Role of *Avicennia marina* (Forssk.) Vierh. of South Sinai, Egypt in Atmospheric CO_2 Sequestration

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Abstract: ***This study focused on valuation of the mangrove (Avicennia marina) sediments organic carbon stock for naturally occurring mature mangrove in all defined habitat types (Intertidal, Shoreline, Salt Plains) distributed along Gulf of Aqaba and the Red Sea in two marine protected areas (Nabq and Ras Mohammed) in South Sinai, Egypt, results were compared with soil organic carbon in sediments from 10 years old planted mangrove, non-mangrove mud flats and the hypersaline ecosystem of Salt Lake in Ras Mohammed National Park. Furthermore, the study estimated the potential of these ecosystems in the process of atmospheric CO_2 sequestration using the low-temperature loss on ignition (^{o}C 375/17 hrs.), sediment samples were also analyzed for dry bulk density (DBD) and percentage of soil organic carbon (SOC) at a depth interval 10 cm to the maximum reached depth. Change in mean DBD of intertidal mangrove soil was increasing gradually passing from uppermost layer to deeper layer but converse pattern obtained in the hypersaline ecosystem while in the rest of studied habitats change in soil DBD with depth did not follow a distinct pattern. SOC for the six studied habitats showed the following descending order 34.4, 25.7, 14.51, 7.24, 5.74 and 3.58 g C kg^{-1} for intertidal mangrove, hypersaline ecosystem, salt plain mangrove, shoreline mangrove, planted mangrove and non-mangrove mud flats respectively. Only 10 years old mangroves had a carbon stock in sediments equal 44.19 % of these mature intertidal mangrove so mangrove plantation is an efficient action for mitigation of climate change especially if it is conducted on previously depleted mangrove sites (restoration) than transplantation in non-mangrove sits. Mangrove of intertidal habitat is contributed with 95% of carbon sequestration process of Sinai mangrove, the overall carbon sequestration potential of Sinai and Egypt mangroves are 116.89 and 1207.5 t C year^{-1} respectively considering that all Egypt's mangroves have similar sequestration potential to studied Sinai mangrove.***

Keywords: Coastal Habitats; Mangrove; Protected Areas; Sinai; Soil Organic Carbon

1. Introduction

„Climate change‟ is the persistent change in the state of the climate properties, which remains for decades [1]. By the late 1950s, several scientists were arguing that the problem of global warming is a direct contribution of elevated levels of atmospheric carbon dioxide resulted from several anthropogenic sources of emissions. Habitat loss and habitat fragmentation are remarkable signs of climate change, with sea level rise, coastal marshes, wetlands, and mudflats migrating further inland [2].

Mangrove ecosystem is highly threatened, based on available evidence of all the climate change outcomes, relative sea-level rise may be the greatest threat to mangroves and most of the mangrove sediment elevation are not able to cope perfectly with sea level rise especially if there is restrictions or barriers prevent landward retrogression [3]. With the increased of world understanding impacts of climate changes, negotiations started in Kyoto, Japan in 1997 trying to provide solutions for lowering emissions of the main six greenhouse gases including CO_2 gas, in February 2005 protocol was signed putting time bound basis for minimizing emissions of main industrial countries by 5.2% compared to their emissions in 1990 [4]. Since coming of Kyoto protocol into force many scientists have suggested that the sequestration of atmospheric CO_2 into soil organic carbon (SOC) could contribute significantly to follow Kyoto Protocol of lowering greenhouse gases emissions [5], [6]. Three strategies for lowering CO_2 emissions: First reducing the global energy use, second developing low or no-carbon fuel, third sequestering CO_2 from point sources or atmosphere through natural and engineering techniques [7].

Wetlands represent one of the largest biological carbon stocks and play a significant role in the global carbon cycle [8], [9]. Mangroves occupy only about 0.4% of the global forests area, they are important sinks for atmospheric CO_2 along tropical coastlines [10], [11] and they are among the most productive ecosystems on earth and account for about 11% of the total input of terrestrial carbon into the world oceans [10].

Only two mangrove species in Egypt, *Avicennia marina* and *Rhizophora mucronata*. Distributed as separate stands on the coastal belt of Red Sea, the southern part of Gulf of Aqaba and the Red Sea islands. *Avicennia marina* grows and predominates along the whole stretch of the Red Sea Coast starting from Hurghada (Latitude 27°12) and continue south to Marsa Halaib (700 km south of Hurghada) at the Sudano-Egyptian frontiers (Latitude 22 °N). *Rhizophora mucronata* occurs only in the most southern section of the Red Sea coast starting from Shalatein (Latitude 23°28 N) southward to Mersa Halaib (Latitude 22 °N) [13]. The total area occupied by the mangrove vegetation in Egypt is about 525 ha [14]. Mangrove of Sinai is presented by two monospecific stands of *Avicennia marina*. The first stand is located in Ras Mohammed national park at the most southern tip of Sinai peninsula where the mangrove is mainly trapped in shallow channel exist between Boa‟ayra island and land side. The second stand occurs in Nabq protected area and represent the most northern limit of the mangal distribution in the Red Sea and Indian Ocean [15], [16].

Avicennia marina in South Sinai is properly protected by being included in two marine protected areas (Nabq and Ras Mohammed) covering a total area of 50.99 ha [17], distributed on four different habitats, intertidal, shoreline, salt plains and sand mounds habitats with a clear difference in trees biomass, density and several ecological settings [18]. In the Arabian region, the blue carbon ecosystems of Abu Dhabi in the United Arab Emirates were studied comparing natural and transplanted mangrove stands [19] while in Egypt soil organic carbon for mangrove and non-mangrove mud flats were compared in Northern Red Sea coast of Egypt [20].

The current work aims providing an evaluation of carbon sequestration potentiality of mangrove ecosystem in the two main stands areas of South Sinai through;

(1) evaluation of sediments organic carbon content, and (2) applying the previous estimate of the total mangrove cover in different habitat types to obtain a relevant estimate of overall blue carbon sequestered by mangrove forests. The obtained results are discussed as a case study representing similar ecosystems in arid regions.

Material and Methods

2.1 Study area

Sinai is a Peninsula located at the Northern east of Egypt where it is the actual junction between Africa and Asia continents (Figure 1). Several supply valleys or streams are running from the central high altitudes to Gulf of Aqaba at the east supplying mangrove stands of Nabq with seasonal rain flush and sediments. In Ras Mohammed stand there is no clear direct watersheds supply to the mangrove channel.

The mean annual temperature in the study area is 24.8 and 25.6 C^{o} for Nabq and Sharm El Sheikh respectively. The annual rainfall in the most southern part of south Sinai is only 10-15 mm/year where Ras Mohammed stands is located, and it increases gradually moving to the north to record 15-20 mm/year along Gulf of Aqaba where Nabq main stand exists [21]. Solar radiation in both Nabq and Ras Mohammed sites is 20.8 Mj/m^2, where the maximum radiation occurs in June (28.4 Mj/m^2) and the lowest in December (12.6 Mj/m^2) [22], [23].

The study sites were selected to represent the different mangrove habitat types in natural and transplanted areas. In Nabq four habitats were selected, the intertidal, shoreline, salt plains and 10 years old planted mangrove, while in Ras Mohammed the hypersaline ecosystem of Salt Lake and mud flats were also selected.

2.2 Sediments sampling and drying

Fashioned core sampler based on Split Core Sampler was used to obtain undisturbed and uncompressed sediment samples to a depth of 100 cm with an internal diameter of 52 mm (cross section area = 21.23 cm^2). Core insertion in sediments continued to a maximum depth of 100 cm at low tide if the basement rock materials not encountered before reaching the maximum depth, two samples separated at each section, which conducted at 10 cm intervals. Samples of 0-10, 10-20, 20-30 cm, so on mentioned as depths 10, 20, 30 cm in the results. Sub-cores of 5 cm^3 collected at each depth interval with a fashioned corer from a cut-off 10 cm^3 hypodermal syringe, collected from the center of the section away from plant rootlets and stones and kept for the estimate of dry bulk density (DBD) and further analysis.

All samples placed in sterilized sealed plastic bags with the site code and sample depth recorded and kept in the icebox at temperature below 4 ^{o}C to reduce microbial degradation until reaching laboratory. The first group of samples was placed directly in the oven for drying at only 55 ^{o}C for 72 hrs in fan circulating Carbolite furnace (Jetec JTC-903 thermo-controller) to avoid any loss of organic carbon during drying [24], while the archive pack up samples were stored in the freezer below -20 ^{o}C.

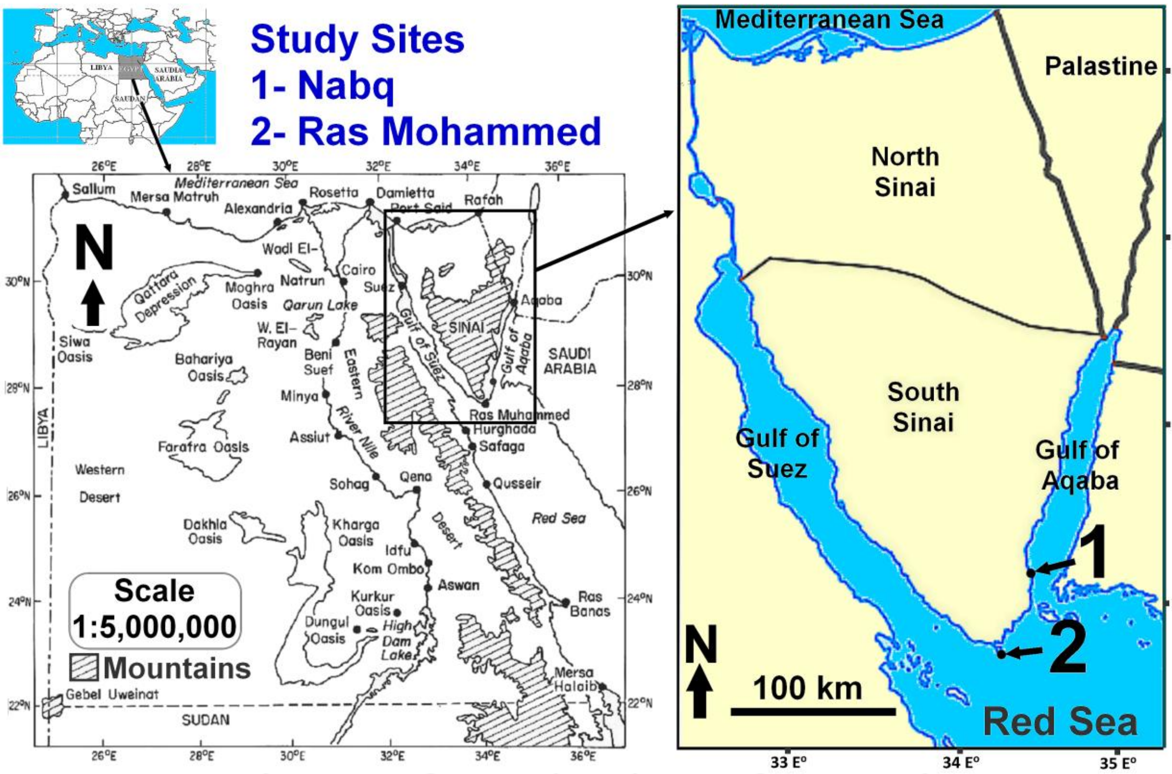

Figure 1: Location of the study area in Sinai peninsula. (1) Nabq managed resources protected area at the southern entry of Gulf of Aqaba and (2) Ras Mohammed National Park at the most southern tip of Sinai Peninsula

2.3 Sample analysis

Oven-dried soil samples were cooled down to room temperature in a desiccator and weighed to determine the DBD (g cm^{-3}). Dry samples were then cleared from fine plant remains and homogenized by grinding mortar and pestle then sieved to pass 2 mm particle size followed by re-drying at 55^{o}C for 24 hrs then cooled in the desiccator and finally preserved in sterilized tagged sealed plastic bags for further analysis.

Aliquots of dried and 2 mm sieved soil samples were used to estimate the soil organic carbon content (SOC) using loss on ignition method (LOI) according to [25]. Pre-weighted dry samples were ashed in a pre-ashed crucibles in furnace at 375°C for 17 hours.

Then soil organic matter (SOM) estimated according to the following equation…

$$SOM_{LOI} = [(Weight_{55^{o}C} – Weight_{375^{o}C}) / Weight_{55^{o}C}] \times 1000$$

Where SOM_{LOI} is soil organic matter (g kg^{-1}), $Weight_{55^{o}C}$ is initial sample dry weight and $Weight_{375^{o}C}$ is final sample weight after ignition at 375 ^{o}C for 17 hrs.

Then further conversion of SOM to SOC according to the following equation;

$$SOC_{LOI} = (SOM_{LOI} – 4.189) / 1.792$$

Where SOC_{LOI} is soil organic carbon (g kg^{-1}), 4.189 is a constant of weight loss resulted from structural water and carbonates during ignition process and 1.792 is the conversion factor of SOM to SOC.

The organic carbon density (C_d) in (g C cm^{-3}) for each depth interval was calculated by multiplying the SOC value for each depth increment by the corresponding DBD as the following equation [26]:

$$C_{di} = SOC_i \times DBD_i$$

Where C_{di} is soil organic carbon density of the horizon i, SOC_i is the soil organic carbon of that horizon i and DBD_i is soil DBD of the horizon i.

To calculate the soil organic carbon pool (SOCP) of the core segment (CC_{segmet}), the following equation was used according to [19]:

$$CC_{segment} = [Z_{(segment)} \times C_{d\,(segment)}] / 100$$

Where $Z_{(segment)}$ is the length of given depth interval (10 cm) and $C_{d\ (segment)}$ is the corresponding carbon density of the segment, dividing the product by 100 is to convert the SOC units from percentage of dry weight to grams carbon per Kg (of sample dry weight). Finally, the total SOCP (Kg C m^{-2}) was calculated by summing CC (segment) values from the length of each core.

Several authors [27], [28], [29] reported that ignition temperature of less than 400 – 430 ^{o}C is safe enough to avoid a bias resulting from calcium carbonate decomposition in calcareous soils during organic carbon estimation by using loss on ignition method.

2.4 Sedimentation Rate

Sedimentation rate (mm year^{-1}) was determined by installing 60 sediment traps (Petri dish lids) held to the sediment by hooks. The sediment traps were deployed homogenously in the different locations according to [30], traps were left for one year with a regular check every 3 months. The traps were carefully covered with a plastic sheet and released from water. Petri dish lids were placed stable on benches until complete settlement of fine sediments, then oven dried at 55 °C for 3 days. The thickness of the dry sediment layer was measured by a calliper. Water salinity in Salt Lake was measured monthly for one year using hand held refractometer.

2.5 Carbon Sequestration Rate

Carbon sequestration rate (CSR) was determined as (g C m^{-2} $year^{-1}$) and calculated according to [31] as following:

$$CSR_h = DBD_h \times SOC_h \times R_h$$

Where CSR_h is CSR (g C m^{-2} $year^{-1}$), DBD_h is corresponding mean DBD (g cm^{-3}), SOC_h is the mean SOC (g C Kg^{-1}) and R_h is the sedimentation rate (mm $year^{-1}$).

Habitat-based estimate of carbon sequestration potential

To estimate the overall carbon sequestration potential (CSP) as based on mangrove distribution in different habitats (intertidal, shoreline and salt plains), the following equation was applied after according to [31].

$$CSP_h = Ah \times CSR_h$$

Where CSP_h is the of carbon sequestration potential as mega gram carbon per year (Mg C $year^{-1}$) of mangrove in habitat h, Ah is the mangrove cover area (m^2) of habitat h and CSR_h is CSR (g C m^{-2} $year^{-1}$) of mangrove in habitat h.

The total mangrove cover in Egypt according to [14] is 525 ha, it is possible to elucidate the overall carbon sequestration potential of Egypt mangroves (definitely for *Avicennia marina*), while according to [32] the total mangrove plantation area in Egypt is 12.55 ha, more reliable estimate of the total CSP of Egypt mangrove could be obtained.

2.6 Statistical Analysis

Data calculations and analysis were carried out using SPSS BASE 19.0 (SPSS Inc., Chicago, IL). Mean, standard deviation, standard error of mean and developed correlation models between measured parameters in addition to illustrating graphs.

3. Results

3.1 Soil Dry Bulk Density

Soil dry bulk density (DBD) was evaluated as a basic step in the evaluation of soil organic carbon density (OCD). The average DBD for the study area habitat types are shown in (table 1). Change in DBD (g cm^{-3}) with sampling depth did not give distinct patterns in the studied habitats apart of intertidal mangrove soil exceptionally followed a gradual increase in DBD getting to lower soil horizons. Also in non-mangrove mud flats, soil DBD had a gradual increase in from 10 to 30 cm depth then further decrease at a maximum depth of 40 cm (table 1), knowing that 90.47% of samples had DBD ranged between 0.9 – 1.5 g cm^{-3} and only two samples were ranged between 1.5 – 1.6 g cm^{-3} (Figure 2).

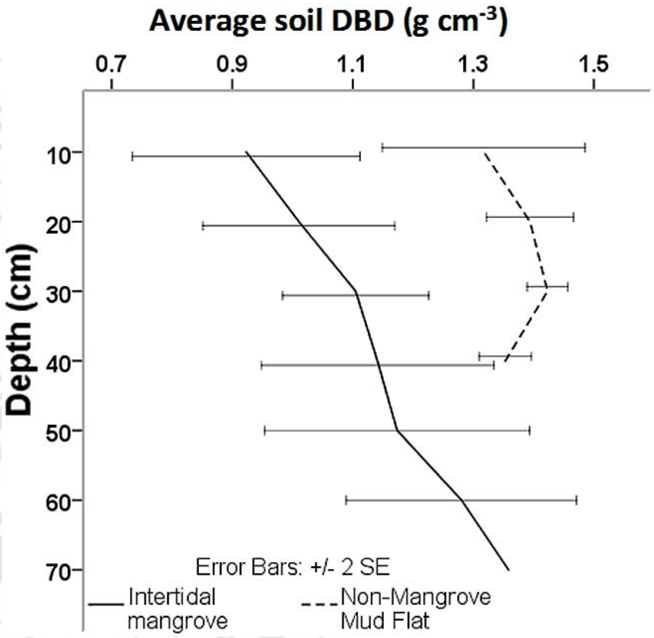

Figure 2: Gradual increase in mean soil DBD (g cm^{-3}) with depth in Intertidal mangrove and non-mangrove mud flat habitats, greater compaction at deeper layers and moving away from rhizosphere results less biological activity and less gapping between soil particles, horizontal bars represent standard error of mean and absence of error bars indicate only one sample was possibly obtained at that depth.

3.2 Soil Organic Carbon

Table 1: Average Soil organic carbon pool (Mg C ha^{-1}), CSR (Mg C ha^{-1}), habitat area in Sinai (ha) and CSP (Mg C $year^{-1}$) of all studied habitats in Sinai, a part of non-mangrove mudflats intertidal mangrove contributed with about 94.97% of CSP of all studied habitats.

Habitat	Soil DBD (g cm^{-3})	SOCP (Mg C ha^{-1})	CSR (Mg C ha^{-1} $year^{-1}$)	Habitat Area (ha)	CSP (Mg C $year^{-1}$)	Habitats Contribution in CSP (%) [d]	Mangrove Habitats Contribution in CSP (%) [e]
Intertidal Mangrove	1.07	428.02	2.382	[a] 48.32	115.1	94.975	98.469
Shore Line Mangrove	1.27	284.35	0.545	[a] 1.55	0.85	0.701	0.727
Salt Plain Mangrove	1.12	656.21	1.041	[a] 0.73	0.76	0.627	0.650
Transplanted Mangrove	1.41	189.14	0.480	[a] 0.37	0.18	0.149	0.154
Non-Mangrove Mudflat	1.37	98.04	0.137	[b] ----	----	----	----
Hypersaline Ecosystems	1.15	599.75	0.814	[c] 5.28	4.3	3.548	----
Total CSP of mangrove habitats only					116.89		
Total CSP of studied habitats in Sinai					121.19		

[a] Source El-Hussieny, (2011) - [b] Habitat area not available, so CSP not estimated - [c] Area of Salt Lake in Ras Mohammed from GooglEarth – [d] All studied habitats contribution in CSP of the total CSP of all habitats – [e] Contribution of each mangrove habitat in CSP

Average soil organic carbon of the studied habitats followed the following descending order 34.4 ±8.9 > 25.7 ±4.45 > 14.51 ±2.95 > 7.24 ± 1.06 > 5.74 ±1.04 > 3.57 ±0.39 g C kg^{-1} for intertidal mangrove > hypersaline ecosystem > salt plain mangrove > shore line mangrove > transplanted mangrove > non-mangrove mud flats, respectively. Change in mean SOC with sampling depth did not follow a distinct pattern in all studied habitats.

3.3 Correlation Model of SOC and DBD

Testing correlation between SOC and DBD of 126 analyzed samples showed a significant negative correlation between tested parameters, *p*-values were < 0.001 for all tested models and R^2 values ranged between 0.629 - 0.883.

The best fitting model was the cubic model, *p*-value < 0.001 and R^2 = 0.883 (Figure 3), so the relation between SOC and DBD presented according to the following equation…

$SOC = 609.428 + [(-1264.829)\ (DBD)] + [(889.923)\ (DBD)^2] + [(-210.698)\ (DBD)^3]$

Testing best fitting SOC and DBD correlation models for mangrove and non-mangrove habitats soils separately gave cubic model where $p< 0.001$, $R^2 = 0.903$ and exponential model where $p< 0.001$, $R^2 = 0.657$ for mangrove and non-mangrove habitats respectively, so relations between SOC and DBD are presented according to the following equations …

$SOC = 607.599 + [(-1246.692)\ (DBD)] + [(853.402)\ (DBD)^2] + [(-192.984)\ (DBD)^3]$ for mangrove habitats and $SOC = 11851.846 \times (e^{(-5.737*\ DBD)})$ for non-mangrove habitats.

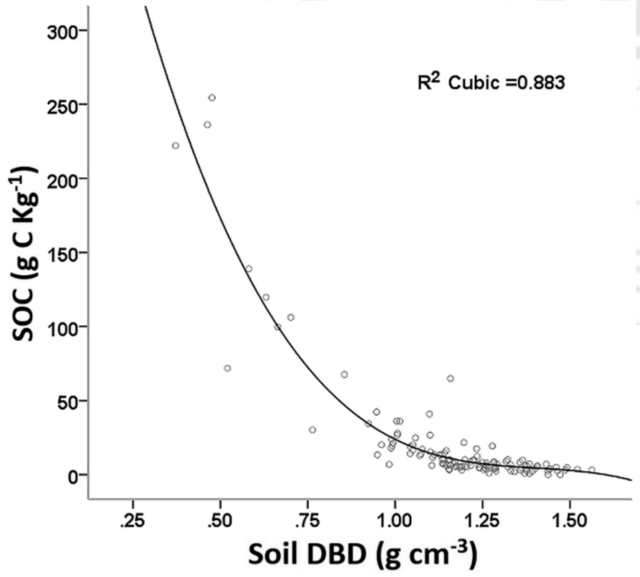

Figure 3: Negative cubic correlation between SOC (g C Kg^{-1}) and DBD (g cm^3), correlation is linked to activity soil microflora indicated with higher levels of SOC followed with the conversion of soil micropores into macropores lowering DBD, *P*-value < 0.001 and R^2 = 0.883.

3.4 Soil Organic Carbon Density

Soil organic carbon density (OCD) in (Kg C m^{-3}) is greatly different from SOC since it is greatly affected with soil DBD, hence soil or soil layers which had high SOC may yield lower OCD because of low DBD and vice versa. Intertidal mangrove soil showed almost gradual decrease in soil OCD passing from upper to deeper soil layers, while other studied habitats mostly showed increase then further decrease in soil OCD passing to deeper layers which are almost having OCD similar to uppermost layers.

3.5 Correlation Model of OCD and SOC

Testing correlation between OCD and SOC of 126 analyzed samples showed significant positive correlation between tested parameters (Figure 4), *p*-values were < 0.001 for all tested models and R^2 values ranged between 0.206 and 0.969.

The best fitting model was the power model, *p*-value < 0.001 and R^2 = 0.969, so the relation between OCD and SOC presented according to the following equation…

$OCD = 1.746\ (SOC)^{0.818}$

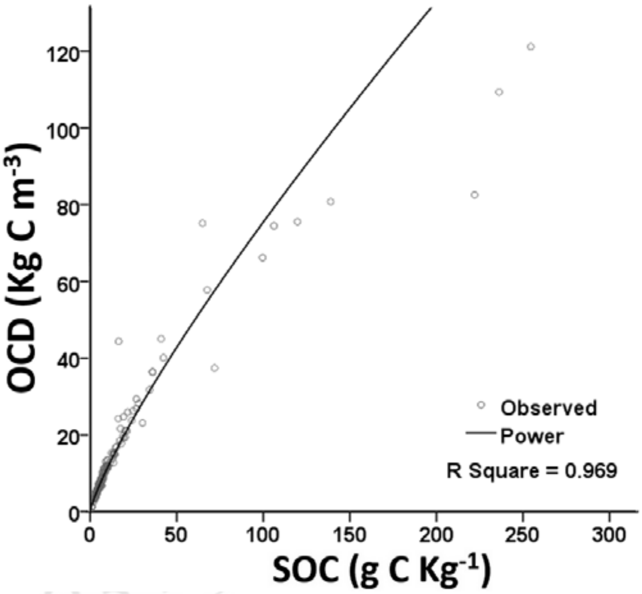

Figure 4: Positive power correlation between OCD (Kg C m^{-3}) and SOC (g C. Kg^{-1}), 91.27% of samples had SOC less than 5% of sample weight, *p*-value < 0.001 and R^2 = 0.969.

3.6 Correlation Model of OCD and DBD

Testing correlation between OCD and DBD of 126 analyzed samples showed a significant negative correlation between tested parameters (Figure 5) where, *p*-values were < 0.001 for all tested models and R^2 values ranged between 0.564 and 0.736. The best fitting model was the cubic model, *p*-value < 0.001 and R^2 = 0.736, so the relation between OCD and DBD presented according to the following equation…

$OCD = 0.736 + [(-73.015)\ (DBD)] + [(-102.888)\ (DBD)^2] + [(62.421)\ (DBD)^3]$.

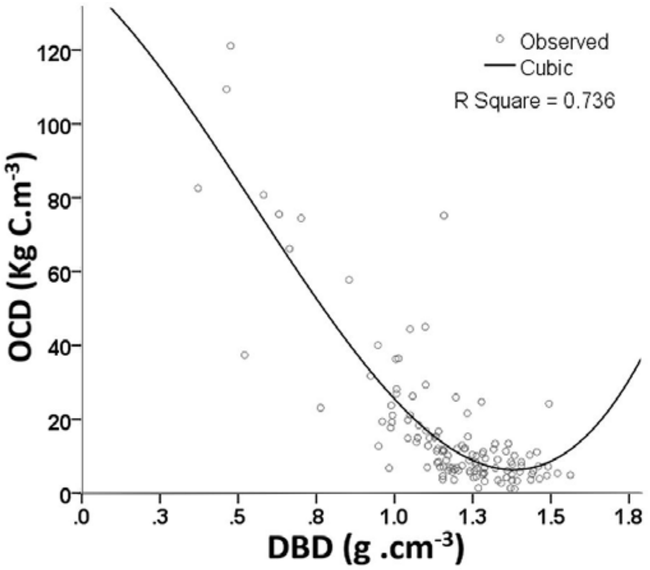

Figure 5: Cubic correlation between OCD (Kg C m^{-3}) and DBD (g. cm^{-3}), where correlation is negative from lower DBD to a maximum DBD inversion point of 1.4 g.cm^{-3} at which correlation become positive, stronger correlation between SOC and OCD (p-value < 0.001 and $R^2 = 0.969$) greatly affects OCD than DBD where p-value < 0.001 and $R^2 = 0.736$ between OCD and DBD. At DBD of 1.4 g. cm^{-3}.

3.7 Soil Organic Carbon Pool

Soil organic carbon pool (SOCP) is the expression of total carbon mass per unit of surface area (Kg C m^{-2}) or (Mg C ha^{-1}) that is referring to estimate of SOC to the maximum reached depth for each site, less sediment thickness in intertidal mangrove compared to salt plain mangrove shifted pushed down SOCP of intertidal mangrove. Cores sampling depth varied between studied habitats and even sites of the same habitat, so estimate of SOCP in different sites was done separately for each core sample and further averaging of resulted SOCP values to estimate habitat SOCP as in (table 1).

3.8 Sedimentation Rates in Studied Habitats

Mean sedimentation rate for intertidal, shoreline, salt plain and planted mangroves were almost similar (6.0 ±0.52 mm year^{-1}) while lower rates obtained in non-mangrove mud flats mean, (1.7 ±0.29 mm year^{-1}) and (1.3 ±0.09 mm year^{-1}) in the hypersaline ecosystem of the Salt Lake in Ras Mohammed national park. Exceptional notably high sedimentation rates obtained from traps installed submerged in Hidden Bay in Ras Mohammed national park, Monquatea‟a lagoon and Caulerpa lagoon in Nabq protected area, where 19.32, 17.50 and 18.2 mm year^{-1} respectively, all were distant from mangrove trees.

3.9 Carbon Sequestration Rate

Study of soil organic carbon pool (SOCP) conducted on habitat level, so more reliable results were obtained due to notable differences in mean sedimentation rate (mm year^{-1}), mean DBD (g cm^{-3}) and mean SOCP (Mg C ha^{-1}) between studied habitats. Therefore, carbon sequestration rates (CSR) in (Mg C ha^{-1} year^{-1}) of the studied habitats presented as in (table 1). Results of CSR showed that habitats other than mangrove (as hypersaline ecosystems) are contributed efficiently in the process of carbon sequestration as well (table 1) clarify that if equal areas of the six studied habitats are existed each will be contributed with the shown percentages of the total CSR of these habitats altogether.

3.10 Carbon Sequestration Potential of Studied Habitats

Carbon sequestration potential (CSP) of the studied habitats was depending on total mangrove cover (ha) in each of studied habitats, the total area of Salt Lake in Ras Mohammed National and CSP of the lake in (table 1). Estimate of Egypt‟s mangrove carbon sequestration potential elucidated depending on the total mangrove cover in Egypt and considering that mangrove of Egypt have almost similar distribution pattern on different habitats to this of Sinai mangrove and having the similar capacity to sequester carbon.

Total mangrove cover in Egypt according to [14] is 525 ha including both *Avicennia marina* and Rhizophora mucronata, the latter species is distributed in the southern part of Egyptian coast of Red Sea starting from Shalatein (Latitude 23°28 N) continued southward to Marsa Halaib (Latitude 22 °N). *Rhizophora mucronata* present scattered in four main aggregates of pure or mixed stands with *Avicennia marina* [13], additional 12.55 ha of planted mangrove were added to the total mangrove cover of Egypt in 2006 [32]. No published information on the *Rhizophora mucronata* cover in Egypt but rapid site assessment of the coast of Elba protected area *Rhizophora mucronata* cover is about 1.0 – 1.5% of total mangrove of Egypt. According to [17] the distribution percentages of Sinai mangrove are 94.76%, 3.04%, 1.43% and 0.77% on intertidal, shoreline, salt plain and sand mounds habitats respectively. If all mangrove of Egypt followed the same distribution pattern on the defined habitats, CSP of Egypt mangrove will be as presented in (table 2).

Table 2: Deduced CSP of Egypt mangroves (Mg C year -1).

Habitat Type	CSR (Mg C ha^{-1}) according to present study	Mangrove distribution percentages cover on the defined habitats (%)	Elucidated mangrove habitat area (ha) in Egypt	CSP of Egypt‟s Mangrove (Mg C year^{-1})
Intertidal Mangrove	2.382	94.76	497.49 ^{c}	1185
Shore Line Mangrove	0.545	3.04	15.96 ^{c}	8.67
Salt Plain Mangrove	1.041	1.43	7.51 ^{c}	7.82
Transplanted Mangrove	0.480	----	12.55 ^{a}	6.02
Total		99.23 ^{b}	533.51	1207.5

[a] Total transplanted mangrove area in Egypt according to ITTO, 2006, value not elucidated.
[b] Remaining 0.77% is the percentage of mangrove cover on sand mound habitat, not evaluated by this study.
[c] Total mangrove cover in Egypt according to Saenger, 2002 and redistribution of occurrence on habitats according to El-Hussieny, S.A. (2011) of Sinai mangrove distribution on different defined habitats.

4. Discussion

Comparing our results with previous similar local and regional studies shows the importance of mangrove ecosystem bordering the arid regions in carbon sequestration. Soil dry bulk density (DBD) which describing the degree of spacing between soil particles that is affecting soil porosity and soil aeration [26]. Comparing the DBD results with results from similar studies from Egypt, United Arab Emirates, Saudi Arabia and China is showed in (table 3). Change in soil DBD with depth didn‟t follow a distinct pattern in shoreline, transplanted and salt plain mangrove soils, but generally in all studied habitats the deepest soil layers were higher in DBD than the uppermost layers, [19], [20], [33].

In intertidal mangrove, soil DBD was increasing gradually passing from uppermost layer to deeper layer (70 cm). Inversely in hypersaline ecosystems, soil in Salt Lake where no *Avicennia marina* exists and the main soil surface biological activity comes by cyanobacterial algal mats. Soil anaerobic bacteria provide the main input of organic matter and microbiological activity, which falls under gradual levels of soil salinity from higher salinity at uppermost layers and less salinity moving to down layers [34]. (Van de Broek et al. 2016). Higher salinity of upper layers, which is covered by thick salt crystals stresses enough to minimize microbiological activity at uppermost layers (lake water salinity reaches 282 ppt. in summer) compared to deeper layers, which fall under dilution effect of seawater. That means higher microbiological activity at deeper layers will convert micropores to macropores [20], [35], [36] increasing spaces and lowering of DBD.

Table 3: Comparing some of reported mangrove soil DBD with present study.

Study	Location	Habitat Type	DBD (g cm^{-3})	Reference
Present study (Role of The Mangrove *Avicennia marina*(Forssk.) Vierh. of South Sinai, Egypt in Atmospheric CO_2 Sequestration Process)	Gulf of Aqaba, Egypt	Intertidal Mangrove	1.07	Present Study
		Shoreline Mangrove	1.27	
		Salt Plain Mangrove	1.12	
		Planted Mangrove	1.41	
		Non-Mangrove Mudflat	1.37	
		Hypersaline Systems	1.15	
Distribution of Soil Organic Carbon in *Avicennia marina*	North Red Sea - Egypt	Mangrove	1.4	[20]
		Mudflats	1.72	
Abu Dhabi Blue Carbon Demonstration Project	Abu Dhabi, Arabian Gulf - UAE	Intertidal Mangrove	1.06	[19]
		Planted Mangrove	1.32	
		Salt marches	1.27	
		Non- Mangrove Mudflat	1.13	
		Coastal Sabkha	1.25	
Decomposition and Soil Carbon Sequestration in Mangrove Ecosystems	Red Sea - Saudi Arabia	Intertidal *Avicennia marina*	1.15	[40]
		Intertidal *Rhizophora mucronata*	0.5	
Ecosystem Carbon Stocks of Mangrove Forest in Yingluo Bay, Guangdong Province of South China	Yingluo Bay China	Intertidal *Avicennia marina*	0.66	[47]
		Non- Mangrove Mudflat	1.13	

The frequency of DBD results in this study showed that 90.47% of measured samples were between 0.9 – 1.5 g cm^{-3} (n=126), which is similar to [19] reported that 92.58% of measured samples were between 1.1-1.6 g cm^{-3}, this slight difference are possibly due to the relatively higher soil DBD values of seagrass soils which is not conducted by present study.

Comparing mean SOC in the six studied habitats showed the following descending order intertidal mangrove > hypersaline ecosystem > salt plain mangrove > shoreline mangrove > planted mangrove > non-mangrove mudflats, respectively. Intertidal mangrove is the most submerged habitat subjecting to the daily tide regime had a higher capacity to trap more downed plant material from different sources together with more secondary and tertiary roots with their exudates enhancing soil microbiological activity [37]. Other mangrove habitats are less inundated and had lower roots density (count per unit area) accompanied with less secondary and tertiary roots density while non-mangrove mudflats are missing both trapping action of mangrove and soil microbiological activity, so less SOC recorded.

Almost similar SOC reported by [17] to salt plain mangrove of present study and provided 17.32% higher SOC than present study estimation for non-mangrove mudflats in northern Red Sea, Egypt, applying high temperature LOI and possible loss part of inorganic carbon in form of carbonates during ignition [38], [39]. Inversely SOC estimate of [20] was less than half estimate of SOC of intertidal mangrove by present study, the lower estimate may due to the several stress conditions mentioned by the author for sampling sites as oil pollution, industrial and solid wastes. Comparable values of SOC reported by [40] to salt plain mangrove of present study for *Avicennia marina* and more than double folds of intertidal mangrove habitat of present study for *Rhizophora mucronata* in Saudi Arabia, Red Sea.

Apart of intertidal mangrove soils, change in SOC with depth did not follow consistent pattern, [19] also report this for all studied habitats in Abu Dhabi including *Avicennia marina* habitat soil, but for intertidal mangrove soils, there are a gradual decrease in SOC passing from surface to deeper layer (70 cm). Similar pattern reported for *Avicennia marina* soils [20], [33] also reported the same pattern for *Kandelia obovata* and *Sonneratia apetala* soil in China. [41], [42], [43] similarly reported a decrease in SOC at deeper layers than upper layers for oceanic mangroves in the indo-pacific region and Lake Mariut in northern Egypt. According to present study results generally, there is a negative cubic correlation between SOC and DBD for 126 analyzed soil samples. An inverse relation reported between SOC and DBD for Ecuadorian mangrove [44]. A negative exponential correlation also developed between SOC and DBE for Red Sea mangrove soil was reported [20].

Comparing mean soil OCD in the six studied habitats showed the following descending order hypersaline ecosystem > intertidal mangrove > salt plain mangrove > shoreline mangrove > planted mangrove > non-mangrove mudflats, respectively. Slightly lower soil OCD reported than present study for the corresponding habitats [20]. [40] Keuskamp (2014) also reported soil OCD slightly less than present study estimate for *Avicennia marina* in Red Sea coast in Saudi Arabia.

Apart from intertidal mangrove where a gradual decrease in OCD passing from upper to deeper layers, the change in soil OCD with depth did not follow a distinct pattern in all other habitats, a similar pattern reported [19]. In spite of negative correlation between DBD and SOC but higher DBD in hypersaline ecosystem resulted in an advance in soil mean OCD (28.61 Kg C m^{-3}) compared to intertidal mangrove habitat (22.92 Kg C m^{-3}), this could be explained with the curve inversion point in the cubic correlation between OCD and DBD at mean DBD = 1.4 g cm^{-3} after which increase of DBD results in an increase of OCD.

For intertidal mangrove, there was a gradual decrease in soil OCD passing from surface to deeper layers, so the mean soil OCD in the uppermost 0-10 cm layer was eight folds that OCD at the maximum depth of 60-70 cm, what means that about 28.7% of the total soil OCD is allocated in the uppermost 10 cm of sediment surface.

Almost of soil OCD is allocated in the uppermost soil layers for north Red Sea *Avicennia marina*, lake Burullus in Egypt, vegetated coastal habitats and loess plateau China respectively [20], [45], [46], [47]. According to current study results, there is a positive correlation between SOC and Soil OCD, best fitting correlation model for both studied mangrove and non-mangrove habitats soil was power model where $p < 0.001$, $R^2 = 0.969$.

There is an almost negative correlation between soil OCD and DBD. Best fitting model was the cubic model, p-value < 0.001 and $R^2 = 0.736$. There is remarkable curve inversion point at DBD = 1.4 g cm^{-3} after which an increase in soil OCD with increased DBD knowing that 11.9% of tested samples had DBD ≥ 1.4 g cm-3 for DBD range (0.375 - 1.562 g cm^{-3}) respectively. Larger range of soil DBD reported (0.137 - 1.726 g cm^{-3}) [19], the study covered seagrass ecosystem, larger study area and a greater number of samples than current study.

Comparing SOCP (Mg C ha^{-1}) in different habitats it was highly affected by the maximum reached depth of sediments during coring, accordingly results for this study may surprisingly provide an exceptional higher estimate of SOCP for example of more stressed mangrove habitats like salt plain mangrove compared with intertidal mangrove (65.6 vs 42.8 Kg C m^2). SOCP of the studied habitats followed the next descending order salt plain mangrove > hypersaline ecosystem > intertidal mangrove > shoreline mangrove > planted mangrove > mudflats.

SOCP was highly linked to maximum coring depth, the deeper sediment layer the higher SOCP is obtained, some habitats have higher OCD Kg C m-3 inversely yield lower SOCP (as intertidal mangrove) as they have thinner sediment layer.

Mangrove soil organic carbon pool (SOCP) in (Mg C ha^{-1}) is of great significance especially at the national and regional levels, results obtained by current work are compared with results obtained from either mangrove or non-mangrove habitats in Egypt, Arabian region, Africa and the world (table 4).

Table 4 Significance SOCP (Mg C ha^{-1}) results of present study to the national and global levels, this study results showed the highest values of SOCP between all studies conducted on lakes and mangrove ecosystems in Egypt, while results almost close to these of Madagascar and four times as these of Abu Dhabi but so far less than results from Mexico and Colombia.

Study	Location	Habitat Type	SOCP (Mg C ha^{-1})	Reference
Present Study (Role of The Mangrove *Avicennia marina* (Forssk.) Vierh. of South Sinai, Egypt in Atmospheric CO_2 Sequestration Process)	Gulf of Aqaba, **Egypt**	Intertidal Mangrove	**428.02**	Present Study
		Shore Line Mangrove	**284.35**	
		Salt Plain Mangrove	**656.21**	
		Planted Mangrove	**189.14**	
		Non-Mangrove Mudflat	**98.04**	
		Hyper Saline Systems	**599.75**	
Distribution of soil organic carbon in *Avicennia marina*	North Red Sea - **Egypt**	Mangrove	85	[20]
		Mudflats	26	
Evaluation of Carbon Sequestration Potentiality for Lake Burullus	Lake Burullus, Mediterranean Coast - **Egypt**	Vegetated	93	[45]
		Un-vegetated	74	

Table 4 Continued

Table 4 Continued

Carbon Storage Capacity of Lake Mariut	Lake Mariut, Mediterranean Coast - **Egypt**	Main basin	30.66	[43]
		Drained areas	3.03	
Carbon sequestration potential of reclaimed desert Soils	Belbes, Sharqya governorate and Sinai, **Egypt**	Desert soils (before reclamation)	3.9	[53]
		Desert soils (30 years after reclamation)	30.3	
Abu Dhabi Blue Carbon Demonstration Project	Abu Dhabi, Arabian Gulf - **UAE**	Intertidal Mangrove	102.3	[19]
		Planted Mangrove	102.3	
		Salt marches	80.4	
		Non- Mangrove Mudflat	96.3	
		Coastal Sabkha	86.1	
Mangrove carbon sink. Do burrowing crabs contribute to sediment carbon storage? Evidence from a Kenyan mangrove system	Gazi Bay - **Kenya**	Intertidal, *Avicennia marina*	180.9	[54]
		Intertidal, *Rhizophora mucronata*	297.2	
Ecological Variability and Carbon Stock Estimates of Mangrove Ecosystems in North-western Madagascar	North-western **Madagascar**	Intertidal, *Avicennia marina* (stunted short and sparse low density)	517.1	[55]
		Intertidal *Rhizophora mucronata* (young short-medium)	324.3	
		Intertidal *Rhizophora mucronata* (Tall and Mature)	446.2	
Biomass and Carbon Stocks of Sofala Bay Mangrove Forests	Sofala Bay, Central **Mozambique**	6 mixed species, *Avicennia marina* forms 53% of relative stem density	160	[56]
Evaluation of carbon sequestration potential in mangrove forest at three estuarine sites in Campeche, Mexico.	Gulf of Mexico Campeche, **Mexico**	4 mixed mangroves species	590-1190	[57]
Quantification of Organic matter and Physical-Chemical Characterization of Mangrove Soil at Hooker Bay, San Andres Island – Colombia.	Mangrove Bay Hooker, San Andres Island - **Columbia**	4 mixed mangroves species	1739.6	[58]
Carbon sequestration potential of *Rhizophora mucronata* and *Avicennia marina* as influenced by age, season, growth and sediment characteristics in southeast coast of India	Pichavaram and Vellar rivers estuary - **India**	*Avicennia marina* *Rhizophora mucronata*	67.47 38.05	[59]

Measured sedimentation rates showed that all mangrove habitats have almost similar mean values which are about 3.5 folds that rate of non-mangrove mudflats and 4.5 folds that of hypersaline ecosystems, but a higher sedimentation rates were obtained from traps installed comparatively submerged in mangrove lagoons, almost 3 folds that of mangrove habitats for three tested mangrove lagoons. [48] measured sedimentation rates in Terengganu mangrove forest, Malaysia using 210Pb dating method, results are between 1.5 – 2 folds of present study, while [49] provided a review of 65 mangrove sediment cores collected all over the world showed a very wide range of sediment accretion rates (1 – 80 mm year^{-1}).

Fluctuation in sedimentation rates in highly dynamic mangrove ecosystem means this parameter is site-specific value must be measured separately for a proper estimate of carbon sequestration rate and further sequestration potential in mangrove ecosystem than depending on global or regional averages. The sedimentation rate is highly linked to habitat submergence, stand location in responding to rivers, streams and lagoons in addition to site exposure level to marine surges, currents and tidal regime. [50] mentioned several factors, such as the topography and landscape position of the wetland, the hydrologic regime, the type of plants present and the morphology of the wetland are of the factors affecting the net result of carbon storage in the wetlands.

Carbon sequestration rates (CSR) in studied habitats followed the descending order intertidal mangrove > salt plain mangrove > hypersaline ecosystems > shoreline mangrove > planted mangrove > non-mangrove mudflats. Lower carbon sequestration rates reported than current study results for either mangrove and non-mangrove mudflats in northern Red Sea, Egypt [17], depending on the global average sedimentation rate of mangrove (2.8 mm year^{-1}) which is less than half of the estimates obtained by present study this was involved in the resulted lower estimate of sequestration potential. Our results of intertidal mangrove showed 1.3 folds CSR that of the global average CSR of mangrove ecosystem, while other studied habitats were between 0.58 – 0.08 folds of the global average CSR [51]. [46] reported concordant CSR for intertidal mangrove habitat in the present study, while [49] reported in Florida Keys, USA closest CSR rate to the mean value of present study salt plain mangrove habitat growing under similar site conditions of absence of riverine system and at near latitudinal range ^{o}25 N (^{o}27, ^{o}28 N for this study).

Few studies conducted on carbon sequestration rates for hypersaline lagoons, [52] reported carbon burial rate of hypersaline coastal lagoon Lagoa de Araruama, Brazil under salinity of 45-56 ppt. which is only 0.13 of that of our tested hypersaline ecosystem (salinity = 282 ppt.). Comparing the contribution of the studied habitats in the process of CSR, surprisingly CSR of only 10 years old planted mangrove is about one-fifth CSR of the mature intertidal mangrove and slightly lower CSR of shoreline mangrove (Figure 6). The efficiency of planted mangrove in CSR proof that plantation of mangrove especially around current mangrove stands or in depleted stands (restoration) is an efficient mitigation tool to elevated levels of the global CO_2.

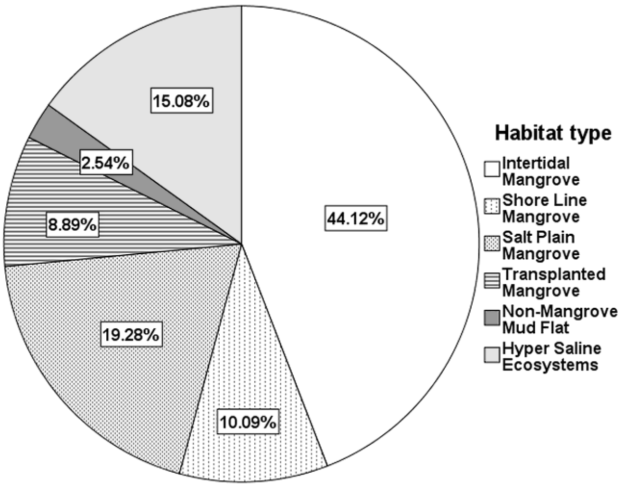

Figure 6: The contribution of each of studied habitats in carbon sequestration process, only 10 years old planted mangrove have CSR equals one fifth of that mature intertidal mangrove while other habitats like non-mangrove mud flats having very low CSR but with its large extended areas may yield competitive values in CSP process.

Estimation of carbon sequestration potential (CSP) of certain habitat or an ecosystem is depending on the total habitat cover area, it was not possible to estimate CSP for mudflats but further remote sensing work with the provided CSR by present study can explain the actual CSP of mudflats habitat. Mangrove of the intertidal habitat is forming about 95% of the total mangrove cover in Sinai [17]. Mangrove of intertidal habitat is contributed with about 98.5% of CSP process performed by the mangrove ecosystem in South Sinai and about 95% of CSP of all studied habitats. Further large-scale sampling from intertidal mangrove in similar stands in arid regions is almost reliable.

Total CSP of Sinai mangrove and hypersaline system of Salt Lake in Ras Mohammed national park are 116.89 and 4.3 Mg C year-1 respectively.

According to [14] the mangrove cover area of Egypt is 525 ha and considering that all mangrove of Egypt distributed along the Red Sea coast and the Red Sea islands according to its distribution percentages on the defined mangrove habitats in Sinai as provided by [17]. While the total area of planted mangrove in Egypt is 12.55 ha according to [32], so the current total mangrove cover of Egypt (naturally occurring and planted) is 533.51 ha can sequester a total of 1207.5 Mg C year^{-1}.

5. Conclusion

This study provided accurate habitat based estimate of organic carbon stock in mangrove sediment and carbon sequestration potential of mangrove ecosystem with highlighting the significance of ten years' old planted mangrove, hypersaline ecosystem and coastal mud flats in the process of carbon sequestration. The study also highlighted accurate, fast, cost effective and environmentally friendly technique suits analysis of large number mangrove sediment samples for organic carbon estimate *via* low-temperature loss on ignition method, which enables resources managers in protected areas and conservation researchers especially in developing countries to properly estimate the contribution of their coastal ecosystems in this process. Mangrove restoration and transplantation process are efficient tools in mitigation of elevated levels of atmospheric carbon dioxide. Present study highlighted values of other coastal habitats (mud flats, Salt flats and hypersaline systems), they may have lower capacities to store carbon compared to mangrove ecosystem, but with their large extended areas can provide a total competitive potential. Proper management of all coastal habitats *via* prohibiting constructions in these locations is preferred otherwise the risk of a reversible liberation of captured CO_2 to the atmosphere will be too high. Final word, mangrove ecosystem is invaluable with endless of services to human, surrounding habitats and marine ecosystems and these values are greatly magnified where mangrove stands are located along one of the world"s poor seas in productivity like the Red Sea, which spans over a large latitudinal range (^{o}12 - ^{o}29 N). Moreover, deserts bordering the Red Sea lacking any dominant riverine estuary, hence mangrove as a pioneer productive ecosystem provide a single key solution to support life in marine ecosystems.

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