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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

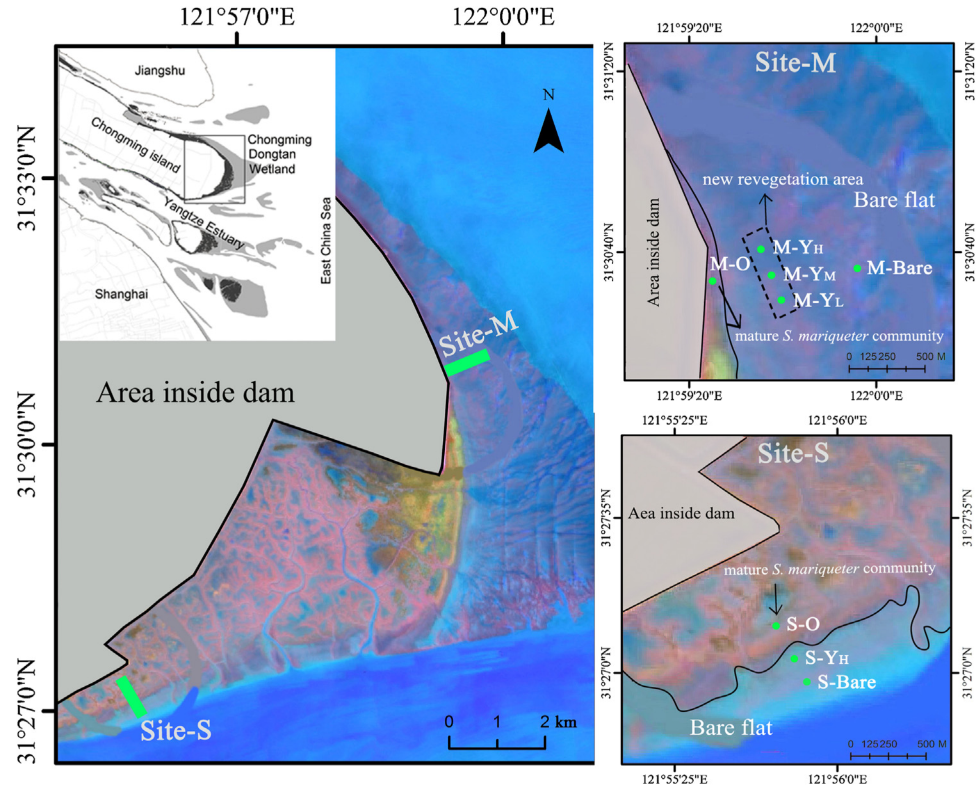

Fig. 1. Location of the study area in the Chongming Dongtan salt marsh of the Yangtze Estuary and the two sampling sites (muddy site (M) in the eastern marsh and silty site (S) in the southern marsh).

restored *S. mariqueter* marsh (M-Y) characterized by each of the three planting densities: 1) low planting density (M-Y_L); 2) medium planting density (M-Y_M); and 3) high planting density (M-Y_H). Sediment samples were also extracted from the original untreated mature (M-O) *S. mariqueter* marsh. These were >10 years old, based on the assessment of past satellite images and previous vegetation resource inventories in the Chongming Dongtan Nature Reserve. In the silt-dominated site (S) (Fig. 1), sediment samples were extracted only from the recently restored *S. mariqueter* marsh which had been treated with a high planting density (S-Y_H). These were again compared with original untreated mature *S. mariqueter* marsh >10 years (S-O) and bare mudflats (S-Bare).

The aerial parts of plants in a sample area of 0.25 m × 0.25 m were harvested and soil samples including the below-ground biomass were collected at the same position from each plot in the muddy site (M) and the silty site (S) firstly in September 2015 (autumn) and secondly between December 2015 and January 2016 (winter), 2 years after revegetation. According to Hu et al. (2015), four separated strips (each 20 m × 5 m) for each treatment of planting density were set up in the recently restored marshes. Three replicates of above-ground plant and below-ground plant and soil materials were sampled randomly in the different strips in both study sites. In the mature marshes, three replicates were taken randomly >5 m apart between each other. A steel corer with an inner diameter of 10 cm was used to extract the soil samples from each clipped square and five soil cores were taken from each square for below-ground biomass and element measurement. The soil cores had a depth of 50 cm and each soil core was sub-divided into 10 sections at 5 cm intervals. The soils from each of the 10 layers were mixed together across each sample replicates.

2.5. Biomass measurement

The above-ground plant samples were washed with clean water and the bulked soil samples were soaked in water for 12 h and then flushed through a 0.28-mm mesh sieve mounted on top of a bucket (Lauenroth and Whitman, 1971). A majority of coarse and fine roots remained on the mesh sieve. Those fine roots that passed through the sieve floated on the surface of the water in the bucket and were then collected in a 0.15-mm mesh sieve. All root tissue in the sieves was handled with tweezers. After sieving, the above-ground and below-ground biomass samples were oven-dried at 105 °C for 2 h to remove any enzymatic activity and then at 60 °C, until a constant weight was recorded. The final dry weights of the biomass samples were expressed as mass per unit area.

2.6. Chemical analysis

Using the standard pre-treatment procedure for sediment samples, the root-free soil samples were first air-dried in a dry ventilated laboratory. Soils were homogenized by passing them through a 1-mm sieve. The soil was then oven-dried at 60 °C and ground to analytical fineness with an agate mortar.

The soil samples were put into centrifuge tubes, acidified with 50 μL of 1 M HCl to remove soil carbonates and dried overnight at 37 °C twice before carbon and nitrogen analyses. Using an elemental analyzer (Elementar Vario EL III CHNOS, Elementar Analysensysteme GmbH), the total organic carbon content (TOC) and total nitrogen content (TN) were analyzed. The soil bulk density measured for each of the 10 soil layers at the start of the study was used to convert the carbon and nitrogen concentrations to area-based SOC and SN storage. The overall soil bulk density of each layer

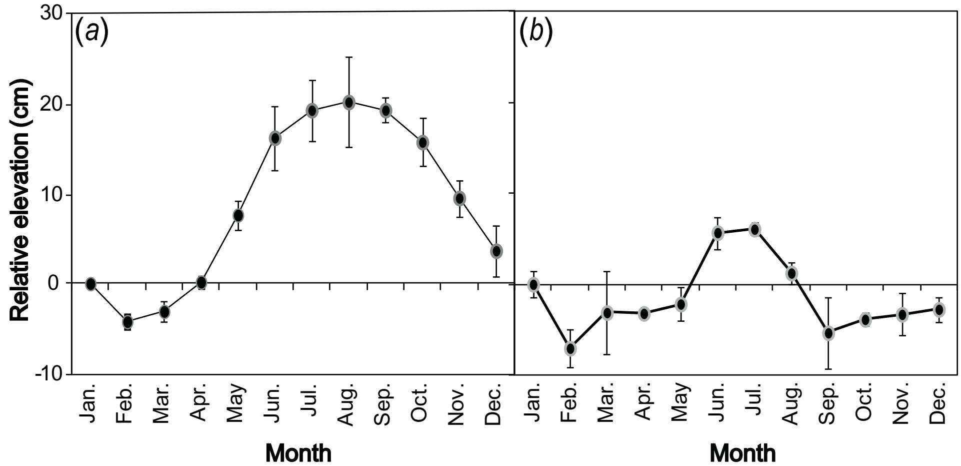

Fig. 2. Monthly sedimentary dynamics in the muddy site (M) (*a*) and the silty site (S) (*b*). The positive values represent accretion and negative values erosion relative to the initial mudflat elevation.

was thus determined from the final dry weight of the soil sample and the volume of the soil corers (50 cm^3).

$$SOC(g\,m^{-2}) = TOC(\%) \times bulkdensity(g\,m^{-3}) \times soilthickness(m)(1)$$

$$SN(g\,m^{-2}) = TN(\%) \times bulkdensity(g\,m^{-3}) \times soilthickness(m)(2)$$

2.7. Data analysis

Firstly, the plant growth (shoot density and biomass) and the storage of SOC and SN measured between autumn and winter were compared to obtain the maxima for further analysis. The values of biomass growth during autumn and SOC and SN storage during winter were then subject to statistical analysis. The measured variables were expressed as the means ± S.E. for each sampling plot in the muddy site (M) and the silty site (S) for each soil layer and all amounts (10 soil layers) respectively. A one-way analysis of variance (ANOVA) with Tukey's HSD test of multiple comparisons was used to compare the means of each variable in the six vegetated plots (six individual groups of M-O, M-Y_H, M-Y_M, M-Y_L, S-Y_H, and S-O) for plant growth and all plots (M-O, M-Y_H, M-Y_M, M-Y_L, M-Bare, S-O, S-Y_H, and S-Bare) for SOC and SN storage. Then, a one-way ANOVA with univariate analysis was conducted to test the effects of site property, planting density and community age on the stocks of SOC and SN separately. The significance level was set at $P < 0.05$. A least squares regression analysis was also used to assess the relationships between SOC and SN storage and plant biomass in terms of planting density and community age in both sites. All of the statistical analyses were performed by the SPSS version 23.0 software (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Sedimentary dynamics

The sedimentary dynamics varied in the two sites (Fig. 2). At the muddy site (M), the mudflat showed gradual accretion during the period April–August (growing season) in 2015, with a mean accretion rate of 4.1 ± 1.8 cm. However, at the silty site (S), sediment accretion was low during the growing season and gradual erosion was observed throughout the year.

Table 2
Effects of site type, planting density and age class of the community on SOC and SN accumulation and storage.

Item	SOC		SN	
	F	*P*	*F*	*P*
Site type	22.78	0.009**	58.89	0.002**
Planting density	37.54	<0.001**	10.11	0.012*
Age class	28.81	<0.001**	26.67	<0.001**

*: significance at P < 0.05, **: significance at P < 0.01

3.2. Scirpus *growth*

Generally, the shoot density and total biomass growth of *Scirpus* in the muddy site (M) were higher than that in the silty site (S) within same age class, and a significant difference ($P < 0.05$) was observed between the M-O and S-O plots and all three young plots (M-Y_H, M-Y_M, and M-Y_L) relative to S-Y_H plots (Fig. 3). In both muddy (M) and silty (S) sites, the shoot density and total biomass in the old plots M-O and S-O were significantly higher ($P < 0.05$) than those in the recently restored plots. The above-ground biomass in the M-Y_H plots, with the highest planting density, approximated to that in the M-O plots (Fig. 3b). Within the recently restored *Scirpus* area of the muddy site (M), over the two years, the high planting density resulted in significantly higher ($P < 0.05$) shoot density and total biomass growth compared to the low planting density.

The below-ground biomass profiles (50 cm depth) showed that the highest root biomass was distributed at 5–20 cm (Fig. 4), regardless of site type, age class and planting density. With increase in depth, the below-ground biomass decreased. The total below-ground biomass in the M-O plots was significantly higher ($P < 0.05$) than that in all three young plots (M-Y_H, M-Y_M, and M-Y_L) (Fig. 3c). The root biomass in the S-O plots was significantly lower ($P < 0.05$) than that in the M-O plots, while it was slightly higher when compared to the M-Y_H plots. The lowest shoot density, above- and below-ground biomass was measured in the S-Y_H plots through the two sites.

3.3. Soil organic canbon (SOC) and soil nitrogen (SN) accumulation and storage

The results of the storage of SOC and SN in the vegetated region and bare flats of the muddy site (M) and the silty site (S) are presented in Fig. 5. Significant effects ($P < 0.05$) of the site type, planting density and age class were found for the SOC and SN stocks (Table 2).

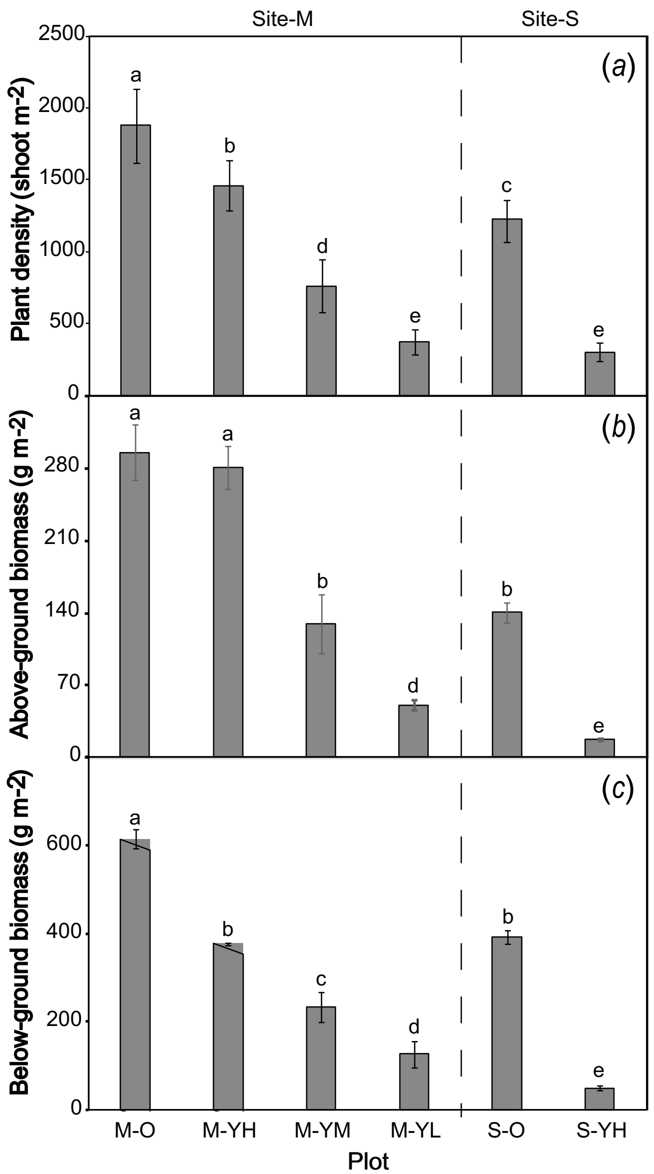

Fig. 3. Plant density (*a*), above-ground (*b*) and below-ground biomass (*c*) in the different study plots. M-O: mature native *S. mariqueter* marsh in the muddy site (M); M-Y_L: recently restored *S. mariqueter* marsh with a low planting density in the muddy site (M); M-Y_M: recently restored *S. mariqueter* marsh with a medium planting density in the muddy site (M); M-Y_H: recently restored *S. mariqueter* marsh with a high planting density in the muddy site (M); S-O: mature native *S. mariqueter* marsh in the silty site (S); S-Y_H: newly restored *S. mariqueter* marsh with a high planting density in the silty site (S). The various lower-case letters above the bars indicate significant differences between the sites ($P < 0.05$).

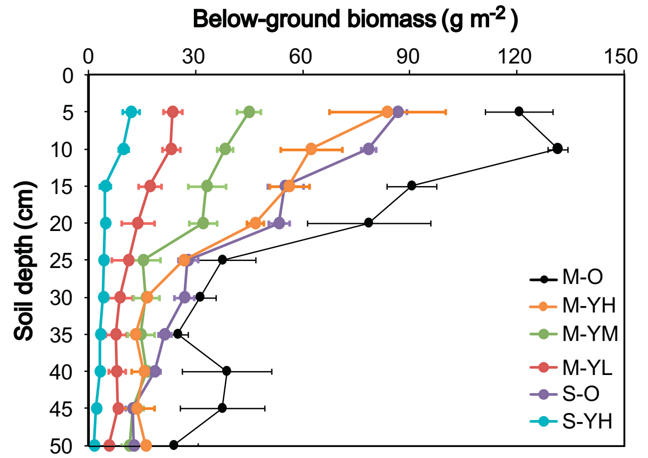

Fig. 4. Profiles of below-ground biomass in the different study plots. M-O: mature native *S. mariqueter* marsh in the muddy site (M); M-Y_L: newly restored *S. mariqueter* marsh with a low planting density in the muddy site (M); M-Y_M: newly restored *S. mariqueter* marsh with a medium planting density in the muddy site (M); M-Y_H: newly restored *S. mariqueter* marsh with a high planting density in the muddy site (M); S-O: mature native *S. mariqueter* marsh in Site-S; S-Y_H: recently restored *S. mariqueter* marsh with a high planting density in the silty site (S).

The SOC and SN stocks in the vegetated region were significantly (except for M-Y_L and S-Y_H) higher ($P < 0.05$) relative to bare flats in the muddy and silty sites. Maximum stocks of $1370 \pm 690\ g\ m^{-2}$ SOC and $240 \pm 12\ g\ m^{-2}$ SN were observed in the M-O plots, which were significantly ($P < 0.05$) higher than those in all other plots.

In the recently restored *Scirpus* area of the muddy site (M), the SOC stock increased with the increase in planting density and the stock was significantly higher ($P < 0.05$) in the M-Y_H plots compared to the M-Y_L plots (Fig. 5a). However, this trend was marginal with regard to the SN stock (Fig. 5b). In the silty site (S), the increment of SOC and SN storage was not significant ($P > 0.05$) in the S-Y_H plots when compared to the non-vegetated area. The SOC stocks in the M-Y_H and M-Y_M plots of the muddy site (M) two years after revegetation were 37% and 24% higher (significance of $P < 0.05$) and

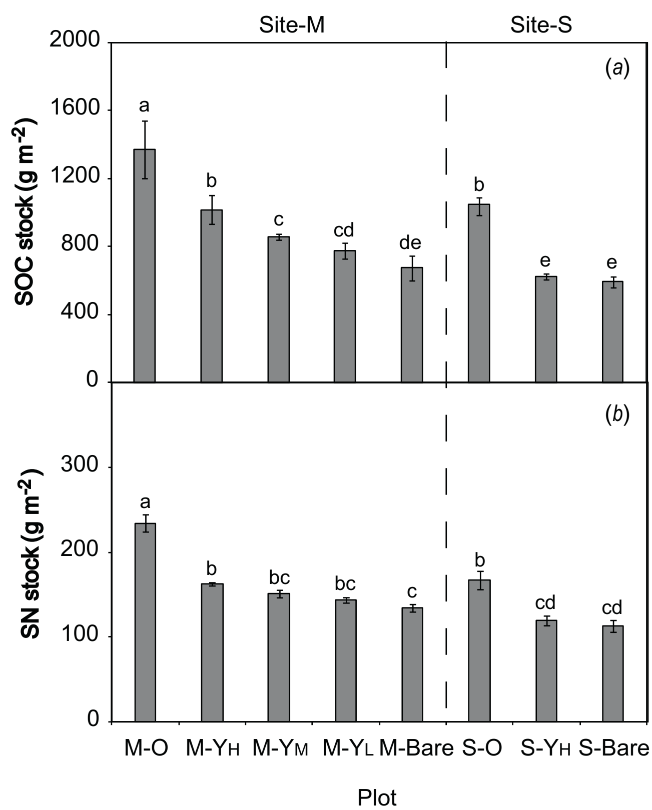

Fig. 5. SOC (*a*) and SN storage (*b*) in the different study plots. M-O: mature native *S. mariqueter* marshes in the muddy site (M); M-Y_L: newly restored *S. mariqueter* marsh with a low planting density in the muddy site (M); M-Y_M: newly restored *S. mariqueter* marsh with a medium planting density in the muddy site (M); M-Y_H: newly restored *S. mariqueter* marsh with a high planting density in the muddy site (M); M-Bare: bare flat in Site-M; S-O: mature native *S. mariqueter* marshes in the silty site (S); S-Y_H: newly restored *S. mariqueter* marsh with a high planting density in the silty site (S); S-Bare: bare flat in the silty site (S). The various lower-case letters above the bars indicate significant differences between the sites ($P < 0.05$).

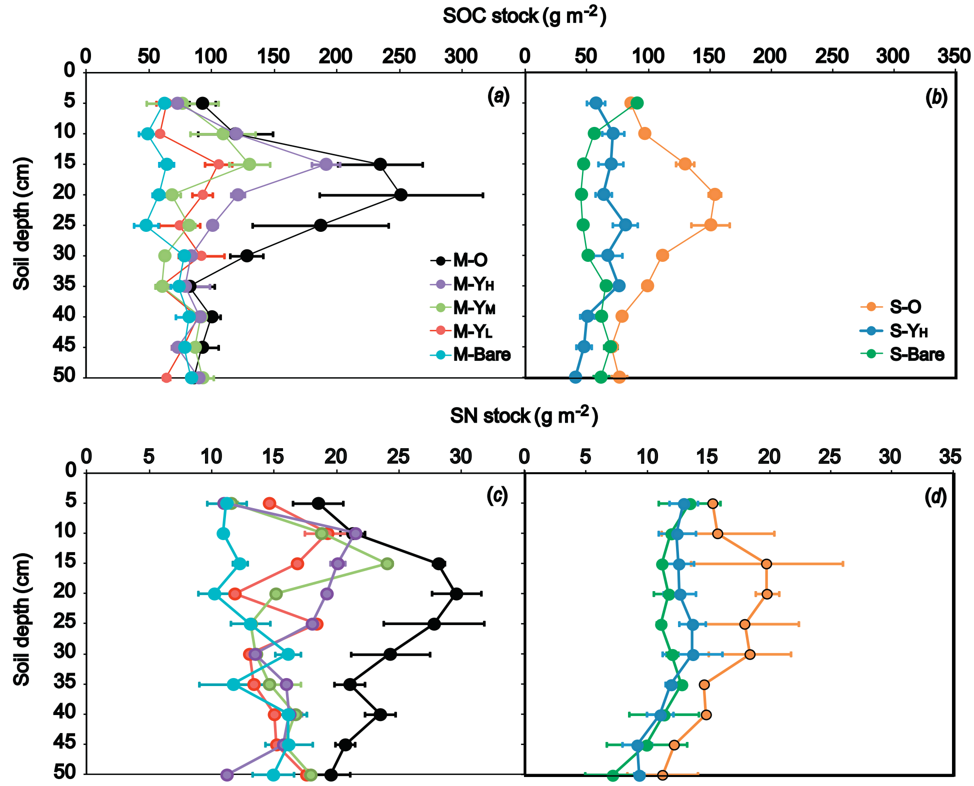

Fig. 6. Depth profiles of SOC (*a*, *b*) and SN storage (*c*, *d*) in different study plots. M-O: mature native *S. mariqueter* marsh in muddy site (M); M-Y_L: newly restored *S. mariqueter* marsh with a low planting density in the muddy site (M); M-Y_M: newly restored *S. mariqueter* marsh with a medium planting density in the muddy site (M); M-Y_H: newly restored *S. mariqueter* marsh with a high planting density in the muddy site (M); M-Bare: bare flat in the muddy site (M); S-O: mature native *S. mariqueter* marsh in the silty site (S); S-Y_H: newly restored *S. mariqueter* marsh with a high planting density in the silty site (S); S-Bare: bare flat in the silty site (S).

the SN stocks were 33% and 32% higher (significance of $P < 0.05$), respectively, than those in the S-Y_H plots located in the silty site (S). Moreover, the storage of SOC and SN in the M-Y_H plots almost reached the amount in the mature S-O plots.

The depth distribution profiles of the SOC and SN stocks are shown in Fig. 6. In the vegetated region, the SOC and SN stocks increased at a depth of 0–25 cm and the highest stocks occurred in the ~15–25 cm layers, regardless of the site type, planting density and age class. Below 25 cm, storage decreased with depth. The SOC and SN stocks presented depth profiles that were quite similar to the profiles of the below-ground biomass in each plot.

Table 3 shows a strong correlation between SOC and SN storage and the below-ground biomass with regard to the planting densities (M-Bare, M-Y_L, M-Y_M, and M-Y_H) and age classes (M-Bare, M-Y_H and M-O) in the muddy site (M). The linear slope of the SOC least squares regression function regarding planting density (0.81) in the recently restored marsh approximated that for community age (1.07), reflecting a fast rate of SOC stocking with increase in planting density, due to rapid vegetation establishment and below-ground biomass growth. However, a notably lower slope of the SOC function based on artificial planting (0.61) in the silty site (S), when compared to that for community age (1.31), revealed a low efficiency of carbon sequestration in the recently restored marsh.

4. Discussion

The salt marshes of the Yangtze Estuary is a useful location for testing the effectiveness of native vegetation restoration and consequent carbon and nitrogen storage because the growth of native species, particularly *S. mariqueter* has been greatly suppressed, due to the extensive invasion of exotic plants along China's coast. In most landscape restoration, the quality of the initial planting effort has been shown to be critically important for community development and revegetation success (Gutrich et al., 2009; Williams and Ahn, 2015). This is true, to an even greater extent, in coastal salt marshes, which have harsh environmental stresses for plant survival, establishment and growth linked to strong hydrodynamic factors involving wind, waves, water currents, tides and the corresponding sediment movement (Mitsch, 2005; Lee et al., 2011).

In this study, corms of *S. mariqueter* were planted at varying densities (Hu et al., 2015) in different regions of a marsh that had a wide heterogeneity of sedimentation processes, hydrological regimes and microtopography. In the muddy site (M), the revegetation practices with high and medium planting densities resulted in rapid plant growth, and the shoot density and the above-ground biomass under a high planting density required two years to achieve equivalence to those of the natural marsh. Shoot density and canopy height of vegetation have been identified as the most important factors for dissipating tidal energy (wave attenuation) (Bouma et al., 2005; Yang et al., 2012). In this study, a high planting density offered significant resistance to tidal energy and was more likely to benefit the survival and establishment of vegetation relative to a low planting density.

The large amount of runoff from the Yangtze River delivers massive quantities of silt, which are then deposited in the Yangtze Estuary (Yang et al., 2001). As a result, the accretion of sediment in the muddy site (M) encouraged the survival of *S. mariqueter* and its colonization on the tidal flats during the growing season. During the establishment phase, the shoot density and biomass growth increased rapidly by vegetative tillering and rhizome development of the standing seedlings. This finding is in accordance with the general assumption of the positive feedback of interactions between sedimentary processes and vegetation establishment that occur in coastal salt marshes (Schwarz et al., 2011; Ge et al., 2015a, 2015b).

Table 3
Linear regression of below-ground biomass (x) with SOC and SN storage (y) with regard to planting density and community age ($y = ax + b$) in the muddy site (M) and the silty site (S).

Site	Item	*a* (slope)	*b* (intercept)	R^2	Plots for function
Site-M	SOC (planting density)	0.81	673.06	0.95	M-Bare, M-Y_L, M-Y_M and M-Y_H
	SOC (community age)	1.07	647.94	0.99	M-Bare, M-Y_H and M-O
	SN (planting density)	0.07	139.94	0.71	M-Bare, M-Y_L, M-Y_M and M-Y_H
	SN (community age)	0.15	123.68	0.80	M-Bare, M-Y_H and M-O
Site-S	SOC (planting density)	0.61	592.74	1.00	S-Bare and S-Y_H
	SOC (community age)	1.31	592.75	1.00	S-Bare and S-O
	SN (planting density)	0.13	112.54	1.00	S-Bare and S-Y_H
	SN (community age)	0.14	112.53	1.00	S-Bare and S-O

However, the relationships between sedimentary processes and vegetation establishment are complicated. For example, the establishment of plants on the tidal flats could also benefit positively from a moderate sedimentation rate during the earlier growing season, while extremely heavy sedimentation during the same period might have the opposite effect due to burial stress. A previous study indicated that the survival threshold of recently planted *S. mariqueter* to sedimentation and burial during the establishment stage was reached at approximately 20 cm (Hu et al., 2015). Regarding the effect of site properties, the two-year growth of *S. mariqueter* with a high planting density (S-Y_H) was significantly lower than that in the S-O plots of mature marsh and was not even in the same class in the M-Y_L plots with a low planting density in the muddy site (M). The probable reason for these observations is that the currents of the Yangtze are strongest in the southern part of the Chongming Dongtan wetland, which includes the silty site (S) and is relatively near to the main Yangtze River channel (Yang et al., 2008). In contrast to the muddy site (M), the newly formed fine sediment layer would be easily removed by the strong currents, and slight erosion was actually observed at the silty site (S) during the revegetation period. As a result, the strong tidal waves and currents and the limited sediment supply reduced the survival and establishment of *S. mariqueter* seedlings. Because of the weak surface accumulation of fine mud in the silty site (S), the soil was mainly composed of coarse silts with a high bulk density, leading to inhibition of root growth and rhizome development below ground, which is in agreement with the findings of Hossler and Bouchard (2010).

With the re-establishment of native vegetation, the soil carbon and nitrogen stocks were investigated as the key indicators of functional recovery in the revegetated marsh. Regardless of planting approach, the stocks of SOC and SN increased with the age of the communities in both the muddy and silty sites. This observation is consistent with other examples of restored salt marshes (Craft, 2001; Craft et al., 2003; Henry and Twilley, 2013; Keller et al., 2015). It is generally hypothesized that SOC and SN accumulation is facilitated by vegetation restoration and that the consequent biomass input and the above-ground and below-ground biomass litter are the main sources of organic matter input into the soil in terrestrial ecosystems (Laganière et al., 2010; Zhao et al., 2015; Deng et al., 2016). In this study, the SOC and SN stocks in the *Scirpus* marsh were closely related to below-ground biomass accumulation because most of the aerial biomass was washed out by the strong tidal flows. The sediment deposition also favored carbon burial. Mudd et al. (2009) demonstrated a close link between root productivity and soil carbon content on the east coast of the United States using analytical and numerical modelling approaches. In the recently restored *Scirpus* marsh in the muddy site (M), the SOC stock increased with the increase in planting density. After two years of revegetation, the SOC storage in the M-Y_H, M-Y_M and M-Y_L plots was 1.52 times, 1.26 times and 1.14 times greater, respectively, as that measured in the non-vegetated plots. The approximate linear functions along planting densities (M-Bare, M-Y_L, M-Y_M, and M-Y_H) and age classes (M-Bare, M-Y_H and M-O) also reflected a fast stocking rate of SOC due to revegetation with high planting density. This further proved that the revegetation approach using corms of *S. mariqueter* was able to restore the root system development and organic carbon input in tidal marshes quite rapidly. However, the degree of increase in SOC storage was much less in the young marsh (S-Y_H) in the silty site (S) than that in the muddy site (M), even when the same approach using a high planting density was applied, which might be attributed to the inhibited below-ground root growth and less sediment deposition and even erosion associated with the higher bulk density in the silty site (S). Thus these results supported the importance of root growth and sedimentary processes in building soil organic matter stocks in the tidal marshes (McCaffrey and Thomson, 1980; Ouyang and Lee, 2014).

Overall, the storage of SN increased less than that of carbon, possibly because the decomposition of litter and roots could contribute to the preferential enrichment of carbon over nitrogen. Zhou et al. (2007) also found that 22–55% of the organic carbon and 0.6–35% of the nitrogen in the sediments were derived from the vegetation in the salt marsh of the Yangtze Estuary.

Throughout the soil profile, storage of SOC and SN was highest in the topsoil (0–15 cm for the newly restored plots, 0–25 cm for the mature plots) and tended to decrease with increasing soil depth. This finding is in agreement with other examples of salt marsh restoration in southern California of the United States described by Keller et al. (2015). They reported that ~50% of the variability in SOC in the topsoil was explained by the below-ground biomass at the same depth interval. The main rooting system of *S. mariqueter* was distributed in the top 20 cm of soil, suggesting that the profile variations of below-ground vegetation processes may be important for carbon and nitrogen dynamics. In deep soil, a higher bulk density and lower oxygen availability or their interaction might limit the biotic processes and decomposition rate, especially in the silty site (S).

5. Conclusions

A major aim of the large-scale salt marsh restoration plan for the Yangtze Estuary is to re-establish the native vegetation and eradicate the exotic species. The accumulation of carbon and nitrogen and their stocking rates in the restored *S. mariqueter* marshes will provide important information for management and conservation practices. This research has found that, in the recently restored marsh of the muddy site, vegetation growth increased with increase in planting densities and the SOC storage was significantly higher than that in non-vegetated plots after two years of revegetation. The storage of SN increased less than that of carbon. The SOC under a high planting density equated to approximately 75% of the carbon stock in the mature marsh. However, the rate of increase in SOC storage was much less in the silty site than in the muddy site, due to less sediment accretion and inhibited root growth. This study has demonstrated that the earlier success of vegetation restoration and below-ground root growth played a key role in determining SOC and SN accumulation and storage in the salt marsh. The restoration of native *S. mariqueter* for SOC and SN stocks will be effective when conducted in the muddy region with suitable sedimentation conditions, while, in the silty (or sandy) region, the investment of manpower and material resources would fail, due to the poor sedimentation conditions for plant growth and carbon accumulation processes.

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