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Distribution of organic carbon storage in different salt-marsh plant communities: A case study at the Yangtze Estuary

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ABSTRACT

The high carbon (C) sequestration potentials of coastal wetlands play an important role in mitigating climate change associated with the greenhouse effect. In the present study, soil samples were collected from the 0–30-cm topsoil layers and from 0 to 100-cm cores for the analysis of the spatial dynamics and vertical distribution of organic carbon (OC) and biomass in different vegetation zones in a small tidal basin in Chongming Dongtan wetland. According to the results, sediments in the region were a mixture of terrestrial and marine sources and the proportions of terrestrial components decreased with an increase in depth. In addition, soil properties were quite similar in the top-soil layer. In the study area, the OC concentration was in the 0.7–10.93 g/kg range, which was positively correlated with halophyte biomass and negatively correlated with soil salinity and particle size. Furthermore, OC content decreased with an increase in depth. The OC content in different halophyte communities was in the order of *Phragmites australis* community > Mixed community > sedge community, and was consistent with the gross biomass. The total C sequestered of 100-cm depth in the area was 31,177 ton, with the *P. australis* community, mixed community, sedge community, and water sequestering 57.7, 49.2, 25.5 t/ha, and 8 t/tidal cycle, respectively. Tidal marshes in Chongming Dongtan exhibited a high C sequestration capacity, indicating that they play a major role in the C cycle in the Yangtze Estuary.

1. Introduction

As the globe begins to transition into a low-carbon (C) economy, decreasing greenhouse gas emissions and mitigating the impacts of climate change by focusing on the self-regulating functions of ecosystems have drawn much attention (HMSO, 2013). Among the ecosystems that provide C sequestration services, vegetative coastal habitats, including seagrass, tidal marshes and mangroves, which are known as 'blue carbon' ecosystems, are the most effective ones (McLeod et al., 2011). Tidal salt marshes have the capacity to sequester high C amounts per unit area. Globally, the C sequestration rate of salt marshes is approximately 4.8–87.3 Tg C/yr, indicating the remarkable capacity of such C sinks (Duarte et al., 2005).

Periodic inundation and exposure to tides influence estuarine and coastal salt marshes, and they receive high amounts of water, and organic matter (OM) and nutrients from rivers, oceans, and the atmosphere (Hopkinson et al., 2012). OC accumulation in salt marsh soil originates from autochthonous accumulation, allochthonous input, and microbial mineralization (Mitsch and Gosselink, 2007). Such processes, in turn, could influence soil moisture content, microbial activity, and climate. Furthermore, such factors could interact and influence tidal salt marshes and their role as C sources or sinks.

As long-term growing C sink, coastal wetlands have high level of primary productivity, biomass regeneration rate, and OM deposition rate, in addition to considerable tidal flat development and vegetation succession, although they are distributed over a relatively small area. Soil OM in coastal wetlands originates mainly from halophytic plant biomass (Valiela et al., 1976), and biomass decomposition influences soil C storage significantly (Elsey-Quirk et al., 2011a). More than 50% of their biomass is often distributed in their roots and rhizomes in the soil, making the coastal wetland soil an efficient C sink (Duarte et al., 2013; McLeod et al., 2011). The composition of halophytic species communities determines the quality of litters and roots, which, in turn, influences the accumulation of OC (Sousa et al., 2010). In addition, factors

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such as marsh age, soil drainage, and redox potential could affect decomposition and production rates (Craft, 2007; Nyman et al., 1993).

Sedimentary dynamics also influence coastal wetland elevations directly, and the elevations, in turn, influence environmental factors such as flooding, soil conditions, and the degree of wind and wave action. Such factors, therefore, directly or indirectly affect salt marsh vegetation growth conditions, which further affect C sequestration capacity (Chmura et al., 2003). Considering the Yangtze River Estuary coastal wetland as an example, the vertical deposition rate of sediments in the tidal flat can reach 16 cm/yr (Zhou et al., 2007). With the development of the tidal flat, the salt marsh vegetation (vegetation coverage 50%) extends to the sea by 4.3 39 m/yr (Zhu et al., 2012). During the development of the tidal flat and vegetation succession, exogenous and endogenous OM continuously enter the sediment, enhancing C and nitrogen (N) accumulation in the soil (Zhou et al., 2007). Although most studies have focused on the surface soil layer (6 30 cm), the characteristics of the surface soil may not estimate C storage in deeper soil levels (Olson and Al-Kaisi, 2015). Considering the complex interactions between root systems and soil OC, samples from deeper soil layers could evaluate the role of salt marshes in the C cycle better (Burd et al., 2016).

Identifying the source of OM in estuarine and coastal salt marsh sediments is a prerequisite for identifying mechanisms of improving soil C storage. The C/N ratio (C/N) is often used as an indicator of the sources of OM. The C/N in marine OM is often 5. Conversely, terrestrial plants have higher C/N, usually greater than 20 or higher (Meyers, 1994). OC sources, therefore, could be divided into terrestrial sources (C/N 20) and marine sources. C/N has also been used extensively as an indicator of recalcitrance. Microorganisms require a C/N value of 20 30:1 to achieve the maximum C degradation rate (Chapin, 2003; Yang et al., 2009). The higher the C/N value, the greater the N demand, and the harder it is to decompose.

Salt marshes are being degraded at alarming rates. Recent estimates suggest that on a global scale, 25% of salt marshes have been lost since the 1800s, with ongoing loss rates of 1 2% per year (McLeod et al., 2011). Currently, the mechanisms by which environmental factors influence the global C cycle and the C sequestration capacities of estuarine and coastal salt marsh ecosystems are poorly understood and require further evaluation. Changes in environmental factors can have cumulative and synergistic effects, which are more unpredictable, challenging to control, and irreversible (Ruckelshaus et al., 2013). Therefore, it is necessary to not only estimate the C reserves but also to understand how vulnerable the blue C ecosystems are (Lewis et al., 2018).

In the present study, we measured soil properties and the concentrations of OC, and total N. We also collected biomass of different halophytes in the small tidal basin at Chongming Dongtan. Spatial dynamics and vertical distribution characteristics of C stocks were calculated with the aim of providing basic data that could facilitate further studies on the C sequestration processes in coastal salt marsh ecosystems.

2. Methods and material

2.1. Study site

Chongming Dongtan was formed by sediment deposition carried by the Yangtze River with an average elevation of 4.2 m, which decreases from land to sea. The reference datum of marsh surface elevation in Chongming Dongtan is local Wusong datum in Shanghai, China, but the datum of tidal frame is 0.27 m lower than that of surface elevation (according to Sheshan tide gauging station, Shanghai, China). Tidal creeks that originate from the long low-lying areas along the shore are typical geomorphological features of Chongming Dongtan. Chongming Dongtan marshes are located at the eastern end of Chongming Island (31 25′ 31 38′ N, 121 50′ 122 05′ E).

The region has an irregular semidiurnal tide and the annual maximum and average tidal ranges are 4.89 m and 2.7 m, respectively. The region has a humid subtropical monsoon climate and the annual average temperature is 15.3 C. The average annual rainfall is 900 1500 mm in the region, mainly concentrated in April September.

The south border of Chongming Dongtan wetlands is close to the south branch of the Yangtze River, by which most of the runoff flows to the sea. The salinity of the adjacent water is in the 0.14 0.75‰ range and the salinity of the soil is 2.07 (Jiang, 2015).

Currently, the entire Chongming Dongtan wetland is in a state of high accretion, with the average vertical deposition rate at 10 20 cm/yr and the progradation rate at 60 m/yr (Yang et al., 2008). The soil matrix in the region is mostly loam or sandy loam with a high degree of maturation. Generally speaking, the sea-to-land hydrodynamic forces keep decreasing, and accordingly, marine sediment particle sizes keep decreasing along the sea-to-land gradient. The climax vegetation in the region is a north subtropical broad-leaved deciduous-evergreen mixed forest. With the growth of marshes, the flat surface was continuously elevated, and the vegetation exhibited a positive succession, generally in the order of bare flat *Scirpus triqueter*, *Scirpus mariqueter*, and *Carex scabrifolia* *Phragmites australis* (Li and Yang, 2009).

2.2. Sample collection and chemical analysis

In October 2013, column samples were collected from a *P. australis* community, a sedge community, and mixed community in Chongming Dongtan. In each of the three sampling sites above, three 1-m^2 sampling quadrats (100 cm l00 cm) were selected randomly, and the distances between the sampling quadrates were not less than 10 m. Aboveground parts of the plants in the sampling quadrates (without dead stand) were collected and transported to the laboratory.

Soil cores were also collected using PVC pipes (inner diameter: 14 cm; length: 100 cm) from each sampling quadrates. In total, nine soil column samples were collected with three replicates at each of the plots in the three sites (Fig. 1). Due to the strenuous nature of the soil sampling activity in the tidal flat, only three typical vegetational zones (*P. australis* community, mixed community and sedge community) were selected for the collection of 100-cm soil core samples in the present study. Each core was divided into 20 5-cm-wide portions for use in the measurement of soil properties. The sub-samples were put into zip-lock bags and immediately transported to the laboratory for the analysis of total organic carbon (TOC), total nitrogen (TN), soil salinity, and other parameters.

The aboveground plant parts were placed in envelopes with openings and transported to the laboratory as soon as possible for subsequent analyses.

To determine belowground biomass, soil samples were air-dried in a cool place, and large rhizomes removed after gently hitting the soil samples and breaking them into pieces using a wooden hammer. The plant roots collected were washed with distilled water and dried to a constant weight at 65 C, and then weighed.

To determine aboveground biomass, the aboveground plant parts were washed with distilled water, enveloped, dried at 105 C for 15 min, and then further dried at 65 C to a constant weight, and then weighed (Jiang, 2015).

To determine TOC and TN concentrations, the soil and plant samples were air-dried in a shaded area. Samples were ground and passed through a 0.150-mm sieve. The sifted samples were acidified with 10% HCl to remove inorganic C, rinsed with Milli-Q water to neutral, and then oven dried again to a constant weight at 40 C. The TOC and TN contents were determined using a Vario elemental analyzer (Elementar, Germany). The duplicates of each sample were analyzed, and the averages of the three measurements were used in the results. The analytical precision was estimated to be 2% and 8% for TOC and TN, respectively.

Soil bulk density and moisture contents were determined from fresh soil samples, generally 100 cm^3, obtained using a ring knife. The samples were weighed *in-situ*, transported to the laboratory and dried to a constant weight at 105 C. They were then weighed and the soil bulk density and moisture content calculated.

Soil particle sizes in soil samples were measured using an ls-100q Laser Particle Size Meter (Coulter company, US). The classification of sand, silt, and clay was based on the sediment classification standard of the American Geophysical Union (AGU) (Lane, 1947).

Soil salinity and pH: Air-dried soil sample (50 g) were dissolved in Milli-Q water with a soil-water ratio of 1:5, after passing through a 0.15-mm sieve, and used form soil salinity and pH measurements. The mixed samples were shaken and filtered to obtain soil extract. Soil conductivity was determined using a conductometer (DDS-11A, Rex Instruments. Shanghai, China) and used to calculate soil salinity. The pH value was measured using a pH meter (pHs-25B, Shanghai DaPu Instrument Co. Ltd. Shanghai, China).

The Kriging spatial analysis tool in ArcGIS 10.2 (Esri, Redlands, California, USA) was used for the interpolation of elevation, soil OC content, total salt content, bulk density, water content, median particle size, and pH value, and to calculate the tidal prism. Interpolations fitting a spherical semi-variogram model in the study were prepared using the ordinary Kriging method with default parameters in ArcGIS, based on the following assumptions: 1) the distance or direction between sample points reflects a spatial correlation that can be used to explain variation in the surface; and 2) the mean of spatial heterogeneity is constant and unknown.

The vegetation cover data were obtained from the RapidEye satellite imagery of Chongming Dongtan in May 2013 with ENVI 5.0 (Exelis Inc. Boulder, CO, USA).

2.3. Statistical analysis

To compare the degrees of variation among different indices, the coefficient of variation (*CV*) for each index was calculated.

(1)

SD is standard deviation.

Dry bulk density (*DBD*) (*g/cm^3*)was determined from the mass of a fully dried sample and its original volume.

(2)

M is the mass of dry soil (g) and *V* is the original volume sampled (cm^3).

Soil C density (*SCD*) (*g/cm^2*) was calculated as a function of dry bulk density *(DBD)* and C_{soc} (Batjes, 1996):

(3)

C_{soc} is the OC content of soil (g/kg); *H* is the soil thickness; *g* is the percentage volume of gravel greater than 2 mm. With low amounts of gravel in Chongming Dongtan wetland, *1-g* can be approximately 1.

The C storage of soil (C_S) is the result of the sampling acreage (S_i) (m^2) multiplied by the soil C density (*SCD*) (Kumar et al., 2013):

(4)

The C storage of wetland vegetation is the C stored in its existing biomass, calculated based on plant biomass.

(5)

Ci (kg) is the total C stored in the *i* th-type of wetland vegetation; every 1 g organic dry matter formed by vegetation during photosynthesis needs to assimilate 1.62 g CO_2 and fix 0.44 g carbon, that is, the p (C conversion factor) is 0.44; *Ai* (m^2) is the area of the *i* th-type wetland vegetation; *Qi* (kg/m^2) is the biomass of the *i* th-type wetland vegetation (Zhang et al., 2012).

Organic C sources are divided into terrestrial sources (C/N 20) and marine sources (C/N 5) (Meyers, 1994). Assuming the C/N of marine OM and terrestrial OM are 5 and 20, respectively (based on zeroth approximation), the above parameters have the following relationships (Jia et al., 2002):

(6)

(7)

(8)

C_m is marine authigenic OM, C_t is terrestrial OM. Without considering the influence of other factors, the above formula (6) and (7), are used to calculate the content of marine and terrestrial OC in sediment samples; $Q_{C\ N}$ represents the ratio of terrestrial OM estimated using the C/N method.

3. Results and discussion

3.1. Spatial variation of sediment properties in the surface layer

3.1.1. Organic carbon

Limited by field accessibility, a total of 101 points were set to sample surface soil (top 30 cm) using Fishnet tool in ArcGIS, which distributed evenly in the whole area of Chongming Dongtan (Jiang, 2015). Based on laboratory analysis for the soil sample data, spatial extrapolation was conducted for soil OC, median particle size, salinity, pH, and bulk density from all sampling points using Ordinary Kriging in ArcGIS, and generated continuous surface of soil properties from discrete points at resolution of 15 m. We clipped the above images with the boundary of this tidal basin that was extracted from DEM, and formed Fig. 2. A total of 5 points are distributed in this area, three of which are profile sampling points showed in Fig. 1.

The range of OC content was 2.32 6.29 g/kg, and the OC content decreased gradually seaward. Generally, the supratidal zone experienced a longer succession than the subtidal and intertidal zones and the vegetation changed gradually from pioneer species to more advanced macrophytes. With vegetation succession, the main C pool would change from the belowground of *S. mariqueter* to the *P. australis* in favor of the sequestration of OC and storage. Liu (2013) measured the belowground C storage of *S. mariqueter*, which was 4 24-fold the aboveground C storage. Compared with sedges, large macrophytes can convert more OM into biomass, and transfer more C into the soil, so that the C sink is also enhanced (Yang et al., 2013). The extensive tidal creeks result in frequent tidal disturbance, which flush away C from the vegetation zone. Therefore lower OC concentrations than in Jiang (2015) (7.29 g/kg) were observed.

3.1.2. Median particle size

The median particle sizes of the surface sediments were in the 7.16 45.50 m range (Fig. 2b). According to the sediment classification standards of AGU, the sediments in the sampling area were mainly silt (Table 1). In our study, the median particle size was positively correlated with soil bulk density (R^2 0.613, *p* 0.01) and negatively correlated with total soil salinity (R^2 0.586, *p* 0.01), but not statistically correlated with soil OC. Marsh soils contain greater proportions of fine-grained sediment and higher OM concentrations at lower elevations than those at higher elevations. The findings were consistent with the results of Yang et al. (2008) based on studies conducted in the Yangtze River Estuary, where particle size tended to grow finer from the bare flat zone to higher elevations, which can be explained by the selective transport of flow and adherence of sediments onto plants.

After further subdivision into different groups, the sediment particle sizes significantly influenced OC content (*p* 0.048), based on variance analysis. According to the correlation analysis, in addition to the coarse silt, other particle sizes of silt were negatively correlated with OC (*p*

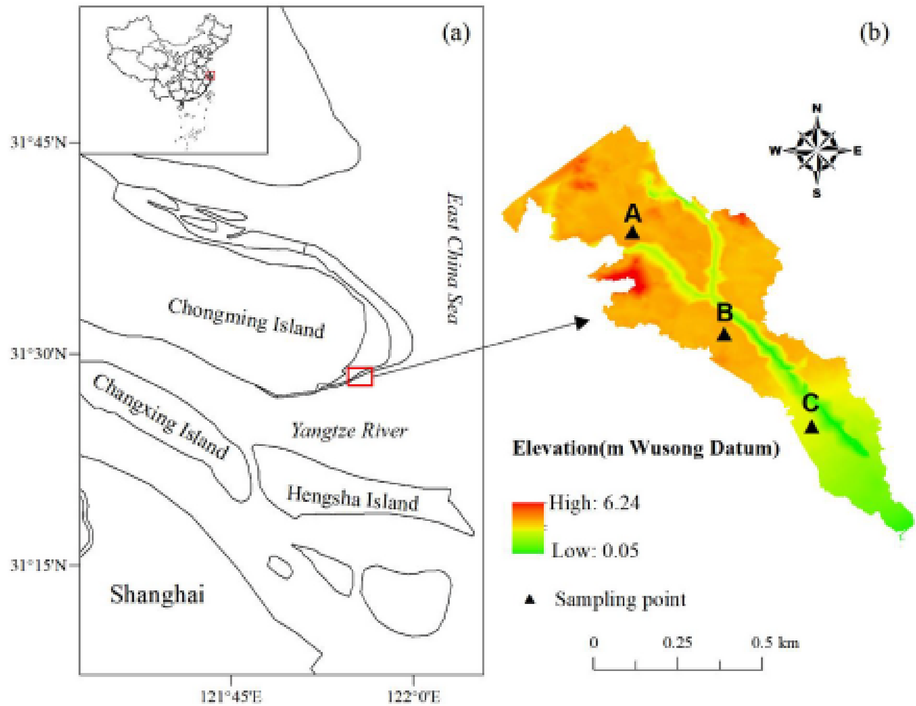

Fig. 1. Study area and sampling sites in the salt marsh in the Yangtze Estuary. Column samples were collected from the *P. australis* community (A), mixed community (B), and sedge community (C).

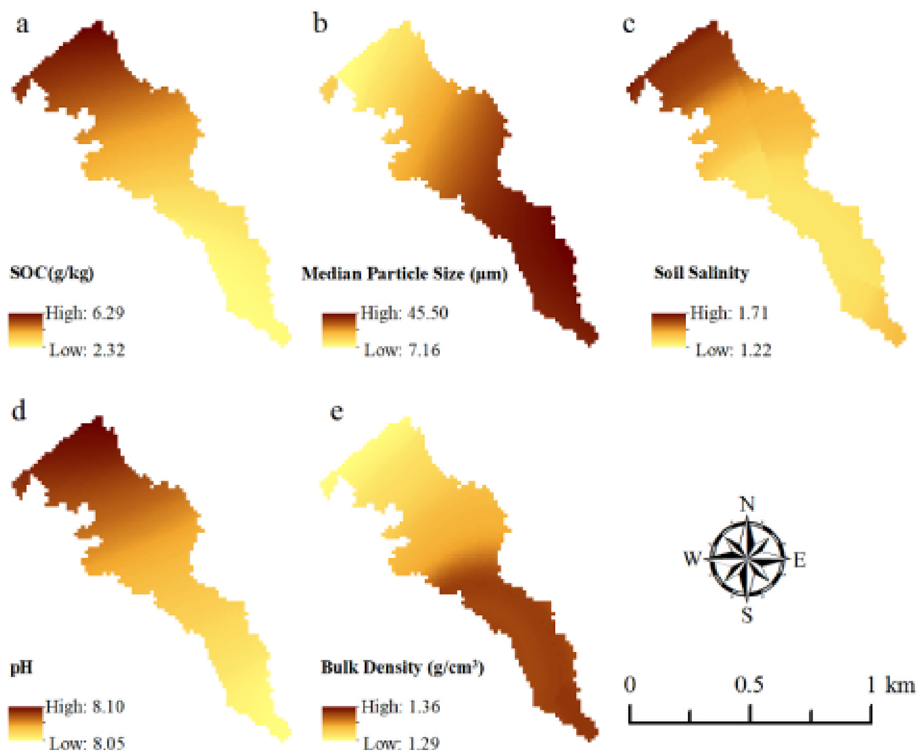

Fig. 2. Spatial distribution of soil properties in the sampling area (a: SOC; b: Median particle size; c: Soil salinity; d: pH; e: Soil bulk density).

0.05, $R^2 = 0.390$). The size of a particle influences the OC adsorption capacity. Earlier studies have showed that when particle size is < 31 μm, sediments exhibit high adsorption capacity, in addition to large specific surface area (Jiao et al., 2010).

The coefficient of variation of median particle size was 36.11%. It is generally considered that a coefficient of variation ranging between 10 and 100 indicates medium variation. Hydrodynamic intensity was a key factor influencing the distribution of soil particle size, as south Chongming Dongtan was densely covered with tidal creeks and was under the influence of tides, which can carry large sediment particles.

Table 1
Sediment classification standard (AGU) (Lane, 1947).

Particle size (m)	Sediment types
0 2	Fine clay and medium clay
2 4	Coarse clay
4 8	Very fine silt
8 16	Fine silt
16 31	Silt
31 63	Coarse silt

3.1.3. Total soil salinity

The range of total soil salinity in the tidal basin was 1.22 1.71, and decreased slightly with a decrease in elevation (Fig. 2c). In the present study, the total soil salinity was relatively low, because the sampling area was located in the south of Chongming Dongtan, which was under considerable influence of the Yangtze River, with more tributaries than in the north (Zhang et al., 2011). The salinity of the low elevation area did not increase as anticipated due to the influence of tidal action because there were numerous tidal creeks in the area with gentle slopes, resulting in slight changes in soil moisture. The total soil salinity basically determined the distribution of vegetation, and made it suitable for the growth of native plants such as sedges and *P. australis* due to the low salinity in the southern section. In the present study, there was a significant negative correlation between soil salinity and soil OC concentration in mathematical statistics (R^2 0.447, p 0.013). However, the data illustrated in Fig. 2c are consistent with the findings of Hu et al. (2014), who demonstrated that the higher the soil salinity, the higher the OC content would be. Xue (2017) showed that the positive correlation was limited within a specified salinity range. Wieski et al. (2010) revealed that the threshold value could be 15, which is much higher than the salinity in our study area.

3.1.4. Soil pH

Soil pH could influence the microorganisms in C fixation and accumulation (Funakawa et al., 2014). As illustrated in Fig. 2d, pH ranged 8.05 8.10, and decreased slightly with a decrease in elevation in the present study.

3.1.5. Soil bulk density

The variation range of soil bulk density is 1.29 1.36 g/cm^3 (Fig. 2e) in our small study area, which was significantly negatively correlated with OC content (p 0.01, R^2 0.439), and increased gradually seaward. Soil bulk density may influence permeability and mineralization rate substantially, and, in turn, affect soil OC accumulation rate. With an increase in elevation, the root system of halophytes became more developed and decreased soil bulk density.

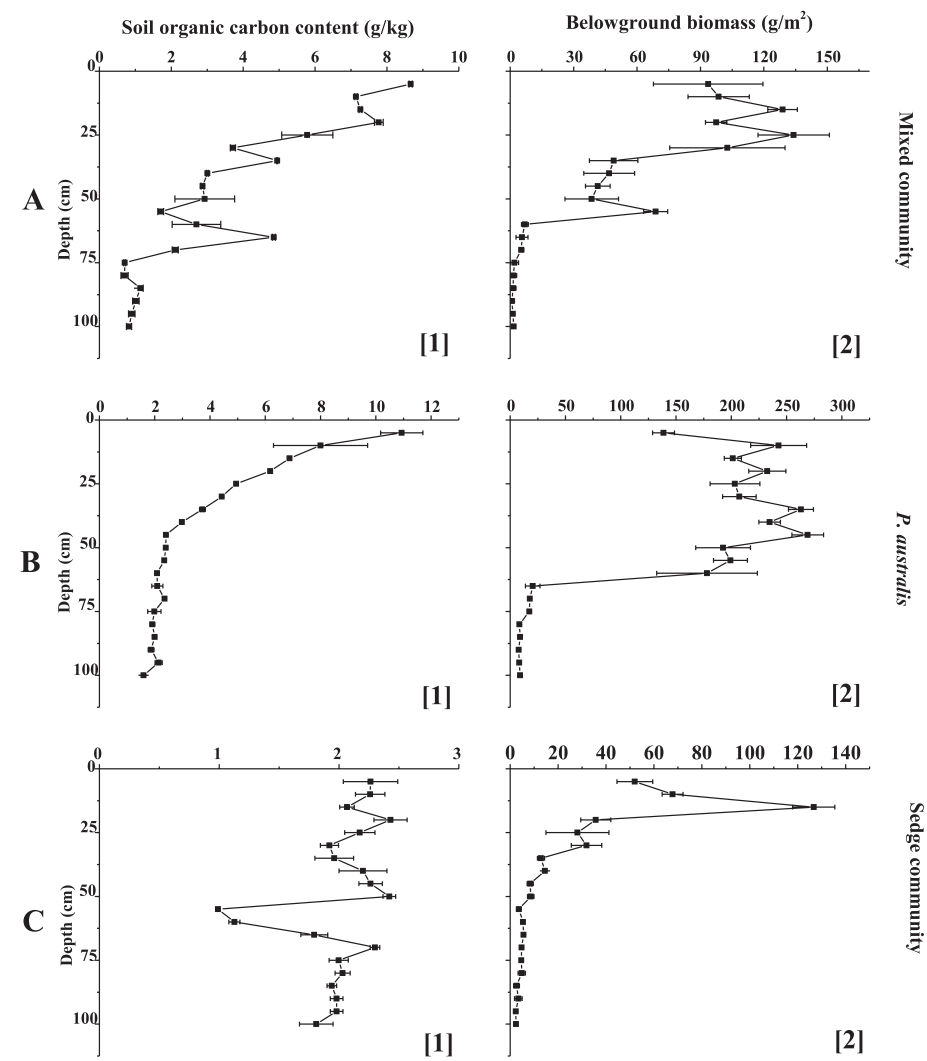

Fig. 3. Vertical distribution of organic carbon and underground biomass of: A, mixed communities; B, *P.australis*; C, Sedge community.

3.2. Vertical distribution of sediment organic carbon content and biomass in different halophytes communities

3.2.1. Vertical distribution of sediment organic carbon content

Dead plant residues and root exudates are deposited and buried in the soil, and they are the major sources of OC input in salt marsh ecosystems (Burd et al., 2016). Fig. 3 demonstrates the vertical distribution of sediment OC in different vegetation zones under current vegetation cover. As shown in Fig. 3A [1], sediment OC content in the mixed community changed within the 0.7 8.66 g/kg range, and the average was 3.54 g/kg. Sediment OC content in the *P. australis* communities was in the 1.59 10.93 g/kg range, with an average of 3.66 g/kg, which was slightly higher than the average in the mixed vegetation zone (Fig. 3B [1]). Sediment OC content in the sedge community was in the 0.99 2.43 g/kg range, with an average of 1.99 g/kg, which was significantly lower than the average in the other communities (p 0.05) (Fig. 3C [1]).

The sediment OC concentrations in the *P. australis* and mixed community generally decreased with an increase in depth, with the peak OC concentrations distributed in the surface sediment. In the mixed community, the OC content decreased significantly in the 0 30-cm layer and rebounded in the 60 65-cm layer. In the *P. australis* community, OC content decreased significantly in the 0 45-cm layer, and tended to be constant in the 45 100 cm layer. The area dominated by the sedge community exhibited irregular changes with depth; however, the fluctuation was not obvious when compared with the fluctuations observed in the other two communities.

3.2.2. Vertical distribution of belowground biomass

Sediment C content is the greatest in areas with dense halophyte roots (Fiala, 1976), indicating OC is positively correlated with belowground biomass. Root systems of the sedge community were concentrated in the 10 20-cm layer, and *P. australis* communities were tall and had developed underground creeping rhizomes, which could reach 30 40-cm depths. Shi et al. (2007) also reported that the soil OC concentrations in the Sanjiang plain, which was mainly concentrated in the dense root layer. The results of the present study showed that soil OC content and belowground biomass in the 5 60-cm depth with dense plant roots were both high.

3.3. Vertical variation of sediment C/N in different halophyte communities

As the third longest river globally, the Yangtze River imports a high amount of terrestrial substances into the East China Sea annually, and the influence of the OM in Yangtze Estuarine sediments on the biogeochemical characteristics cannot be ignored.

C/N in the sediments in the present study ranged from 3.1 to 12.6, as shown in Fig. 4, indicating that a large proportion of the sediment was marine. With an increase in soil depth, sediment C/N increased in the subsurface and then decreased slightly in the *P. australis* and mixed community. With an increase in sediment accumulation over time, plant roots and litter could have been buried in the shallow layer and broken down gradually. However, tides affect the upper sediment layer considerably. In addition, algae and plankton introduced by tides can be

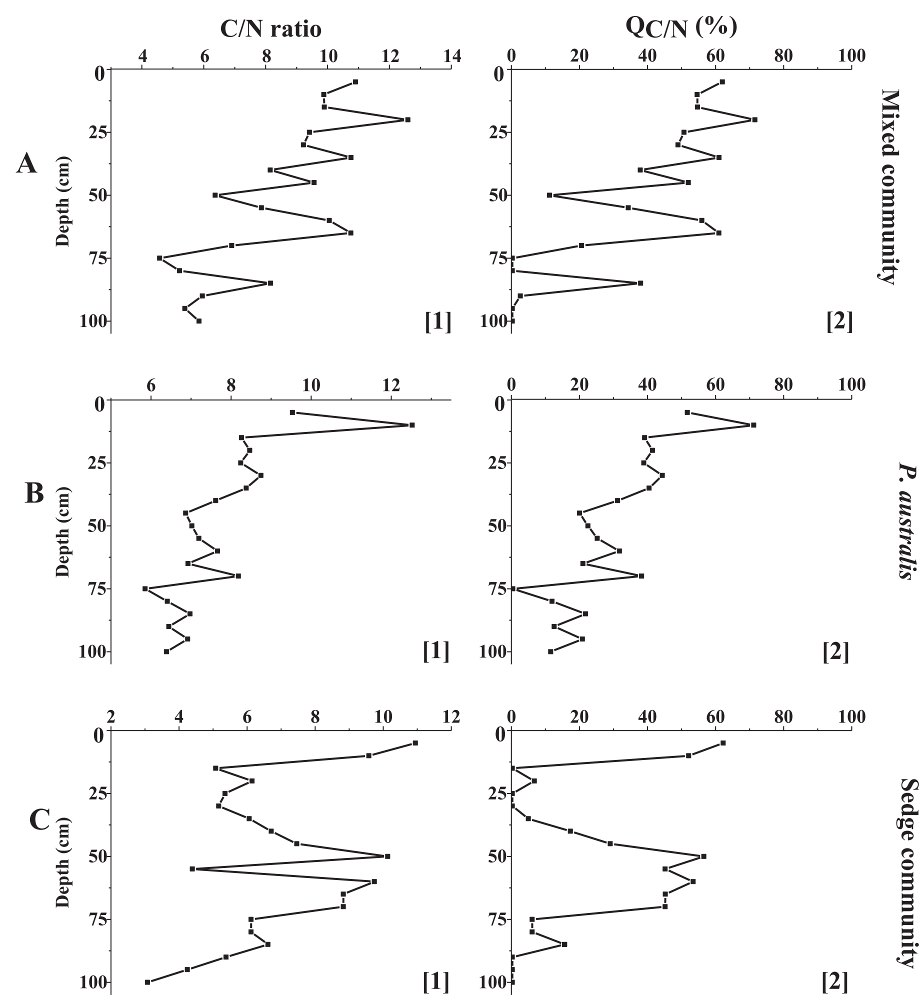

Fig. 4. Vertical distribution of sediment C/N and $Q_{C/N}$ of: A, mixed community; B, *P. australis*; C, Sedge community in the saltmarsh of Chongming Dongtan.

absorbed easily by the upper sediments; therefore, the proportions of terrestrial materials in the upper sediment would be relatively low. In mixed communities, C/N in the sediments varied from 4.5 to 12.6, with an average of 8.4 (Fig. 4A [1]). In the *P. australis* community, C/N ranged between 5.9 and 12.5, with an average of 7.7 (Fig. 4B [1]), while in the sedge community, C/N varied between 3.1 and 10.9, with an average of 6.8 (Fig. 4C [1]), potentially because the sedge community was located further offshore and got high OM input from algae in the water. According to Xue et al. (2011), the C/N is closely linked to the geographical locations of the sampling sites.

Fig. 4 illustrates the proportion of terrestrial OC ($Q_{C/N}$) in the total OC in the sediment samples at different depths. Based on Fig. 4A [2], in the mixed community, the average $Q_{C/N}$ in the column is 35.9%, and the proportion of marine OC is 64.1%, indicating higher proportions in marine spontaneous sources. The $Q_{C/N}$ exhibited a downward zigzag trend, and the maximum value was observed at 15 20 cm. In the *P. australis* community, the average $Q_{C/N}$ was 29.8% in the entire column, which was slightly lower than the $Q_{C/N}$ in the mixed community. The maximum value was observed in the 5 10-cm layer, and the trend was similar to the trend observed in the mixed community (Fig. 4B [2]). The vertical distributions of $Q_{C/N}$ and C/N were consistent. The $Q_{C/N}$ in the sedge community changed more obviously than the $Q_{C/N}$ in the other two communities, with no obvious trends (Fig. 4C [2]). The maximum $Q_{C/N}$ was 62.2%, which was significantly lower than the values in the other zones (p 0.05), and was observed in the surface layer, which was also different from the cases in the other two communities. $Q_{C/N}$ decreased and then increased to 45.2 56.6% at 45 70 cm, and diminished below 90 cm, where terrestrial OM barely exists.

Notably, the C/N and $Q_{C/N}$ trends in the sedge community were significantly different from the trends in the other two communities. The proportion of marine source OM was higher than the proportions in the other communities. Furthermore, washover sand bodies may bury halophytes after a typhoon. In the summer and autumn of 2012 and 2013, typhoons (1211 Haikui, 1216 Sanba, and 1323 Fitow) repeatedly affected the Yangtze estuary. As we excavated the covered sediment, residual stems of marsh plants (mainly *S. mariqueter*) were exposed, and Yang et al. (2019) measured the maximum deposition in the Yangtze Delta in the center of washover sand bodies, which reached 31 cm in the post-storm period, explaining significant increases in C/N and $Q_{C/N}$ increased at 30 cm.

C/N is used extensively as an indicator of decomposition capacity in plant tissues. The order of halophyte C/N has been reported to be *P. australis* *S. mariqueter* (Xue, 2017), which corresponds to the decomposition rates of their litter. The higher the C/N value, the greater the N demand, and the harder it is to decompose. Compared with recalcitrant C, labile C is exploited more easily by soil microorganisms and can combine with minerals in the soil more easily, in addition to exhibiting relatively high stability and low sensitivity to changes in environmental factors (Cotrufo et al., 2013; Mioko and Nishanth, 2014). Therefore, recalcitrant C may have relatively low stability and could be highly sensitive to changes in environmental factors. In other words, *P. australis* litter could be more susceptible to environmental changes following incorporation into the soil, which may impair associated long-term soil organic C sequestration.

3.4. Carbon storage of the sampling tidal basin

3.4.1. Organic carbon density

C density in the sediment was significantly higher than the density in the halophytes (Table 2). Due to the limited growth period of plants, and compared with the long-term and stable accumulation of OC in the soil, the vegetation only acted as a temporary pool for OC storage (Minden and Kleyer, 2011). As a key environmental factor, temperature influences soil microbial activity, soil respiration, and carbon dioxide emission during decomposition of stored OC (Kirwan et al., 2014). Since sampling was conducted in autumn in the present study, the soil mineralization rate declined with a decrease in temperature and an increase carbon accumulation.

Table 2
Organic carbon density at 100-cm depth of 'halophyte-soil system .

Halophyte Community	Aboveground (g/m^2)	Sediment (g/m^2)	Belowground (g/m^2)	Total (g/m^2)
P. australis community	663.3	4489.7	614.7	5767.7^{a}
Sedge communities	17.1	2445.8	90.5	2553.5^{b}
Mixed community	201.1	4335.4	388.2	4924.7^{a}

Note. Different lowercase letters indicate significant differences among treatments of the same group according to the Tukey test (p 0.05).

The concentrations of aboveground and belowground OC varied in different vegetation zones (Table 2). The aboveground OC of *P. australis* was almost equivalent to the belowground OC, while the aboveground OC density in the other two communities were significantly lower than the belowground concentrations. Neves et al. (2007) found that N, phosphorus, and other elements in plants accumulate upwards or transport downwards seasonally. In addition, Feng et al. (2015) observed similar migration trends for OC. After October, the aboveground OC shifted to the underground sections and accumulated. In autumn, when the ambient temperature decreases, the soil respiration rate decreases, which is more conducive for the accumulation of C and N (Pietikainen et al., 2005). Soil C in the sedge community, which is most affected by tidal action, mainly originates from sediment with the OM attached to the particles (Shi et al., 2003).

C storage in halophytes is considerable and should not be ignored in climate change mitigation efforts. Our study showed that differences in halophyte biomass community are the major factors influencing C density. The C densities in the *P. australis* and mixed community were significantly higher than the density in the sedge community (Table 2).

The quantities, compositions, and properties of plant are key factors influencing soil OM formation and humification in wetland ecosystems (Kogel-Knabner, 2002). Sedge communities are considered to contain no lignin or refractory compounds (Li et al., 2014). They are mainly composed of cellulose, which decomposed slowly under aerobic environments (Xue, 2017). In a *P. australis* community, lignin was resistant to microbial decomposition and was decomposed completely by white-rot fungi only under aerobic environments (Lorenz et al., 2007). In addition, in *P. australis* communities, soil dehydrogenase catalyzes the dehydrogenation of organic substances in soil and participates in the degradation of lignin, in combination with peroxidase and phenol oxidase, with impacts on the C pool (Kuppusamy et al., 2017; Liu et al., 2013). The decomposition and transformation of low-quality organic matter such as lignin and cellulose, which were repeatedly washed and submerged by tide, were potentially inhibited further in the salt marshes, and their OC accumulation and preservation activities were enhanced. With an increase in soil depth, influence from external factors decreases and C storage is influenced mainly by halophyte root growth and microbial activity (Davidson and Janssens, 2006). A large proportion of aboveground and underground biomass would be transferred to the soil, and, in turn, lead to increased soil C accumulation (Sistla et al., 2013).

3.4.2 carbon storage

The OC storage in the sedge community was the largest, followed by in the mixed community, while soil C storage in *P. australis* was the lowest, largely because the area under the *P. australis* community was the smallest (Table 3, Fig. 5). In general, endogenous input and "exogenous capture and their combined action in halophytes promoted the vertical silting and expansion of the salt marsh, which is very important for the carbon sink function of salt marsh ecosystems (Davy et al., 2011).

Table 3
Area and carbon storage under different vegetation communities.

Cover type	Area (m^2)	Proportion (%)	C (kg)	Proportion (%)
P. australis community	369,950	4.63	2,133,761	6.84
Sedge communities	3,593,325	44.94	9,175,555	29.43
Mixed community	4,032,700	50.43	19,859,919	63.70
Water			8009	0.03
Total	7,995,975		31,177,244	

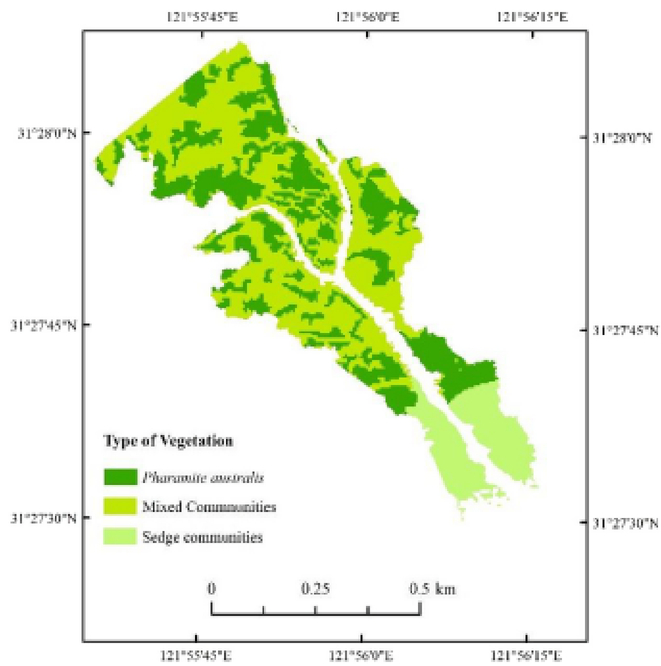

Fig. 5. Vegetation classification in the small tidal basin, East Chongming Island.

The spatial distribution of C storage in Chongming Dongtan was significantly heterogeneous. In our study area, the *P. australis* and mixed community were mainly distributed in the mid-high flat, and the sedge communities were mainly distributed in the mid-low flat (Fig. 5). Sedge communities can capture more carbonaceous sediment directly, including dissolved or particulate OM carried into marshes by surface runoff, groundwater inflow, and ocean tides (Bauer et al., 2013).

The contribution rate of sediment OC storage of vegetation in a sedge region was less than of the contribution of the exogenous sediment input (Wu et al., 2015), which demonstrated that the deposition of exogenous particulate matter and buried OC were the major sources of the C pool. In addition, local vegetation C fixation and input have important contributions to the C storage in sediment. Particularly in the sediment C cycle, the OC input of local vegetation represents the main proportion of degraded organic C, so that the C storage capacity can be maintained and preserved (Kristensen et al., 2008). C input in a sedge community is relatively lower than the C input in a *P. australis* community; in addition, soil microbial respiration in a sedge community is significantly higher than that in a *P. australis* community (Tang et al., 2011), leading to a significantly lower C density than that in the other communities (Table 2). In addition, tidal action greatly affects the marshes, and soil surface OC can be brought into the sea, with the tide decreasing retention capacity (Chen et al., 2007).

Plants and soil are two major carbon pools in salt marsh ecosystems (McLeod et al., 2011), and also the tidal water. Based on our field sampling and analyses, the average dissolved organic C and particulate organic C concentrations in the tidal basin were 3.55 mg/L and 5.48 mg/L, respectively. During a tidal process, the amount of C that the study tidal basin can hold was approximately 8.0 t (Yuan et al., unpublished). The result confirmed the conclusion that the sedimentary C sink is a major component of the ocean C sinks, and that it can be a long-term (millennial timescale) or even permanent C sink (Zhang et al., 2017).

Global climate change and strong influence from human activities will increase the frequency and intensity of storm surges, sea level rise, and saltwater intrusion, resulting in a rise in BASE water levels under tidal action and alterations to vegetation habitats (Cazenave and Le Cozannet, 2014). According to Mueller et al. (2016), under projected higher sea-level rise, a decline in soil OM decomposition rate would compensate for a decline in halophyte biomass accumulation rate. In addition, according to Roner et al. (2016), in low salt marsh areas, the degradation of OM is slow under anaerobic conditions, and most of the recalcitrant OM can be preserved to compensate for the lower primary productivity of halophytes.

3.5. Discussion

The biomass of halophytic plant communities at Chongming Dongtan wetland exhibited varying characteristics. On the regional scale, the aboveground biomass of the sedge community in the current study (43 g/m^2) was significantly lower than the biomass reported previously in the north of the Chongming Dongtan Wetland (67 ± 36.7–650 ± 360 g/m^2) (Zhang, 2016), which suggested the grazing affected vegetation productivity. Notably, belowground biomass in the sedge community was 426.05 g/m^2, which was comparable to figures reported in the adjacent coastal regions (63.4 ± 19.4 g/m^2–590 ± 180 g/m^2) (Zhang, 2016). In addition, such differences were closely correlated with sedimentation environment, hydrodynamics, grain size, vegetation production, and so on.

Compared with previous data from eight wetland sites distributed across Europe (308–4165 g/m^2) (Brix et al., 2001) and north Chongming Dongtan (905 ± 94.7–1720 ± 180 g/m^2) (Zhang, 2016), the aboveground biomass of *P. australis* was 1520 g/m^2, which was within the ranges reported. *P. australis* belowground biomass reported at Hangzhou Bay (less than 1000 g/m^2) (Shao et al., 2013) was significantly lower than our result (2659 g/m^2). Shao et al. (2013) demonstrated the productivity of a similar plant in different regions could vary significantly, which may be related to the different physiology and community composition, in addition to different latitudes and wetland soil environments. Meanwhile, our samples were collected from different locations and belowground biomass under the same vegetation type was estimated based on average data, which could also introduce some bias in the estimates.

The C stocks of *P. australis* in our study were comparable to those reported at Minjiang River Estuary, slightly less than those reported at Jiuduan shoal, and significantly lower than those reported at Yellow River Delta and Baiyangdian Wetland, which is directly related to soil salinity and canopy density (Table 4).

S. mariqueter grows mainly in low tidal flats and has a poor trophic basis. The current C storage in the sedge community is significantly lower than the C storage levels at Jiuduan shoal (Table 4). In addition to the tide and other hydrodynamic effects, the study area was affected considerably by anthropogenic activities and disturbance such as land reclamation and grazing, which limited the C fixation capacity of the sedge community.

The C stocks of the mixed community were in between the two mentioned above. Therefore, the protection of *P. australis* plant communities would facilitate the accumulation of more total OC per unit area when compare with the protection of *S. mariqueter*.

The total C storage was much lower than the storage in other parts of the globe (Table 4). The reasons could be due to the measurement methods adopted, vegetation composition, geographical age, and sampling time.

Table 4
Comparison of carbon stocks in the Yangtze Estuarine salt marsh, adjacent coastal areas, and other coastal regions globally.

Study Site	Vegetation	Core depth (cm)	Plant C stocks (g/m^2)	Total C stocks (g/m^2)	Reference
Southeast Chongming Dongtan Wetland	*P. australis*	100	1278	5767.7	This study
	Sedge community		107.6	2553.5	
	Mixed community		589.3	4924.7	
Global	Subtropical tidal marsh			59,300	Alongi (2014)
Chongming Dongtan Wetland	*P. australis*		4020 1210		Mei and Zhang (2007)
	S. mariqueter		510 150		
Jiuduansha Shoal, the Yangtze Estuary	*P.australis*	30	1757 2443	3212	Liu (2013)
	S. mariqueter		155.6 441.6	636	
The Yellow River Delta	*P. australis*		1950 2720		Zhang et al. (2012)
Baiyangdian Wetland	*P. australis*		2520 3440		Li et al. (2009)
Minjiang River Estuary	*P. australis*	60	744 1497	9337	Huang (2008)
Little Assawoman Bay Marshes	*Juncus roemerianus*	30	3047	11,984	Elsey-Quirk et al. (2011b)
	Spartina alterniflora		4944	15,635	
	Spartina patens		5619	16,645	
Vasa Sacos Salt Marshes	*Spartina maritima*, *Halimione portulacoides* and *Arthrocnemum perenne*	40	837 1761	5971 7482	Cartaxana and Catarino (1997)
Tampa Bay Marshes	*Spartina alterniflora*, *Juncus roemerianus* and *Sporobolus virginicus*, *Sesuvium portulacastrum*, and *Fimbristylis castanea* (small contributor)	50		6640 2500	Radabaugh et al. (2018)
East coast of Florida Marshes	*Spartina alterniflora*, *Distichlis spicata*, *Salicornia bigelovii*, and other halophytes	50		12,300 503	Simpson et al. (2017)
Coastal Wetlands, in the Yucatan Peninsula, Mexico	*Typha domingensis*, *Cladium jamaicense*, *Eleocharis cellulosa*, and *Eleocharis interstincta*	100		17,700 7300	Adame et al. (2013)
Near-shore and coastal ecosystems within the United Arab Emirates	*Arthrocnemum macrostachyum* dominated	200		3140 20,500	Schile et al. (2017)

Most of the C fixed in belowground C pools originates from *in-situ* plant production (Valiela et al., 1976). *Spartina alterniflora*, *Spartina patens*, and other poaceae plants have highly similar niches and morphological characteristics (Chen et al., 2004), with much higher biomass and carbon sequestration capacity than *S. mariqueter*, resulting in the higher C stocks.

The surface C density (3541.46 g/m^2) observed was equivalent to that of Liu (2013) in Jiuduan shoal, but much lower than that of Elsey-Quirk et al. (2011b). Elsey-Quirk et al. (2011b) considered that small roots and large organic debris are important contributors to soil C pools, and, therefore, calculated their C stocks separately. However, here, we did not consider fine roots, which can be one of the reasons for the lower C pools than those observed in Elsey-Quirk et al. (2011b).

Our study area was conducted in a relatively young marsh. Young marshes require several decades to increase organic C stock levels to the levels in relatively older marshes (Lunstrum and Chen, 2014).

4. Conclusions

Land-ocean interactions, such as strong tidal dynamics, frequent sediment transport, and material exchange, which may significantly impact C stocks in the salt marshes, affect the tidal flats along the Yangtze River Estuary. Because of the strong tidal dynamics, sediment particle sizes tend to decrease from the bare flat to the high elevation through interaction of flow and vegetation.

The Yangtze River Estuary is still experiencing high rates of sediment deposition. The C/N of OM in the sediments, which originate from the high deposition, range from 3.1 to 12.6, indicating the sediment OM has a predominant marine source, with minor contributions from marsh vegetation within the three vegetation zones.

The contribution of vegetation to the sediment OC concentration seemed to vary, with 1.59 10.93 g/kg in the *P. australis* community, 0.7 8.66 g/kg in the mixed community, and 0.99 2.43 g/kg in sedge community. In addition, all contributions decreased with an increase in depth in the vertical direction. However, in the horizontal direction, soil OC decreased with a decrease in elevation.

Soil OM in coastal wetlands is mainly derived from halophytic plant biomass (Valiela et al., 1976). Therefore, the gross biomass and C density in the *P. australis* (57.7 t/ha) community was significantly higher than that in the sedge (25.5 t/ha) and mixed community (49.2 t/ha). The total C stock in the tidal basin was 31, 177, 234.5 kg, with 8000 kg in the tidal water and 31,169,233 kg in the vegetation zone. In general, the C stock of the young salt marsh at the Yangtze Estuary is relatively less than the stocks in marshes that have been established for years, indicating that it has a potential to sequester great C amounts in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Yiquan Yuan: Conceptualization, Formal analysis, Writing - original draft. **Xiuzhen Li:** Resources, Supervision, Writing - review & editing. **Junyan Jiang:** Investigation. **Liming Xue:** Visualization. **Christopher B. Craft:** Writing - review & editing.

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Appendix A. Supplementary data

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