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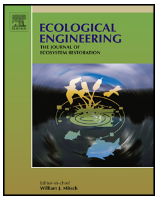

Research Paper

Soil carbon and nitrogen storage in recently restored and mature native *Scirpus* marshes in the Yangtze Estuary, China: Implications for restoration

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ABSTRACT

As part of research into the re-establishment of the native species *Scirpus mariqueter* in the salt marshes of the Yangtze Estuary, the roles of revegetation mode (planting density), site characteristics (sediment texture and hydrological regime) and community age (recently restored and mature marshes) in the storage of soil organic carbon (SOC) and nitrogen (SN) were examined. In recently restored marsh characterized by muddy sediments with moderate sediment accretion, vegetation growth and SOC and SN storage increased along with the increase in planting densities and the SOC storage was 1.14–1.52 times greater than that in non-vegetated plots after two years of revegetation. The SOC storage under a high planting density equated to approximately 75% of the carbon stock in the mature marsh. However, the increase in SOC storage was much less in those sites characterized by silty sediments than that in sites with muddy sediment, even when a high planting density was applied. This is attributed to a lower rate of sediment deposition and inhibition of below-ground root growth, which was found to be strongly correlated with carbon and nitrogen stocks in the soil. Additionally, the main rooting system of *S. mariqueter* and SOC and SN storage were concentrated in the top ~20 cm in the recently restored marshes. These results demonstrate that successful vegetation restoration plays a key role in determining SOC and SN storage within a salt marsh. The restoration of native *S. mariqueter* for SOC and SN stocks is most effective when conducted in muddy sediments with good sedimentation rates and using a high planting density. In contrast, costs will be higher and recovery time longer in silty (or sandy) sediments, due to their poorer conditions for plant growth and significantly lower rates of carbon and nitrogen accumulation.

1. Introduction

Coastal salt marshes have been identified as globally important carbon sinks and nitrogen reservoirs and play invaluable roles in mitigating climate change due to their high carbon sequestration rates and low levels of greenhouse gas emissions (Chmura et al., 2003; Choi and Wang, 2004; Laffoley and Grimsditch, 2009). Although vegetated salt marshes have been termed 'blue carbon' because of their efficiency in trapping suspended matter resulting in organic carbon burial (Mcleod et al., 2011), worldwide coastal development due to intense human activities has led to widespread losses or degradation of the marsh habitat (Mitsch, 2005; Barbier et al., 2011). A global study revealed that habitat degradation caused significant carbon release from coastal ecosystems to the atmosphere (Pendleton et al., 2012).

To mitigate the degradation of coastal ecosystems, many restoration programs have been implemented to re-establish the vegetation structure and enhance carbon and nitrogen storage (Connor et al., 2001; Callaway et al., 2003; Craft et al., 2003; Irving et al., 2011; Mitsch, 2014). Therefore, the quantification of ecosystem carbon and nitrogen storage in restored habitats is important to provide information for management and conservation practices. As part of this, the chronosequence approach with respect to ecosystem histories has proved crucial for assessing the recovery process of ecosystem functions and in determining the critical

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factors involved in site restoration (Craft, 2001; Craft et al., 2003; Ballantine and Schneider, 2009; Erwin, 2009). Specifically, the recovery characteristics of soil carbon and nitrogen accumulation appear to be driven strongly by the establishment of vegetation, the development of heterotrophic activity, hydrological processes and sediment deposition (Craft et al., 2003; Ballantine and Schneider, 2009; Sheng et al., 2015). The restoration of ecosystem functions also depends on the soil texture and disturbance regime of the site (Marton et al., 2014). Keller et al. (2015) suggested that vegetation may influence soil properties, with a clear relationship between below-ground biomass and soil organic carbon. Similarly, the soil nitrogen conditions support the growth of emergent vegetation in restored marshes. Callaway et al. (2003) showed that biomass and nitrogen accumulation increased with species richness and that manipulating the richness and the composition of revegetation plantings could help to accelerate the rate of functional development.

During the past three decades, over one-third of the tidal salt marshes in the Yangtze Estuary have disappeared due to reclamation and the ever-increasing tension between the needs of the natural system and socio-economic development (Ge et al., 2008). Furthermore, *Spartina alterniflora* was introduced from North America into the estuary in the 1990s and has expanded rapidly. As a result, the area of native *Scirpus mariqueter*, which was a dominant pioneer plant in the estuary, has been greatly reduced and the related ecological functions of the local community have been adversely affected (Li et al., 2009; Ge et al., 2013, 2015a). To halt the invasion of *S. alterniflora* and re-establish the original habitats, starting in 2010, a large ecological engineering project aimed at *S. alterniflora* removal and *S. mariqueter* revegetation has been conducted in the Chongming Dongtan wetland, which is the largest salt marsh in the Yangtze Estuary.

In this research, the accumulation of soil organic carbon (SOC) and total nitrogen (SN) in the soil profile of recently restored (2 years) and mature (natural vegetation) native *S. mariqueter* marshes in the Chongming Dongtan wetland were investigated. As part of the research, the variables relating to sedimentary dynamics and plant growth were measured. The main objectives of the study were: (1) to explore the rate of soil carbon and nitrogen accumulation in the restored marsh at the earlier vegetation stage and over a subsequent decade; and (2) to examine the effects of the mode of revegetation as expressed in the planting density, site properties (sediment texture and hydrological regime) and community age on the storage of carbon and nitrogen in relation to depth in the soil profile. The research should provide valuable information on suitable techniques for the larger-scale restoration engineering design required for the restoration and recovery of ecological functions in degraded salt marshes.

2. Material and methods

2.1. Study site

The research area is located within a National Nature Reserve in the salt marshes of the Chongming Dongtan wetland on the east side of Chongming Island in the Yangtze River estuary (31°25′–31°38′N, 121°50′–122°05′E, Fig. 1). The island has a northern sub-tropical ocean climate, with an average rainfall of 1022 mm yr^{-1} and temperatures ranging from 15.2 °C to 15.8 °C. The salt marshes of the Chongming Dongtan wetland maintain an expansion rate of approximately 150–200 m yr^{-1} towards the East China Sea resulting from the deposition of the very large quantities of silt transported by the Yangtze River (Yang et al., 2001). Tidal movement in the salt marsh is irregular and semi-diurnal, with maximum and average tide heights of 4.62–5.95 m and 1.96–3.08 m respectively (Ge et al., 2008). A large ecological engineering project aiming to control and eliminate the exotic species *S. alterniflora* and enable revegetation with the native *S. mariqueter* was launched by the local government in 2010 (Hu et al., 2015). Barrier fences erected outside the engineering area stimulated increased sediment accretion, leading to the growth of newly formed tidal mudflats with an elevation >2.0 m above sea level, providing suitable sites for revegetation by the native species *S. mariqueter*.

Table 1
Summary of the features of the soil of the muddy site (M) and the silty site (S) in the study area. The values are in the form of the mean ± S.E. (standard error) at 30 cm of soil depth.

	Muddy site (M)	Silty site (S)
Grain size (μm)	11.68 ± 1.35	43.31 ± 3.02
Bulk density ($g\,cm^{-3}$)	0.96 ± 0.09	1.32 ± 0.14
pH	8.15 ± 0.03	8.09 ± 0.03

In the Chongming Dongtan wetland, the spatial variability of the sediment grain size is predominantly governed by physical controls, notably flow velocity and river discharge and also sediment supply (Yang et al., 2008). In the study area of the eastern and southern marsh, the depositional layers are composed mainly of fine mud (~10 μm grain size) and coarse silt (~50 μm grain size). Therefore, the research design stratified the sample areas on the basis of sediment type into the muddy habitat (Site-M) and silty habitat (Site-S). The characteristic data on grain size, bulk density and pH in the two different sample areas are listed in Table 1.

2.2. Revegetation practice

Hu et al. (2015) demonstrated a successful revegetation approach using transplanted soil cores containing corms of *S. mariqueter* on the tidal flats of the Yangtze estuary. Soil cores with a diameter of 7.5 cm and a depth of ~15 cm containing *S. mariqueter* corms were buried with their tops level with the surface of the bare mudflat. On average, 15 corms were found in these transplanted soil cores that were used for revegetation. In the early spring season (April) of 2014, three treatments with different levels of planting densities were applied in the mud-dominated site (M): low – one soil core per 1 m^2, medium – two soil cores per 1 m^2 and high – four soil cores per 1 m^2. Although the three densities were applied in the silt-dominated site (S), only the high density approach planting succeeded. Few plants emerged when the approach with a low planting density was applied, primarily because of the strong tidal currents in the silt-dominated areas. The two sites and the above planting designs of Hu et al. (2015) were thus used as the experimental design for the research presented here into SOC and SN.

2.3. Sedimentation dynamics

From January to December in 2015, the sedimentation dynamics in both the mud-dominated (M) and silt-dominated sites (S) were measured at monthly intervals. In order to assess the accumulation or loss of sediment, adjacent to each sampling area twelve wooden poles (1.5 m in length) were inserted into the soil at 5 m intervals, leaving the top 40 cm of each pole exposed above the soil surface. The initial elevation was set to zero as a reference point, and the accretion/erosion rates were determined as the relative positive or negative change from the initial elevation.

2.4. Plant and soil sampling

In the mud-dominated site (M) (Fig. 1), sediment samples were extracted from the non-vegetated area (M-Bare) and the recently