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Distribution of soil organic carbon in the mangrove *Avicennia marina* (Forssk.) Vierh. along the Egyptian Red Sea Coast

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HIGHLIGHTS

- Mud flat stands have soil bulk density higher than mangrove stands.
- Mangrove stands have soil organic carbon content higher than mud flat stands.
- Soil organic carbon content and soil bulk density were negatively correlated.
- Carbon sequestration rate of mangrove stands was 6.1 g C m^{-2} $year^{-1}$.
- Total carbon sequestration potential of mangrove stands in Egypt was 3.17 Gg C $year^{-1}$.

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ABSTRACT

The objectives of present study are: (1) to quantify the vertical distribution of the soil bulk density (SBD), soil organic carbon (SOC) content and SOC density in the soil of the mangrove forests in comparison with a reference site along the Egyptian Red Sea Coast; (2) to provide estimates of the carbon sequestration rate (CSR) and the carbon sequestration potential (CSP) of mangrove forests in Egypt; and (3) to establish a baseline data on SOC pools for future studies on SOC dynamics. Sampling was carried out in three stations along the Egyptian Red Sea Coast. The sampled station were classified to mangrove and reference (mud flat) stands. In each of the sampling station, five sampling sites were selected to assure representative samples to each of the mangrove and mud flat stands. Three soil cores were taken in each sampling site and were pooled together into one composite core per sampling site. In total, 120 soil samples were collected, i.e., one sample from each four soil layers (0–10, 10–20, 20–30 and 30–40 cm) at each of the 30 sampling sites (15 sampling sites per each of mangrove and mud flat stands). The mean distribution of SBD in the mangrove and mud flat stands increased significantly with depth. SOC content in the mangrove stands declined significantly with depth from 20.0 g C kg^{-1} at depth 0–10 cm to 11.4 g C kg^{-1} at depth 20–30 cm. SOC content in the mud flat stands declined significantly with depth from 9.0 g C kg^{-1} at depth 0–10 cm to 1.9 g C kg^{-1} at depth 30–40 cm. The stand type affected significantly the SOC pool, where the total mean of SOC pool of the mangrove stands (8.5 kg C m^{-2}) was higher than that of the mud flat stands (2.6 kg C m^{-2}). The average CSR of the mangrove stands (6.1 g C m^{-2} $year^{-1}$) was higher than the mud flat stands (2.0 g C m^{-2} $year^{-1}$). Based on the area of mangrove stands (525 km^2) and CSR, the total CSP of mangroves in Egypt was 3.17 $\pm$ 0.05 Gg C $year^{-1}$.

1. Introduction

Combustion of fossil fuel and changes in land use, such as those resulting from deforestation, are considered the primary causes for the increasing concentration of atmospheric CO_2 (IPCC, 2007). Nowadays, there is a growing public and scientific concern on the CSP of various wetland ecosystems with the increase of CO_2 concentration. As a result, the Kyoto Protocol was signed to mitigate the greenhouse gas concentrations in the atmosphere through improving the terrestrial carbon sinks (Eid and Shaltout, 2013).

The mangrove term is ecological (Odum et al., 1982) and is used to include both shrubs and trees (dicots and monocots) that

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occur in the intertidal and shallow subtidal zones of tropical and subtropical tidal marshes (Lee et al., 2014). The mangrove forest is a fringing community of shallow sandy or muddy areas, ranging from highest-tide mark to the intertidal fringe and subtidal regions (Dawes, 1981). It provides a wide range of ecosystem goods (fuel wood, medicine, food and construction materials) and services (fisheries nursery grounds, sediment trapping, coastal protection from storm surges and tsunamis, sewage phytoremediation and carbon sequestration) of huge value to local, national and global communities (Bouillon, 2011; Hegazy, 1998; Mumby et al., 2004).

Mangrove forests play an important role in the terrestrial and oceanic carbon cycling (Alongi, 2012; Donato et al., 2012; Liu et al., 2014), where they contribute to 10% of the total net primary production and 25% of the carbon burial in the global coastal zone although they colonize only 0.7% of the global coastal zone (Alongi, 2007; Kathiresan and Bingham, 2001). They are important carbon sinks and have high capabilities to sequester carbon (Kathiresan et al., 2013; Liu et al., 2014). Thus, they play an important ecological role in addressing the mitigation of the climate change (Wang et al., 2013).

The role of mangroves in global carbon cycles has been somewhat overlooked, because of their relatively small total area and often lower physical build than many adjacent tropical moist forests. In fact, they may be of considerable importance (Spalding et al., 2010). Globally, the total net primary production of mangrove ecosystems has been estimated at 218×10^9 kg C year^{-1} (Bouillon et al., 2008; Twilley et al., 1992), ranking as one of the most productive biomes on the earth (Tue et al., 2012). Therefore, the role of mangrove forests in the global carbon budget is significant (Bouillon et al., 2008), but a more refined regional assessment of mangrove CSP is needed to better assess the global carbon budget, particularly in the mangrove ecosystems of Egypt where no data has been published.

In Egypt, the mangrove forests cover about 525 km^2 distributed along the Red Sea Coast, Ras Muhammed, and the southern section of the Gulf of Aqaba. The northern sites along the Gulf of Aqaba (Lat. 28° 12′N, long. 34° 25′E) represents the northernmost latitudinal limit of the Indo-Pacific-East African natural growing mangrove forests (Shaltout et al., 2005). Mangrove areas are generally found in the intertidal zone of brackish and seawater shores (Shaltout et al., 2005). Two mangrove species are recognized, namely: *Avicennia marina* (black mangrove) and *Rhizophora mucronata* (red mangrove). *A. marina* is wide spread, whereas *R. mucronata* occurs only in the most southern section of the Red Sea in the Sudano-Egyptian border (Zahran and Willis, 2009).

Many studies were carried out on the mangrove forests in Egypt such as ecology (Abd El-Wahab, 2004; Zahran, 2007), distribution (Saleh, 2007; Zahran, 1993), rehabilitation (Kairo and Hegazy, 2003; Saenger, 2002), adaptation (Khalaf Allah, 2002), morphology (Teraminami et al., 2014), environmental characteristics (Shaltout et al., 2005; Shaltout and El-Bana, 2006), monitoring (Abdel Razik and Hanafy, 2003), pollution (Dicks, 1986; Naim, 2004) and soils chemistry (Dar, 1998; Madkour and Mohammed, 2008; Madkour et al., 2014). On the other hand, no study has been attempted to quantify CSP of mangrove forests in Egypt. Such information is needed for designing management policy and approaches for mangrove forests in Egypt.

This study is a part of a series of papers to provide estimates of CSP in the Egyptian wetlands (Eid and Shaltout, 2013). Thus, the present study serves as an active response to the major scientific challenges and social problems facing the world today. According to the author's knowledge, so far no country assessment of CSP of mangrove forests along the Red Sea Coast has been carried out in Egypt. Thus, the aims of the present study are: (1) to quantify the vertical distribution of the SBD, SOC content and SOC density in the soil of the mangrove forests in comparison with a reference site (mud flat) along the Egyptian Red Sea Coast; (2) to provide estimates of the CSR and the CSP of mangrove forests in Egypt; and (3) to establish a baseline data on SOC pools for future studies on SOC dynamics. The definition of a SOC pool baseline is essential for future evaluation of the status of this pool. Furthermore, the identification of a baseline for the SOC pool in mangrove forests could contribute to assess the potential role of this ecosystem as CO_2 sinks. Such type of data and information are important for putting any management plan for the mangrove ecosystems along the Egyptian Red Sea Coast, and provide arguments for the restoration of mangrove forests in Egypt.

Table 1
Population characteristics of mangrove (*Avicennia marina*) forests along the Egyptian Red Sea Coast.

Characteristic	Range
Tree height (cm)	150.0–350.0[a]
Tree size index (cm)	130.0–214.5[a]
Trunk circumference (cm)	24.8–41.4[a]
Tree density (individual per 100 m^2)	3.4–27.6[b]
Phytomass (t ha^{-1})	5.4–47.0[b]
Leaf litterfall (g m^2 year^{-1})	78.6–405.3[b]

[a] Shaltout and El-Bana (2006).
[b] Galal (1999).

2. Materials and methods

2.1. Study area

The Red Sea coastal land of Egypt extends from Suez (Lat. 29° 58′N, Long. 32° 32′E) to Marsa Halaib (Lat. 22° 14′N, Long. 36° 39′E) at the Sudano-Egyptian border and it belongs to the category of "warm coastal deserts" (Meigs, 1973). The climate of the Red Sea coastal land of Egypt is arid, where the mean annual rainfall ranges from 25 mm in Suez, 4 mm in Hurghada (Lat. 27° 15′N, Long. 33° 48′E) to 3.4 mm in Qusseir (Lat. 26° 06′N, Long. 34° 16′E) (Shaltout et al., 2005). The main bulk of rain occurs in winter, i.e. Mediterranean affinity, and summer is, in general, rainless and the variability of annual rainfall is usual. Temperature is high and ranges between 14.0 and 21.7 °C in winter and 23.1–46.1 °C in summer. Relative humidity ranges from 43% in summer to 65% in winter. The daily evaporation is higher in summer (13.7–21.5 mm day^{-1}) than in winter (5.2–10.4 mm day^{-1}) (Anonymous, 1980). The sampling area (Lat. 27° 24′N, Long. 33° 41′E) represents the northernmost stands of *A. marina* along the Red Sea Coast, located approximately 27 km north of Hurghada. The stands consist of clumped or isolated trees along the coast and on lagoonal islands (Table 1).

2.2. Soil sampling

Sampling was carried out in three stations to represent the mangrove forests along the Egyptian Red Sea Coast (Fig. 1). The sampled stations were classified to mangrove (*Avecinia marina*) and reference (the mud flat at seaward without mangrove trees) stands. Our null hypothesis is that the mangrove and mud flat stands have the same SBD, SOC content, SOC density, SOC pool and CSR. In each of the sampling station, five sampling sites were selected to assure representative samples to each of the mangrove and mud flat stands. Three soil cores were taken in each sampling site, spaced in a triangular pattern with 50 cm between each core, and were pooled together into one composite core per sampling site. In total, 120 soil samples were collected to determine SBD, SOC content, density and pool, i.e., one sample from each four soil layers (0–10, 10–20, 20–30 and 30–40 cm) at each of the 30 sampling sites (15 sampling sites per each of mangrove and mud flat stands). The

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