i*th layer, respectively, k is the number of the layers, and D_r is the reference depth.

Plant organic-carbon (POC) stock in mangrove trees was calculated based on total biomass per unit of area. Total biomass per hectare was calculated according to Mokany, et al. [21]. POC stock (t C ha^{-1}) was calculated using the following equation:

$$OC_p = DM \times CF \quad (4)$$

where OC_p is plant carbon stock (t C ha^{-1}), DM is dry biomass (t dry matter ha^{-1}), and CF is carbon fraction (t C t^{-1}dry matter), which equals 0.47 for tree vegetation [22].

2.4. Statistical Analysis

Two-way analysis of variance (ANOVA) was applied on the calculated SBD and SOC values, with site and depth as the two independent factors, via Statistical Package for the Social Sciences SPSS® Statistics 28 (IBM, Armonk, NY, United States). One-way ANOVA was applied to examine the changes in the studied parameters in different sites. The differences between means were evaluated using Duncan's multiple range test ($P \leq 0.05$). The correlation between SBD and SOC was examined via Pearson's correlation analysis.

3. Results

The obtained findings revealed that Yanbu industrial city had the lowest SBD (g cm^{-3}) among the studied locations, followed by Umluj, while Ar-Rayis soils had the highest SBD at various depths (Figure 3). The SBD gradually increased with depth in all locations. In Yanbu, the SBD increased, from 0.32 g cm^{-3} at 0–8 cm deep, to 0.94 g cm^{-3} at 33–40 cm deep. A similar trend was observed in the other two sites, although with higher values. In Ar-Rayis and Umluj, the SBD ranged between 1.43–1.99 and 0.90–1.57 g cm^{-3}, respectively.

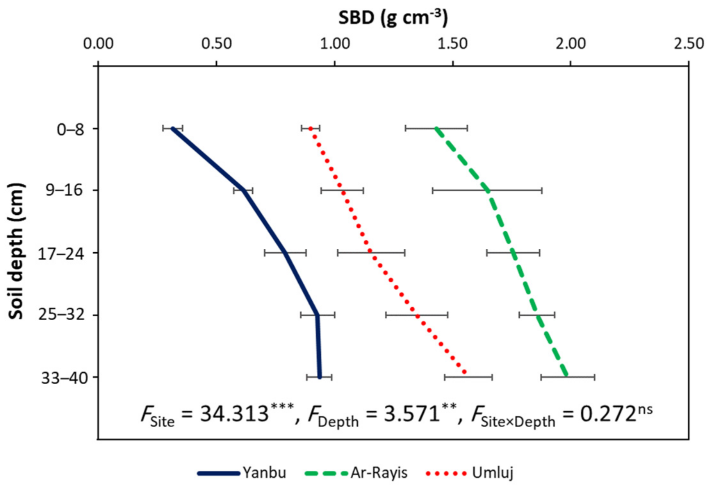

Figure 3. Mean distribution of soil bulk density (g cm^{-3}), with soil depth (cm), in Yanbu, Ar-Rayis, and Umluj cities, Saudi Arabia. Horizontal bars indicate the standard error of the mean (N = 3). *F*-values represent the two-way ANOVA results. Site: Yanbu, Ar-Rayis, and Umluj. Depth: 0–8, 9–16, 17–24, 25–32, 33–40 cm. ***: $P \leq 0.001$, **: $P \leq 0.01$, ^{ns}: not significant (i.e., $P > 0.05$).

Inversely, the SOC in all the studied sites showed an opposite pattern compared to that observed with regard to SBD. In Yanbu, for example, the SOC decreased, from 242.94 g C kg^{-1} at 0–8 cm deep, to 124.43 g C kg^{-1} at 33–40 cm deep (Figure 4). In general, Yanbu soils showed the highest SOC among all the studies locations. Umluj and Ar-Rayis soils showed almost the same SOC, especially in the superficial sediment layers (from 0 to 16 cm below the soil surface). The average SOC in Yanbu, Umluj, and Ar-Rayis was 165.19, 30.82, and 18.90 g C cm^{-3}, respectively. In all sites, the SOC decreased with depth, i.e., the deeper layers of the soil samples had lower SOC levels.

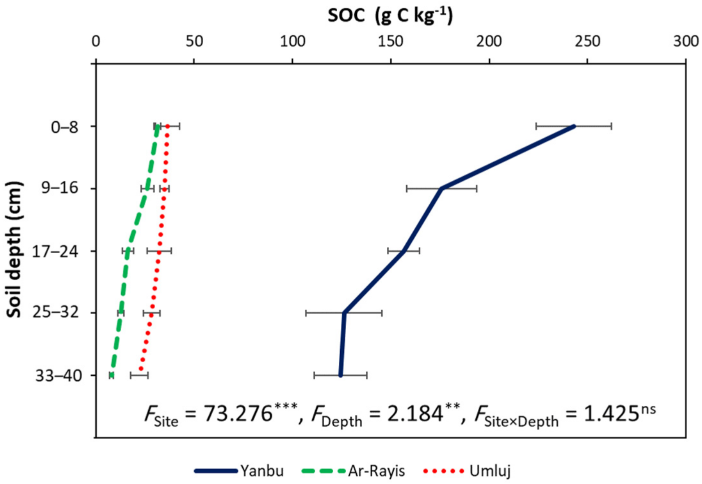

Figure 4. Mean distribution of soil organic-carbon concentration (g C kg^{-1}), with soil depth (cm), in Yanbu, Ar-Rayis, and Umluj cities, Saudi Arabia. Horizontal bars indicate the standard error of the mean (N=3). *F*-values represent the two-way ANOVA results. Site: Yanbu, Ar-Rayis, and Umluj. Depth: 0–8, 9–16, 17–24, 25–32, 33–40 cm. ***: $P \leq 0.001$, **: $P \leq 0.01$, ^{ns}: not significant (i.e., $P > 0.05$).

A significant inverse association between SOC concentration (g C kg^{-1}) and SBD (g cm^{-3}) was seen in all of the locations studied (Figure 5). These correlations could be described by non-linear regression equations, as follows, in Yanbu (SBD = 2.4238 $e^{-0.008 \times \text{SOC content}}$, R^2 = 0.8087, $P \leq 0.01$), Umluj (SBD = 1.8463 $e^{-0.004 \times \text{SOC content}}$, R^2 = 0.1333, ns), and Ar-Rayis (SBD = 2.2053 $e^{-0.025 \times \text{SOC content}}$, R^2 = 0.6525, $P \leq 0.01$) cities.

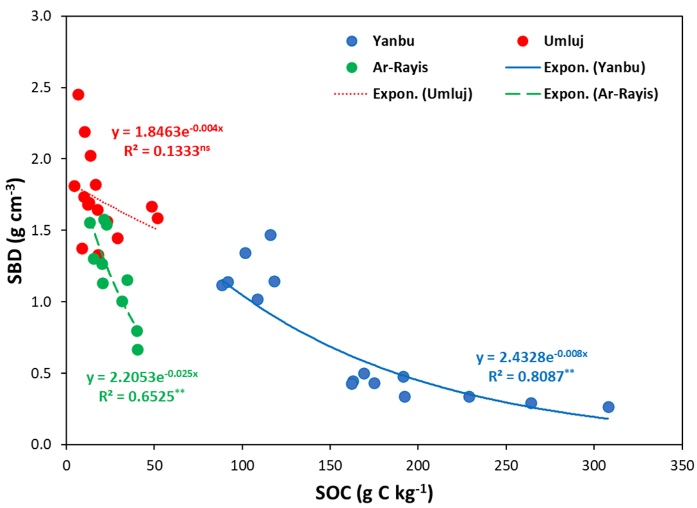

Figure 5. Non-linear correlation between sediment organic-carbon concentration (SOC; g C kg^{-1}) and sediment bulk density (SBD; g cm^{-3}) of 27 sediment samples collected from nine studied stands along the Saudi Arabian Red Sea coast in Yanbu, Umluj, and Ar-Rayis cities. In the equations, y: SBD, x: SOC, **: $P \leq 0.01$, ^{ns}: not significant (i.e., $P > 0.05$).

Our results showed significant variation among SBD values in all the studied sites (Table 2, $P \leq 0.001$). The average SBD values in Yanbu, Ar-Rayis, and Umluj were 0.72, 1.20, and 1.74 g cm^{-3}, respectively. The SOC content and stock per area-unit of the soil ranged from 25.99 g C kg^{-1} and 0.11 t C ha^{-1}, respectively, in Ar-Rayis, to 165.18 g C kg^{-1} and 0.39 t C ha^{-1}, respectively, in Yanbu industrial city. The one-way ANOVA revealed no statistically significant differences between SOC content and stock per area-unit in Umluj or Ar-Rayis. On the other hand, mangrove soils in Yanbu showed the highest SOC content and stock per area-unit among all the studied sites ($P \leq 0.001$). Similarly, mangrove trees in Yanbu industrial city showed the highest POC stock (13.93 t C ha^{-1}). There was no significant difference ($P \leq 0.05$) between POC stock in Umluj and Ar-Rayis sites.

Table 2. Total summation of soil bulk density (SBD; g cm^{-3}), soil organic-carbon concentration (SOC) (g C kg^{-1}), SOC stock (t C ha^{-1}), and plant organic-carbon (POC) stock (t C ha^{-1}) in Yanbu, Ar-Rayis, and Umluj cities, Saudi Arabia.

Site	SBD (g cm^{-3})	SOC (g C kg^{-1})	SOC Stock (t C ha^{-1})	POC Stock (t C ha^{-1})
Yanbu	0.72 ± 0.14 ^{a}	165.18 ± 14.85 ^{a}	0.39 ± 0.03 ^{a}	13.93 ± 1.01 ^{a}
Ar-Rayis	1.20 ± 0.30 ^{b}	25.99 ± 4.86 ^{b}	0.11 ± 0.01 ^{b}	8.80 ± 0.71 ^{b}
Umluj	1.74 ± 0.31 ^{c}	38.90 ± 5.21 ^{b}	0.12 ± 0.02 ^{b}	8.06 ± 0.88 ^{b}
F-value [1]	30.41 ***	57.13 ***	40.84 ***	10.21 *

[1] *F*-value represents the one-way ANOVA results. ***: $P \leq 0.001$, *: $P \leq 0.05$. Values are shown as mean ± standard error. Means in the same column followed by the same letter are not significantly different ($P \leq 0.05$), by Duncan's multiple range test.

4. Discussion

As an indicator of soil productivity, porosity, and/or mechanical stress to plant growth, SBD is one of the most important soil measures in soil studies and soil-processes-prediction models [2,23]. In general, SBD is influenced by soil organic-carbon content, as well as other factors [24]. The results of the current study showed significant variations in SBD values among the studied locations, with Yanbu industrial city having the lowest SBD when compared to Umluj and Ar-Rayis. The lower SBD values in Yanbu industrial city indicate the potential benefits of mangrove conservation in these sites, which led in SBD reduction. The reduction in SBD might be due to mangrove trees' rapid growth and vegetation, as well as their ability to generate organic materials from trash and protect coastal regions from erosion processes. Furthermore, the respiratory roots of mangroves provide shelter and habitat for a wide range of marine organisms. The activities of these fauna enhance sediment pores and the formation of macropores. Previous studies [10,25–28] confirmed the lower SBD values in mangrove protected regions as compared to other areas, which validate our results and demonstrate the importance of mangrove conservation. In the current study, SBD values were higher than those observed earlier in New Zealand (0.20–1.40 g cm^{-3}) [29], Sri Lanka (0.90–1.40 g cm^{-3}) [28], and Indonesia (0.16–0.76 g cm^{-3}) [25,26]. However, the SBD values were similar to those observed earlier in Saudi Arabia (1.66–1.82 g cm^{-3}) [27] and Egypt (1.27–1.88 g cm^{-3}) [30]. These discrepancies might be attributed to changes in soil properties between regions, since the sediments of mangrove areas in the Red Sea are finer and sandier than those in the surrounding areas. In all of the locations investigated, our findings indicated a gradual rise in SBD with depth. This finding is consistent with prior studies on mangrove forests, or distinct ecosystems, conducted in many places across the world [2,11,25–28,30].

Based on SOC content, the distribution of organic carbon in the studied locations along the Saudi Arabia Red Sea coast was explored. Our findings revealed that the soils of mangrove tress in Yanbu industrial city had the highest SOC content as compared to Umluj and Ar-Rayis ($P \leq 0.001$), with no significant differences between the two. In mangrove forests, SOC results mainly from litter fall and underground roots. The conservation plans in Yanbu industrial city led to stronger vegetation and, thus, higher SOC. Previous studies indicated continuous reduction of SOC content in unprotected areas, or areas subjected to land use changes [2,12,25–27,29–31]. Most of the previous studies observed a similar pattern of SOC to that observed in the current study, in terms of decreasing SOC with greater depth. The functions of organic matter in enhancing sediment porosity might explain the negative connection between SBD and SOC concentration in all of the locations studied. Our results, concerning SOC content in mangrove soils, are in accordance with earlier studies in Saudi Arabia [27] and Egypt [30].

A comparison of average SOC stock in the three studied sites indicated that mangrove forests in Yanbu industrial city store more carbon than those in Umluj and Ar-Rayis cities ($P \leq 0.01$). However, these results were lower than those reported previously in Saudi Arabia [6,27]. This might be related to the variability of the studied ecosystems. Moreover, our study examined the top 40 cm of the soil only, whereas prior studies studied up to 75–100 cm deep. Furthermore, the severe climatic conditions that exist in the central region of the Saudi Arabian Red Sea coast impede the growth of mangrove trees due to nutrient limitations, which results in poor SOC pool capacity [32,33].

Previous studies suggested that soil might store more than twice the amount of organic carbon as compared to living biomass, and that SOC stock accounts for the majority of the ecosystem organic-carbon pool [19]. However, in mangrove forests, organic-carbon stock in biomass substantially exceeds that found in soil [10]. The results of our study showed that POC stock was significantly higher than SOC stock in all the studied sites (Table 1), indicating that biomass has a larger carbon storage potential than soil. The results obtained in the current study showed lower POC stock as compared to previous studies in southeast Brazil [11,34], but a higher value than those observed in Brazilian northeastern semiarid [35] and Brazilian Amazon [36].

5. Conclusions

Mangrove conservation plans in Yanbu industrial city play a pivotal role in maintaining and enhancing the roles of mangrove forests in mitigating climate change effects via CO_2 sequestration into their sediments. The results of the current study showed that conservation plans significantly improved the SBD of mangrove sediments in Yanbu industrial city as compared to Umluj and Ar-Rayis cities, that had no implemented mangrove conservation plans. When compared to the other two cities, Yanbu industrial city had a greater SOC content and stock, showing that conservation plays a positive role in carbon storage and mitigating the negative consequences of climate change. Our findings show that conserving mangrove forests will significantly aid in reducing the consequences of climate change. However, further studies encompassing more conserved sites and larger numbers of mangrove sites are required to ensure the significance of mangrove conservation in reducing the consequences of climate change.

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