Ecological Engineering 106 (2017) 132–139

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Effects of exotic *Spartina alterniflora* on vertical soil organic carbon distribution and storage amount in coastal salt marshes in Jiangsu, China

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A R T I C L E I N F O

Article history:
Received 24 December 2015
Received in revised form 18 May 2017
Accepted 29 May 2017
Available online 4 June 2017

Keywords:
Salt marsh
Soil organic carbon
Spartina alterniflora
Carbon sequestration
Vertical distribution

A B S T R A C T

Coastal wetlands soil organic carbon (SOC) plays an important role in global carbon sequestration, and exotic *S. alterniflora* affects the coastal ecosystem's functions including SOC storage (SOCS). We investigated the vertical deep soil SOC distribution (0–300 cm) in Jiangsu salt marsh and estimated its changes. The results show that (1) exotic *S. alterniflora* increases the SOC, with higher densities (g kg^{-1}) in both topsoil and deep soil in its colonized area, and subsequently increases the SOCS vertical depth (cm) distribution. Such influences become more prominent with time since the introduction of *S. alterniflora*. The deepest SOC distribution (180 cm) and the highest SOC content (2.14 ± 0.19 g kg^{-1}) in the deep layer (50–300 cm) were found in the zones where *S. salsa* – *S. alterniflora* co-exist (SSI). The vertical SOC distribution in zones where multi-species co-exists is deeper than that in mono-species dominated zones; (2) The deep soil (100–300 cm) SOC accounts more than 50% of 0–300 cm SOC in Jiangsu salt marsh, suggesting that SOC content of deep soil should not be ignored when calculating the global soil carbon stock; (3) Total SOCS within 0–300 cm in Jiangsu salt marshes (107.84 × 10^6 m^2) is 84.90 × 10^{10} g, of which 0–100 cm, 100–200 cm and 200–300 cm layer accounts for 38.25%, 30.72% and 31.03%, respectively. The size of the SOCS (0–300 cm) in the Jiangsu salt marshes relatively to the global biome (0.36 × 10^{-6}) is in a lower proportion of the range of salt marsh area to global biome area (0.89 × 10^{-6}). The *S. alterniflora* salt marsh contributes most of the SOCS in the 0–300 cm and 0–100 cm soils.

1. Introduction

Accounting 6% of global land area, wetlands are important reservoirs of carbon, representing about 15% of the terrestrial biosphere carbon pool (Gitay et al., 2001; Olaleye et al., 2014). When boreal forests and tropical forested wetlands are included, the amount of wetland carbon reservoirs reaches 37% of the total terrestrial carbon pool, out of which soil organic carbon (SOC) plays an important role in the global carbon cycle (Gitay et al., 2001; Olaleye et al., 2014). Dynamics of SOC is determined by the balance between inputs (e.g., addition of plant residues) and outputs (e.g., SOC decomposition), which is influenced by several factors including climate conditions, soil properties, and land use management (Jobbágy and Jackson, 2000a; Wang et al., 2001). In terrestrial soils, wetland ecosystems are estimated to hold 20–25% of the total soil carbon stock (Zhang et al., 2008a). Some researchers suggest that the global carbon stock down to one-meter depth in wetlands is 225 Pg (1 Pg = 10^{15} g) (IPCC, 2000). Natural and restored wetlands are generally sinks for atmospheric CO_2 with potential implications for global climate change (IPCC, 2000; Lal, 2004), because they make an important contribution to global carbon sequestration (Furukawa et al., 2004; Inubushi et al., 2003; Roulet, 2000).

S. alterniflora, a perennial halophyte native to the eastern coastal wetlands of the USA, has a proliferated root system distributed mainly in the top 30 cm of sediment and sometimes extending to 50–100 cm belowground. *S. alterniflora* uses a C4 photosynthetic strategy with high efficiency, salt and flooding tolerance and a large amount of biomass, making *S. alterniflora* salt marsh among the

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http://dx.doi.org/10.1016/j.ecoleng.2017.05.041
0925-8574/

most productive ecosystems (Gallagher and Pfeiffer, 1980; Wang et al., 2006). Since *S. alterniflora* was introduced into the intertidal zones of the coastal wetlands of Jiangsu, China thirty years ago, it has expanded quickly and led to progressive displacement of *Suaeda salsa*, a native plant of the local ecosystem. The local community structure has been consequently changed, and accordingly ecosystem processes including soil carbon storage have been affected.

Both positive and negative influences on the soil carbon pool have been reported associated with the introduction of *S. alterniflora* (Wang et al., 2009; Wang et al., 2010). In Minjiang Estuary of Fujian Province, exotic *S. alterniflora* improves the soil carbon stock and enhances the rhizosphere carbon fraction of *Phragmities australis* salt marsh, while the short-term *S. alterniflora* colonization changes the methane potential in the 0–5 cm topsoil (Wang et al., 2010). In the Yancheng coastal wetlands of Jiangsu Province, exotic *S. alterniflora* significantly increases SOC in the upper 0–30 cm soil layer compared with bare mudflat and native C3 plant communities (Wang et al., 2013). It enhances the carbon sink capacity of the intertidal ecosystem, and reduces CO_2 emissions to the atmosphere (Liu et al., 2007). The amount of SOC provided by *S. alterniflora* to the local salt marsh varies greatly due to the different duration of colonization, which has been shown to culminate in the 12-year *S. alterniflora* salt marsh (Liu et al., 2007; Wang et al., 2013; Yang et al., 2013; Hang et al., 2014). In Bohai Bay, the level of total carbon (TC) in *S. alterniflora* sediment after the colonization is higher compared with the mudflat (Chai et al., 2014). In summary, exotic *S. alterniflora* increases the SOC in the local ecosystems by altering the ecophysiological processes, resulting in changes in NPP and litter decomposition, and ultimately the enhancement of carbon stocks in the native ecosystems (Liao et al., 2007).

Others reported negative effects on soil carbon stock caused by *S. alterniflora* development. In the Yangtze River Estuary, the organic carbon storage in the surface soil (0–30 cm) from *P. australis* community (1048.62 g m^{-2}) is almost two times that of the *S. alterniflora* community (583.33 g m^{-2}) (Liu et al., 2013). In the Zhangjiang Estuary of Fujian Province, the topsoil carbon storage declines where *S. alterniflora* has displaced native mangrove ecosystems and co-exists with them (Zhang et al., 2008b). Furthermore, *S. alterniflora* grows deep roots to 50–100 cm and possibly does not contribute much to SOC in the top layer of sediments (Zhang et al., 2008b).

It was reported that global SOC storage in the top 3 m of soil is 2344 Pg, or 56% more than the 1502 Pg estimated for the top 1 m, which is similar to the total SOC storage estimates of 1500–1600 Pg made by other researchers (Post et al., 1982). Global total SOC storage in the 100–200 cm and 200–300 cm soils are 491 and 351 Pg C, respectively, and the biomes with the most SOC storage at 100–300 cm depth are tropical evergreen forests (158 Pg C) and tropical grasslands/savannas (146 Pg C) (Gitay et al., 2001). However, specific SOC in deep soil based on experimental data is insufficient to estimate the SOC storage, especially in the coastal wetlands. The effects of *S. alterniflora* on SOC distribution to 3 m depth in salt marshes is poorly understood due to the lack of data.

In this paper, soil cores of 3 m were sampled and analyzed, SOC measured to (1) study the effects of exotic *S. alterniflora* on vertical SOC distribution in local salt marshes, (2) compare the SOC at different depths between *S. alterniflora* and native salt marsh and (3) estimate the vertical SOC storage of the saltmarshes in the Jiangsu coastal region.

2. Materials and methods

2.1. Study area and sampling sites

The study area is located at Xinyanggang Estuary (32°34′-34°28′N, 119°48′-120°56′E) (Fig. 1), North Jiangsu Province, with sub-tropical and warm-temperate climate of clearly distinct seasons, mean annual temperature of 13.7–14.6 °C, annual total precipitation of 980–1070 mm, mean annual solar radiation of 485–506 kJ cm^{-2}, mean annual sunlight duration of 2241–2390 h a^{-1}, a frost-free period of 209–218 d a^{-1}. The tidal range is 3.75 m, and tidal periodicity is irregular semidiurnal. The local soil is of alluvial origin, composed of 19.6% sand, 40.1% silt, and 40.3% clay. Soil pH and soluble total salt concentration ranges are 8.30–8.63 and 2.00–8.00 g kg^{-1}, respectively. There are typical horizontal salt marsh vegetation zones in parallel with the shoreline, corresponding to the occurrence sequence landward as follows: mudflats without plant coverage and flooded by the tide twice a day; *S. alterniflora* vegetation zone where tidal flooding occurs twice a day, daily or weekly; native plant *Suaeda salsa* vegetation zone where tidal flooding occurs weekly or monthly depending on the meteorological conditions; grass flat at the supratidal zone covered with co-existing native plants *Aeluropus littoralis, Phragmites australis, Imperata cylindrical, Scripus karuizawensis,* and/or *Zoysiam jacrostachys* sheltered from tide where hydrological conditions depend on rainfall.

S. alterniflora was introduced into Xinyanggang Estuary in 1989, and since that time a series of permanent markers at *S. alterniflora* expansion fronts have been set to identify its development stages. A transect through the coastal wetlands from sea to land in the study area including ten sampling sites arranged as follows: (1) Mudflat (MF), the initial stage of coastal wetlands, where soil carbon content is used as a reference to that in the vegetation zones, (2) *S. alterniflora* salt marsh marked in 2009 (SAF2009), (3) *S. alterniflora* salt marsh marked in 2007 (SAF2007), (4) *S. alterniflora* salt marsh marked in 2003 (SAF2003), (5) *S. alterniflora* salt marsh marked in 1998 (SAF1998), (6) *S. alterniflora* salt marsh marked in 1989 (SAF1989), (7) *S. alterniflora* patches (SAP) at *S. salsa* salt marsh, (8) *S. salsa* salt marsh co-existing with *S. alterniflora* marked in 1989 (SS), (9) *S. salsa* salt marsh located in the inner part of that vegetation zone (SSI), (10) Grass flat sheltered from tide (GF).

2.2. Experimental methods

The sampling was conducted during the diurnal ebb-tide hours in July, 2012. At each sampling site, a stainless steel corer was applied to take three 3 m soil cores, which were sliced in the field. The top 0–100 cm of the cores was sliced at a 5 cm interval, the 100–200 cm sliced at a 10 cm interval, the 200–300 cm sliced at a 20 cm interval, totaling 35 soil slices from each soil core. The soil slices were put into sampling bags and transported to laboratory, air-dried naturally. Dry samples were then sieved (<2 mm) from which plant residue and shells were removed, milled in a mortar, and sieved through 100-mesh screen. Five grams of screened soil from each sample were weighed, treated with 1 mol L^{-1} hydrochloric acid solution for 24 h, and oven-dried at 60 °C, SOC was determined by stable isotope mass spectrometer (Sercon intergra CN) based on standard procedures.

2.3. SOCS estimation methods

Saltmarsh soil organic carbon storage (SOCS) at different depths was calculated as:

$$SOCS = A \times B \times C \times L$$

Where A is the specific saltmarsh area in Jiangsu (m^{-2}); B is the specific soil bulk density at different depth (kg m^{-3}); C is the specific soil organic carbon content at different depths (g kg^{-1}); L is the soil depths (m) at specific intervals.

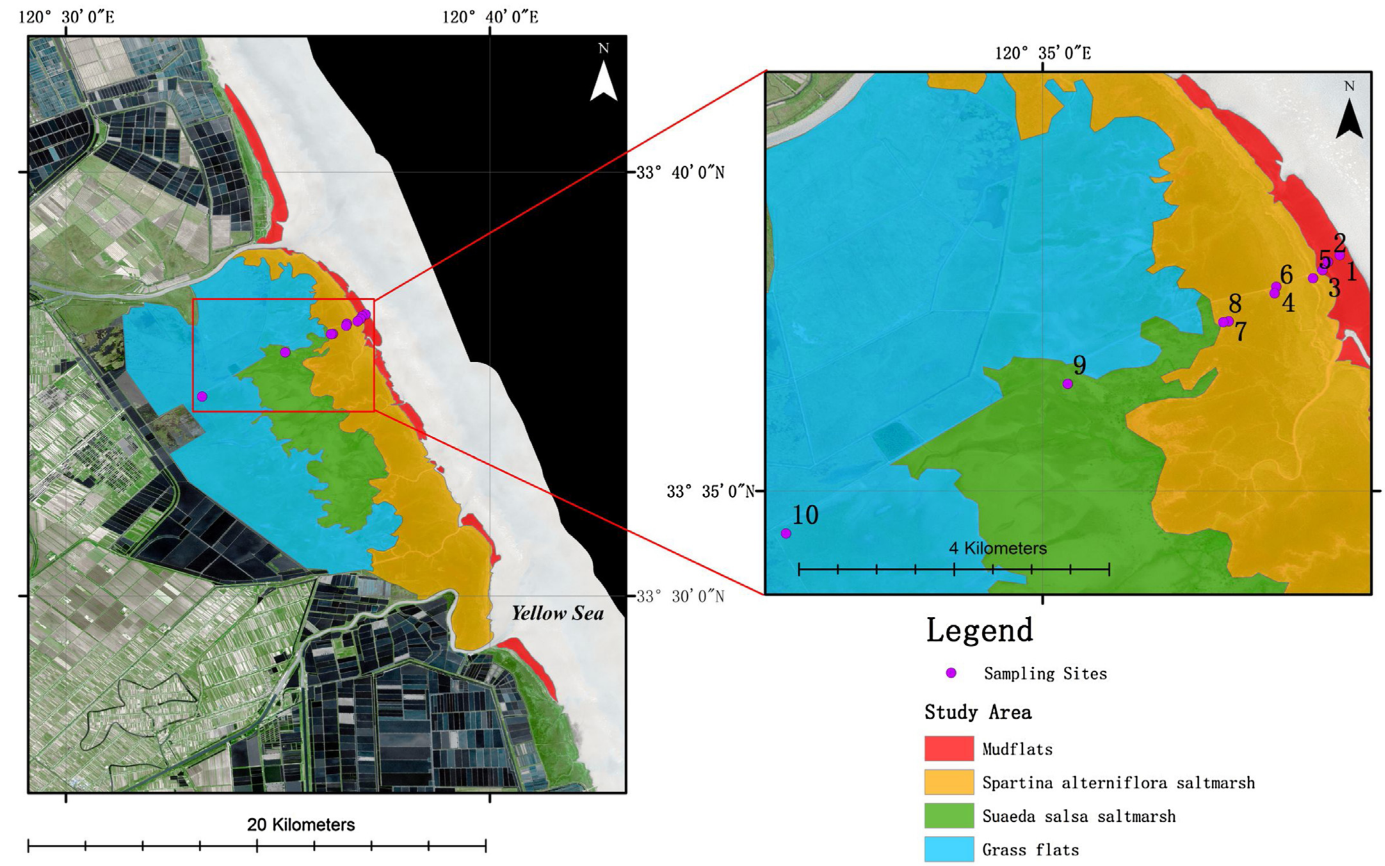

Fig. 1. The study area and sampling sites.

Data calculation was fulfilled on Excel 2003 and SigmaPlot 12.0; one way ANNOVA was used to test the SOC vertical fluctuation by SPASS 17.0.

3. Results and discussion

3.1. Effects of S. alterniflora developments on dynamics of vertical SOC distribution

S. alterniflora affects SOC reaching different depths among the sampling sites (Fig. 2). The mean SOC in mudflat (MF) ($1.57 \pm 0.08\,g\,kg^{-1}$) is set as control, and saltmarsh with SOC higher than that is considered to be affected by the vegetation cover. In the *S. alterniflora* zones, SOC is affected as deep as 50 cm–95 cm, revealing that general effects belowground of *S. alterniflora* on SOC reach deeper where *S. alterniflora* saltmarsh develops earlier. *S. alterniflora* affects SOC deeper (40 cm–95 cm) in the soil than a native plant *S. salsa* (SS, 40 cm) does, but less intensive in its effects than native grass (GF, 120 cm). *S. alterniflora* was reported to change the vertical SOC distribution in soil layers less than 100 cm (Liu et al., 2013), indicating same effect with our results. Interestingly, the plants co-existence zones, GF (120 cm) and SSI (180 cm), find the deepest effects on vertical SOC content distribution. The GF and SSI co-existing zones grow more plant species than other zones, indicating the edge effects of critical transition zones between different communities. Native plants in GF include *Aeluropus littoralis, Phragmites australis, Imperata cylindrical, Scripus karuizawensis,* and/or *Zoysiam jacrostachys* sheltered from tide where hydrological conditions depend more on rainfall, showing the complicated habitat characteristics between brackish water wetlands and salt marshes. The fact that the SSI (180 cm) grows *S. salsa* and *S. alterniflora* showing much deeper effects on SOC than mono-species plant zones indicates the edge effects between exotic salt marsh (50 cm – 95 cm) and native *S. salsa* salt marsh (40 cm). Such special edge effects shown in the transition zones are attributed to the habitat heterogeneity that leads to higher biodiversity. The impact depth increases with the vegetation development time. However, in SAF2009, the SOC content in the surface layer was significantly lower than any other sampling sites, followed by an increase at the 60 cm or deeper levels. SAF2009 lies in the frontier flooded by tide twice a day with around 12 h, capturing new sediments cover of low SOC, showing different vertical SOC distribution from other zones. The depth influenced by *S. salsa* is the lowest because its poor root system developed with a smaller biomass deposit into soil compared with *S. alterniflora*.

With the mudflats as a reference, the *S. alterniflora* increases the SOC content in the surface layer (0–50 cm) by 151%–275% with a range $0.73 \pm 0.04\,g\,kg^{-1}$–$5.70 \pm 0.74\,g\,kg^{-1}$, and the mean SOC content in the surface layer (0–50 cm) increased with development time of *S. alterniflora* salt marsh. The surface layer SOC content (0–50 cm) in *S. salsa* salt marsh is 11% lower than that in *S. alterniflora* salt marsh. However, at the ecotone of *S. alterniflora* and *S. salsa* (SSI), a significant increase by 120% in surface SOC content (0–50 cm) is observed, probably due to the synergistic influence of *S. alterniflora* and *S. salsa* on carbon storage. Similar effects also were observed in other *S. alterniflora* instruction region. In the Yangtze River Estuary, Seven years after the introduction of *S. alterniflora*, carbon and nitrogen concentrations had increased at most examined soil depths, with higher SOC in the soil dominated by *S. alterniflora* than native *Scirpus mariqueter*, except at deeper soil layers (>80 cm) (Cheng et al., 2006). Furthermore, the ten-year *S. alterniflora* developments significantly increased SOC

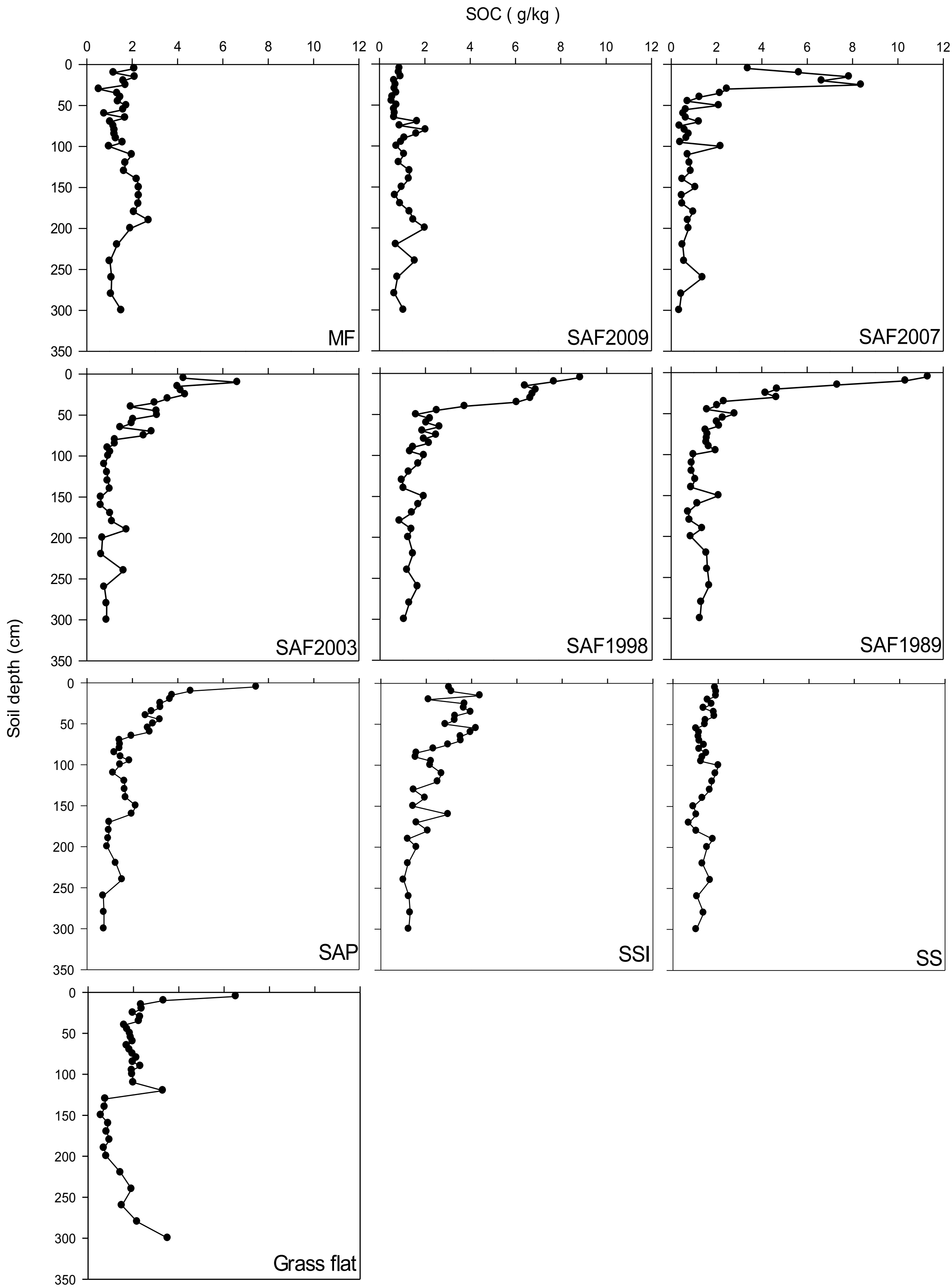

Fig. 2. Vertical distribution of the soil organic carbon content in *S. alterniflora*, *S. salsa* and grass flats in Xinyanggang Estuary in Yancheng coastal wetlands, China.

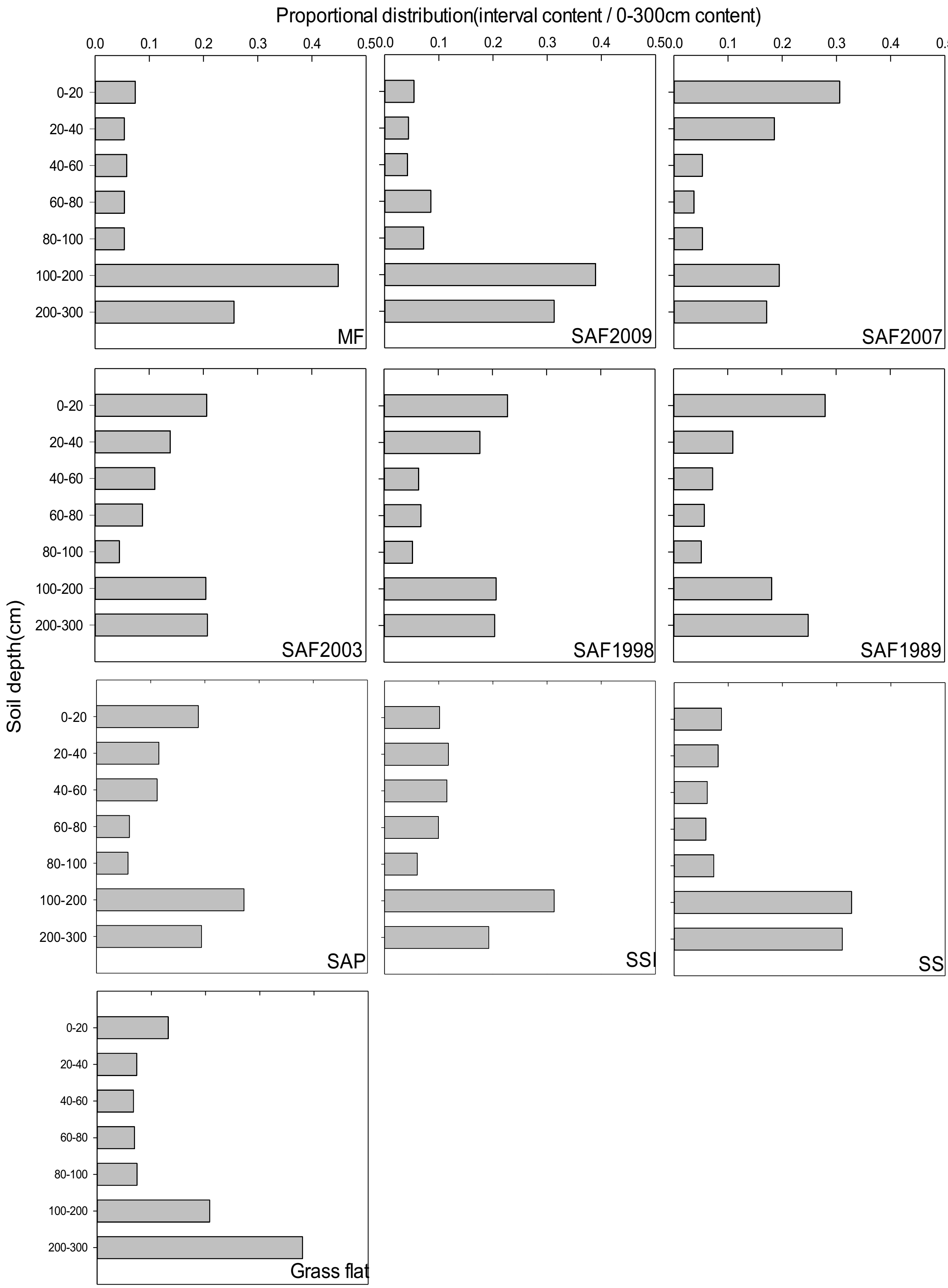

Fig. 3. Profiles of soil organic carbon distributions.

Table 1
Soil organic carbon (SOC) density, soil organic carbon storage (SOCS) and vertical distribution in Jiangsu salt marsh.

Biome	Land area (10^6 m^2)	SOC density (kg m^{-2})				Total SOCS (10^{10} g)			
		0–3 m	0–1 m	1–2 m	2–3 m	0–3 m	0–1 m	1–2 m	2–3 m
Mudflat	25.72[a]	8.26	2.44	3.71	2.12	21.24	6.28	9.54	5.45
S. alterniflora	39.19[a]	7.28	3.52	1.87	1.89	28.53	13.79	7.33	7.41
S. salsa	16.25[a]	6.71	2.10	2.37	2.25	10.90	3.41	3.85	3.66
Grass flat	26.68[a]	9.08	3.38	2.02	3.68	24.23	9.02	5.39	9.82
Jiangsu salt marsh	107.84[a]					84.90	32.20	26.11	26.34
Global average[b]	1.21×10^{14} m^2					2.34×10^{18} g	1.50×10^{18} g	4.91×10^{17} g	3.51×10^{17} g

[a] Hou et al. (2013).
[b] Esteban and Robert (2000).

by 1.69-5.3 fold compared with native species communities and bare mudflat (Yang et al., 2013). Compared with MF, the SOC content of GF increases by 73% in the 0–50 cm layer, but considerably decreases in the 140–200 cm layer, suggesting the ingredients and decomposition of SOC might be different in the grass flat dominated by native C3 species.

The deep soil (50–300 cm) has lower SOC content than that of the surface layer. In the *S. alterniflora* salt marsh, mean SOC in deep soil is 0.76 ± 0.08 g kg^{-1} 1.61 ± 0.09 g kg^{-1}, of which the highest deep SOC content is recorded at SAF1998, the *S. alterniflora* salt marsh with 14-year development time. Among native salt marshes, the sampling site co-existence zone (SSI) has the highest SOC content of 2.14 ± 0.19 g kg^{-1}, higher by 32.9% than that of SAF1998. SOC both in surface and deep layers shows vertical fluctuations (Fig. 2). The top 50 cm SOC in SAF1989, SAF1998, SAF2003, SAF2007 and SAP changes with higher amplitude, where the gap between adjacent soil layers is up to 5.92 g kg^{-1} with statistically significant differences ($P < 0.05$). In contrast, the deep SOC (50–300 cm) is more stably distributed, where the average gap between adjacent soil layers is between 0.00 and 2.54 g kg^{-1} without significant differences ($P > 0.5$) among them. As for the sites MF, SAF2009, SS, SSI and Grass flat, in the 0–300 cm soil layer, the average gap of SOC between adjacent soil layers is from 0.00 to 3.19 g kg^{-1} without significant differences among them ($P > 0.5$).

Generally, *S. alterniflora* affects the vertical SOC distribution, and the distribution depth increases with the development time of *S. alterniflora* as well as the surface layer SOC (0–50 cm) content.

3.2. Effects of *S. alterniflora* developments on vertical SOC proportional distribution

The SOC content in the mudflat (MF) and newly developed *S. alterniflora* salt marsh (SAF2009) is distributed in similar vertical proportions going through the 300 cm soils while the 100–200 cm accounts for major proportion (Fig. 3). Whereas the SOC content in *S. alterniflora* salt marsh developing for longer time than SAF2009 contains the major proportion of the SOC in 0–100 cm soils, which ranges between 49.47% (SSI) to 63.41% (SAF2007). For these sites the surface layer (0–100 cm) contains half of that in the 0–300 cm layer showing the significant effects of *S. alterniflora* growth on the SOC distribution. In addition, *S. alterniflora* promotes greater distribution of SOC in 0–50 cm soil than native plants.

When compared with MF, the SOC proportion in the surface soil layer, especially in 0–20 cm layer of *S. alterniflora* salt marsh increases, while the proportion in the deep soil layer (100–300 cm) decreases. Besides, the SOC content of SSI and GF increases in both the surface (0–100 cm) layer and bottom layer (200–300 cm). The above results reveal the relevancy between plant types and vertical distribution of SOC content (Esteban et al., 2000). *S. alterniflora* has sufficiently proliferated roots distributed mainly in the top 30 cm of soil occasionally extending to 50–100 cm belowground on salt marsh (Wang et al., 2006). And *S. salsa* has slim, short roots of lower biomass than that of *S. alterniflora*, while *P. australis* has subterraneous stems and a limited number of underdeveloped adventitious root. Tanner et al. (2007) has demonstrated that the SOC distribution is recognizably related to the plant root distribution. At the global scale the SOC contents increase with rainfall and decrease with temperature (Post et al., 1982), but at local scales the life form, functional type and above- and belowground allocation of biomass are considered the major determinants of the depth of SOC distribution (Jobbágy and Jackson, 2000b). In the present study, plants species and tidal flooding are attributed as major factors to the diverse vertical distribution of SOC among coastal wetlands sampling sites. Overall, the percentage of SOC in deep soil (100–300 cm) is greater than or close to 50%, higher than that reported by Esteban G et al. (2000), suggesting that SOC content of deep soil should not be ignored when calculating the global soil carbon stock.

3.3. Vertical SOCS amounts in Jiangsu salt marsh

In mudflat, *S. alterniflora* salt marsh, *S. salsa* saltmarsh and grass flat, all the SOC densities are not monotonically decreasing (Table 1) as reported cases (Jobbágy and Jackson, 2000b; Tanner et al., 2007). Looking just at the SOC density *S. alterniflora* is an improvement over native marsh for surface and total SOC density, but not for lower levels 100–200 cm and 200–300 cm. It is third overall in SOC density for 0–300 cm and first form 0–100 cm. In the 200–300 cm layer, SOC density in *S. alterniflora* salt marsh is less than that other sites, and decreases by 0.98 kg m^{-2} compared with the mudflat, while increases by 0.57 kg m^{-2} compared with *S. salsa* salt marsh. SOC density by depth changes with covered vegetation types, which keeps accordance with reported research (Yang et al., 2007). Overall SOC density in this study is lower than reported cases. According to Wang et al. (2004), mean SOC densities in the top 1 m in China ranged from 4.65 kg m^{-2} for bare ground to 17.32 kg m^{-2} in grassland land cover. In addition, Yang et al. (2007) reported that China's SOC storage to a depth of 1 m was estimated as 69.1 Pg (10^{15} g), with an average density of 7.8 kg m^{-2} which is higher than our results. Therefore, the salt marshes in Jiangsu are young ecosystems with the SOC density.

In Jiangsu, the total salt marsh area of 107.84 km^2 is composed of mudflat (23.85%), *S. alterniflora* salt marsh (36.34%), *S. salsa* salt marsh (15.07%) and grass flat (24.74%), respectively (Hou et al., 2013). Total SOCS within 0–300 cm in Jiangsu salt marsh is 84.90×10^{10} g, of which 0–100 cm, 100–200 cm and 200–300 cm layer counts 38.25%, 30.72% and 31.03%, respectively. The size of SOCS (0–300 cm) in Jiangsu salt marsh relative to the global biome (0.36×10^{-6}) is in a lower proportion than the salt marsh area to global biome area (0.89×10^{-6}) (Esteban et al., 2000). The amount of total SOCS at the global scale decreases with soil depth, which is not observed in this study. The total SOCS in 200–300 cm (26.34×10^8 g) is higher than that in 100–200 cm (26.11×10^8 g) due to the contributions of *S. alterniflora* salt marsh and grass flat, implying that *S. alterniflora* and native grass increase SOCS both in topsoil and deep soil. SOCS in 0–300 cm of mudflat, *S. alterniflora* salt marsh, *S. salsa* salt marsh and grass flat are 21.24×10^{10} g, 28.53×10^{10} g, 10.90×10^{10} g and 24.23×10^{10} g, respectively, and *S. alterniflora* salt marsh contributes more SOCS than native salt marsh, indicating that *S. alterniflora* enhances both topsoil SOCS (Liu et al., 2007) and deep SOCS. In mudflat, *S. alterniflora* salt marsh, *S. salsa* salt marsh and grass flat, the SOCS in 0–1 m accounts 29.50%, 48.33%, 31.23% and 37.20% of that in 0–300 cm, indicating that plants increase the proportion of the vertical SOCS distribution in the surface layer of salt marsh, and *S. alterniflora* affects the distribution more than *S. salsa*. Overall, the highest SOCS of the mudflat and *S. salsa* salt marsh distribute in 100–200 cm soils; the highest SOCS of the *S. alterniflora* salt marsh distribute in 0–100 cm soils; while the highest SOCS of the grass flat distributes in 200–300 cm soils. Furthermore, the *S. alterniflora* salt marsh contributes most of SOCS in the 0–300 cm and 0–100 cm soils; the mudflat contributes most of the SOCS in 100–200 cm soils; the grass flat contributes most of the SOCS in the 200–300 cm soils. Overall, it indicates that different vegetation types determine the vertical distribution of SOCS. SOCS is also determined by area currently occupied as well as density of SOCS, and *S. alterniflora* occupies the most area than other salt marshes zones, which makes the most amount of SOCS.

4. Conclusions

Based on the results we came to the conclusions that (1) *S. alterniflora* increases the SOC content and SOC density in 0–100 cm topsoil local salt marsh, and increases the vertical SOC distribution depth; and such effects increase with the development time of *S. alterniflora*. The percentage of SOC in deep soil (100–300 cm) is greater than 50% suggesting that SOC content of deep soil should not be ignored when calculating the global soil carbon stock; (2) The vertical SOC distribution in the transition zones with co-existing plants is deeper than that in mono-species sites; (3) Total SOCS within 0–300 cm of Jiangsu salt marsh is 84.90×10^{10} g, which is a lower proportional relationship than the salt marsh area to global biome area. *S. alterniflora* contributes most of SOCS in the 0–3 m and 0–1 m soils. Thus, the effects of introducing *S. alterniflora* apparently have increased the SOCS more than native plants.

Conflict of interest

All authors claim that they do not have any actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations.

Acknowledgements

We thank Zhao-yuan Yu (School of Geography Science, Nanjing Normal University, Nanjing 210023, China) for the assistance in improving the manuscript. This work was supported by the NSFC (41273082, 41403064), The National Key Basic Research Development Plan (973 Plan)(2014CB953801) of the Ministry of Science and Technology of China, and the Natural Science Foundation of the Jiangsu Higher Education Institutions of China(14KJB610007), Ph.D. Programs Foundation of Ministry of Education of China (20123207110013). We also thank assistance of Ya-ping Wu, Jie Xu, Peipei Yu and Fei Ye in the field sampling and laboratory treatments.

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