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Do short-term increases in river and sediment discharge determine the dynamics of coastal mudflat and vegetation in the Yangtze Estuary?

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ABSTRACT

Sediment loads by large rivers play a crucial role in determining the fate of estuarine and coastal ecosystems. From 2013 to 2017, this study investigated the dynamics of mudflats and marsh pioneering vegetation (*Scirpus* species) in the coastal wetland at downstream end of the Yangtze Estuary. The results showed that, even with the historically lowest scale of upstream sediment load, the mudflat accretion (increase in elevation) and vegetation expansion in the marsh frontier still occurred. In the different monitoring sites, the net increases in the mudflat elevation were 24.34–57.51 cm, and the area of the pioneering vegetation increased by 2.18–4.74 times over 5 years. During the 2016–2017 period, with higher water discharges, the rates of mudflat accretion and vegetation colonization were much higher than those in former years. It was declared that a single-year high water discharge could trigger an intensive increase in sediment transport to the coastal region. Relative to water discharge, the year-to-year sediment load recorded upstream (Datong hydrographical gauging station) might not be a suitable indicator to interpret the mudflat and vegetation dynamics in the Yangtze Delta due to the high uncertainty of sediment loading processes along the transportation path. The recent monitoring indicated that positive interaction between vegetation establishment and sedimentary processes probably contribute to a continuous mudflat accretion and vegetation expansion in the mudflat frontier. We also suggest that a short-term substantial impulse in river and sediment discharge highly stimulated the accretion of coastal mudflat and the consequent expansion of marsh vegetation in the Yangtze Estuary.

1. Introduction

Coastal salt marshes colonized by halophytic macrophytes are among the most productive ecosystems in the world (Chmura et al., 2003; Duarte et al., 2005), serving in numerous ecosystem roles such as coastal protection, carbon sequestration, nutrient storage, supporting wildlife habitats, etc. (Turner, 1991; Costanza et al., 1997). However, salt marshes are vulnerable to natural and anthropogenic interference, for instance, rigorous hydrological conditions, sediment availability, marine pollution, and wetland reclamation and expected sea level rise (Kirwan and Megonigal, 2013; Ferronato et al., 2018). Along the coastal mudflat, salt marshes frequently expand and retreat in response to external forcing such as wind waves, tidal flush and sediment input (Marani et al., 2011; Fagherazzi et al., 2012; Ganju et al., 2017).

The establishment of a vegetated marsh is one of the most important indicators of mudflat development and successful functioning of coastal wetlands since it affects many biogeophysical processes in the ecosystems (Thompson, 1991; Chmura et al., 2003; Duarte et al., 2005). Once the vegetation settles on the tidal flat, the community shows an expansion phase or a retreat phase based on the accretion/erosion of mudflats and the resilience of marsh species to geomorphologic change (Silvestri et al., 2005; van der Wal et al., 2008; Mariotti and Fagherazzi, 2010; Wang and Temmerman, 2013; Bouma et al., 2016). Therefore, sediment availability is one of the most important factors for vegetation establishment and marsh stability on the tidal flat (Ganju et al., 2017; Donatelli et al., 2018).

Many studies have shown a potential relationship between sediment load with upstream river runoff and growth of coastal wetlands in the estuary (Sanchez-Arcilla et al., 1998; Stanley and Warne, 1998; Temmerman et al., 2003; Day et al., 2007; Syvitski et al., 2009; Yu

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et al., 2011). Day et al. (2007) and Blum and Roberts (2009) showed that 25% of the coastal wetlands degraded in the Mississippi Delta and that the sediment load of the Mississippi River simultaneously declined by 50% due to dam construction in the basin. Yu et al. (2011) found that the shoreline retreat of the Yellow River Delta was directly determined by the rapid reduction of sediment load with runoff during the last decades. On the contrary, Ma et al. (2014) reported that the three largest salt marshes in the Oosterschelde estuary still can vertically accrete, even under conditions of low suspended sediment concentrations (52–70% reduction due to barrier dam construction). Huang (2011) argued that there was a time lag between the disruption of the sediment supply by dam and coastal erosion. On the other hand, the functions of marsh macrophytes on the capture of inorganic and organic particles and wave attenuation were shown to benefit the growth of the plants and accretion of the salt marsh, showing a typical self-adaptation to sediment reduction (Fagherazzi et al., 2012; Ge et al., 2016).

The Yangtze River (also Changjiang River) is the largest river in China. Historically, the Yangtze River delivered a large amount of sediment to the estuary area, supporting the accretion of coastal wetland and the consequent expansion of marsh vegetation (Yang et al., 2003; Ge et al., 2015a). Since the 1950s, more than 50,000 dams (especially including the Three Gorges Dam, TGD) have been built throughout the Yangtze's watershed, leading to a dramatic decrease in sediment load and sedimentation rate in the Yangtze Estuary (Hu et al., 2009; Yang et al., 2011; Dai et al., 2016). Subsequently, many reports predicted a recession of coastal wetlands and river delta in the estuary (Yang et al., 2003, 2005, 2011). However, until now, not enough information is known on the linkage between upstream sediment transport and the response of coastal salt marshes in the Yangtze Estuary. Previous studies have employed a relatively wide phase span (generally 5–10 years on average) to present the historical changes in the sediment load (Yang et al., 2005, 2011; Dai et al., 2014, 2016), while the response of coastal wetlands and marsh vegetation dynamics might be sensitive to the year-to-year variations of the river runoff with sediment discharge.

In this study, a recent 5-year (2013–2017) examination of the dynamics of pioneering vegetation (*Scirpus* spp.) and mudflat accretion of a salt marsh was investigated in the largest coastal wetland (Chongming Dongtan wetland) in the Yangtze Estuary, which experiences rapid reduced suspended sediment inputs. The main aim of this study is to explore whether the establishment and expansion of marsh vegetation are affected by the variations of upstream river runoff and sediment discharge on a year-to-year timescale.

2. Materials and methods

2.1. Study area

The study area was located in the Chongming Dongtan wetland (31°25′–31°38′N, 121°50′–122°05′E), which is also a national nature reserve for international migratory birds in the Yangtze Estuary (Fig. 1). The Chongming Dongtan wetland is located on the eastern fringe of Chongming Island. An eastern Asian monsoon climate is present, with an average temperature of 15.5 °C and annual precipitation of 1022 mm yr^{-1}. In the estuary, mean current velocity is less than 1.0 $m\,s^{-1}$ without regard for extreme weather. The tidal movement in the Chongming Dongtan wetland is semidiurnal and mixed tides, with maximum and average tide heights of 4.62–5.95 m and 1.96–3.08 m, respectively (Ge et al., 2008). On tidal mudflats, the maximum current velocity is less than 0.5 $m\,s^{-1}$ in marshes and 1.0 $m\,s^{-1}$ in lower flats without regard for extreme weather (Yang et al., 2003, 2005).

Generally, in the Chongming Dongtan wetland, low-lying tidal flats are grown by the pioneering marsh species of *Scirpus* spp. (mainly including *Scirpus mariqueter*, *Scirpus triqueter* and *Scirpus planiculmis*), and the high land are characterized by *Phragmites australis* and *Spartina alterniflora* (Ge et al., 2015a). From 2013 to 2015, almost all of the invasive species of *S. alterniflora* had been eradicated based on a large restoration engineering project launched by the managers of the nature reserve (Hu et al., 2015). The frontier tidal flat is at present dominated by the native *Scirpus* spp.

For this study, two frontier monitoring sites (area of 2 km × 1 km) located at the eastern (E-site, 31°30′10″N, 121°59′18″E) and southern (S-site, 31°27′25″N, 121°55′42″E) parts of the Chongming Dongtan were selected to trace the year-to-year dynamics of pioneering *Scirpus* spp. (Fig. 1).

2.2. Vegetation dynamics based on remote sensing data and field survey

A set of multitemporal remote sensing images during 2013–2017 were used (Table 1) to interpret the dynamics of vegetation at the mudflat frontier. The multispectral satellite data were geometrically corrected by a series of nautical charts using ENVI 5.1 Imagine software (Harris Geospatial Solutions, Inc., USA) for generating suitable image bands based on spectral transformation. Quadratic polynomials were applied to correct equations according to the random 40–50 control points selected automatically by ENVI software, and the error was less than 0.5 pixels.

All of the panchromatic and multispectral images (except CBERS-2) were fused using Pan-sharpening fusion method. The spectral enhancement methods of the tasseled cap transform (IKONOS images), false color composition (Landsat-8 images), and Normal Difference Vegetation Index (all images) were used to initialize the data for efficient interpretation. As a result, the habitat and vegetation classes of water, muddy flats, seawalls, and pioneering *Scirpus* spp. were identified and selected as training samples. Additionally, a supervised classification was carried out based on the Support Vector Machine in ENVI Imagine.

In order to validate the results of habitat and vegetation classification, the Yuma 2 Rugged Tablet Computer with GIS applications (Trimble Inc. USA) was used to provide accurate land type information as well as validation of training samples. Based on an in situ field survey, some misclassifications of unvegetated and vegetated habitats were corrected, and the overall accuracy for the revised classification reached roughly 85% during the investigation period.

2.3. Sedimentary dynamics and shoreline interpretation

From 2013 to 2016, the sedimentary dynamics in the mudflat of the two observation sites were monitored monthly or seasonally. Following O'Brien et al. (2000), at each site the wooden poles (1.3–1.5 m) were inserted into the soil at > 5 m intervals, leaving approximately 40–50 cm of each pole exposed at the top above the soil surface. The initially exposed poles were considered a reference (zero point), and the accretion or erosion rates were determined as the relative positive or negative change from the initial length. 6 poles were used at both E-site and S-site during 2013, 32 poles at the E-site and 12 poles at the S-site during 2014, 12 poles at both E-site and S-site during 2015, and 6 poles at both E-site and S-site during 2016. The set-up location of poles was renewed every year. Based on the measurement of pole length, we calculated the continuous changes in relative elevation change that means the measurements relative to measurements made during the previous sampling period. In order to avoid the potential effects of seawall on sediment transport and wave reflection, we set up the monitoring poles at the distance around 500 m from the seawall at the E-site.

Over the investigation period, the absolute flat elevation was further calculated as the accumulation of relative elevation. Additionally, in early 2013 (January) and 2018 (January and May), the absolute flat elevation of the observation sites was determined using a Real Time Kinematic Global Position System (RTK-GP, Ashtech Corp., USA) based on the local Wusong bathymetric benchmark.

Besides the site-scale sedimentary dynamics, shoreline (waterline) change is on regional scale one of the important indicators for

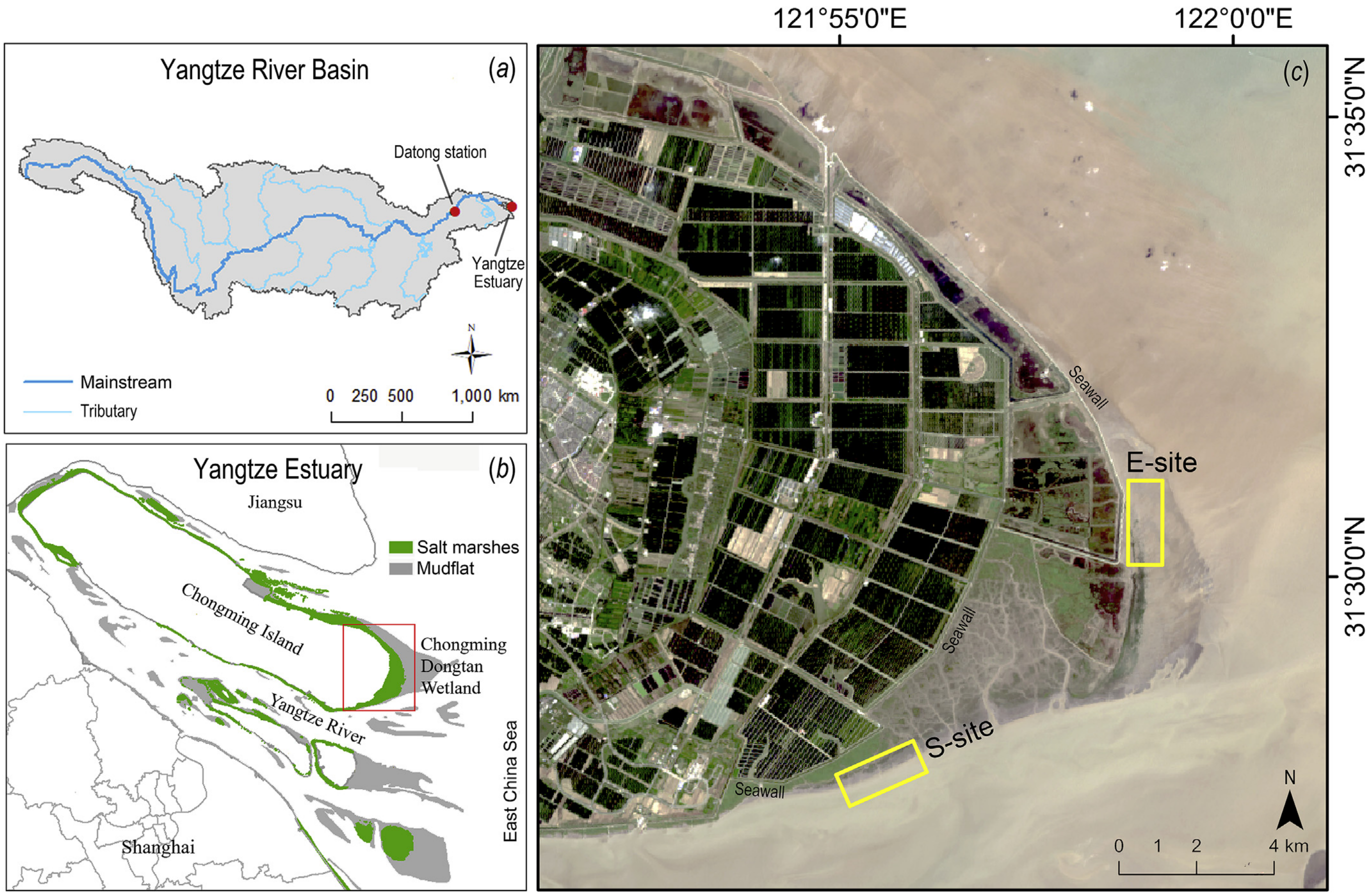

Fig. 1. Location of the Datong hydrographical gauging station in the Yangtze River Basin (*a*), Chongming Dongtan wetland (*b*), and the monitoring sites (*c*, site E and site S) for pioneering marsh vegetation.

Table 1
Remote sensing data used to trace the year-to-year vegetation dynamics.

Data source	Image Data	Spatial Resolution
IKONOS	2013.05.25	4 m (multispectral)
		1 m (panchromatic)
Landsat-8	2013.08.29	30 m (multispectral)
		15 m (panchromatic)
CBERS-2	2014.07.31	3 m (panchromatic)
Landsat-8	2014.07.31	30 m (multispectral)
		15 m (panchromatic)
SPOT-7	2015.04.25	6 m (multispectral)
		1.5 m (panchromatic)
Landsat-8	2015.08.03	30 m (multispectral)
		15 m (panchromatic)
Landsat-8	2016.09.22	30 m (multispectral)
		15 m (panchromatic)
Pleiades	2017.07.24	2 m (multispectral)
		0.5 m (panchromatic)
Landsat-8	2017.08.24	30 m (multispectral)
		15 m (panchromatic)

understanding the evolution of coastal wetland and topographical changes. Following Zhao et al. (2008), the annual variation (2013–2017) of shorelines in the Chongming Dongtan wetland are extracted from the Landsat-8 images either by identifying grayscale thresholding waterlines or using computer algorithms of digital elevation model. The remote sensing images with producing time at similar stages of the tide were used for interpretation of shoreline positions.

2.4. *Runoff and sediment load of the Yangtze River*

Upstream runoff and suspended sediment data since the 1950s had been collected at the hydrographical gauging station at Datong (30°84′60″N, 117°83′70″E) by the Changjiang Water Resource Committee (CWRC, http://www.cjw.gov.cn/zwzc/bmgb, dataset in the annual 'Changjiang Sediemnt Bulletin' from 2013 to 2017), Ministry of Water Conservancy of China. The Datong gauging station located at the tidal limit of the Yangtze Estuary at a distance of approximately 640 km from the estuary. It is a Grade-A gauging station locating downstream of about 95% of the Yangtze River catchment area (Yang et al., 2005, 2011; Dai et al., 2014, 2016). The monitoring of the river flow and suspended sediment concentration at the surface, the 20%, 40%, 60% 80% depths and near the bottom, strictly follows the national stands (Protocol for River Suspended Sediment Measurements-GB 50159–92). The CWRC demonstrated in the released documents that the discharge of suspended sediment is used to represent the total sediment load because the Yangtze River bed load is less than 1% of the suspended load (Yang et al., 2003). Therefore, the daily data collected at the Datong gauging station can reflect the total discharges of water and sediment input to the estuary (Yang et al., 2005, 2011; Dai et al., 2014, 2016). For this study, we first find the historical changes in the discharges. Specifically, we gathered monthly and annual runoff and suspended sediment discharges from 2013 to 2017 at the Datong gauging stations.

2.5. *Data analysis*

The classified images were integrated into a GIS 10.0 platform (ESRI Inc., USA) to calculate the changes in the vegetation area. The

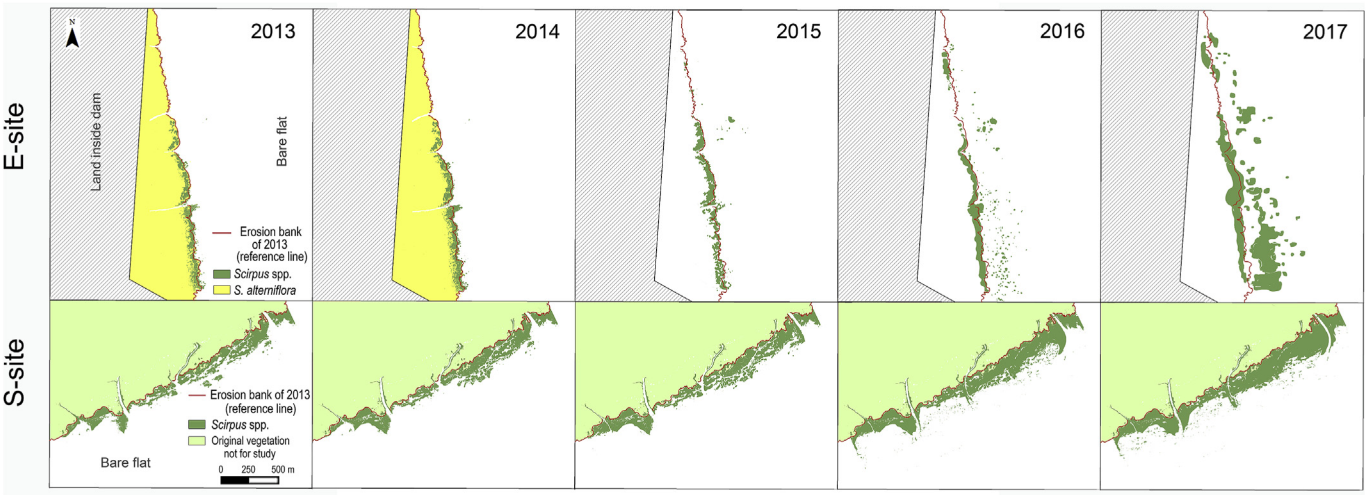

Fig. 2. Changes in pioneering *Scirpus* in the frontier marsh of the E-Site (upper panel) and S-site (bottom panel) during the 2013–2017 period. Note: The *Spartina* plants in the E-site were eliminated in 2015.

relationship between the upstream river and sediment discharge and the elevation change of mudflat and vegetation dynamics was analyzed based on a linear regression model using the SPSS 23.0 statistical software package (SPSS Inc., Chicago, IL, USA). The level of statistical significance was set to P (probability) < 0.05.

3. Results

3.1. Changes in pioneering marsh vegetation

To detect the changes in the area of the pioneering *Scirpus*, we identified the erosion bank at the marsh frontier at the E-site and S-site as references (Fig. 2). In the initial survey year of 2013, the area of the pioneering *Scirpus* was 35,830 m^2 at the E-site and 98,121 m^2 at the S-site. In 2014, 2015, the area of the pioneering *Scirpus* increased by 18.73% and 29.71% at the E-site and 11.85% and 24.73% at the S-site, respectively, compared to the area in 2013 (Table 2). Relative to the slow expansion rate during 2014–2015, the area of the pioneering *Scirpus* has increased rapidly at both study sites since 2016 (Fig. 2). Up to 2017, the seaward width of the pioneering *Scirpus* increased by ~500 m and ~250 m at the E-site and S-site, respectively, compared to the width in 2013. The area of the pioneering *Scirpus* in 2017 was 4.74 times higher at the E-site and 2.18 times higher at the S-site than in 2013 (Table 2).

3.2. Sedimentary dynamics in mudflat elevation

Based on the changes in the relative elevation of mudflats, the mudflat generally showed gradual accretion from April to August (which includes the flooding seasons of the Yangtze River) at both sites (Fig. 3). Over the period of 2013–2016 (no seasonal data for the S-site at 2014), the mean monthly accretion rate at the E-site (3.17 cm) was higher than that at the S-site (1.08 cm) from April to August. From October to next March (including dry seasons of Yangtze River), the mudflat generally showed a stable state or weak erosion (negative change) at both sites (Fig. 3). Over 2013–2016, the mean monthly elevation change was −0.49 cm and 0.42 cm at the E-site and S-site, respectively, from October to the following March.

The absolute elevation showed a continuous increase in mudflat elevation in both sites from January 2013 to May 2018 (Fig. 3). The net increases in the mudflat elevation were 57.51 cm and 24.34 cm at the E-site and S-site, respectively, over 2013–2018. The mean annual increment rate of absolute elevation at the E-site (9.63 cm) was higher than that at the S-site (3.82 cm).

Fig. 4 shows the shoreline (contour line) dynamics, revealing an accretion status in most parts of the Chongming Dongtan wetland from 2013 to 2017 at similar low and high tidal level. An apparent phenomenon showed that the erosion bank identified in the marsh frontier were obviously deep (~20 cm) before 2015 (Fig. 5, S-site), while the erosion bank was filled up quickly since 2016 and almost disappeared in 2017 due to the substantial sediment accumulation.

Table 2
Changes in the area of the pioneering *Scirpus* spp. at the marsh frontier in the E-site and S-site during the 2013–2017 period.

Sites	Items	2013	2014	2015	2016	2017
E-site	Area (m^2)	35,830	42,543	46,474	80,827	169,850
	Annual increment (m^2)	/	6713	3931	34,353	89,023
	Relative change (%)	/	+18.73	+29.71	+125.58	+374.04
S-site	Area (m^2)	98,121	109,749	122,385	169,973	213,748
	Annual increment (m^2)	/	11,628	13,971	25,021	174,904
	Relative change (%)	/	+11.85	+24.73	+73.23	+117.84

3.3. Interannual river discharge and sediment load

As recorded at the Datong station for the Yangtze River downstream, although the river water discharge remained relatively constant over the long term of 1954–2017, the interannual variations of water discharge was apparent, including extremely wet or dry years (Fig. 6a). However, the total sediment discharge past the Datong station had been decreasing from $\sim 4.83 \times 10^8$ ton year^{-1} in the 1950s and 1960s to $\sim 1.19 \times 10^8$ ton year^{-1} in the 2010s. Especially since the complete construction of TGD in 2003, the suspended sediment discharge from the river has been reducing sharply (Fig. 6a).

Focusing on our current short-term period of 2013–2017, the water discharge from April–September contributed significantly relative to the other seasons. The annual river runoffs were highest during 2016–2017 regarding both annual and seasonal amounts (Fig. 6b and c), with a peak of water and sediment discharge in 2016. Over the past 30 years (1987–2017), the water discharge recorded in 2016 in the Datong station was the second highest and the runoff volume in following 2017 was also higher than the historical average value.

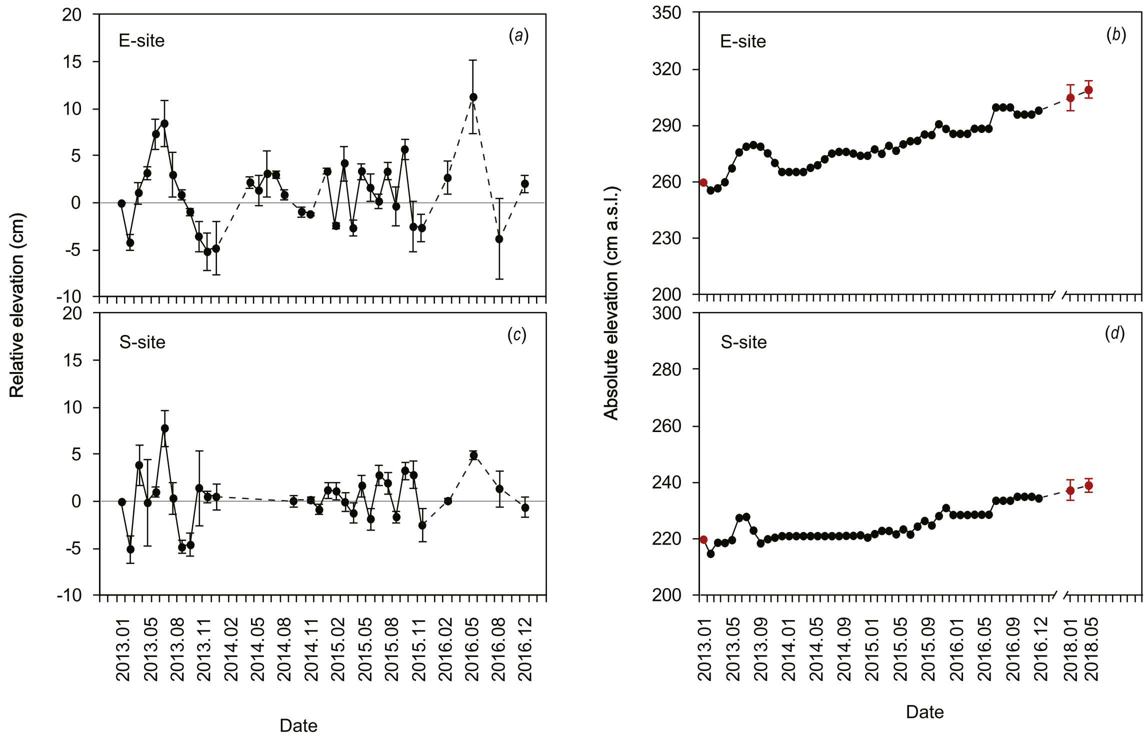

Fig. 3. Accretion/erosion dynamics in the E-Site and S-site in terms of the relative elevation change (measurements relative to previous-period ones) (*a, c*) during the 2013–2016 period and absolute elevation change (*b, d*) (local Wusong bathymetric benchmark) during the 2013–2018 period. Dashed lines mean short-term interruption of monitoring (seasonal monitoring interrupted in the S-site during January–August in 2014, thereafter it restarted). Red symbols show the measurement of flat elevation using the RTK-GP systems). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3.4. Mudflat growth and vegetation expansion in relation to sedimentary dynamics

During the study period of 2013–2017, the mudflat elevation enhanced in both study sites in the Chongming Dongtan wetland, with an increase in annual water discharge upstream measured at the Datong station, showed a strong positive relationship (Table 3). The correlation coefficient at the E-site (0.70) was higher than that at the S-site (0.38). However, the functions of annual sediment load recorded at the Datong station to the mudflat accretion were weak in the two sites (Table 3). At both sites of the intertidal salt marsh, the yearly increment rate of pioneering *Scirpus* increased with rising mudflat elevation, showing a significant positive relation (Table 3).

4. Discussion

Development of salt marsh and colonization of pioneering vegetation are determined by the hydrological features, mainly including sediment deposition and mudflat accretion, inundation duration, tidal flow and wave motion (van der Wal et al., 2008; Balke et al., 2011; Bouma et al., 2009; Davy et al., 2011). The upstream sediment source is absolutely crucial for coastal wetlands and marsh vegetation to grow in the Yangtze Estuary (Yang et al., 2005; Ge et al., 2016). The coastal wetlands in the estuary have grown at a rate of ~5 km^2 $year^{-1}$, and the

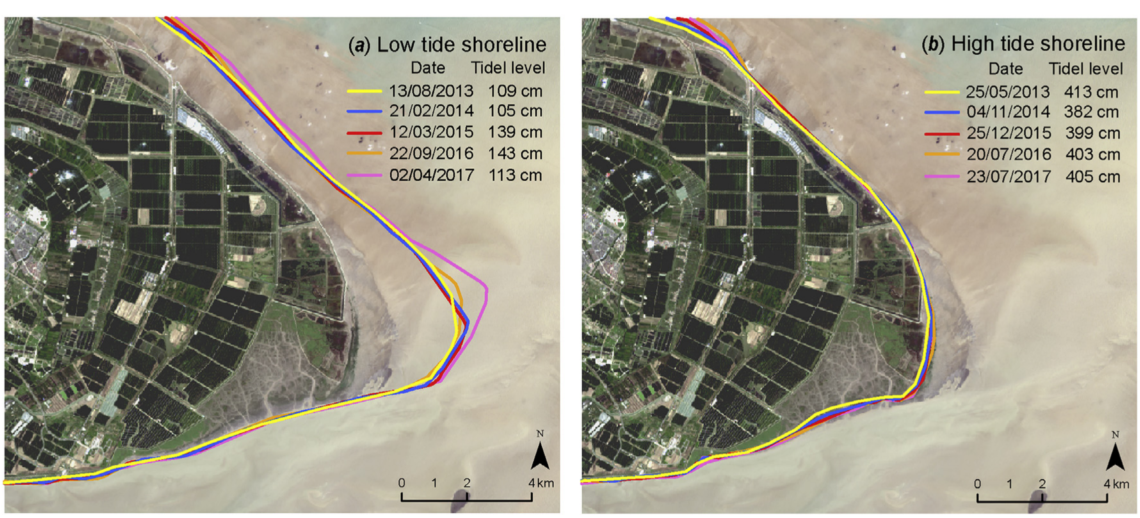

Fig. 4. Shoreline dynamics in the Chongming Dongtan wetland at low (*a*) and high tidal levels (*b*) during the 2013–2017 period. The tidal level is adopted as the local Wusong tidal datum.

Fig. 5. The eroded bank in the S-site gradually disappeared from 2014 to 2017 (Photos by Ge Z.M. Additionally, Hu M.Y.).

delta coastline has prograded at a rate of 10–20 m year^{-1} over the past few centuries (Yang et al., 2003). However, since the 1950s, a huge number of seawalls were constructed along the Yangtze River basin, resulting in an extreme decline of sediment loads by approximately 70% to the downstream delta, mainly due to reduced suspended sediment concentration (Hu et al., 2009; Yang et al., 2011; Dai et al., 2014). Decreases in suspended sediment discharge to the ocean adjusting to the Yangtze Estuary can also be attributed to soil/water conservation and other sediment erosion control programs (Dai et al., 2016). Coastal wetlands at the delta front were sensitive to changes in sediment supply with river runoff. Due to the long-term decline of sediment discharge, the total growth rate of coastal wetlands in the Yangtze Delta front decreased (Yang et al., 2005). In the past decade, the current sedimentation rate in the intertidal wetlands may not have supported the expansion rate of marsh vegetation that occurred before the 2000s (Ge

Table 3
Linear regression ($y = ax + b$) of yearly upstream water discharge (x_1) and yearly changes in the mudflat elevation (y_1) in the study area, yearly upstream sediment load (x_2) and yearly changes in mudflat elevation (y_2) in the study area, and cumulative increases in mudflat elevation (x_3) and yearly increment rate of pioneering *Scirpus* (y_3) in the study sites, during the 2013–2017 period.

Site	Item for function	*a* (slope)	*b* (intercept)	R^2	*P*
E-Site	x_1 *vs.* y_1	0.285	−16.437	0.704	$< 0.01^{**}$
	x_2 *vs.* y_2	3.687	5.135	0.0445	$> 0.05^{ns}$
	x_3 *vs.* y_3	0.0269	−0.250	0.903	$< 0.01^{**}$
S-Site	x_1 *vs.* y_1	0.215	−15.885	0.375	$< 0.01^{**}$
	x_2 *vs.* y_2	2.349	0.963	0.0169	$> 0.05^{ns}$
	x_3 *vs.* y_3	0.0150	0.0534	0.598	$< 0.01^{**}$

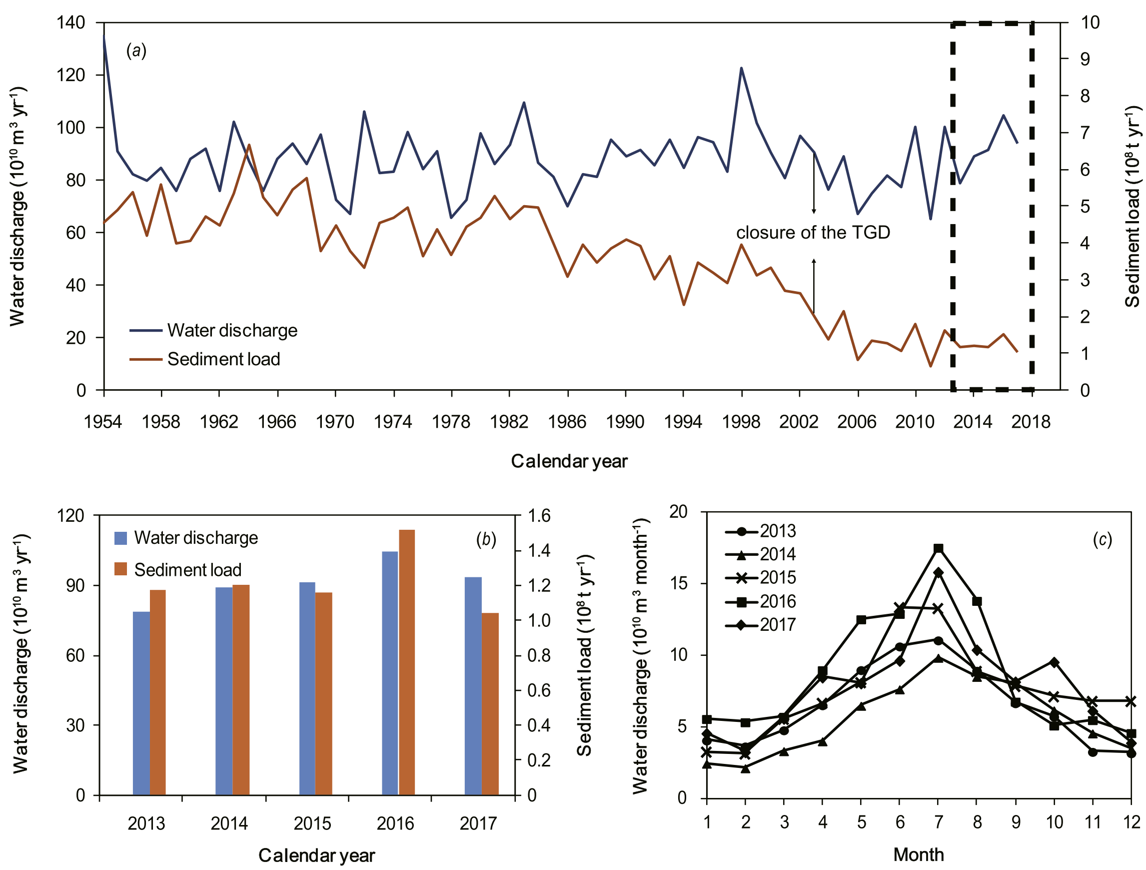

Fig. 6. Annual water discharge and sediment load recorded at the Datong station during the 1954–2017 period (*a*, dashed box indicates the study period in the Yangtze Estuary), annual water discharge and sediment load recorded in the Datong station during from 2013 to 2017 (*b*), and monthly water discharge recorded in the Datong station from 2013 to 2017 (*c*). Note: The tendency of seasonal variations of sediment load are similar to those of the water discharge and thus not shown here.

et al., 2015b) because the rapid expansion of pioneering vegetation depends on the increment in available niches. As predicted by Yang et al. (2005, 2011), sediment discharge to the estuary will decrease more, and the intertidal wetlands in the Yangtze Estuary will degrade. As in the case of the S-site, the erosion of the mudflat was serious for a long time (before 2014) due to inadequate sediment accumulation (as the eroded bank shown in Fig. 5). The eroded bank generally increase the wave height and reflection of waves, which makes the frontier unsuitable for vegetation survival (Möller and Spencer, 2002).

Many studies have highlighted that sediment supply reduction may be exacerbated by increasing the number of built dams within river catchments, resulting in a high risk for coastal wetland loss (Yang et al., 2005; Ganju et al., 2017). Although the sediment input into the Yangtze Estuary area has decreased to its historically lowest level in the past decades, the trend of mudflat accretion (increase in elevation) and vegetation expansion in the marsh frontier can be detected in the Chongming Dongtan wetland. Over the 5-year survey period of 2013–2017 (survey on sedimentary dynamics extended to 2018), the net increases in the mudflat elevation were 57.51 cm and 24.34 cm in the E-site and S-site, respectively. The area of pioneering *Scirpus* increased from 3.6 to 17.0 ha (by 4.7 times) at the E-site and from 9.8 ha to 21.4 ha (by 2.2 times) at the S-site. This indicates that there is still a substantial amount of sediment entering the estuary region with Yangtze runoff; consequently, the sedimentary process is in favor of mudflat accretion. There is typically positive feedback between vegetation colonization and sedimentation accretion in the vegetated marshes. That is, vegetation establishment promotes mudflat accretion and reduces hydrodynamic energy by sediment trapping and wave attenuation so that the intensity of tidal disturbance further decreases with the increasing canopy density and marsh elevation, which further improves vegetation colonization when the alternative stable state is presented (Van De Koppel et al., 2001; Mudd et al., 2010; Vandenbruwaene et al., 2011). As estimated by Kirwan et al. (2011), if suspended sediment concentrations are maintained at 10–100 mg L^{-1}, unvegetated mudflats at fringing marshes could accrete faster than the rate of the sea level rise and support vegetation colonization. As measured in 2016, the concentration of suspended sediment in tidal water at our study site were quite high, reaching 223.81–539.28 mg L^{-1} depending on the seasons and tide regimes (details not presented). This is profitable for mudflat accretion and vegetation colonization at the fringing marsh. The increase scale of *Scirpus* was large at the E-site, especially since 2015 when the adjacent *Spartina* was executed by using the herbicide. A portion of *Scirpus* expanded to the original flat of *Spartina*, nevertheless, the fraction of re-colonized area by *Scirpus* was only around 15% up to 2017, probably due to herbicide residual in soil. Most new colonization area (around 85%) of *Scirpus* seedlings spread to the mudflat seaward.

With the historically lowest loading amount of upstream sediment, the continued accretion of tidal flats in estuary could be partially attributed to the "time lag" of morphological responses to riverine sediment supply changes. The Yangtze Estuary is synchronously controlled by river and tides. Dai et al. (2014) demonstrated that the long-term decrease in sediment source from the upstream had little effect on the Changjiang submerged delta. Wang et al. (2018) presented that The Nanhui tidal flat of the Yangtze Estuary did not suffer erosion with the large decrease of riverine sediment, based on a LiDAR-approach morphdynamic monitoring. The Yangtze River delivers the suspended sediments seaward to the estuary, and then the deposited sediments in inner shelf on the East China Sea can be later resuspended and translocated landward by wind-driven currents (Dai et al., 2014). On the other hand, sediment redistribution (erosion and accretion) induced by tidal pumping within the estuary could also explained the resilience of tidal flats under long-term reduction in sediment loading (Guo et al., 2014; Zhao et al., 2018).

When focusing on the year-to-year variations of vegetation expansion, we found that the increment rates of the pioneering *Scirpus* were relatively low (14% in the E-site and 12% in the S-site) during the 2013–2015 period, while the rates were much higher (92% in the E-site and 33% in the S-site) during the 2016–2017 period than those in former years. Interestingly, it was apparent that the water discharge recorded in 2016 in the Datong station was the second highest (due to flood events within the basin) over the past 30 years, and the runoff volume in following 2017 was also higher than the historical average value. Correspondingly, the discharge of suspended sediment in 2016 (152 million tons) was the highest and in 2017 (104 million tons) the lowest during the 2013–2017 period, and the sediment amount transported to the estuary area is the great majority (~70%) during the vegetation growing season (April–September). The most convincing evidence showed that there was a long-term (more than 10 years) stable eroded bank in the S-site before 2014, while the eroded belt has rapidly filled with sediment accumulation since 2016 and has almost disappeared (see Fig. 5b). Well-known negative feedback between marsh elevation and sediment deposition demonstrates that low-lying mudflats are inundated longer and more frequently by tidal floods, leading to high rates of sedimentation and then a rapid increase in elevation (Temmerman et al., 2003; Wang and Temmerman, 2013). As presented by Dai et al. (2014), yearly changes of the tidal level measured at Wusong gauging station in the Yangtze Estuary was almost in line with the yearly water discharges recorded at the Datong station over 1955–2010. We also found that there was a strong linear relation between the annual runoff and mean tidal level in the Yangtze Estuary region, based on the recent observations (Fig. 7). Higher tidal level would increase amount and residence time of tidal water in the coastal salt marsh, resulting in more sediment deposition on the low-lying mudflat. Within our study period, the positive relationship between mudflat accretion in the Chongming Dongtan wetland and upstream water discharge was strong. This indicated that a short-term substantial impulse of river and sediment discharge might greatly benefit the accretion of coastal wetlands and the consequent expansion of salt marsh vegetation. Therefore, water discharge plays a crucial role in determining the sediment supply for the downstream delta and could be considered a key indicator for accretion potential in the estuarine wetlands. However, the function of the sediment load from upstream was weak. That is, the sediment amount recorded at the Datong station may be not absolutely suitable to be used to interpret the changes in sediment transportation in the coastal wetlands of the Yangtze Delta due to the high uncertainty of sediment loading processes along the transportation path.

The development of shoreline in whole area of the Chongming Dongtan wetland indicated a rough accretion status of mudflat from 2013 to 2017 at similar low and high tidal level. However due to the uncertainty of tidal level error, it is often difficult to compare topographical changes and morphodynamics in highly variable estuarine

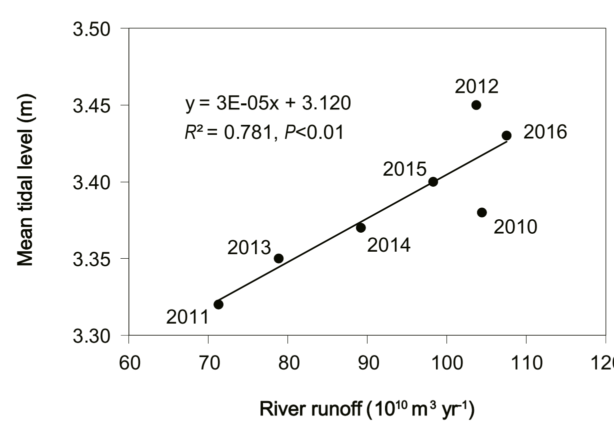

Fig. 7. Relation between annual river runoff and mean tidal level at Gaoqiao station (local Wusong bathymetric benchmark) in the Yangtze Estuary (data from Shanghai Municipal Oceanic Bureau).

flats from satellite images. In this study, we also found that the degree of flat accretion was different between the eastern and southern sites. The possible cause is that the runoff current and tidal velocity are strong in the southern part of the Chongming Dongtan wetland, which is adjacent to the main estuary stream and a 10-m deep trough (see Fig. 2 in Hu et al., 2015). Relative to the S-site, the loss of newly deposited sediments at the E-site might be lower due to weaker tidal energy. On the other hand, some extreme hydrological events such as typhoon (or storm) are also identified as the critical drivers for changes in salt marsh morphological evolution (Leonardi and Fagherazzi, 2015; Xie et al., 2017).

With regard to the Chinese endemic species in the coastal area, the native *Scirpus* spp., mainly including *S. mariqueter*, *S. triqueter* and *S. planiculmis,* are the original pioneering vegetation, and the *Scirpus* marsh is recognized as the most favorable habitat for wildlife (Ma et al., 2004; Ge et al., 2009; Li et al., 2009). However, the introduced *S. alterniflora* from the 1970s had been invading the *Scirpus* marsh and has resulted in a sharp decrease in native species in East China (Li et al., 2009; Ge et al., 2015b). Fortunately, since the 2010s, the local government has ecologically engineered *S. alterniflora* removal, and the most successful practice for invasive plant control was achieved in the Chongming Dongtan wetland. Aiming at the incoming marsh restoration objective of native *Scirpus* revegetation, our current study could provide a threshold mudflat elevation for *Scirpus* establishment and expansion. In the frontier, the shifts from the bare mudflat to stable large-area *Scirpus* marsh occur once the threshold of elevation reached approximately 2.9 m in the E-site and 2.5 m in the S-site (local Wusong bathymetric benchmark). We expected that when the mudflat elevation is above the threshold, the hydrological disturbance will decrease, after which young vegetation can survive and develop into a stable community. Once the dense tussocks are formed, the mudflat elevation enhances rapidly due to increased sediment deposition as a result of the positive feedback between vegetation establishment and sedimentary processes (Van De Koppel et al., 2001; Kirwan et al., 2011).

5. Conclusions

Under the background of the historically lowest level of upstream sediment load, this study investigated the dynamics of mudflat and marsh vegetation (*Scirpus* spp.) in a frontier salt marsh of the largest coastal wetland in the Yangtze Estuary over the past 5 years (2013–2017). The results showed that in the different monitoring sites, the increase in mudflat elevation and expansion of pioneering vegetation still occurred in the marsh with the current sediment discharge. The cause could be attributed to the positive interaction between vegetation establishment and sedimentary processes in the mudflat frontier. Especially in years with higher water discharge (2016 and 2017), the rates of mudflat accretion and vegetation colonization were much higher than in the other years. Relative to water discharge, the sediment load recorded upstream might not be a suitable indicator to interpret the mudflat and vegetation dynamics in the coastal wetlands due to high uncertainty of sediment loading processes along the transportation path. We also found that a short-term significant increase in water discharge could intensively stimulate sediment transport to the coastal region for mudflat accretion and salt marsh growth.

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