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Effects of water and salinity regulation measures on soil carbon sequestration in coastal wetlands of the Yellow River Delta

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ABSTRACT

Water and salinity regulation measures have been widely taken to restore the ecological structures and functions of degraded coastal wetlands. To investigate the effects of different water and salinity regulation measures on soil carbon stocks in coastal wetlands, soil samples were collected to a depth of 50 cm in four types of wetlands (i.e., restored tidal salt marshes (RTSM, covered with *Suaeda salsa*) and degraded tidal salt marshes (DTSM, bare land); freshwater restored wetlands (FRW) and degraded wetlands without freshwater inputs (DWFI), covered with *Phragmites australis*) during the period from August to October in 2015 in the Yellow River Delta, China. Our results showed that the mean values of total carbon (TC), soil organic carbon (SOC), readily oxidizable organic carbon (ROOC) and dissolved organic carbon (DOC) were higher in restored wetlands (e.g., RTSM and FRW) than those in degraded wetlands (e.g., DTSM and DWFI). Along the whole soil profile, TC, SOC, ROOC and DOC were higher in RTSM soils than those in DTSM soils except for TC and SOC in the 0–10 cm soils and DOC in the 40–50 cm soils. FRW soils contained higher TC, SOC, ROOC and DOC than DWFI except for DOC in the 0–10 cm soils. Soil TC density (TCD), SOC density (SOCD), ROOC density (ROOCD) and DOC density (DOCD) in the top 50 cm soils in restored wetlands were higher compared with degraded wetlands. Multivariate analysis showed that soil carbon was significantly influenced by EC, soil base cations and anions (e.g., K^+, Ca^{2+}, Cl^- and SO_4^{2-}), pH, TN, C/N ratio, bulk density (BD) and soil texture ($p < 0.05$). The findings of this study indicated that these two water and salinity regulation measures are effective in increasing soil carbon stocks of coastal wetlands.

1. Introduction

Although the coastal zone only covers 4% of the earth total land area, coastal wetlands are among the most productive ecosystems and provide invaluable ecological services (Barbier, 2013; Zhao et al., 2016a). It's estimated that coastal wetlands accumulate approximately 30–100 kg organic C m^{-2}, while an adjacent upland accumulates 5–10 kg organic C m^{-2} within one year (Chambers et al., 2013). With the increasing global average atmospheric carbon dioxide (CO_2) concentration, a single emission reduction strategy has been switched to a plan that combines reducing anthropogenic sources of CO_2 (mitigation) with strengthening carbon storage of natural ecosystems due to their high C sequestration rates and capacity (Canadell and Raupach, 2008). As an important part of blue carbon sinks, coastal wetlands play a critical role in the global carbon sequestration and mitigating global climate changes (Mcleod et al., 2011). However, coastal wetlands are suffering from serious degradation even great losses caused by intense anthropogenic activities (i.e., wetland reclamation, pollution and drainage) (Newton et al., 2012), which would cause the conversion from carbon sinks to net sources of CO_2 in these coastal wetlands (Erwin, 2008; Couwenberg et al., 2010).

Wetland restoration refers to the return of wetlands from a disturbed or altered status caused by anthropogenic activities to a pristine status (Mitsch and Gosselink, 2015), restoring lost biodiversity or ecological services (Zedler, 2000). Restoring degraded wetland soils and ecosystems has a high potential for sequestrating soil carbon and makes restored wetlands once again become a sink of atmospheric CO_2 (Erwin, 2008; Lal, 2008). Hydrological regime restoration or re-establishment (i.e. dike removal and tide flow restoration) is considered to be a fundamental restoration measure (Zhao et al., 2016a; Luke et al., 2017), as hydrological conditions provide the basic control of wetland structures and functions (Zedler, 2000). Moreover, hydrological restoration has been a pathway to optimize coastal blue carbon sequestration and increase blue carbon values of coastal wetlands (Simpson, 2016; Macreadie et al., 2017). The dike removal would reintroduce tidal flow to degraded marshes and promote recovery of vegetation, initiating recovery processes toward mature marsh structure and function (Raposa et al., 2017; Zackey et al., 2017). The freshwater inputs have

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also been proved to be effective to reconstruct degraded coastal wetlands affected by drainage or seawater intrusion (Wang et al., 2011). Changes in the hydrological regimes of coastal wetlands can remarkably alter soil salinity, leading to variations in soil carbon sequestration (Wang et al., 2011; Zhao et al., 2016b). Setia et al. (2013) predicted a decrease in soil carbon stock under high salinity ranges by model simulating. This is because higher salinity would reduce plant productivity, inhibit soil organic matter breakdown through slowing transformation of organic substrates and microbiological activities (Kaur et al., 2000; Rasul et al., 2006). Meanwhile, soil hydrological conditions could regulate the diffusion of O_2 and the soil oxidation/reduction status in addition to soil salinity, thus affecting the mineralization of soil organic carbon and the alteration of carbon accumulation rates (Elberling et al., 2011; Baustian et al., 2017). Craft (2007) reported that freshwater inputs could meditate soil carbon accumulation through its influence on decomposition. Ma et al. (2017) demonstrated that freshwater inputs elevated microbial biomass and shifted the community composition of microbes, contributing to organic residues accumulation. Therefore, the water and salinity regulation in degraded coastal wetlands would considerably change soil carbon sequestration and further provide guidelines for coastal wetlands restoration and serving as carbon sinks.

The Yellow River Delta (YRD) in China is the youngest wetland ecosystem and plays a great role in biodiversity conservation and carbon sequestration (Zhao et al., 2016c). Degradation and shrunk in the natural wetlands of the YRD are still going on due to intense exploitation for industrial and agricultural developments (Wang et al., 2011; Zhao et al., 2015). Large-scale freshwater restoration projects have been conducted in the degraded coastal wetlands in the YRD National Nature Reserve since 2002 to obtain freshwater *Phragmites australis* wetlands (Tang et al., 2006). In the YRD, many earth-filled dams were built to facilitate oilfield exploitation in the past decades. These dams blocked the tidal flow into salt marshes and caused the death of *Suaeda salsa*, resulting in the conversion of salt marshes to bare lands. After the embankment of dams, some degraded salt marshes were restored due to the restoration of tidal flows in these salt marshes. We hypothesized that soil carbon in these coastal wetlands would be improved after freshwater inputs and tidal flow restoration due to plant restoration. The primary objectives of this study were: (1) to investigate the changes in soil carbon contents and stocks in coastal wetlands after freshwater inputs and tidal flow restoration, and (2) to identify the relationships between soil carbon and soil properties in these coastal wetlands.

2. Materials and methods

2.1. Site description

The study area is in the YRD National Nature Reserve. The YRD is located in Dongying City, Shandong Province of China, which is adjacent to the Bohai Bay and the Laizhou Bay. It has a semi-humid continental climate in the warm Temperate Zone, with four distinct seasons. The annual mean air temperature is 12.4 °C, with the rain and heat over the same period. The annual mean precipitation and evaporation are 551.6 mm and 1928.2 mm, respectively (Zhao et al., 2015). In the study area, four types of coastal wetlands were selected, including restored tidal salt marshes (RTSM), degraded tidal salt marshes (DTSM), freshwater restored wetlands (FRW) and degraded wetlands without freshwater inputs (DWFI) (Fig. 1). Freshwater from the Yellow River was input to FRW wetlands since 2002 and *Phragmites australis* communities were restored in FRW. Meanwhile, the coastal *Phragmites australis* wetlands without freshwater input (DWFI) adjacent to FRW wetlands were selected as the reference wetlands. *Phragmites australis* grows better in FRW wetlands than in DWFI wetlands due to the decline in salinity after freshwater inputs (Bai et al., 2015). In the Nature Reserve of the YRD, the degradation of tidal salt marshes occurred due to the retirement of tidal cycles caused by the earth dams built for oil exploration. One earth-fill dam was destroyed by seawater erosion in 2014, resulting in the *Suaeda salsa* restoration in some tidal salt marshes after restoring tidal flow. The restored tidal salt marshes (RTSM) were selected in this region and the adjacent degraded tidal salt marshes (DTSM) were considered to be the reference wetlands to identify the effects of tidal flow restoration.

2.2. Soil sample collection and analysis

Six soil cores were randomly collected to a depth of 50 cm in each of the four types of wetlands during the period from August to October in 2015. The soil cores were stratified into five layers at 10 cm intervals and placed in polyethylene bags. All soil samples were put in portable incubators and brought to the laboratory. One part of soil samples were stored in 2–4 °C refrigerator to analyze dissolved organic carbon (DOC). The rest part of soils was air dried at room temperature for three weeks and sieved by a 2-mm sieve to remove coarse debris and stones. To determine soil pH and electric conductivity (EC), one part of dried soils were grounded and passed through a 1 mm sieve. The rest of dried soils were grounded and sieved by a 0.149 mm sieve for determination of total carbon (TC), soil organic carbon (SOC), soil readily oxidizable organic carbon (ROOC), total nitrogen (TN) and soil base cations and anions. Another three soil cores (100 cm^3) were collected at each soil layer in each of these four wetlands to determine soil bulk density (BD) and soil water content (WC) by drying at 105 °C for 24 h in an oven (Zhao et al., 2016c). Soil particle size distribution was analyzed on a laser particle size analyzer (Microtrac S3500, America). Soil pH and EC were measured in the supernatant of 1:5 (w/v) soil – water mixtures using a pH meter (Sartorius, Germany) and an electronic conductivity meter (Mettler Toledo, USA). Sodium chloride (NaCl) has been proved to be the dominant type of soil salinity in the Yellow River Delta, showing a significant linear correlation with the soil EC (Weng and Gong, 2006). The changes in EC were used to represent variations of salinity (Yu et al., 2011). TC and TN were measured on an Element Analyzer (Vario EL, Germany). SOC was determined by the dichromate oxidation - colorimetric determination (Sims and Haby, 1971). The DOC was extracted with high purified water and was measured using the high-temperature catalytic combustion method on a total organic carbon analyzer (TOC-L CPN, Shimadzu). ROOC was determined by the modified Bhattacharyya's method (Bhattacharyya et al., 2013). Anions (e.g., Cl^- and SO_4^{2-}) and base cations (e.g., Na^+, K^+, Mg^{2+}, Ca^{2+}) were determined on ICS-2000 and DX-600 ICP-chromatography (Thermo Fisher Scientific, USA), respectively. Sodium adsorption ratio (SAR) was calculated according to the given equation (Rietz and Haynes, 2003):

$$\mathrm{SAR}\ (\mathrm{mmol}^{-1})^{0.5} = \mathrm{Na}^+/((\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})/2)^{0.5} \tag{1}$$

TC, SOC, ROOC and DOC density at each sampling site was calculated as follows:

$$\mathrm{TCD} = \sum \mathrm{B_i} \times \mathrm{TC_i} \times \mathrm{T}_i \tag{2}$$

$$\mathrm{SOCD} = \sum \mathrm{B_i} \times \mathrm{SOC_i} \times \mathrm{T_i} \tag{3}$$

$$\mathrm{ROOCD} = \sum \mathrm{B_i} \times \mathrm{ROOC_i} \times \mathrm{T_i} \tag{4}$$

$$\mathrm{DOCD} = \sum \mathrm{B_i} \times \mathrm{DOC_i} \times \mathrm{T_i} \tag{5}$$

where TCD, SOCD, ROOCD and DOCD are TC, SOC, ROOC and DOC densities, respectively, which means TC and SOC content per unit area (kg C/m^2), and ROOC and DOC content per unit area (g C/m^2). Bi is the bulk density of soil (g/cm^3), and Ti is the soil depth at layer i (cm). TCi, SOCi, ROOCi and DOCi are the TC, SOC, ROOC and DOC content at soil layer i (i = 1, 2, 3, 4 and 5), respectively.