Effect of the conversion of mangroves into shrimp farms on carbon stock in the sediment along the southern Red Sea coast, Saudi Arabia

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Abstract

The conservation of coastal ecosystems and specially mangroves ‘‘blue carbon’’ is receiving more attention because of their recognition as high ecosystem carbon stocks and for the fact that these areas are undergoing land conversion. The aim of the present study was to evaluate the impact of land use changes due to conversion of mangroves to shrimp farms on the sediment bulk density (SBD), sediment organic carbon (SOC) concentration, and SOC stock in the sediments along the southern Saudi Arabian Red Sea coast. Shrimp farms and mangrove locations showed significant (t -value = 9.3, $P < 0.001$) SBD differences with higher mean values in the sediments of shrimp farms. Shrimp farms and mangrove locations showed significant (t -value = 11.1, $P < 0.001$) SOC concentration differences with higher mean values in the sediments of mangroves. Considering the whole depth of sediment interval (0-100 cm), the highest value of SOC stock was recorded at mangroves (29.2 kg C m⁻²) and the lowest SOC stock was recorded at the locations of shrimp farms (19.9 kg C m⁻²). The results show that SOC stock of mangroves is 147 % higher than that of shrimp farms confirming the fact that anthropogenic factors contributed significantly to SOC stock value. The mean cumulative potential CO₂ emission due to loss soil carbon stock from mangrove conversion to the shrimp ponds was 34.9 kg CO₂ m⁻². In conclusion, the conversion of mangroves into shrimp farms contributed to the loss of SOC stock, therefore, the preservation of mangrove areas has an important value especially in arid areas such as Saudi Arabia.

Key words: Blue carbon, Carbon sequestration, Coastal wetlands, Land use change, Red Sea, Shrimp aquacultures.

1. Introduction

Mangrove forest is one of the world's richest ecosystems that supplies a number of ecosystem services contributing to human wellbeing (Atwood et al., 2017; Bao et al., 2013; Eid and Shaltout, 2016). Of these multiple services, which can be grouped into provisioning, habitat and cultural (Abuodha and Kairo, 2001), one of the most important (considering the progress of the global change effects) is their action as carbon sinks (Andreetta et al., 2016; Chen et al., 2018; Ragavan et al., 2019; Sanderman et al., 2018). Mangroves are capable of absorbing and storing carbon from the atmosphere, which ends up buried in the sediments of coastal areas, named as "blue carbon". However, these ecosystems are threatened by pollution, deforestation, fragmentation, rising sea levels and, most importantly, by their transformation for other land uses. These other uses are mainly for aquaculture ponds, but also for urbanization, agriculture or infrastructures development (Arshad et al., 2018; Atwood et al., 2017; Grellier et al., 2017). This environmental problem has a clear global dimension being described by the mangrove disappearance or their transformation to other types of uses in America (Kauffman et al., 2018; Kauffman et al., 2016; Lovelock et al., 2011; Meyer et al., 2019), Asia (Grellier et al., 2017; Kusumaningtyas et al., 2019; Nehren and Wicaksono, 2018; Perera and Amarasinghe, 2019; Vaiphasa et al., 2007; Xin et al., 2014), Africa (Abuodha and Kairo, 2001; Andreetta et al., 2016) and New Zealand (Pérez et al., 2017). To give an idea of the problem, recently the United Nations Environmental Program (UNEP, 2014) reported that one fifth (around 35,500 km²) of the world's mangroves have been lost since 1980, with shrimp aquaculture accounting for roughly 38 % of this loss. This mangrove deforestation generates approximately 0.12 Gt of CO₂ emissions annually, approximately 0.3 % of total anthropogenic CO₂ emissions, becoming an important adverse effect that accentuate global change.

On the contrary, some places are experiencing an increase in the extent of mangrove cover. In Saudi Arabia, the total coverage of Red Sea's mangrove forests in 1972, 2000 and 2013 was 120, 132 and 135 km², respectively (Almahasheer et al., 2017). The mangroves of Saudi Arabian Red Sea coast have special characteristics as they growth in the most unfavorable conditions (high salinity values, rivers non-existent, rainfall minimum, hard bottom and very oligotrophic sea). Many studies were carried out on mangrove forests in Saudi Arabia focusing on bioaccumulation (Usman et al., 2013), biomass production (Abohassan, 2013b), distribution of soil organic carbon

(Almahasheer et al., 2017; Eid et al., 2016), ecology (Almahasheer et al., 2016b), geographical distribution (Khan, 2010; Kumar, 2010), growth dynamics (Almahasheer et al., 2016a), phenology (Almahasheer et al., 2016c), plantation (Elsebaie, 2013; Monsef et al., 2013), pollution (Abohassan, 2013a; Al-Ghanem, 2010; Arshad et al., 2018), population demography (Elhag et al., 2015), restoration (El-Juhany, 2009), sediment composition and stability (Almahasheer et al., 2016a).

In the last years, the economic growth in Saudi Arabia have favored an increase in the carbon emissions in the country (Alkhathlan and Javid, 2015). Mangrove ecosystems offer an unlimited potential to support blue carbon strategies to mitigate these CO₂ emissions. Furthermore, Saudi Arabia is not exempt from changes in land use that threaten these ecosystems, and it has been described how coastal development, logging, camel grazing and, particularly, the implementation of shrimp farms led to the loss of mangrove forests (Almahasheer et al., 2016b; Khan, 2010). This study focuses on the latter because their economic incomes in developing countries have brought more attention to this activity. However, to our knowledge, no study has been carried out in Saudi Arabia to evaluate the effect of the conversion of mangroves into shrimp farms on sediment bulk density (SBD), sediment organic carbon (SOC) concentration, and SOC stock. Hence, the aim of this study was to evaluate the impact of land use changes due to conversion of mangroves to shrimp farms on the SOC stocks in the soils along this area. To this end, several partial objectives were established: (1) to assess the vertical distribution of SBD, and SOC concentration in three mangrove locations in comparison with three shrimp farm locations along the southern Red Sea coast of Saudi Arabia; (2) to estimate SOC stock of these locations and (3) to establish potential CO₂ emissions arising from mangrove conversion to shrimp ponds. The results of this study are worldwide relevant because could be extrapolated to similar high-value ecosystems to mitigate carbon emissions in other parts of the planet and serve to mitigate their degradation, as these ecosystems are kept in fragile equilibrium with changing climatic conditions.

2. Materials and methods

2.1. Study area

The Red Sea stretches out between 30° N at the northern end of the Suez Gulf and about 13° N at its southern end at Bab El-Mandeb (Fig. 1). The Red Sea coast of Saudi Arabia extends in NW-SE way to a range of 1,700 km, comprising around 80 % of the total length of the sea. Mangroves cover an area around 135 km² of the Red Sea coastline (Almahasheer et al., 2016a). Mangroves are recognized as fragmented stands in the intertidal zones along the Red Sea coast of Saudi Arabia (Khan, 2010). The stands are dominated by *Avicennia marina* (El-Juhany, 2009), and are characterized by peak flowering and propagule development in November and January (Almahasheer et al., 2016c). The distribution of mangroves is patchy in this region, and mangrove growth rates are generally low compared to the deltaic zones and estuaries. Previous studies have reported that mangrove forests along the Red Sea coast do not grow in optimal conditions, fundamentally due to high salinity (> 40 g L⁻¹), hot summer air temperature (37.5 - 42.0 °C), low rainfall (2.8 - 22.3 mm yr⁻¹), sandy sediment, low sediment fertility due to low nutrient supply and no permanent freshwater inputs (Almahasheer et al., 2017).

2.2. Sediment sampling

Sampling was carried out during December 2017 in three locations (17° 48' 28.7" N, 41° 51' 57.0" E; 17° 47' 31.5" N, 41° 53' 18.5" E; 17° 10' 43.9" N, 42° 22' 2.1" E) to represent the monospecific stands of mangroves (*A. marina*) and another three locations (17° 47' 37.5" N, 41° 53' 49.9" E; 17° 46' 40.8" N, 41° 54' 37.3" E; 17° 13' 17.0" N, 42° 20' 20.5" E) to represent the shrimp farms along the Saudi Arabian Red Sea coast (Fig. 1). Six soil cores were collected from the six sites in each sampling location. Samples at both shrimp farms and mangroves locations were collected randomly with the aid of hand sediment corer (made of stainless steel, 75 cm long with an inner diameter of 70 mm). The corer was inserted into the sediment and pushed down to a depth of 100 cm, and the sediment core removed from the corer slowly and immediately sectioned with a blade into 10 cm thick layers (0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70, 70-80, 80-90 and 90-100 cm) and packed in plastic containers. Parafilm was used to tighten the sample containers, after which they were stored on ice to prevent volatilization losses and to reduce the microbial activity till analysis (Eid and Shaltout, 2016). In total, 360 sediment samples were collected to determine SBD, SOC concentration, and SOC stock, i.e., one sample from each ten soil layers at each of the 36 sampling sites (18 sampling sites per each of shrimp farms and mangroves locations).

2.3. Sample analysis

Each sediment sample was oven-dried at 105 °C for three days and weighed to determine the SBD (g cm⁻³) following the method of (Wilke, 2005). Dry samples were ground and sieved to pass through 2 mm particle size. Each sample was analyzed for SOC concentration by measuring the sediment organic matter (SOM) using loss-on-ignition method at 550 °C for two hours as described by (Jones, 2001), where SOC concentration (g C kg⁻¹) = 0.50 (Pribyl, 2010) × SOM (g C kg⁻¹). As the authors did not possess a carbon hydrogen and nitrogen (CHN) analyzer, they relied on loss-on-ignition method being recommended by Nóbrega et al. (2015) for an accurate estimation of SOC in mangrove sediments. SOC stock (kg C m⁻²) was calculated as follows (Meersmans et al., 2008):

$$SOC_s = \frac{\sum_{j=1}^k p_{sj} \times SOC_j \times T_j}{\sum_{j=1}^k T_j} \times D_r$$

where SOC_s is SOC stock (kg C m⁻²), p_{sj} is the SBD (g cm⁻³) of the j^{th} layer, SOC_j is the SOC concentration (g C kg⁻¹) of the j^{th} layer, D_r is reference depth (= 1 m), T_j is thickness (m) of the j^{th} layer and k is the number of layers (= 10).

The ecosystem losses due to the transformation of mangrove into shrimp farms (only due to the C stocks stored in sediments) are reported as potential CO₂ emissions, or CO₂ equivalents (CO₂e) obtained by multiplying C values by 3.67, the molecular ratio of CO₂ to C (Kauffman et al., 2018).

2.4. Statistical analysis

The data were examined for their normality of distribution and homogeneity of variance, and when required, log-transformed before performing analysis of variance (ANOVA). Two-way analysis of variance (ANOVA-2) was used to identify statistically significant differences in SOC concentrations and SBD among mangroves and shrimp farms in each sediment layer. To identify significant difference between means, the Tukey's HSD test at $P < 0.05$, was used. The relationship between SBD and SOC concentration was examined with non-linear regression (Eid and Shaltout, 2016). To identify statistically significant differences in the total means of SBD, SOC concentration, and SOC stock among mangroves and shrimp farms, a student's t -test was performed. SPSS 15.0 software (SPSS, 2006) was used to perform all the statistical analyses.

3. Results

With respect to SBD, differences (t -value = 9.3, $P < 0.001$) were found between shrimp farms and mangroves, with higher mean values in the sediments of shrimp farms (Table 1). There was a noticeable variation in SDB at mangroves showing an increase in from 1.21 g cm^{-3} at a depth of 0-10 cm to 2.08 g cm^{-3} at a depth of 90-100 cm (Fig. 2), while the SBD distribution at the shrimp farms varied from 1.28 g cm^{-3} at a depth of 0-10 cm to 2.43 g cm^{-3} at a depth of 90-100 cm. Mangroves and shrimp farms showed significant (t -value = 11.1, $P < 0.001$) SOC concentration differences with higher mean values in the sediments of mangroves (Table 1). SOC concentrations in mangroves have declined from 32.8 g C kg^{-1} at a depth of 0-10 cm to 6.9 g C kg^{-1} at a depth of 90-100 cm (Fig. 3) and in the shrimp farms from 22.9 g C kg^{-1} at a depth of 0-10 cm to 4.5 g C kg^{-1} at a depth of 90-100 cm. SOC concentration (g C kg^{-1}) and SBD (g cm^{-3}) had a significant and inverse relationship described by the following non-linear regression equations: $\text{SBD} = 0.969 + 1.778 e^{-0.065 \times \text{SOC concentration}}$ ($r = -0.761$, $P < 0.001$) and $\text{SBD} = 0.705 + 1.884 e^{-0.041 \times \text{SOC concentration}}$ ($r = -0.854$, $P < 0.001$) for the locations of shrimp farms and mangroves, respectively (Fig. 4). Considering the whole depth of sediment interval (0-100 cm), the highest value of SOC stock was recorded at mangroves (29.2 kg C m^{-2}) and the lowest SOC stock was recorded at shrimp farms (19.9 kg C m^{-2}). It was observed that the SOC stock of mangroves is 147 % higher than that of shrimp farms confirming the transformation of mangrove areas to shrimp farms contributed significantly to SOC stock value.

4. Discussion

The lower SBD of mangroves compared to shrimp farms highlights the positive effect on the sediment of the Red Sea resulting in a lowering of the SBD in comparison to that of the shrimp farms, particularly important at lower depths. This could be attributed to the growth of *A. marina*, plant species relevant for the reduction of SBD as contribute organic matter and also protect the coastal areas from erosion processes. Both roots and litter, and the consequent activity of wild aquatic biota, result in an increase in pore and macropore development. This agree with most of the studies that compared the SBD of preserved mangrove areas to other that have changed the land cover (Arifanti et al., 2019; Atwood et al., 2017; Cameron et al., 2019; Perera and

Amarasinghe, 2019). The SBD values found in Saudi Arabia are slightly higher than those reported in similar ecosystems of Indonesia and New Zealand but similar to those of Sri Lanka. This is clearly related with the sediment variability among different areas and at different depths and could indicated just different characteristics.

Significant increases in SBD with depth was observed in the shrimp farm and mangroves (F -value = 164.2, $P < 0.001$). This has been reported in many other studies carried out not only in mangroves but also in a variety of ecosystems (Arifanti et al., 2019; Atwood et al., 2017; Cameron et al., 2019; El-Sheikh et al., 2018; Perera and Amarasinghe, 2019). The main differences between the SBD of mangroves and shrimp farms sediments were observed at depths between 0 and 20 cm and more markedly at depths greater than 40 cm. On the contrary, at depths of 20 to 40 cm, the sediment SBD did not show any significant difference between mangroves and shrimp farms. The progressive decrease with depth (up to 50 cm) of the differences in SBD between mangrove areas and shrimp farms has been described by Grellier et al. (2017). However, these authors did not study greater depths and therefore it is not possible to establish whether the behaviour described is fully in line with that found in the Red Sea. Contrarily, Arifanti et al. (2019) who perform the study up to 3 m depth only reflect a progressive increase SBD with depth. One potential explanation to this behaviour that needs further confirmation is that sediments in mangrove areas are more affected by sediment dynamics than shrimp ponds. These areas are a buffer between the sea and the land. They actively accumulate sediments from the tidal creeks and coastal oceans. Contrarily, the shrimp pools are static and the water inlet and outlet are regulated by the human being.

The SOC content provide novel insights on its distribution in the mangrove and shrimp farm land in the Red Sea Coast of Saudi Arabia. The mangrove sites of Red Sea showed higher SOC content than their adjacent shrimp farms that partly reflect the differences in SBD previously discussed. The SOC content decrease due to conversion of mangrove to shrimp farm could be observed along the whole sediment profile (see Fig. 3). SOC in mangrove areas is likely a result of *A. marina*, mainly due to litter fall and underground roots instead, in the shrimp farm, the vegetal cover has been eliminated. Other studies on the variation of SOC content in mangrove areas due to changes in land use coincide with the present finding by always indicating a significant decrease in SOC content in the transformed areas (Andreetta et al., 2016; Arifanti et al., 2019; Bhomia et

al., 2016; Cameron et al., 2019; Gevana et al., 2015; Kauffman et al., 2018; Kauffman et al., 2016; Pérez et al., 2017). The decline in the amount of organic matter in the shrimp farms has been attributed to decomposition of the organic matter in soils especially during periods when the ponds were drained after shrimp harvests. Draining and limiting tidal flows likely created aerobic conditions favorable for carbon oxidation (Arifanti et al., 2019).

A general trend observed with respect to SOC contents in sediments of tropical forests including mangroves was decreasing SOC with increasing depth. A similar trend was observed in both, mangrove area and shrimp farm. Our results are in accordance with numerous studies (e.g., Arifanti et al., 2019; Eid and Shaltout, 2016; Eid et al., 2016; Gevana et al., 2015; Khan et al., 2018; Kauffman et al., 2018; Perera and Amarasinghe, 2019), which documented the high capacity for organic carbon sequestration of Mangrove soils in comparison to that reported when these mangroves are transformed to other land used. The SOC depth profile for both study sites also reflects the differences in the SBD. Negative correlations between SBD and SOC content were easily explainable as organic matter increases the porosity. Differences in SOC content between mangroves and shrimp farms decrease from surface to depths of 20-40 cm to become more pronounced at greater depths. SOC content in Saudi Arabia mangrove areas ($32.8\text{--}6.2 \text{ g C kg}^{-1}$) is in line with other study in Egypt (other side of Red Sea) ($20.0\text{--}11.4 \text{ g C kg}^{-1}$) (Eid and Shaltout, 2016).

The comparison of mean soil C stocks in the 1 m between mangroves ($29.2 \pm 0.4 \text{ kg C m}^{-2}$) and shrimp farms ($19.9 \pm 0.8 \text{ kg C m}^{-2}$) resulted in soil loss of 9.3 kg C m^{-2} . These SOC stocks are higher than those previously reported by (Atwood et al., 2017) ($72 \text{ Mg C h}^{-1} \equiv 7.2 \text{ kg C m}^{-2}$) and for Serrano et al. (2018) (4.5 kg C m^{-2}) for mangroves of Saudi Arabia. Results of our study triplicate the SOC stocks in mangrove area and duplicate them in shrimp farms. These discrepancies can be due to the scarce number of existing data and the variability of the own ecosystems across the Red Sea since Atwood et al. (2017) already mention that the data represent less than 30 % of Saudi Arabia marine eco-regions with mangroves.

Comparing with the other studies worldwide, SOC stocks in Saudi Arabia mangrove areas (29.2 kg C m^{-2}) was lower than that of the mangrove forests in Sri Lanka (59.0) (Perera and Amarasinghe, 2019), Indonesia (68.8 kg C m^{-2}) (Kusumaningtyas et al., 2019), Brazil (41.8 kg C m^{-2}) (Kauffman et al., 2018), Dominican Republic (70.8-113.1) (Kauffman et al., 2014) and

Micronesia (Kauffman et al., 2011). On the other hand, SOC stocks in the studied area were higher than the reported values in Egypt (8.5 kg C m^{-2}) (Eid and Shaltout, 2016), Vietnam (5.8 kg C m^{-2}) (Grellier et al., 2017) and New Zealand (6.9 kg C m^{-2}) (Pérez et al., 2017). The results obtained in our study are not totally discrepant with the previous ones that included this area (Almahasheer et al., 2017; Atwood et al., 2017). However, the low capacity to act as carbon sinks that has been attributed to the mangroves of this area may not really be as low and that its importance in mitigating the effects of global change may be greater than that traditionally attributed to it. Shrimp farms present a decline in the carbon stocks compared to adjacent mangroves of 31.8 %. Soils were the almost only carbon pool for shrimp farms where the vegetative cover overlaying ponds has disappear (Fig.1) and carbon stock was limited to that contained in soil. That means that the decline of carbon stocks are higher than those due only to the loss of soil carbon stocks.

The mean cumulative potential CO_2 emission due to soil carbon stock from mangrove conversion to the shrimp ponds was $34.9 \text{ kg CO}_2 \text{ m}^{-2}$. Kauffman et al. (2018) reported the mean potential carbon emission associated with mangrove conversion to shrimp ponds was $139 \text{ kg CO}_2 \text{e m}^{-2}$ in Brazil that is higher than that reported in our study. Similarly carbon losses from soils at depths $>100 \text{ cm}$ were found in Mexican cattle pastures converted from mangroves ($143 \text{ kg CO}_2 \text{ m}^{-2}$) (Kauffman et al., 2016) as well as in shrimp ponds in Indonesia ($226 \text{ Kg CO}_2 \text{ m}^{-2}$) (Arifanti et al., 2019). The significant losses of carbon from the shrimp ponds reported here are likely underestimates because the carbon accumulate in the mangrove areas as biomass have not been taken into account and this land use affects carbon dynamics outside of the boundaries of the shrimp ponds. Another aspect less taken into account is the effects that the discharges from the shrimp farms may have on the neighboring mangroves. Vaiphasa et al. (2007) reported that shrimp pond effluents had dramatic effects on the survival of mangroves surrounding ponds. Given the importance of these ecosystems as carbon sinks, these aspects must be taken into account much more than they have been so far.

5. Conclusions

The SOC content and density profile and SBD distribution in mangroves and shrimp farms have shown that mangroves have lower SBD and more organic matter than fish farms. The organic matter contents in the 0-10 cm sediment depth accounts for 34.9 % of total SOC content in the

studied sediments, which indicates that the mangrove layer can be carbon sink. This study demonstrated how mangroves improve the SOC content of the sediments. One of the ecosystem services provided by mangrove areas is the increased efficiency of soil carbon sequestration because mangrove trees are appropriate organic matter sources. This study is an example of how the transformation of mangroves by anthropogenic pressure in some areas, can degrade sediments organic matter store and pinpointed the importance of preservation and afforestation projects that will help to increase the mangrove areas. The preservations of these areas, instead of their transformation in aquaculture ponds can help to fight against climate change and reduce the effect of the anthropogenic pressure.

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Table 1

Mean $\pm$ standard error of sediment bulk density (SBD; g cm⁻³), sediment organic carbon (SOC) concentration (g C kg⁻¹) and SOC stock (kg C m⁻²) in the locations of shrimp farms and mangroves (*Avicennia marina*) along the southern Red Sea coast of Saudi Arabia. *t*-values represent the student's *t*-test. ***: $P < 0.001$.

Location	SBD (g cm ⁻³)	SOC concentration (g C kg ⁻¹)	SOC stock (kg C m ⁻²)
Shrimp farms	1.82 $\pm$ 0.03 ($n = 180$)	12.9 $\pm$ 0.6 ($n = 180$)	19.9 $\pm$ 0.8 ($n = 18$)
Mangroves	1.66 $\pm$ 0.02 ($n = 180$)	17.7 $\pm$ 0.6 ($n = 180$)	29.2 $\pm$ 0.4 ($n = 18$)
<i>t</i> -value	9.3***	11.1***	9.5***

Figures captions

Fig. 1. Map of the study area indicating the six sampling locations.

Fig. 2. Distribution of sediment bulk density (g cm^{-3}) in relation to sediment depth (cm) in the locations of shrimp farms and mangroves (*Avicennia marina*) along the southern Red Sea coast of Saudi Arabia. Horizontal bars indicate the standard errors of the means ($n = 18$). F -values represent the two-way ANOVAs. Location: shrimp farms/mangroves; Depth: 0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70, 70-80, 80-90, 90-100 cm. ***: $P < 0.001$. Means followed by different letters are significantly different at $P < 0.05$ according to the Tukey's HSD test.

Fig. 3. Distribution of sediment organic carbon concentration (g C kg^{-1}) in relation to sediment depth (cm) in the locations of shrimp farms and mangroves (*Avicennia marina*) along the southern Red Sea coast of Saudi Arabia. Horizontal bars indicate the standard errors of the means ($n = 18$). F -values represent the two-way ANOVAs. Location: shrimp farms/mangroves; Depth: 0-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60-70, 70-80, 80-90, 90-100 cm. **: $P < 0.01$, ***: $P < 0.001$. Means followed by different letters are significantly different at $P < 0.05$ according to the Tukey's HSD test.

Fig. 4. Non-linear correlation between sediment organic carbon concentration (g C kg^{-1}) and sediment bulk density (g cm^{-3}) of 360 sediment samples from the locations of shrimp farms and mangroves (*Avicennia marina*) along the southern Red Sea coast of Saudi Arabia.

Fig.1.

Fig.2.

Fig.3

Fig.4