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Soil Organic Carbon Contents and Stocks in Coastal Salt Marshes with *Spartina alterniflora* Following an Invasion Chronosequence in the Yellow River Delta, China

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Abstract: Plant invasion alters the fundamental structure and function of native ecosystems by affecting the biogeochemical pools and fluxes of materials and energy. Native (*Suaeda salsa*) and invasive (*Spartina alterniflora*) salt marshes were selected to study the effects of *Spartina alterniflora* invasion on soil organic carbon (SOC) contents and stocks in the Yellow River Delta. Results showed that the SOC contents (g/kg) and stocks (kg/m^2) were significantly increased (P < 0.05) after *Spartina alterniflora* invasion of seven years, especially for the surface soil layer (0–20 cm). The SOC contents exhibited an even distribution along the soil profiles in native salt marshes, while the SOC contents were gradually decreased with depth after *Spartina alterniflora* invasion of seven years. The natural ln response ratios (LnRR) were applied to identify the effects of short-term *Spartina alterniflora* invasion on the SOC stocks. We also found that *Spartina alterniflora* invasion might cause soil organic carbon losses in a short-term phase (2–4 years in this study) due to the negative LnRR values, especially for 20–60 cm depth. And the SOCD in surface layer (0–20 cm) do not increase linearly with the invasive age. Spearman correlation analysis revealed that silt + clay content was exponentially related with SOC in surface layer (Adjusted R^2 = 0.43, P < 0.001), suggesting that soil texture could play a key role in SOC sequestration of coastal salt marshes.

Keywords: plant invasion; soil organic carbon; salt marshes; *Spartina alterniflora*; Natural ln response ratios (LnRR); the Yellow River Delta

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1 Introduction

Plant invasion, an emerging driver of global change, is disturbing both the structure and function of native ecosystems worldwide (Belnap et al., 2005; Ehrenfeld, 2010; Pyšek et al., 2012). The impacts on the plant-soil element variation caused by alien plant invasion are drawing more attention (Ehrenfeld, 2003; Peng et al., 2011; Souza-Alonso et al., 2015; Sardans et al., 2017) because plant can play a pivotal role in biogenic element cycling of plant-soil interaction interface (Jobbágy and Jackson, 2000; Matamala et al., 2003). Previous studies has demonstrated that invasive plants significantly alter soil carbon/nitrogen stocks, the availability of nitrogen, phosphorus and potassium, and stoichiometric ratios of soil (Jackson et al., 2002; Liao et al., 2008; Cheng et al., 2008; Stark and Norton, 2014; Yang et al., 2016; Sardans et al., 2017) by changing the shoot/root allocations, net primary productivity (NPP), the quality and quantity of plant litter, rate of decomposition and so forth.

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Coastal wetlands are considered to be highly effective ecosystems in regulating the atmospheric carbon dioxide (CO_2) concentrations and maintaining regional ecological security (Chmura et al., 2003; Lu et al., 2017). Meanwhile, coastal wetland soil can sequester a large amount of organic carbon due to the low microbial decomposition rate caused by anaerobic conditions and high siltation rate of sediment. Recent study (Lu et al., 2017) also showed that coastal wetlands had higher net CO_2 uptake rates compared with inland wetlands, which verifies the importance of coastal wetlands in enhancing the capacity of carbon sinks. The changes of distribution patterns of vegetation might induce the coastal wetlands shifted from carbon sink to carbon source or vice versa (Liao et al., 2008; Chmura, 2013; Bai et al., 2016). Therefore, plant invasion in coastal region could make these carbon ecosystems disequilibrated, which resulted in increased variabilities in carbon budgets.

As the most widely distributed alien species in coastal wetlands of China, *Spartina alterniflora* was initially introduced in 1979 for promoting sediment deposition and protecting coastline and seaside embankments. Its high ecological adaptability make this species explosive growth and its spread area is nearly 34 137 ha in coastal salt marshes of China until 2013, mainly in South China (Lu and Zhang, 2013). Numerous studies have been conducted about the effects of *Spartina alterniflora* invasion on the variation in SOC in South China with subtropical or tropical climate, such as Jiangsu Yancheng (Yang et al., 2013; 2016; Zhou et al., 2015), Jiangsu Wanggang Estuary (Zhang et al., 2010b), Yangtze River Estuary (Liao et al., 2007), Minjiang River Estuary (Pan et al., 2015; Jin et al., 2016), Hangzhou Bay (Shao et al., 2011; Zhang et al., 2014), Fujian Zhangjiang Estuary (Zhang et al., 2008), Jiulong River Estuary (Chen et al., 2015). Little information is available about the SOC contents in soil profiles and carbon stocks in up one meter along a short-term invasion chronosequence in the Yellow River Delta (YRD), a vital estuary with a warm semi-humid monsoon climate in North China (Yang et al., 2011).

The primary objectives of this work were: 1) to investigate the profile distribution pattern of SOC in salt marshes with native species (Suaeda salsa) and invasive species (Spartina alterniflora), respectively; 2) to identify the changes in SOC stocks caused by short-term *Spartina alterniflora* invasion using natural ln response ratio (LnRR); and 3) to reveal the relationship between soil physicochemical properties and SOC stocks in surface layer (0–20 cm) and bottom layer (20–100 cm).

2 Materials and Methods

2.1 Site description

The study area is located in the Yellow River Delta National Wetland Nature Reserve (118°58′–119°21′E, 37°35′–37°55′N), which is characterized by a warm-temperate and continental monsoon climate. Its annual mean air temperature is from 12.1 ℃ to 12.9 ℃, and annual mean precipitation ranges from 576.7 mm to 596.9 mm, and the annual mean evaporation is three to four times the amount of rainfall (Bai et al., 2011; Jiang et al., 2013), approximately 70% of the total annual precipitation occurs in summer (Fig. 1). Soil type in this region is mainly coastal saline soil, derived from the upstream parent materials of loess plateau (Huang et al., 2012).

In the salt marshes zone of this area, native dominant plant species are *Suaeda salsa* and saltwater *Phragmites australis* due to the effects of tidal fluctuation. In 1990, *Spartina alterniflora* was successfully bred and established in the Wuhaozhuang zone, close to the Gudong oil mining area. Then this alien species spread quickly in the study area due to the tidal carrying effect, and the distribution area reached maximum in 1997 according to the remote sensing interpretation (Ren et al., 2014).

Because of the seawater erosion caused by the decreasing inputs of freshwater and sediment of the Yellow River, its occupied area declined during the period from 1998 to 2007. And the variation in precipitation combined with extreme storm surge also contributed to the fluctuation of the spread area. *Suaeda salsa* is the dominant native species in this region before the *Spartina alterniflora* invasion. Therefore, *Suaeda salsa* is considered to be the reference when we identify the ecological impacts caused by alien plant species. According to remote sensing image and field survey, three invasive plots with different invasive ages (2, 4 and 7 years old; named SA2, SA4 and SA7 in this study, respectively) and one native plot were selected to study the effects of *Spartina alterniflora* invasion on SOC contents and stocks in coastal salt marshes.

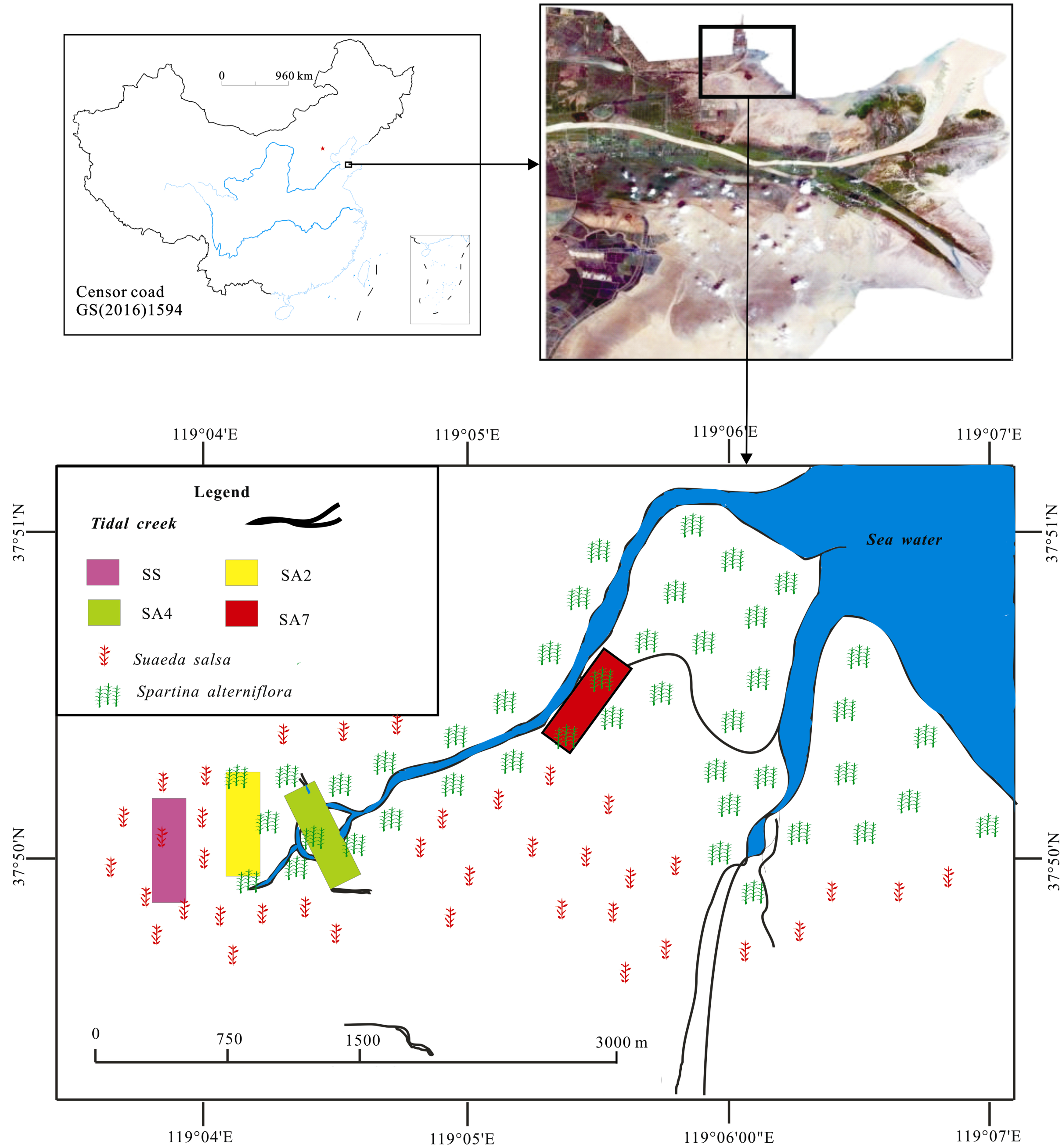

Fig. 1 The location map of study area and the sampling zone. SS was the *Suaeda salsa* salt marsh, SA was the *Spartina alterniflora* salt marsh, the number behind SA is the invasive age until to the sampling time. These rectangles were the sampling zones. There were three sampling sites in each sampling zone (n=3)

2.2 Soil sampling and analysis

Three sampling sites were randomly selected in each plot, and it is approximately ten meters away between sampling sites. Soil samples were taken out using a stainless steel soil sampler equipped with a hollow drill (50 mm diameter, 200 mm length) in August of 2016. In each sampling site, five soil cores (20 cm interval, deep to 100 cm) were firstly collected, and surface soil layer (0–20 cm) was divided into three sub-cores (0–5 cm, 5–10 cm and 10–20 cm). Another seven soil samples were collected in each layer using soil cutting ring (50.46 mm diameter, 50 mm height; 100 cm^2 volume) for the determination of soil bulk density (BD). Totally, eighty four soil samples were collected in four sampling plots (21 samples in each plot). Soil samples were air dried for two or three weeks. Soil samples in soil cutting rings were dried in an oven at 105 ℃ for 24 hours to determine the soil moisture (SM) and soil bulk density (BD).

All air-dried samples were ground manually and sieved through a 2-mm nylon sieve to remove coarse debris and stones. One part of each dried sample was used to measure soil particle size distribution on a Laser Particle Size Analyzer (Microtrac S3500, America). The other part was pulverized with a mortar and pestle until all particles passed through a 0.149 mm nylon sieve for the determination of soil physicochemical properties.

Soil organic carbon (SOC) was determined using the potassium dichromate oxidation and external heating method (Nelson and Sommers, 1982). Soil pH was measured using a Hach pH meter (Hach Company, Loveland, CO, USA) (soil : water = 1 : 5). Soil electric conductivity (EC) was measured in the supernatant of 1 : 5 soil-water mixtures using a electric conductivity meter (Hanna HI98192, Italy).

2.3 Plant collection

Aboveground biomass (AGB) and belowground biomass (BGB) of *Spartina alterniflora* and *Suaeda salsa* were collected in each sampling site. Three 0.5 m × 0.5 m quadrat were established in each sampling plot, aboveground parts of plant were cut and count the stem number, the stem height was also measured by a steel tape. Belowground parts of plant were digged out (30 cm depth) in the same quadrat and placed into a nylon net bag. All plant samples were washed cleanly with running tap water to remove any soil particles attached to the plant surfaces, then oven-dried at 60℃ for 48 h.

2.4 Soil organic carbon density (SOCD)

Soil organic carbon density (SOCD, kg/m^2) is the organic carbon content per unit area in a desired depth, whose value is dependent on both the soil organic carbon mass content and bulk density. *SOCD* in a desired depth was calculated from the following equation:

$$SOCD = \sum_{i=1}^{n} SOC_i \times BD_i \times Hi \quad (1)$$

where SOC_i is the soil organic carbon mass content (g/kg) at soil layer i (i = 1, 2, 3, …, 7); BD_i is the soil bulk density (g/cm^3) at soil layer i; H_i is the height of soil layer i (m).

2.5 Ln response ratio (LnRR)

Ln response ratio (LnRR) is a particularly useful tool for many applications in ecology (Hedges et al., 1999). In order to examine the effects of invasive plant on the soil organic carbon contents and stocks between successful invasive plants and their native species, the natural ln response ratio (LnRR) was calculated by following equation (Sardans et al., 2017):

$$LnRR = \ln(X_i) - \ln(X_n) \quad (2)$$

where X_i and X_n are the values of each observation in the invaded soil and in the native soil, respectively. Positive value of LnRR means invasive species increase the soil organic carbon, but which is opposite when the value is negative.

2.6 Statistical analysis

One-way analysis of variance (ANOVA) was used to test for differences in soil properties, SOC and SOCD among different salt marsh types. Differences were considered to be significant if $P < 0.05$. Spearman correlation analysis was carried out to reveal the relationship between SOC and soil physicochemical properties. All statistical analysis was performed using SPSS17.0 for Windows software package.

3 Results

3.1 Plant characteristics and soil physicochemical properties

The biomass (both aboveground biomass (AGB) and belowground biomass (BGB)) of *Spartina alterniflora* (SA) was significantly higher than that of *Suaeda salsa* (SS) despite of the variation among SA at different invasive ages ($P < 0.05$, Table 1). Moreover, older SA salt marshes showed higher belowground biomass than the young one, therefore, the ratios of BGB/AGB in older SA salt marshes were significantly higher than those in the young SA salt marshes, which were 4 to 10 times of SS salt marshes.

As shown in Fig. 2, no statistical differences were found among SS, SA2 and SA4 in soil pH, electrical conductivity, bulk density, soil moisture and soil texture. However, older SA salt marsh exhibited higher values in electrical conductivity, soil moisture, silt + clay content

Table 1 Plant characteristics in the tidal wetland, belowground biomasses were collected from the top 30cm. SS is the *Suaeda salsa* salt marsh, SA is the *Spartina alterniflora* salt marsh, the number behind SA is the invasive age until to the sampling time. There were three sampling sites in each patch (n=3)

Patches	Aboveground biomass (AGB, g/m^2)	Belowground biomass (BGB, g/m^2)	Stem density (stem/m^2)	Average stem height (m)	Ratio of BGB and AGB (BGB/AGB)
SA2	361.01±56.18^a	273.97±76.60^a	229±51^a	0.54±0.26^a	0.76±0.18^a
SA4	1881.71±469.11^b	718.08±329.66^b	197±24^a	1.26±0.21^b	0.42±0.24^a
SA7	798.19±173.34^c	854.77±209.43^b	218±76^a	1.17±0.21^b	1.07±0.09^b
SS	20.13±8.86^d	2.40±1.36^c	63±16^b	0.16±0.01^c	0.11±0.04^c

Note: ^{ab} Values in each column with different letters represent significant differences (LSD) among different sites ($P < 0.05$)

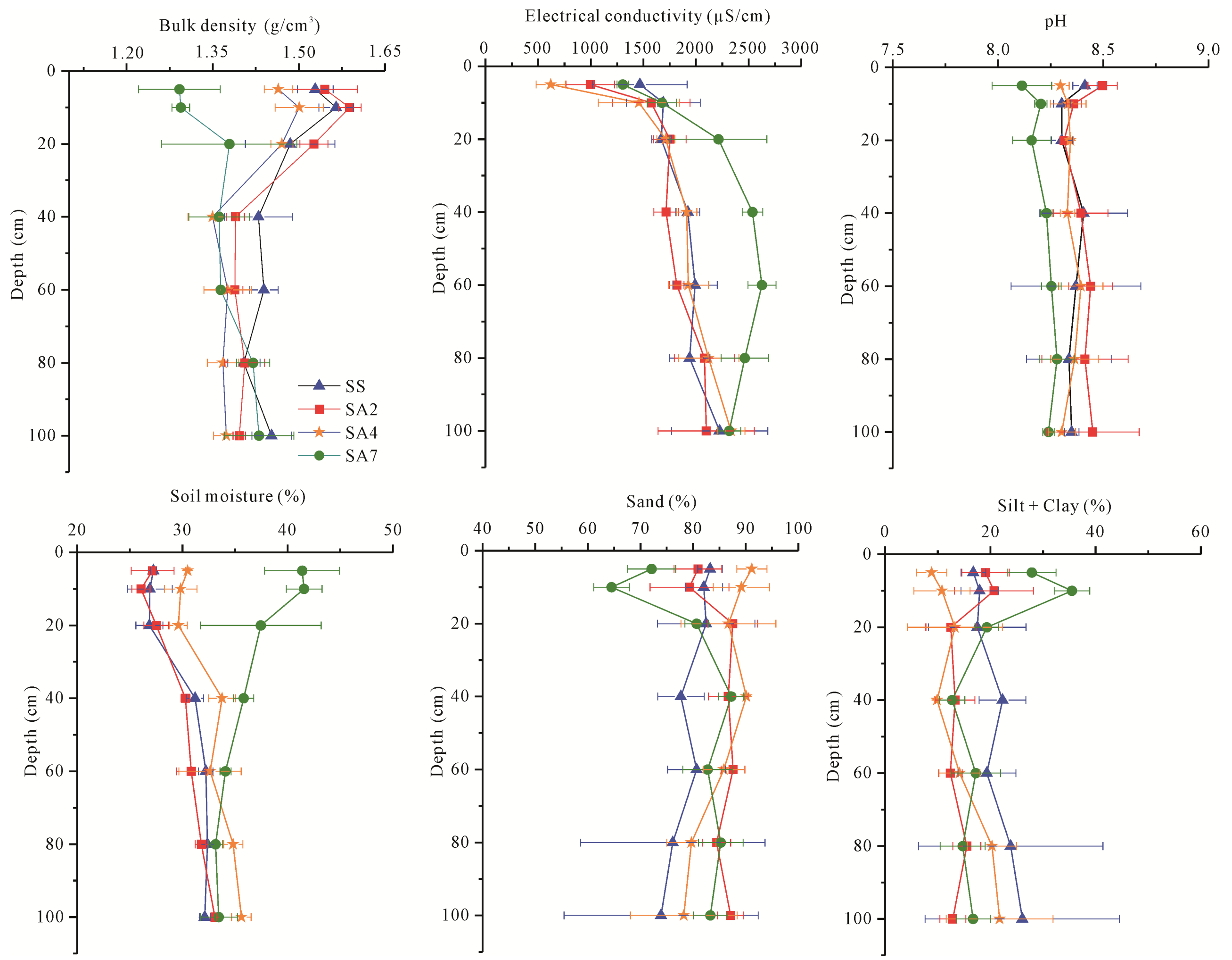

Fig. 2 Depth distribution of soil physicochemical properties in coastal salt marshes of *Suaeda salsa* (native species) and *Spartina alterniflora* (invasive species). SS is the *Suaeda salsa* salt marsh, SA is the *Spartina alterniflora* salt marsh, the number behind SA is the invasive age until to the sampling time

and lower bulk density, pH, sand content than SS and young SA salt marshes, especially in the surface layer (0–20 cm). The pH values ranged from 7.95 to 8.71, indicating the weakly alkaline soil environment in the study area. A decreasing trend of electrical conductivity from top to bottom was found in four salt marshes. The soil type is sandy soil with approximately 80% of sand particles.

3.2 Soil organic carbon contents and vertical distribution

The soil organic carbon mass contents in different soil layers from four salt marshes were illustrated in Fig. 3. In surface soil layer (0–20 cm), the SOC values in the older invasive salt marshes (SA7) were significantly higher than that in young SA salt marshes and native salt marshes (SS) ($P < 0.05$), which were approximately 1 to 2 times (calculated from mean values) higher than that in SA2, SA4 and SS. However, no significant differences were found in SOC value for all soil layers among SA2, SA4 and SS ($P > 0.05$). In bottom soil layers (20–100 cm), there were no significant differences in SOC content among four kinds of salt marshes in the same soil layer ($P > 0.05$), except for the 20–40 cm layer (Fig. 3).

SOC nearly kept stable along the soil profile in SS and SA2 because no statistically significant differences were observed among different soil layers ($P > 0.05$). However, SOC decreased gradually with soil depth in the older *Spartina alterniflora* salt marshes (SA7) with the exception of 0–5 cm layer. Interestingly, lower SOC content in the 0–5 cm layer was found compared with the 5–10 cm and 10–20 cm layers in SA7 salt marshes. Conversely, SOC of SA4 in the 80–100 cm layer was significantly higher than that in the soil layers above 80 cm ($P < 0.05$).

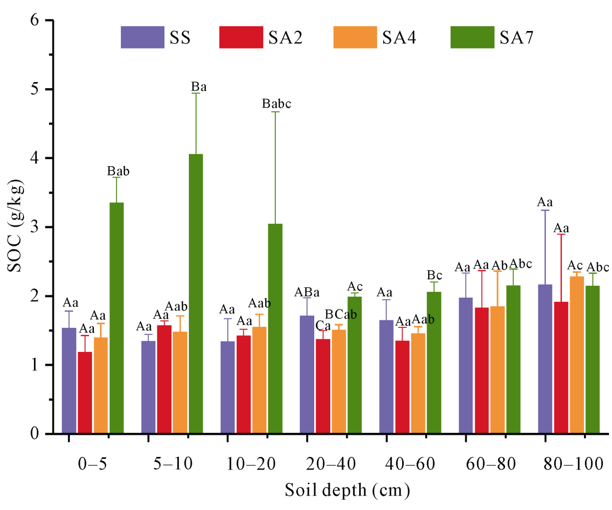

Fig. 3 The soil organic carbon (SOC, g/kg, mass content) in different soil depth from four types of coastal salt marshes in this study. ABC Values in the same soil layers with the same letters are not significantly different (Least Significant Difference, LSD) among different salt marsh types ($P < 0.05$). abc Values in each salt marsh types with different letters represent significant differences (LSD) among different soil depth layers ($P < 0.05$). SS is the Suaeda salsa salt marsh, SA is the *Spartina alterniflora* salt marsh, the number behind SA is the invasive age until to the sampling time

3.3 Soil organic carbon stocks

Soil organic carbon densities (SOCD) at three depths (0–20 cm, 0–40 cm and 0–100 cm) from three invasive salt marshes and one native salt marshes were calculated based on Equation (1). For three different thickness layers, SOCDs in SA7 salt marshes were significantly higher than that in both native and younger salt marshes (SA2 and SA4) (Fig. 4, $P < 0.05$). For 0–20 cm soil layer, the SOCD values on average in SA2, SA4 and SA7 were 1.03, 1.05 and 2.11 times in SS salt marshes, respectively. However, the SOCD values, in top 100 cm soil layer, in SA2, SA4 and SA7 were 0.87, 0.93 and 1.25 times the native species salt marshes, respectively.

3.4 Ln response ratio (LnRR)

In this study, the native species (*Suaeda salsa*) salt marshes were considered to be the control plot, the natural ln response ratios (LnRR) were calculated using Equation (2) by comparing the SOC volumetric content (kg/m^3) between invasive species and native species. We supposed that the SOC contents and its vertical distribution pattern in SA2, SA4 and SA7 patches were similar with native species salt marshes (*Suaeda salsa* patch) before *Spartina alterniflora* invasion. For seven-year- old *Spartina alterniflora* salt marshes, the average LnRR values in both surface and bottom layers were positive. Whereas the LnRR values of SOC volumetric content from young invasive patches (SA2 and SA4)

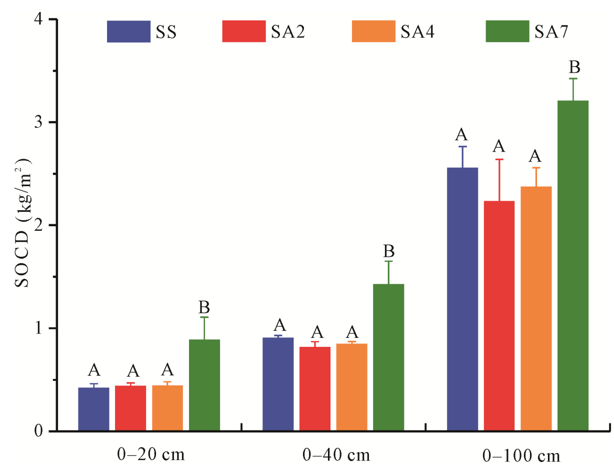

Fig. 4 Soil organic carbon density (SOCD, kg/m^2) in four types of coastal salt marshes from 0–20 cm, 0–40 cm and 0–100 cm soil depth. AB Values from the same soil layers with different letters are significantly different (Least Significant Difference, LSD) among different salt marsh types ($P < 0.05$), SS is the Suaeda salsa salt marsh, SA is the *Spartina alterniflora* salt marsh, the number behind SA is the invasive age until to the sampling time

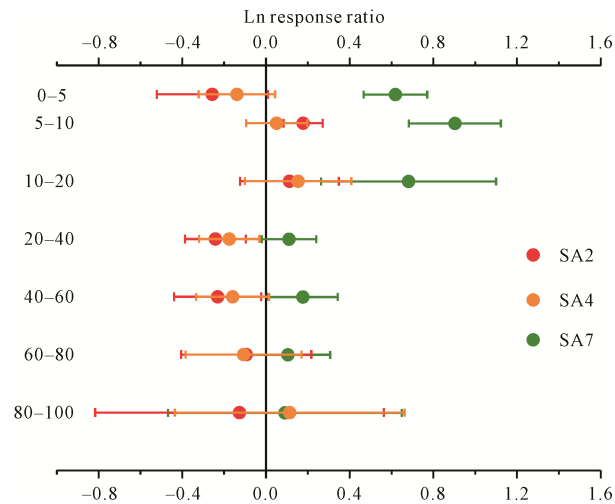

Fig. 5 Ln response ratio of soil organic carbon in the soil profile between coastal salt marshes of *Suaeda salsa* (SS, native species) and *Spartina alterniflora* (SA, invasive species). Zero in the X-axes represents neutral response ratio that means equal values in native than in invasive species. Plus (+) and minus (–) represent positive and negative log response ratios, respectively

were negative in the 20–80 cm layer, which was consistent with the results of SOC stocks in bottom layer of them (Fig. 5).

4 Discussion

4.1 The effects of *Spartina alterniflora* invasion on the SOC

Plant invasion is an emerging driver of global change worldwide (Sardans et al., 2017), which can influence soil organic carbon (SOC) pool by altering the quantity and quality of plant materials entering the soils (Liao et al., 2007; Yang et al., 2013). *Spartina alterniflora* is a major invasive species in Chinese coastal salt marshes, whose distribution area spans nearly 12 latitudinal values in China. However, there was no consensus on the SOC stocks caused by *Spartina alterniflora* invasion. Numerous studies were prone to that *Spartina alterniflora* invasion significantly enhance SOC stocks (Liao et al., 2007; Cheng et al., 2008; Zhang et al., 2014; Yuan et al., 2015; Jin et al., 2016; Yang et al., 2016). Conversely, some studies have shown that *Spartina alterniflora* invasion would cause soil carbon loss (Zhang et al., 2008; Shao et al., 2011; Liu et al., 2013) compared with the native soil carbon stocks. Regional variation, different invasive ages and the plant physiological difference between the native species and *Spartina alterniflora* may be the cause of the above controversy.

In our study, SOC stocks were observably increased after *Spartina alterniflora* invasion of seven years, especially for the surface soil layer (0–20 cm; Fig. 4). Xiang et al. (2015) also pointed out that SOC accumulation rate in 0–30 cm layer exponentially increased with invasion time. And a quadratic regression relationship was also found between soil organic carbon density and invasive age for 0–20 cm soil layer in our study (Table 2), which is consistent with the result of Jin et al. (2016), who presented that *Spartina alterniflora* invasion obviously promoted carbon sequestration potential of 0–20 cm soil layer. However, highest SOC content (g/kg) was

Table 2 Relationship between soil organic carbon density (SOCD, kg/m^2) in different soil depth with invasive age, *Y* is the SOCD, and *X* is the invasive age. The age of native specie (*Suaeda salsa*) was set zero in the regression analysis. Only quadratic polynomial equation and exponential function were used to fit the trend due to their better fitting outputs

Equation type	Soil layer (cm)	Regression equation	Adj R^2	*F* value	*P* value	Significant level
Quadratic polynomial	0–20	Y=0.0174X^2 –0.0593X+0.4354	0.92259	111.63209	0.06678	–
	0–40	Y=0.01589X^2–0.08152X+0.9178	0.66376	7384.01346	0	***
	0–60	Y=0.0385X^2-–0.185X+1.3825	0.99492	4320.01263	0.01076	*
	0–80	Y=0.04517X^2–0.2238X+1.93723	0.99275	4420.88905	0.01063	*
	0–100	Y=0.04797X^2–0.24103X+2.54337	0.99401	8201.933	0.00781	**
Exponential function	0–20	Y=0.01617exp(X/1.99102)+0.36232	0.98193	25240.0739	0	***
	0–40	Y=1.63936E(–7)exp(X/0.46483)+0.85299	0.94624	317.17636	0.03967	*
	0–60	Y=9.90161exp(X/0.44337)+1.26767	0.85607	152.27846	0.05721	–
	0–80	Y=-430061.098exp(X/4.37674)+430062.7	–0.47941	21.33275	0.15133	–
	0–100	Y=1.63876E–7exp(X/0.4538)+2.38229	0.71577	172.62598	0.05374	–

Notes: – $P > 0.05$; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$

observed after *Spartina alterniflora* invasion of five years by studying comparatively SOC under 1, 3, 5 and 12 years' invasion in Xinyanggang coastal wetlands, North Jiangsu (Wang et al., 2013). According to analysis of soil organic carbon fractions, soil labile carbon (LC) or light fraction (LF) of SOC was positively correlated with the *Spartina alterniflora* invasion time (Wang et al., 2013; Yang et al., 2016).

When we calculated SOCD in up 100 cm soil depth, a small decrease in SOCD in SA2 and SA4 salt marshes was observed compared with native species, which should be paid sufficient attention (Fig. 4). On the one hand, *Spartina alterniflora* invasion could increase the SOC content of salt marshes by increasing the litter and root exudates inputs (Zhang et al., 2010a) due to its high aboveground and belowground biomass (Table 1). On the other hand, *Spartina alterniflora* facilitates the oxygen transport from above stems into the soil anaerobic layer by its developed aerenchyma (Huang et al., 2011), which might accelerate the SOC decomposition in bottom soils. What is more, root exudates from *Spartina alterniflora* would provide more suitable carbon source for soil microorganisms in deep soils, which also be known as 'rhizosphere priming effects' (Cheng, 2009). These two phenomena could possibly explain why the SOC stocks in deep soil layer (20–100 cm) was lower in younger invasive salt marshes (SA2 and SA4) than that in native salt marshes (Fig. 3 and Fig. 4).

Coastal salt marshes have been suggested to be valuable carbon sinks due to their high carbon burial ability and relatively low greenhouse gases (GHGs) emissions (Chmura, 2013). Although most of researches agreed that *Spartina alterniflora* invasion enhanced the soil carbon sequestration potential in coastal salt marshes. It still should be noticed that *Spartina alterniflora* invasion could also alter GHGs emissions, studies of methane (CH_4) and nitrous oxide (N_2O) emission stimulated by *Spartina alterniflora* invasion have been carried out, mainly in South China (Zhang et al., 2010a; Ding and Cai, 2002; Yuan et al., 2014; Xiang et al., 2015). And the global warming potentials of CH_4 and N_2O are 25 and 298 times than that of carbon dioxide (CO_2) over a 100-year time horizon (IPCC, 2007), respectively. Therefore, it is necessary to estimate the global warming potential (GWP) based on the SOC sequestration rates and GHGs emissions for better understanding the effects of *Spartina alterniflora* invasion on the carbon sinks or sources in coastal salt marshes (Yuan et al., 2015).

4.2 The vertical distribution pattern of SOC in coastal salt marshes

In native *Suaeda salsa* salt marshes, no significant differences in SOC were found among seven profile layers (Fig. 3, $P < 0.05$), while a conspicuous increase in SOC in the 0–20 cm soil layer after seven-year invasion indicated that *Spartina alterniflora* invasion significantly affected the vertical distribution pattern of SOC in coastal salt marshes. Similarly, Cheng et al. (2006) also reported that the SOC content in 0–5 cm was lower than that in 5–20 cm, highest SOC content in 5–20 cm was found and then decreased from 20 cm to 100 cm in the Jiuduansha is land in the Yangtze River estuary. Whereas Pan et al. (2015) pointed out that the SOC content was significantly increased from 0 cm to 60 cm in a bare land after *Spartina alterniflora* invasion in Minjiang River Estuary.

Our study also showed that the biomass of *Spartina alterniflora* was significantly greater than that of native plant, especially for belowground biomass ($P < 0.05$; Table 1), whose aboveground biomass was close to the values reported by Yuan et al. (2015). Larger litter inputs from *Spartina alterniflora* may contribute to the higher SOC content of surface layer in invasive salt marshes. Belowground biomass could play an important role in SOC variation along the soil profiles (Jin et al., 2016). Feng et al. (2015) also observed the remarkably positive relationship between the belowground biomass of *Spartina alterniflora* and SOC content.

Plant functional types affect the distribution of SOC with depth via the shoot/root allocations combined with vertical root distributions (Jobbágy and Jackson, 2000). Mora et al. (2014) also demonstrated that plant roots play a major role in the supply of organic matter in volcanic soils. Meanwhile, higher ratios of belowground biomass and aboveground biomass could accelerate sediment deposition (Liu et al., 2010). Sediment deposition not only input SOC directly, but also slowed the SOC turnover by burying plant-derived organic materials into salt marshes (Chmura et al., 2003). Additionally, tidal pumping also regulated the soil carbon pool in coastal salt marshes (Zhou et al., 2009). For instance, increased SOC in *Spartina alterniflora* salt marsh was partly owing to the contribution of phytoplankton (Gebrehiwet et al., 2008).

4.3 The relationship between soil physicochemical properties and soil organic carbon

Plant invasion could change soil physicochemical properties such as soil compaction (bulk density, soil porosity, soil moisture holding capacity), soil nutrient content (element stoichiometric characteristic), and soil micro-environment (soil microorganisms) (Hawkes et al., 2005; Chacón et al., 2009; Souza-Alonso et al., 2015; Sardans et al., 2017), which, in turn, alter the soil carbon cycling.

Soil texture plays an important role in controlling the SOC distribution patterns with similar soil environment (Tan et al., 2004). Soil texture mainly influences the SOC storage in two ways (Yang et al., 2008). Firstly, increasing clay and silt content reduces microbial decomposition through stabilizing SOC and decreasing C leaching and thus leads to an accumulation of SOC. Secondly, increasing clay and silt content stimulates plant production via increasing water holding capacity and thus increases C inputs to soil. In our study, strong correlations were also found between SOC (volumetric content, kg/m^3) and silt + clay content in surface and bottom soil layers (Appendix Table 1, Appendix Table 2 and Fig. 6), and the SOC content increased exponentially with the increasing silt + clay percentage values for surface layer (Adj. $R^2 = 0.43$, $P < 0.001$). Similarly, Zinn et al. (2005) also reported that a SOC = a + b (clay + silt) function was efficient to describe the mathematic relation between them within the soil profiles. In coastal salt marshes, more fine particulate matters were easily captured by *Spartina alterniflora* (Jin et al., 2016; Fig. 2 in this study) due to its large biomass, then deposited into the soil, which potentially enhanced the soil carbon sequestration capability (Chmura et al., 2003). This may partially be helpful for the SOC burial in surface soil layer.

Bulk density can be viewed as important indicator of soil physical health with a strong influence on SOC (Hobley et al., 2015), which was important to SOC contents but not stocks because it was needed in calculating the carbon stocks. As reported by Chmura (2013), a tidal salt marsh soil that contains 5% C but has a bulk density of 5 kg/m^2 can hold the same amount of carbon as a soil that contains 50% C but has a bulk density 0.5 kg/m^2. After *Spartina alterniflora* invasion of seven years, salt marshes exhibited significantly lower bulk density than that in natives (Fig. 2), the inverse relationship between

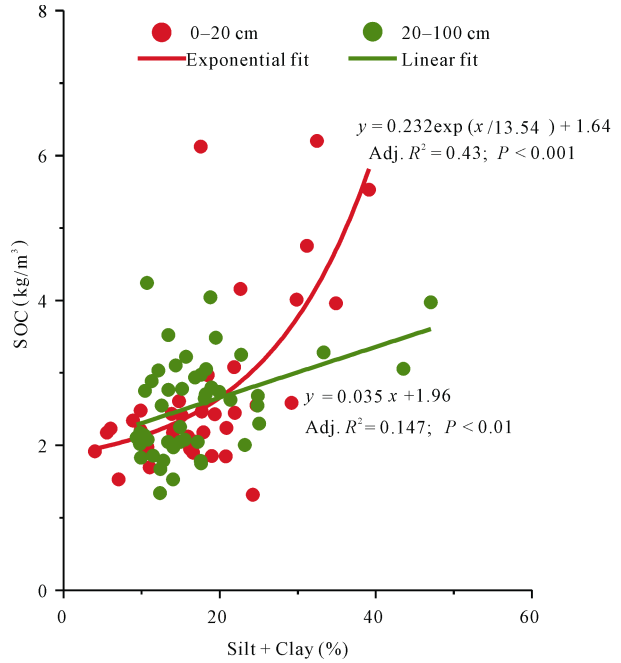

Fig. 6 Relationship between soil organic carbon (*y*, volumetric content, kg/m^3) and soil texture (*x*, silt + clay content, %) in surface layer and bottom layer. Red and green points represent the SOC values in 0–20 cm and 20–100 cm, respectively. SOC: the volumetric content of soil organic carbon; Silt + Clay: the total percentage of soil silt + clay

SOC and bulk density (Appendix Table 1) was also observed by other researchers (Hobley et al., 2015; Jin et al., 2016). Plant growth and root penetration would soften the compacted soil layer and increase SOC content, then affect the bulk density (Ruehlmann and Körschens, 2009). Although lower bulk density was exhibited after *Spartina alterniflora* invasion (Fig. 2), significant higher SOCD values from different profile depth (0–20 cm, 0–40 cm and 0–100 cm) were still found in SA7 than native salt marshes, which was caused by a high contribution of SOC contents in (especially in 0–20 cm) calculating SOCD.

5 Conclusions

In native salt marshes (*Suaeda salsa*), there was no statistical differences in SOC contents among seven soil layers ($P > 0.05$), while the SOC contents were gradually decreased along the soil profile after *Spartina alterniflora* invasion of seven years (SA7), and significant difference were found in SOC contents between 0–20 cm and 20–100 cm layers ($P < 0.05$). The SOC contents and stocks in surface soil layer (0–20 cm) were significantly increased in SA7 compared with the native salt marshes in the Yellow River Delta. In upper 100 cm, SOCD was significantly increased after invasion in SA7 (3.04 to 3.45 kg/m^2) compared with native salt marshes (2.32 to 2.73 kg/m^2). However, the SOCD in surface layer (0–20 cm) do not increase linearly with the invasive age, with the exception of plant litter inputs, sediment position and tidal fluctuation also played important role in regulating the SOC pool for coastal salt marshes. The natural ln response ratio (LnRR) was also an efficient tool for identifying the effects of plant invasion on the SOC stocks in coastal salt marshes.

Meanwhile, *Spartina alterniflora* invasion would also affect the SOC content by altering the soil physicochemical properties, and an exponential relationship was found between SOC and soil silt+clay content for the surface soil layer. Despite its high SOC stocks in *Spartina alterniflora* salt marshes, the greenhouse gases (GHGs) emissions induced by its invasion is urgently required to study, especially in coastal salt marshes, for quantifying its contribution to eliminating 'greenhouse effect' at the regional, national or global scales.

Appendix Table 1 Spearman correlation matrix of soil organic carbon (volumetric content, kg/m^3) and soil physicochemical properties in surface layer (0–20 cm, n=36)

	SOC	BD	SM	pH	EC	Sand	Silt+Clay
SOC	1.000						
BD	–0.513**	1.000					
SM	0.550**	–0.870**	1.000				
pH	–0.495**	0.677**	–0.637**	1.000			
EC	0.219	–0.011	–0.064	–0.261	1.000		
Sand	–0.540**	0.268	–0.319	0.200	–0.054	1.000	
Silt+Clay	0.540**	–0.268	0.319	–0.200	0.054	–1.000**	1.000

Note: *Significant correlation at $P < 0.05$, ** Significant correlation at $P < 0.01$

Appendix Table 2 Spearman correlation matrix of soil organic carbon (volumetric content, kg/m^3) and soil physicochemical properties in bottom layer (20–100 cm, n=48)

	SOC	BD	SM	pH	EC	Sand	Silt+Clay
SOC	1.000						
BD	0.046	1.000					
SM	0.337*	–0.396**	1.000				
pH	–0.226	0.004	–0.307*	1.000			
EC	0.794**	–0.241	0.560**	–0.370**	1.000		
Sand	–0.364*	–0.139	0.036	–0.018	–0.239	1.000	
Silt+Clay	0.364*	0.139	–0.036	0.018	0.239	–1.000**	1.000

Notes: * Significant correlation at $P < 0.05$; ** Significant correlation at $P < 0.01$

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