Evaluation of Soil Organic Carbon Stock in Coastal Sabkhas under Different Vegetation Covers

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Abstract: There has been increasing focus on conserving coastal ecosystems as they have been recognized as high ecosystem carbon stocks and are in the process of land conversion. The present study aims to examine how different vegetation covers impact the soil organic carbon (SOC) stock in coastal sabkhas. To this end, the study was carried out at ten sampling sites represent ten sabkhas in Saudi Arabia’s southern Red Sea coast for two main goals: (1) to examine the vertical distribution of SOC content, SOC density, and the soil bulk density (SBD) based on different vegetation covers, and (2) to assess these locations’ SOC stocks. This study posits that sabkhas with different vegetation covers had distinct parameters specified above. Significant SBD differences were observed in sabkhas with different vegetation covers, with the lowest mean values of sabkhas having >75–100% vegetation cover and the highest mean values of sabkhas having 0–25% vegetation cover. The studied sabkhas also showed significant difference in the total means of SOC density, SOC content, and SOC stock in terms of different vegetation covers, with the highest mean values of sabkhas having >75–100% vegetation cover and the lowest mean of sabkhas having 0–25% vegetation cover. The present study is the first to focus on Saudi Arabia’s sabkha blue carbon stocks and its results can help add to the literature on sabkhas carbon stock, thus aiding relevant government agencies working towards sabkhas management, encouraging public awareness regarding sabkhas conservation stocks, and their part in climate change mitigation.

Keywords: blue carbon; carbon pool; carbon vertical distribution; coastal wetlands; global warming; red sea

1. Introduction

The term “sabkha” (plural: Sabkhas) is Arabic for a coastal and inland saline mud flat on playas that is developed by silt, clay, and sand deposits in shallow and often extensive depressions [1]. These sabkhas tend to be drenched in brine [2]. Sabkhas have a geographically large habitat range, with its presence in Southeast Europe, the Californian siliciclastic coast, North Africa, Mexico, Somalia, Morocco, Asia, the Middle East, Australia, and the Arabian Peninsula [3,4]. Kinsman and Park [5] identified two types of sabkha landforms: coastal sabkha and inland sabkha. Coastal sabkhas typically develop in arid regions’ coastal areas that have high net evaporation and minimal soil washing because of limited freshwater supplies, poor soil drainage, and scanty rainfall [1]. Moreover, sabkhas form approximately 6% of the coastal areas in Gulf Cooperative Countries [6]. In Saudi Arabia, sabkhas are often found in the coastal areas and sometimes inland [1]. These
Saline ecosystems are dominated by perennial halophytes, which form a variety of plant communities (see [7]).

There has been global interest in blue carbon (the carbon that is concealed in coastal ecosystems; [8]) as it can mitigate CO$_2$ emissions [9,10]. It is, thus, important for the global carbon cycle community and local jurisdictions to quantify coastal blue carbon stocks as carbon sequestration is motivated by restoring and conserving coastal blue carbon habitats [11,12]. In addition, both international and domestic parties interested in developing regulated carbon markets have been establishing new monetary value on coastal blue carbon as well as enabling its open market trading [13]. It is necessary to quantify carbon stocks accurately and in a location-specific manner for better understanding spatial variability concerning coastal blue carbon and assessing future carbon stocks in terms of habitat preservation, degradation, loss, or restoration [10,12,14,15].

If there is insufficient data for a region, using universal global estimates instead of site-specific data is not recommended as it can lead to inaccurate carbon stocks estimates [16] because local carbon dynamics differ in their responses to various site-specific factors, such as hydrodynamic pressures, geological processes, vegetation assemblages, soil type, and age [17–21]. Therefore, to ensure that sabkhas are included in climate mitigation efforts, it is crucial to have the necessary knowledge regarding the sabkhas soil organic carbon (SOC) stocks’ spatial distribution, for which quantification of carbon stocks can aid in developing local, regional, and national carbon strategies and help with conservation and rehabilitation efforts [22].

The present study is a part of a series of papers that aim to assess SOC stocks in various coastal ecosystems of Saudi Arabia [23–28]. Hence, by quantifying blue carbon ecosystem services in areas like sabkhas can provide new avenues for attaining carbon reduction goals through the emerging economic carbon market. Thus far, no study has focused on Saudi Arabia for assessing the carbon stock of sabkhas on the southern Saudi Red Sea coast. This study, therefore, evaluates SOC content, soil bulk density (SBD), SOC stock, and SOC density in sabkhas with varying vegetation covers on the southern Red Sea coast of Saudi Arabia.

For the salt marsh ecosystem, vegetation plays a crucial role in terms of the organic carbon cycle [29], with plants being the primary organic matter origin in the majority of salt marshes [30,31]. This study, thus, aims to assess how plant cover effects can possible impact “blue carbon.” The study focused on questions such as “what are the SOC stocks of the sabkhas along the southern Saudi Red Sea coast?” and “how do they differ between locations with different vegetation covers?” Our hypothesis was that the SOC content, SBD, SOC stock, and SOC density would all vary among sabkhas in response to the various of vegetation covers. Such types of data and information are important for putting any management plan sabkhas along the Saudi Arabi Red Sea coast and provide argue for the restoration of sabkhas in Saudi Arabia. The present study’s findings can have global implications as they can be applied to similar ecosystems to help reduce carbon emissions in other regions and alleviate their ecological degradation, as these ecosystems struggle to establish a fine balance with changing climatic conditions.

2. Materials and Methods
2.1. Study Area

The Red Sea expands from 28°45′ N at the Aqaba Gulf’s northern end to approximately 13° N at its southern end at Bab El-Mandeb (Figure 1). Saudi Arabia’s Red Sea coast spans in a NW-SE manner for 1700 km and forms nearly 80% of the total sea length (see [28]). Coastal regions can be very different geomorphologically, such as coast caused by marine terraces, coastal sabkhas, alluvial plains, and wadis spanning 30 km in width with a few Neogene sediments. There are numerous alluvial fans, dry riverbeds, and estuaries. Several fluvial channels can also be detected in the mountains to the east and the coastal plains, which transport sediment and water during monsoon into the open sea or the lagoons [32].
Figure 1. Satellite images of the study area indicating the ten sampling sites represent ten sabkhas.

The weather in the area of study is hot and dry [33]. The average high temperature is about 38 °C and the average low temperature is about 22 °C [34]. From June to September are the hottest months in the study area. Based on records from 2002 to 2012, the average annual rainfall is 6.6 mm and the average annual evaporation is 1200 mm [34]. January, April, November, and December are the months with the most rain. Rain falls on steep mountain slopes, which flow through wadis to the Red Sea. This often causes flash floods [33]. Wind speed and direction change with the seasons. In summer, the wind blows from the west, and in winter, it blows from the southwest. The speed of the wind ranges from 2 to 50 km/h [34]. From June to August, a strong west wind blows on and off, causing dust storms along the southern coast of the Red Sea [35]. In the study area, the winds that blow most often cause southward longshore currents [33]. Along the Red Sea, normal tides are low and range from 0.2 to 0.3 m. Spring tide is 0.9 m and fall tide is 1.4 m [36]. Large tides and storms flood lowlands along the coast, and sabkhas are flooded through tidal inlets [33].

2.2. Soil Sampling

This study was conducted from 17 December 2020 to 2 January 2021 and focused on 10 sites for sampling represent 10 sabkhas (Table S1). These sites were all located on...
the Saudi Arabia Red Sea’s southern coastline (Figure 1). The water depth of the sampling sites was less than 50 cm. In particular, the uppermost layers of the sabkha soils are typically rich in carbonates, sulfates, halite, and chloride [37]. Clastic fraction in sabkha soils ranges from coarse silt to coarse sand with moderate sorting, and is transported by currents and wind [33]. Sabkhas areas range from 0.08 km$^2$ to 2.30 km$^2$ in size, and occur 0.28 km to 4.57 km landward of the shoreline (Table S1). The total vegetation cover was visually assessed [38,39] to classify the sampling sites into four categories: 0–25%, >25–50%, >50–75% and >75–100%. The recorded species in the sampling sites were *Arthrocnemum macrostachyum* (Amaranthaceae, subshrub), *Binertia cycloptera* (Amaranthaceae, annual herb), *Halocnemum strobilaceum* (Amaranthaceae, subshrub), *Halopeplis perfoliata* (Amaranthaceae, shrub), *Limonium axillare* (Plumbaginaceae, subshrub), and *Salicornia europaea* (Amaranthaceae, annual herb). The dominant species in all sampling sites was *L. axillare*, while *B. cycloptera*, *H. perfoliate*, and *S. europaea* were found as a codominant species.

A hand soil corer (made of stainless steel, 100 cm long with an inner diameter of 70 mm) was used to collect 10 to 15 soil cores (Table S1) from every sampling site. Based on field observation, soil cores have a typical sabkha soil series [40] (detailed typical description of soil sabkha series can be found here: “SABKHA SERIES. Available online: https://soilseries.sc.egov.usda.gov/OSD_Docs/S/SABKHA.html (accessed on 13 August 2022)”). Sabkha soil profiles were characterized by high sea salt content and somewhat poorly drained soils [41]. For collecting the core, the researchers pushed the hand soil corer down 50 cm into the soil as there were a few centimeters of thick salt crusts below 50 cm depth [2]. The soil core was then slowly extracted from the corer and separated into 10 sections of 5 cm each: 0–5, 5–10, 10–15, 15–20, 20–25, 25–30, 30–35, 35–40, 40–45, and 45–50 cm. All of these sections were placed in a plastic container sealed with parafilm. The container was then stored on ice until further analysis to avoid volatilization loss and to reduce the activity of microbes [42,43]. Therefore, one sample each was gathered from all 10 layers of soil at all of the 10 sites sampled using 125 soil cores. A total of 1250 soil samples were collected to assess SBD, SOC content, SOC stock, and SOC density.

### 2.3. Sample Analysis

First, the soil samples were oven-dried for 3 days at 105 °C. Next, the samples were weighed to determine SBD [g/cm$^3$] according to Wilke’s [44] methodology:

$$\rho_{sj} = \frac{m_j}{v_j}$$  \hspace{1cm} (1)

where $\rho_{sj}$ refers to the SBD [g/cm$^3$] of the $j$th layer, $m_j$ refers to the $j$th layer’s soil sample mass [g] dried at 105 °C, and $v_j$ refers to the $j$th layer’s soil sample volume [cm$^3$]. Each sample’s SOC contents were determined by calculating the soil organic matter (SOM; g/kg). For this, the loss-on-ignition method was carried out for two hours at 550 °C as outlined by Jones [45]. To determine SOC content, Craft et al.’s [46] method was applied:

Below is how SOC density [kg C/m$^3$] was calculated [47]:

$$\text{SOC content [g C/kg]} = (0.40 \times \text{SOM}) + (0.0025 \times \text{SOM}^2)$$  \hspace{1cm} (2)

$$\text{SOC}_{dj} = \rho_{sj} \times \text{SOC}_j$$  \hspace{1cm} (3)

where $\text{SOC}_{dj}$ refers to the $j$th layer’s SOC density [kg C/m$^3$], $\rho_{sj}$ refers to the $j$th layer’s SBD [g/cm$^3$], and $\text{SOC}_j$ refers to the $j$th layer’s SOC content [g C/kg]. Based on the methodology presented by Meersmans et al. [48], the following equation was used to calculate SOC stock [kg C/m$^2$]:

$$\text{SOC}_s = \frac{\sum_{j=1}^{k} p_{sj} \times \text{SOC}_j \times T_j}{\sum_{j=1}^{k} T_j} \times D_r$$  \hspace{1cm} (4)
where $SOC_s$ refers to SOC stock [kg C/m$^2$], $\rho_{sj}$ refers to the $j$th layer’s SBD [g/cm$^3$], $SOC_j$ refers to the $j$th layer’s SOC content [g C/kg], $D_j$ refers to the reference depth [= 0.5 m], $T_j$ refers to the $j$th layer’s thickness [m], and $k$ refers to the number of layers [= 10].

2.4. Statistical Analysis

Prior to the analysis, the data were assessed through the Shapiro–Wilk’s W test to determine normality of distribution and using the Levene’s test to determine homogeneity of variance. The data fail tests for homogeneity of variance ($p < 0.001$) and for normality of distribution ($p < 0.001$); thus, log transformation was carried out on the data before executing analysis of variance (ANOVA). Statistically significant variances were determined in SBD, SOC density, and SOC content in sabkhas having different vegetation covers for all 10 soil depths using two-way ANOVA. In addition, Pearson correlation coefficient and non-linear regression were applied for determining the relationship between the SBD and SOC content [28]. One-way ANOVA was then implemented for determining major differences among the sabkhas having different vegetation covers for the total means of SBD, SOC stock, SOC density, and SOC content. To identify whether the vegetation cover of the 10 sabkhas sites impacted the SBD, SOC stock, SOC density, and SOC content using linear regression analysis. SPSS 23 was used for statistical analyses [49].

3. Results

An analysis of the sabkhas having different vegetation covers showed a significance SBD difference with 52.1 $F$-value ($p < 0.001$) where sabkhas having vegetation cover >75–100% had the lowest mean values (1.46 g/cm$^3$) and sabkhas having vegetation cover 0–25% had the highest mean values (1.78 g/cm$^3$). This affirms the present study’s hypothesis (Table 1). A significant rise was also observed in the SBD distribution of the sabkhas having vegetation cover >75–100% from 0.97 g/cm$^3$ at a 0–5 cm depth to 1.76 g/cm$^3$ at a 45–50 cm depth (Figure 2). However, the SBD distribution in the sabkhas having vegetation cover 0–25% considerably increased from 1.33 g/cm$^3$ at a 0–5 cm depth to 2.25 g/cm$^3$ at a 45–50 cm depth.

**Table 1.** Mean ± standard error of soil bulk density [SBD; g/cm$^3$], soil organic carbon [SOC] content [g C/kg], SOC density [kg C/m$^3$], and SOC stock [kg C/m$^2$] of ten sampling sites represent ten sabkhas with different vegetation covers along the southern Red Sea coast of Saudi Arabia.

| Vegetation Cover (%) | SBD     | SOC Content | SOC Density | SOC Stock |
|----------------------|---------|-------------|-------------|-----------|
| 0–25                 | 1.78 ± 0.02 d [n = 320] | 4.9 ± 0.2 a [n = 320] | 7.3 ± 0.3 a [n = 320] | 3.6 ± 0.2 a [n = 32] |
| >25–50               | 1.69 ± 0.02 c [n = 300] | 11.5 ± 0.4 b [n = 300] | 17.8 ± 0.5 b [n = 300] | 8.9 ± 0.3 b [n = 30] |
| >50–75               | 1.61 ± 0.02 b [n = 330] | 19.0 ± 0.5 c [n = 330] | 30.8 ± 0.6 c [n = 330] | 15.4 ± 0.4 c [n = 33] |
| >75–100              | 1.46 ± 0.02 a [n = 300] | 27.6 ± 0.6 d [n = 300] | 38.9 ± 0.6 d [n = 300] | 19.4 ± 0.7 d [n = 30] |

$F$-values represent one-way analysis of variance (ANOVA); degrees of freedom (df) = 3; means in the same column followed by different letters are significantly different at $p < 0.05$ according to Tukey’s HSD (Honest Significant Difference) test; ***: $p < 0.001$. 

The data fail tests for homogeneity of variance ($p < 0.001$) and for normality of distribution ($p < 0.001$); thus, log transformation was carried out on the data before executing analysis of variance (ANOVA). Statistically significant variances were determined in SBD, SOC density, and SOC content in sabkhas having different vegetation covers for all 10 soil depths using two-way ANOVA. In addition, Pearson correlation coefficient and non-linear regression were applied for determining the relationship between the SBD and SOC content [28]. One-way ANOVA was then implemented for determining major differences among the sabkhas having different vegetation covers for the total means of SBD, SOC stock, SOC density, and SOC content. To identify whether the vegetation cover of the 10 sabkhas sites impacted the SBD, SOC stock, SOC density, and SOC content using linear regression analysis. SPSS 23 was used for statistical analyses [49].
while sabkhas having vegetation cover 0–25% had lowest mean values (4.9 g C/kg). This vegetation covers 0–25%, >25–50%, >50–75% and >75–100%, respectively (Figure 4).}

Significant differences were also observed in the total mean of SOC content among the studied sabkhas having different vegetation covers with a 475.6 F-value ($p < 0.001$). Here, sabkhas having vegetation cover >75–100% had highest mean values (27.6 g C/kg), while sabkhas having vegetation cover 0–25% had lowest mean values (4.9 g C/kg). This affirms the present study’s hypothesis (Table 1). There was also a major decrease in the SOC contents of the sabkhas having vegetation cover >75–100% from 44.0 g C/kg at a 0–5 cm depth to 15.9 g C/kg at a 45–50 cm depth (Figure 3). On the other hand, the SOC contents in the sabkhas having vegetation cover 0–25% dropped considerably from 11.7 g C/kg at a 0–5 cm depth to 1.8 g C/kg at a 45–50 cm depth.

The study showed a significant and inverse relationship between SOC content [g C/kg] and SBD [g/cm$^3$], as presented by these exponential equations: SBD = $1.2055 + 0.9502 \times e^{-0.1222 \times SOC content}$ ($R^2 = 0.3596$, $n = 320$), SBD = $1.0332 + 1.0857 \times e^{-0.0527 \times SOC content}$ ($R^2 = 0.5297$, $n = 30$), SBD = $1.1876 + 1.2712 \times e^{-0.0618 \times SOC content}$ ($R^2 = 0.3999$, $n = 330$) and SBD = $-1.2924 + 3.3742 \times e^{-0.0075 \times SOC content}$ ($R^2 = 0.5297$, $n = 30$) for sabkhas with vegetation covers 0–25%, >25–50%, >50–75% and >75–100%, respectively (Figure 4).

There was a significant difference in the total mean of SOC density of the studied sabkhas having different vegetation covers with a 756.9 F-value ($p < 0.001$). The sabkhas having vegetation cover >75–100% had the highest mean values (38.9 kg C/m$^2$) while sabkhas having vegetation cover 0–25% had the lowest mean values (7.3 kg C/m$^2$). Hence, these findings affirm the present study’s hypothesis (Table 1). A significant drop was noticed in the SOC density in the sabkhas having vegetation cover >75–100% from 42.3 kg C/m$^2$ at a 0–5 cm depth to 32.3 kg C/m$^2$ at a 45–50 cm depth (Figure 5). However, SOC density in the sabkhas having vegetation cover 0–25% significantly reduced from 14.4 kg C/m$^2$ at a 0–5 cm depth to 3.2 kg C/m$^2$ at a 45–50 cm depth.
Soil bulk density [g/cm³]

| Soil depth [cm] | 0-5 | 5-10 | 10-15 | 15-20 | 20-25 | 25-30 | 30-35 | 35-40 | 40-45 | 45-50 |
|----------------|-----|------|-------|-------|-------|-------|-------|-------|-------|-------|
| 1.5            |     |      |       |       |       |       |       |       |       |       |
| 2.0            |     |      |       |       |       |       |       |       |       |       |
| 0.5            |     |      |       |       |       |       |       |       |       |       |
| 1.0            |     |      |       |       |       |       |       |       |       |       |
| 2.5            |     |      |       |       |       |       |       |       |       |       |
| 3.5            |     |      |       |       |       |       |       |       |       |       |

**Figure 2.** Distribution of soil organic carbon content [g C/kg] in relation to soil depth [cm] in ten sites represent ten sabkhas with different vegetation covers along the southern Red Sea coast of Saudi Arabia. Horizontal bars indicate the standard errors of the means; *F*-values represent the two-way analysis of variance (ANOVA); Vegetation cover: 0—25%, >25—50%, >50—75% and >75—100%; Depth: 0—5, 5—10, 10—15, 15—20, 20—25, 25—30, 30—35, 35—40, 40—45 and 45—50 cm; ***: *p* < 0.001; *n* = 30 for vegetation cover >25—50 and >75—100%; *n* = 32 for vegetation cover 0—25%; *n* = 33 for vegetation cover >50—75%.

**Figure 3.** Distribution of soil organic carbon content [g C/kg] in relation to soil depth [cm] in ten sites represent ten sabkhas with different vegetation covers along the southern Red Sea coast of Saudi Arabia. Horizontal bars indicate the standard errors of the means; *F*-values represent the two-way analysis of variance (ANOVA); Vegetation cover: 0—25%, >25—50%, >50—75% and >75—100%; Depth: 0—5, 5—10, 10—15, 15—20, 20—25, 25—30, 30—35, 35—40, 40—45 and 45—50 cm; ***: *p* < 0.001; *n* = 30 for vegetation cover >25—50 and >75—100%; *n* = 32 for vegetation cover 0—25%; *n* = 33 for vegetation cover >50—75%.

**Figure 4.** Non-linear regression between soil organic carbon content [g C/kg] and soil bulk density [g/cm³] of soil samples in ten sites represent ten sabkhas with different vegetation covers along the southern Red Sea coast of Saudi Arabia.
These findings affirm the present study’s hypothesis (Table 1). A significant drop was noticed in the SOC density in the sabkhas having vegetation cover >75–100% from 42.3 kg C/m³ at a 0–5 cm depth to 32.3 kg C/m³ at a 45–50 cm depth (Figure 5). However, SOC density in the sabkhas having vegetation cover 0–25% significantly reduced from 14.4 kg C/m³ at a 0–5 cm depth to 3.2 kg C/m³ at a 45–50 cm depth.

![Soil organic carbon density vs Soil depth](image)

Figure 5. Distribution of soil organic carbon density [kg C/m³] in relation to soil depth [cm] in ten sites represent ten sabkhas with different vegetation covers along the southern Red Sea coast of Saudi Arabia. Horizontal bars indicate the standard errors of the means; F-values represent the two-way analysis of variance (ANOVA); Vegetation cover: 0—25%, >25—50%, >50—75% and >75—100%; Depth: 0—5, 5—10, 10—15, 15—20, 20—25, 25—30, 30—35, 35—40, 40—45 and 45—50 cm; ***: p < 0.001; n = 30 for vegetation cover >25—50 and >75—100%; n = 32 for vegetation cover 0—25%; n = 33 for vegetation cover >50—75%.

There were also major differences in the SOC stocks with 229.2 F-values (p < 0.001) for the sabkhas having different vegetation covers (Table 1). Considering the entire soil interval depth from 0 to 50 cm, the soil from sabkhas having vegetation cover >75–100% had the highest SOC stock value (19.4 kg C/m²) and the sabkhas having vegetation cover 0–25% had the lowest SOC stock value (3.6 kg C/m²). That is, there was 533% greater SOC stock in sabkhas having vegetation cover >75–100% compared to sabkhas having vegetation cover 0–25% (Table 1). Overall, there was in increase in SOC content, SOC density, and SOC stock in correlation with increased vegetation cover of sabkhas (r = 0.729, p < 0.001; r = 0.801, p < 0.001 and r = 0.919, p < 0.001, respectively). However, SBD showed the opposite trend (r = −0.330, p < 0.001) (Figure 6).
was also observed by Drake et al. [53] on tidal salt marshes of the northeast United States, by (see [54]). The results suggest that the soil from sabkhas having vegetation cover 0–25% of soil samples in ten sites represent ten sabkhas with different vegetation covers along the southern high SBD (>1.45 g/cm³) may also be caused by the breakdown and serious compaction of the organic matter content, compaction, and porosity [50]. The present study's relatively plant remains collecting on the soil's surface and sub-surface layers [57], which may alter on coastal salt marshes of Spain. This SBD behavior may be the result of the tailings and plant remains collecting on salt marshes of Tasmania in Australia, and by Gispert et al. [56] on coastal salt marshes of Spain. This SBD behavior may be the result of the tailings and plant remains collecting on the soil's surfacemembrane sub-surface layers [57], which may alter the organic matter content, compaction, and porosity [50]. The present study's relatively high SBD (>1.45 g/cm³) may also be caused by the breakdown and serious compaction of the coastal areas' soil structure (see [54]). The results suggest that the soil from sabkhas having vegetation cover 0–25% had the greater average SBD and the sabkhas having vegetation cover >75–100% had the lowest mean value. Moreover, rising vegetation cover was also found to increase leaf and stem production, which makes them easy to incorporate into the soils. 

4. Discussion

A dynamic feature that changes based on the soil's structural conditions, SBD is the specific soil volume's dry weight [50]. SBD can help determine soil compaction, as well as soil water permeability and/or mechanical resistance to plant growth [47,51]. Furthermore, it can impact the SOC content distribution and is crucial for its evaluation [52]. According to the present study's results, in all study sites, SBD increased gradually with depth, which was also observed by Drake et al. [53] on tidal salt marshes of the northeast United States, by Bai et al. [54] on salt marshes of the Yellow River Delta in China, by Ellison and Beasy [55] on salt marshes of Tasmania in Australia, and by Gispert et al. [56] on coastal salt marshes of Spain. This SBD behavior may be the result of the tailings and plant remains collecting on the soil's surface and sub-surface layers [57], which may alter the organic matter content, compaction, and porosity [50]. The present study's relatively high SBD (>1.45 g/cm³) may also be caused by the breakdown and serious compaction of the coastal areas' soil structure (see [54]). The results suggest that the soil from sabkhas having vegetation cover 0–25% had the greater average SBD and the sabkhas having vegetation cover >75–100% had the lowest mean value. Moreover, rising vegetation cover was also found to increase leaf and stem production, which makes them easy to incorporate into the soils. 

SOC contents differ spatiotemporally and are impacted by geomorphological conditions and the sabkha communities’ compositions [58,59]. Moreover, SOC contents are also influenced by climate change effects as well as human activities including pollution, land-use inversions, reclamation, and deforestation [24,60,61]. SOC contents and dynamics are also impacted by the sabkhas species composition, the sabkha age, biomass, productivity, and vegetation age structure [62,63]. According to previous studies, SOC content differs depending on changes in vegetation cover, decomposition, and vegetation primary

Figure 6. The relation between vegetation cover [%] and soil bulk density [g/cm³], soil organic carbon content [g C/kg], soil organic density [kg C/m³], and soil organic carbon stock [kg C/m²] of soil samples in ten sites represent ten sabkhas with different vegetation covers along the southern Red Sea coast of Saudi Arabia.
productivity, all of which are impacted by bioturbation, species composition, and other physico-chemical factors [54,64]. The present study showed that the soil from sabkhas having vegetation cover >75–100% had the greater average SOC content and the sabkhas having vegetation cover 0–25% had the lowest mean value. Moreover, in the coastal wetland, SOC temporal and special distributions were significantly impacted by vegetation and the below-ground production of roots and rhizomes [65]. Overall, more than 50% plant biomass production was assigned to the below-ground that was further buried in the soil due to the tides’ sediment deposit [66]. Lai et al. [67] and Gispert et al. [56] in their studies referred that denser vegetation and plant canopy are paramount for long-term carbon enrichment in soil and found comparatively higher carbon inputs in soils under the main vegetation than out the main vegetation.

The reducing incline of SOC content with depth in the present study can be attributed to the downward migrating of SOC resulting from the surface soil’s leaching and microbial activities [54]. Several studies have observed that, in arid and semi-arid ecosystems, plant production is a significant SOC input to soil [63,68]. On the other hand, apart from plant litter input, both tidal flooding input and the organic carbon burial resulting from sediment accumulation [69] play a major role in the SOC budgets and SOC’s depth distribution patterns for coastal salt marshes [54]. The progressive decrease in SOC content from the surface to the bottom of soil cores was similar to previous studies conducted on salt marshes in China [54,70], Australia [55], USA [53,71], Canada [17], UK [72], Germany [73], and Spain [56]. Several studies have shown that carbon content reduces at deeper soil depths because of diagenesis of labile material and on-going decomposition [19,54,74,75].

The SBD plays a major role in assessing the SOC density and the SOC stock; however, not many studies have observed SBD with SOC content for sabkhas soil. The present study observed a non-linear reduction of the SBD level in the soil as SOC content increased. Hence, this non-linear relationship can be regarded as a useful tool to determine the SOC stock and SBD density in the sabkhas–especially for those sabkhas that characterized by vegetation that has a plant cover of 75% or higher ($R^2 = 0.5297$). The present study also noted a negative correlation between SBD and SOC content, which indicated that SBD can impact soil porosity, ventilation, soil structure, and soil permeability, as well as impact SOC accumulation [76]. Several studies have observed a negative correlation between SOC content and SBD in salt marshes sediments in Tampa Bay, Florida, USA [12]; Tasmania, Australia [55]; and tropical salt marshes of Sri Lanka [77].

Organic carbon gets collected in soils due to autochthonous material being input through primary production or allochthonous material getting deposited compared to the output resulting from erosion, decomposition/mineralization, and leaching [78,79]. The SOC stocks may also vary due to different factors such as abiotic (e.g., climate, mineralogy, frequency, topography, soil type, nutrients, and extent of inundation) and biotic conditions including plant functional traits (e.g., above- and below-ground production inputs, carbon allocation, and turnover); decomposition; vegetation type; vegetation biomass; the influence of other biota on retention, consumption, or exposure to oxidation; and anthropogenic influences (e.g., carbs and saprophytes) [64,80–84]. In the present study, the soil from sabkhas having vegetation cover >75–100% had the greater average SOC stock and sabkhas having vegetation cover 0–25% had the lowest mean value. This finding is supported by previous studies concerning various salt marshes from around the globe. Zhao et al. [85] on tidal salt marsh of the Yellow River estuary in China noted that, during summer, SOC stock was higher in plant-covered salt marshes than in mudflat salt marshes with no plants. Moreover, the study by Kelleway et al. [86] on salt marshes on SE Australia’s NSW coast showed that carbon gains can be increased by conserving rush communities and maintaining high density vegetation cover. The study by Hansen et al. [87] conducted in Elbe estuary, Germany, noted that the reduction in SOC pool correlated to the increasing salinity was primarily caused by reducing biomass production. Previous studies show that above-ground vegetation cover helps improve the SOC accumulation in numerous
ways [79,88,89] leading to greater carbon burial in vegetated soils than in non-vegetated habitats [64].

SOC stocks vary significantly across countries, hemispheres, latitudes, and plant community compositions [61]. In addition, hydrological fluctuations, burial processes, and vegetation succession lead to the SOC in salt marshes to have a considerable spatial variation [54]. There have been problems comparing salt marsh sediment carbon stock to other studies due to varying geomorphology, sediment depths, and delineation of vegetation types [90]. Compared to the estimated 250 Mg C/ha global SOC stock [65], the present study’s core SOC stocks of 36.0 Mg C/ha for sabkhas having vegetation cover 0–25% and 194.0 Mg C/ha for sabkhas having vegetation cover >75–100% are lower. However, the present study’s values were consistent with many other studies carried out in arid and semi-arid countries (Table 2). This difference is primarily caused by the fact that the global estimate calculated the top meter of soil [66], whereas the present study’s SOC stocks reached only a 50 cm depth. The relatively low sabkhas’ SOC stock may have been the result of high salinity, low soil fertility, and poor soil textures [91]. Due to the significantly arid conditions, the sabkhas vegetation growth has inadequate nutrient content [92]. Moreover, it may also be due to the study’s measurement methods or the study area’s climate, geographical age, sampling time, and vegetation composition [93].

Table 2. Mean of soil bulk density [SBD; g/cm$^3$], soil organic carbon [SOC] content [g C/kg] and SOC stock [kg C/m$^2$] in ten sampling sites represent ten sabkhas with different vegetation covers along the southern Red Sea coast of Saudi Arabia compared with those reported for different salt marshes around the globe.
Table 2. Cont.

| Location                                                                 | SBD       | SOC Content | SOC Stock | Depth [cm] | Reference                          |
|--------------------------------------------------------------------------|-----------|-------------|-----------|------------|------------------------------------|
| Three marshes in Barnegat Bay and three marshes in Delaware estuary, USA | 0.14–0.49 | 63.0–302.0  |          | 50         | Unger et al. [105]                 |
| Two marshes on the Gulf of St. Lawrence coast of New Brunswick, Canada and one on the southern coast of Maine, USA | 0.28–0.50 | 21.0–30.0   | 26.1      | 50         | van Ardenne et al. [71]            |
| Salt barrens in Tampa Bay, Florida, USA                                  | 1.27–1.44 | 5.0–10.0    | 2.7       | 50         | Radabaugh et al. [12]              |
| Salt marshes in Tampa Bay, Florida, USA                                  | 0.95–1.27 | 16.0–66.0   | 6.6       | 50         | Radabaugh et al. [12]              |
| Salt marsh in southern Puget Sound, Washington, USA                      | 0.17–0.65 | 33.0–208.0  | 50        |            | Drexler et al. [106]               |
| Salt marsh in Boundary Bay, Delta, British Columbia, Canada              | 0.53–0.65 | 43.0–113.0  | 3.9–8.3   | 29         | Gailis et al. [22]                 |
| Tropical salt marshes, Mexico and El Salvador                           | 2.0–303.0 | 3.0–46.5    | 100       |            | Ruiz-Fernández et al. [107]        |
| Salt marshes of the Amazon region, Brazil                               | 0.86–1.57 | 3.4–41.5    | 9.5–12.0  | 100        | Kauffman et al. [108]              |

*: depth as 5 cm.

5. Conclusions

Coastal marshes constitute a fragile ecosystem that is in a state of rapid decline at 0.66% per year [109]. According to estimates, in the next 100 years, 30–40% coastal wetlands [110] may be eliminated based on the present rate of loss [111]. Coastal wetlands are at high risk, with a major portion already lost or fragmented because of different anthropogenic activities, including drainage and construction works, reclamation, and unrestricted stock access, while also being endangered by rising global sea levels and corresponding mangrove encroachment [112,113]. The present study examined the coastal sabkhas’ SOC stock by considering the vegetation cover on Saudi Arabia’s Red Sea coast. An increase in SOC density, SOC stock, and SOC content was observed with increased vegetation cover of sabkhas, and the opposite trend was observed for SBD. However, ten small Saudi Arabia Red Sea coast sabkhas indicates that the data can help estimate the possible storage impacts of local managed sites on the southern Red Sea coast, while also being generally suggestive of sabkhas on the whole Red Sea coast. Moreover, the data may help foresee how the vegetation cover can possibly impact sabkhas carbon stock. These sabkhas’ SOC stock is motivation enough for prioritizing sabkha ecosystems for conservation. It is, therefore, crucial to protect and restore these ecosystems for carbon sequestration along with other ecosystem services. It is also necessary to consider the climate mitigation projects for managing the sabkha ecosystems on Saudi Arabia’s coastal regions and protecting as well as conserving the existing SOC stocks.

6. Limitations and Uncertainties

The present study aimed to examine how vegetation cover impacts SOC stock in sabkhas by focusing on 10 sites represent 10 sabkhas on Saudi Arabia’s southern Red Sea coast. All 10 sites were chosen to reflect varied vegetation covers, but other factors apart from vegetation cover may also lead to diverse soil (SBD, SOC content, SOC density, and SOC stock) parameters in different sites. Examples of factors are the variability resulting from species composition, community structure, geomorphological settings, intertidal location, human interference, soil fertility, and seasonal variations (which impacts the changing pattern of carbon dynamics in arid ecosystems; [114]). Future studies must, therefore, assess how other factors impact carbon dynamics of sabkhas.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jmse10091234/s1, Table S1. Coordinates of each sampling site from sabkhas with different vegetation covers along the southern Red Sea coast of Saudi Arabia.

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