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The impact of sea embankment reclamation on soil organic carbon and nitrogen pools in invasive *Spartina alterniflora* and native *Suaeda salsa* salt marshes in eastern China

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ABSTRACT

The construction of sea embankments is an increasingly common approach for controlling the spread of the exotic C_4 perennial grass *Spartina alterniflora* Loisel. in coastal wetlands of eastern China. However, the impact of sea embankment reclamation on the soil organic carbon (C) and nitrogen (N) dynamics in salt marshes is not fully understood. In this study, we examined the stocks of the total, labile and recalcitrant organic C and N, the recalcitrant indices of C and N, and the concentrations of water-soluble organic carbon (WSOC), microbial biomass carbon (MBC) and cumulative CO_2-C mineralization (MINC) in sea embankment-reclaimed *S. alterniflora* and *Suaeda salsa* (Linn.) Pall. salt marshes through comparisons with adjacent unreclaimed *S. alterniflora* and *S. salsa* salt marshes in a coastal wetland of eastern China. Sea embankment reclamation significantly decreased plant biomass by 55.34%, soil salinity by 81.71%, soil moisture by 43.16%, soil total organic C by 50.60% and total organic N by 49.99%, and also lowered labile and recalcitrant organic C and N, WSOC, MBC and MINC in the invasive *S. alterniflora* salt marsh. However, sea embankment reclamation did not significantly affect the stocks of the soil organic total C and N, recalcitrant organic C and N, and soil organic C dynamics in the native *S. salsa* salt marsh, possibly because the total quantity of *S. salsa* materials entering the soil, soil salinity, moisture and bulk density were not affected by sea embankment reclamation. Our results suggest that the impact of sea embankment reclamation on soil organic C and N pools is much more profound in *S. alterniflora* salt marsh than in *S. salsa* salt marsh. Sea embankment reclamation could greatly weaken the C and N sinks of *S. alterniflora* salt marsh and potentially affect C and N sinks in the coastal wetlands of eastern China.

1. Introduction

Coastal wetlands are interfaces between marine and terrestrial ecosystems and are considered to be important components of 'blue carbon (C)' sinks, playing a crucial role in the global C cycle and ultimately global climate change (Laffoley and Grimsditch, 2009; Crooks et al., 2011; Bu et al., 2015). At least 430 Tg of C is sequestrated in the upper 50 cm of the soils of the world's coastal salt marshes (Chmura et al., 2003; Han et al., 2014). The ability of coastal wetlands to sequester C and nitrogen (N) may be dependent on high levels of primary productivity coupled with low soil organic matter (SOM) decomposition rates, as well as high water levels (Whitting and Chanton, 2001; Mitra et al., 2005; Kayranli et al., 2010). Coastal wetlands provide many ecosystem services, including a habitat for water birds and other wildlife, preservation of biodiversity, control of shoreline erosion, and retention of pollutants, among others (Santín et al., 2009; Jiang et al., 2015). Over the past several decades, however, rapidly rising economic and urbanization pressures, along with numerous other human activities, have led to significant degradation and loss of coastal wetlands in many countries (Santín et al., 2009; Koh and de Jonge, 2014; Ma et al., 2014). China is increasingly undertaking intense coastal reclamation projects (Sun et al., 2015). Currently, China's coastal wetlands have been enclosed by thousands of kilometers of seawalls which cover 60% of the total length of coastline along mainland China (Ma et al., 2014). A large number of seawalls construction led to dra-

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matic decline in biodiversity and associated ecosystem services in coastal wetlands (Ma et al., 2014).

In some reclamation activities in China, coastal wetlands are fully embanked (Ma et al., 2014) or only partially embanked and retain natural vegetation following embankment (Bu et al., 2015). In other instances, coastal wetlands are fully embanked and reclaimed for agricultural or urbanization purposes (Iost et al., 2007; Han et al., 2014; Wang et al., 2014). The destruction or conversion of coastal wetlands can largely alter hydrological conditions and the redox environment of coastal wetlands, because embankments impede tidal inundation (Dick and Osunkoya, 2000). Additionally, the reclamation of coastal wetlands has been reported to modify the physical and chemical properties of coastal soils (Wang et al., 2014), and further affect sequestration and stability of soil organic C pool in coastal wetlands (Bu et al., 2015). Many previous studies have focused on the effects of coastal salt marsh conversion to agriculture or urban land on soil C and N pools, with inconclusive results (Connor et al., 2001; Laudicina et al., 2009; Fernández et al., 2010; Sun et al., 2011; Cui et al., 2012); for instance, salt marsh conversion to farmland has been reported to either increase (Connor et al., 2001; Fernández et al., 2010; Sun et al., 2011; Cui et al., 2012) or decrease (Laudicina et al., 2009; Wang et al., 2014) soil C and N accumulation. These contradictory results may be the result of multiple factors, such as differences in reclamation history, hydrological conditions, reclamation intensity, and land-use patterns following reclamation (Wang et al., 2014). Moreover, it is difficult to distinguish between the effects of reclamation and the subsequent agricultural land use (e.g., crop cultivation, fertilization, and tillage practices) on soil organic C and N pools following the conversion (Bu et al., 2015) because the form of land use significantly influences soil organic C and N dynamics (Bai et al., 2013). Direct evidence for the impact of reclamation (i.e., embankment) on soil organic C and N pools in salt marshes is still lacking; as such, research on the changes in the dynamics of previously sequestered soil organic C and N pools in salt marshes following embankment reclamation are urgently needed (Ma et al., 2014; Bu et al., 2015).

Soil organic C and N pools are traditionally divided into labile and recalcitrant pools via chemical fractionation (Rovira and Vallejo, 2002; McLauchlan and Hobbie, 2004). Soil labile organic C and N pools have high biological activity and fast turnover but are normally quite small and generally considered to be reservoirs for available nutrients (McLauchlan and Hobbie, 2004; Cheng et al., 2008). Conversely, soil recalcitrant organic C and N pools have slower turnover rates but are large and are the primary determinants of soil organic C and N storage quantities over the long-term (McLauchlan and Hobbie, 2004; Yang et al., 2015). Changes in soil labile and recalcitrant organic C and N pools after sea embankment reclamation may exert a profound influence on the accumulation and stabilization of soil organic C and N pools in coastal marshes. Thus, analyses of the impacts of sea embankment reclamation on soil labile and recalcitrant organic C and N pools are propitious to fully and accurately evaluate changes in the dynamics of soil organic C and N pools in salt marsh ecosystems.

The range of *Spartina alterniflora* Loisel., a perennial C_4 grass introduced to China from the United States in 1979 for use in coastal erosion control, extends from Tianjin in the north to Beihai in the south (An et al., 2007). Currently, *S. alterniflora* patches cover approximately 112,000 ha, with the largest zone on the Jiangsu coast (Zhang et al., 2004; An et al., 2007; Yang et al., 2013). Although many studies have reported that *S. alterniflora* has enhanced soil C and N pools due to the large input of litter biomass (Cheng et al., 2006; Liao et al., 2007; Zhang et al., 2010; Yang et al., 2016), the exotic grass has also numerous negative effects on the coastal wetlands of China (Wan et al., 2009), such as intensely competing with and replacing native plants (Liao et al., 2007), altering mudflat habitats (Wan et al., 2009), and threatening macrobenthic invertebrate communities (Li et al., 2009). Because of this, agencies in China have explored various ways to prevent *S. alterniflora* from expanding its range, with sea embankment construction considered to be an effective means of impeding the spread of *S. alterniflora* (An et al., 2007). *Suaeda salsa* (Linn.) Pall., a native C_3 halophyte and annual grass, is an important component of vegetational succession in the coastal wetlands of eastern China (Yang et al., 2015, 2016). *S. salsa* typically prefers the irregularly flooded high intertidal zone, whereas *S. alterniflora* is normally found in the mid-intertidal zone (Yuan et al., 2015). For the purpose of controlling the spread of *S. alterniflora* and restoring native salt marsh systems, extensive sea embankments have been constructed in *S. alterniflora* marsh, but because *S. salsa* grow further inland (Yang et al., 2015), they have also been enclosed by sea embankment (Fig. 1). We hypothesize here that sea embankment reclamation may affect soil organic C and N dynamics due to changes in plant growth and soil physiochemical properties following sea embankment reclamation in invasive *S. alterniflora* and native *S. salsa* salt marshes. To test this, we compared the stocks of soil organic carbon (SOC), soil labile organic carbon (LOC), recalcitrant organic carbon (ROC), soil organic nitrogen (SON), labile organic nitrogen (LON), and recalcitrant organic nitrogen (RON) pools, recalcitrant indices for C (RIC) and N (RIN), and the concentrations of water-soluble organic carbon (WSOC), microbial biomass carbon (MBC), cumulative CO_2-C mineralization (MINC), and soil physiochemical properties in sea embankment-reclaimed *S. alterniflora* and *S. salsa* marshes with adjacent unreclaimed *S. alterniflora* and *S. salsa* marshes in a coastal wetland of eastern China. The objectives of this study were to evaluate (1) whether soil organic C and N pools in invasive *S. alterniflora* and native *S. salsa* salt marshes are affected by sea embankment reclamation; (2) whether the responses of soil organic C and N pools to sea embankment reclamation differs between *S. alterniflora* and *S. salsa* marshes; and (3) whether alterations in soil organic C and N pools are related to changes in soil physiochemical properties and inputs of plant materials that result from sea embankment reclamation.

2. Materials and methods

2.1. Site descriptions

This study was conducted in the third core region of Dafeng Milu National Nature Reserve (DMNNR), Jiangsu Province, China (32°59′–33°03′N, and 120°47′–120°53′E) (Fig. 1). DMNNR is located on the Yellow Sea and lies within the subtropical to warm temperate monsoon climate transition zone (Liu et al., 2011). The mean annual temperature in this region is approximately 14.1 °C, and the mean annual precipitation exceeds 1000 mm (Liu et al., 2011). DMNNR was established in 1986 and has the world's largest population of wild Père David's deer (*Elaphurus davidianus*) (Li et al., 2005; Liu et al., 2011). DMNNR is designated as a Ramsar Site and has been included in the directory of Wetlands of International Importance since 2002 (Wang and Wall, 2010).

S. alterniflora was intentionally introduced to the intertidal zone of the estuary of the Dongtai River, located in the city of Dongtai in Jiangsu Province, in 1988, but rapidly expanded its range 100 km to the north, colonizing coastal beaches in the city of Dafeng, Jiangsu Province (Ding, 2009). At present, *S. alterniflora* community dominate the third core area of the DMNNR (Fig. 1), occupying approximately 70% of the entire area (Ji et al., 2011), with native *S. salsa* and *Phragmites australis* (Cav.) Trin. ex Steud. communities covering the remaining 30% of the third core area. Based on analyses of Thematic Mapper satellite images, a 2400-m long, 2-m wide and 2-m tall sea embankment was constructed in the third core area of the DMNNR in 2011 to prevent further *S. alterniflora* expansion and