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Differences in carbon sink capacity and carbon storage of several typical modified tidal wetlands in the Yangtze River Estuary

Zhang Jialu
Tongji University
Dong Haoyu
Tongji University
Wang Lupei
Shanghai Puhai Surveying&mapping Co., ltd
Qian Liwei
Tongji University
Lv Daming
Shanghai Yuyou Survey and Design Co., ltd
Tao Weiguo
Shanghai marine monitoring and forecasting center
Qian Xiaofeng
Shanghai Administration Center for Ocean Affairs
Fu Xiaohua
Tongji University
Wang Lei (celwang@tongji.edu.cn)
Tongji University

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Abstract

Although tidal wetlands in the Yangtze River Estuary are important carbon sinks, some are modified by different engineering measures to protect beaches, prevent corrosion, and promote tidal flat siltation. Nevertheless, some basic characteristics of these modified wetlands are still retained for their ecological service functions. Elucidation of the differences in carbon sink capacity and carbon storage of different types of modified tidal wetlands and the underlying reasons can provide theoretical guidance and a scientific basis for the protection and rational utilization of tidal wetlands, so as to maintain and enhance their carbon sink capacity. In this study, five typical modified tidal wetlands in the Yangtze River Estuary, namely, enclosure coastal wetland with *Spartina alterniflora* (ECS), enclosure coastal wetland with *Phragmites communis* (ECP), siltation coastal wetland with *S. alterniflora* (SCS), rock rip-rap riverside wetland with *P. communis* (RRP), and reclamation riverside wetland with *P. communis* (ReRP), were selected as study zones, and their carbon sink capacity and carbon storage were evaluated by analyzing soil organic carbon density, plant carbon fixation, and soil CO_2 emissions. The possible reasons for the differences among these modified wetlands were considered based on elevation, average waterlogging time, tidal salt content, and vegetation types. The results showed that all the modified wetlands were net carbon sinks, with SCS exhibiting the highest carbon sink capacity (8.34–8.52 kg CO_2 m^{-2} $year^{-1}$), reaching the level of natural wetland, owing to its higher plant biomass and lower soil respiration intensity, followed by ReRP (2.68–3.15 kg CO_2 m^{-2} $year^{-1}$), ECP (2.56–3.37 kg CO_2 m^{-2} $year^{-1}$), RRP (2.94–3.04 kg CO_2 m^{-2} $year^{-1}$), and ECS (1.24–1.86 kg CO_2 m^{-2} $year^{-1}$). ReRP (26.89–27.82 kg CO_2 m^{-2}) with long carbon accumulation history and SCS (24.57–28.6 kg CO_2 m^{-2}) with high annual carbon sink capacity presented higher carbon storage (< 40 cm), followed by RRP (22.52–24.97 kg CO_2 m^{-2}), ECP (16.14–18.18 kg CO_2 m^{-2}), and ECS (5.74–6.70 kg CO_2 m^{-2}). The difference in waterlogging time caused by diverse elevation, salinity, and vegetation types significantly affected soil respiration and plant carbon fixation, thus impacting CO_2 emission and carbon sink capacity of different modified tidal wetlands. `

Introduction

Natural wetlands are important carbon sinks owing to their high primary productivity, low temperature, and anaerobic environment created by perennial waterlogging period, resulting in low activity of heterotrophic microorganisms and low decomposition rate, which can lead to low soil respiration (Bernal & Mitsch, 2012; Gallagher et al., 2022). Estuary wetlands are located in the transitional zone between fresh water and salt water, and comprise a variety of habitats, including mudflats, tidal flats, salt marshes, sandbars, and islands (Wang et al., 2012). In recent years, with the intensification of global warming trend, the carbon sink capacity and carbon storage of natural estuary wetland have gradually attracted wide attention (Barbier et al., 2011), and many studies have evaluated the function of estuary carbon sink through carbon budget (Mitsch et al., 2013). For instance, (Sutton-Grier & Howard, 2018) pointed out that estuary wetland is a typical carbon sink, while (Qian et al., 2019) estimated the carbon

storage of different types of Jiuduansha wetlands and found that the carbon storage in soil was closely related to carbon accumulation, and that the spatial pattern differences in carbon accumulation were mainly related to plant biomass and properties as well as tidal water properties.

Some factors influencing the carbon sink capacity and carbon storage of tidal wetlands have also been investigated (Qian et al., 2019; L. Wang et al., 2021). Plant properties directly determine the primary carbon fixation input into the wetland soil pool (Dong et al., 2020). Wetland elevation and water condition are the major influencing factors of CH_4 and CO_2 emissions from soils (Zhao et al., 2020). Tidal input can transport organic matter to the soil, which can increase the organic carbon content as well as CO_2 emission (Zhang et al., 2015). Temperature has a negative effect on wetland carbon storage capacity (Zhang et al., 2019), although high temperature is conducive to plant photosynthesis and can increase primary productivity, it can also enhance soil respiration (Wu et al., 2022). The annual sediment input and sedimentation rate can also affect plant growth and microbial activities in soil, controlling and restricting the carbon cycling process in wetland soil (Das et al., 2016; Zhang et al., 2022).

The Yangtze River Estuary wetland, including Jiuduansha wetland, Chongming Dongtan wetland, and Nanhui Dongtan wetland, provides important ecological service function for Shanghai, China. *Phragmites communis* is the most widely distributed vegetation type in the intertidal zone of the Yangtze River Estuary (Yan et al., 2020). In recent years, invasion of *Spartina alterniflora*, with high primary productivity, developed root system, and high carbon fixation capacity, has been detected (Li et al., 2020). With the decrease in sand from the upper reaches of the Yangtze River during the past two decades, the Yangtze River Estuary wetland faces the risk of erosion; hence, some measures such as siltation promotion, riprap, and revetment have been adopted to protect beaches, prevent corrosion, and promote tidal flat siltation (Xie & Yan, 2011). Besides, enclosure and reclamation measures had also been taken in response to land shortages (Zhong et al., 2016). These engineering measures have resulted in different types of modified tidal wetlands. In recent years, with increasing attention on wetlands, some modified wetlands are still protected, retaining their basic characteristics, such as high primary productivity, perennial waterlogging period, and vegetation diversity; as a result, certain ecological service functions might still be retained, including nutrient storage and recycling, purification and degradation of toxic substances, and climate regulation.

Materials And Methods

The enclosure coastal wetland is located in the north bank of Hangzhou Bay (121° 18' 45" E, 30° 42' 9" N and 121° 19' 59" E, 30° 42' 3" N) (Fig. 1c, 1d). In 1985–1990, the area was surrounded when the dike axis was laid on the mud surface of 0.3–0.5 m of beach elevation. The beach protection project in front of the dike was groin, and the length of the groin was about 90 m. There were culverts under the groin, allowing the tide to pass through. In 1997, the soil was filled to about 3 m in the area. In the second year, *S. alterniflora* and *P. communis* were planted (Li et al., 2021). In the present study, ECS and ECP were established in this area with high tidal salinity (26.1–30.8 psu) (Wu, 2016).

RRP is located on the east side of Sancha Port (121° 46' 10" E, 31° 13' 16" N) at the confluence of the Yangtze River and Huangpu River in Pudong New Area (Fig. 1f), which is a riverside wetland created by the confluence of the rivers. To prevent erosion, the tidal flat was treated by ripped rock. The elevation of the beach surface at the convex bank of the section has been about 3 m. The flat surface increases slowly, and the main vegetation is *P. communis* with low tidal salinity (≈ 0 psu) (Tao, 1992).

ReRP is located at the junction between Chongming North Lake and Chongqi Bridge (121° 48' 53" E, 31° 36' 59" N) (Fig. 1g). The flat is naturally formed by the continuous deposition of sediment discharged from the Yangtze River under the interaction of river and sea, which is a typical impact plain terrain. From December 2002 to February 2004, the Yongxing Dam Project was implemented in the 3006.67-ha area along the northern edge of Chongming in the first phase. The deposition was obvious, and the deposition thickness was more than 3 m in some places (Chi et al., 2020). At present, it has become a lakeside wetland owing to tidal isolation. In recent years, the elevation of the flat is stable, and the vegetation is mainly *P. communis* with low tidal salinity (≈ 0 psu) (Shi et al., 2007). The location, main vegetation, and tidal conditions of the five typical modified tidal wetlands are shown in Table 1.

Table 1
Basic information of the studied zones

Area	Location	Main vegetation	Tidal input	Tidal salinity
ECS	121° 18' 45" E, 30° 42' 9" N	*S. alterniflora*	√	High (26.1–30.8 psu)
ECP	121° 19' 59" E, 30° 42' 3" N	*P. communis*	√	High (26.1-30.83 psu)
SCS	121° 55' 58" E, 31° 0' 25" N	*S. alterniflora*	√	High (6.9–16.6 psu)
RRP	121° 46' 10" E, 31° 13' 16" N	*P. communis*	√	Low (≈ 0 psu)
ReRP	121° 48' 53" E, 31° 36' 59" N	*P. communis*	×	Low (≈ 0 psu)

Site setup and sampling

The five study zones are located in the Yangtze River Estuary (Fig. 1b). Three belt transects were established in each zone from high to low flat. In each belt transect, three points were selected at equidistance and soil samples were collected from these points and mixed to obtain a single sample of that belt transect (Fig. 1c–1g). For soil carbon density analysis, soil samples (0–40 cm) were collected in summer and autumn of 2020 and spring of 2021. All the soil samples were packed in individual sterile plastic bags, immediately stored at 4°C, and transported to the laboratory.

Plant samples were collected in autumn 2020 (November 10), with one plant sample obtained from each of the soil sampling points. In each sampling point, the plant sample was selected in a quadrat of 50 × 50 cm. The plant tissues were obtained from the plant parts, treated in an oven at 105 C for 15 min, and then dried at 80 C to a constant weight.

Analysis methods

Elevation measurement

The elevation was measured according to the technical standard of the fourth grade leveling line (Table 2) (GB/T 12898 – 2009). Before the measurement, the leveling instrument and leveling ruler were checked. For level observation, Suguang DSZ2 leveling instrument with grid double-sided leveling ruler was used, and the middle wire method was employed to record the data. The elevation of the starting point was determined using the control point results of the “18-mile pile repair survey and supplement survey project” to measure the elevation control points in the area according to the fourth level. All the limits met the requirements of the fourth grade leveling line (Table 2). To better reflect the elevation of each vegetation zone, the elevation of vegetation zone was measured by cross-section observation. According to the elevation control points, the elevation of cross-section points was directly ascertained by geometric leveling method.

Table 2
The technical standard of the fourth grade leveling line

Line of sight length	backsight and foresight length difference	Cumulative disparity of sight distance	Accidental median error per kilometer level	Total median error per kilometer level measurement	misclosure in leveling
≤ 100m	≤ 5.0m	10.0m	5.0mm	10.0mm	$20\sqrt{L}$mm

Plant sample analysis

Plant biomass

The harvested aboveground plants were rinsed with water, treated at 105°C for 15 min, and then dried at 80°C to a constant weight. It has been reported that many factors affect the proportional relationship between total biomass and aboveground biomass of *S. alterniflora* and *P. communis* (Liu et al., 2022; Negrin et al., 2012; Shao et al., 1995; Wang et al., 2022). As the annual growth of underground biomass is limited, aboveground plant biomass was used for subsequent calculations of plant CO_2 fixation capacity in the present study. The plant biomass in each zone was ascertained based on the average values of triplicate measurements.

Plant organic carbon content

The organic carbon content was determined by total organic carbon analyzer (Shimadzu TOC-VCPN, Japan) as described previously (Dong et al., 2020).

Plant carbon fixation

The annual plant carbon fixation per unit area in different wetlands was calculated as follows: Plant carbon fixation (kg CO_2 m^{-2} $year^{-1}$) = Plant biomass (g m^{-2} $year^{-1}$) × Plant organic carbon content (g C

kg^{-1}) /100 × Mr (CO_2) / Mr (C).

Soil sample analysis

Bulk density

Bulk density refers to the ratio of a certain volume of soil (including soil particles and pores between them) to the volume of soil before drying. The surface soil samples were transported to the laboratory and transferred to an aluminum box. After drying (105°C–110°C, 24 h), the dry soil weight was determined, and the dry soil mass per unit volume was further calculated as follows: Bulk density = Dried soil sample mass / Aluminum box volume.

Soil organic carbon content

The soil organic carbon content was determined using total organic carbon analyzer (Shimadzu TOC-VCPN, Japan). Approximately 50 mg of soil were passed through a 60 mesh sieve, and the sample was directly loaded into a TOC analyzer. The absolute error of parallel samples was not > 5% (Dong et al., 2020), and was calculated for each area based on the average soil organic carbon content values of the three sampling points.

Soil respiration

Soil respiration was determined by LI-8100 automatic soil carbon flux measurement system (Li-Cor Inc., Lincoln, NE, USA). During the sampling period of each quarter, PVC soil rings were arranged at each sample point (arranged at low tide), and the position of the soil ring was kept unchanged throughout the measurement period. Each sample was measured three times in a season, totaling to 12 times in four quarters. The seasonal soil respiration intensity of each zone was calculated by the average value of the data obtained from all the detection points in the zone (Dong et al., 2020). The average soil respiration in each zone during the plant growth period was calculated using the average soil respiration values for four quarters.

CO_2 Emission

During the waterlogging period, soil respiration can be extremely low or even negative (absorbing CO_2). Therefore, the average waterlogging time in 365 days should be excluded when calculating the amount of CO_2 emission from soil in each zone in the four seasons (365 days). The average time of water surface exposure in each zone in 365 days was assessed according to the average elevation and tidal level of each zone, and the annual CO_2 emission per unit area of soil in each vegetation cover zone was determined as follows:$$\mathrm{S}R_y = 3600 \times 365 \times (24 - T) \times SR_s \times M_{CO_2} \times 10^{-9}$$

where SR_y is the CO_2 emission (kg m^{-2} $year^{-1}$), T is the average waterlogging time (h day^{-1}), SR_s is the average soil respiration intensity (μmol m^{-2} s^{-1}), and M_{CO_2} is the molar mass of CO_2 (44 g mol^{-1}).

Carbon budget

The carbon budget per unit area in each zone was obtained by subtracting the soil CO_2 emission (365 days in four seasons) from the annual plant carbon fixation (CO_2) per unit area in each zone as follows: Carbon budget (kg CO_2 m^{-2} $year^{-1}$) = Plant carbon fixation (kg CO_2 m^{-2} $year^{-1}$) – CO_2 emission (kg m^{-2} $year^{-1}$).

Carbon storage

The soil carbon storage in different zones was determined as follows: Soil organic carbon density (kg CO_2 m^{-2}) = Soil organic carbon content (g C kg^{-1}) × Bulk density (g cm^{-3}) × Soil thickness (m) × Mr (CO_2) / Mr (C).

Statistical analysis

All the results were calculated based on the average values of parallel samples in each region. Least significant difference (LSD), Duncan, and correlation analyses were performed using SPSS, with P = 0.05, and the error was represented by standard deviation (SD).

Results

Elevation and average waterlogging time of the five typical modified tidal wetlands in the Yangtze River Estuary

Table 3
Physical parameters[a]

Zone	Main vegetation	Mean (and range) Elevation(m)	Mean waterlogging time (h day^{-1})
ECS	*S. alterniflora*	3.89(3.25 ~ 4.52)	7.2
ECP	*P. communis*	4.26(4.01 ~ 4.50)	5.3
SCS	*S. alterniflora*	3.57(3.12 ~ 4.02)	8.7
RRP	*P. communis*	3.39(1.96 ~ 4.82)	10.4
ReRP	*P. communis*	3.95(2.85 ~ 5.05)	≈ 0

[a]Average waterlogging time was calculated according to the average elevation and tidal level of each zone, the average time of water surface exposure in each zone within 365 days was calculated. Content in ( ) is the elevation range of zones.

There were differences in the elevation of the five typical modified tidal wetlands. ECP exhibited the highest average elevation (4.26 m), followed by ReRP (3.95 m), ECS (3.89 m), SCS (3.57 m), and RRP (3.39 m) (Table 3). When compared with the siltation wetland and rock rip-rap wetland, the reclamation wetland and enclosed wetland generally presented higher average elevation because blowing artificial sand led to obvious sediment accumulation and rapid formation of flat.

The average waterlogging time for each zone was calculated according to the average elevation and tidal level of each zone, and was found to be 10.4, 8.7, 7.2, 5.3, and 0 h day^{-1} for RRP, SCS, ECS, ECP, and ReRP, respectively. As ReRP was reclaimed almost without tidal input, its waterlogging time was almost 0 h day^{-1}.

Figure 3a shows the soil respiration of the five zones in the four seasons. Soil respiration was highest in summer and lowest in winter in all sites. The average soil respiration of ReRP (1.64 ± 0.03 μmol m^{-2} s^{-1}) was the highest, followed by ECS (0.95 ± 0.04 μmol m^{-2} s^{-1}), ECP (0.9 ± 0.03 μmol m^{-2} s^{-1}), SCS (0.58 ± 0.02 μmol m^{-2} s^{-1}), and RRP (0.39 ± 0.02 μmol m^{-2} s^{-1}).

The amount of CO_2 emission per unit zone (excluding waterlogging time) was calculated based on the average soil respiration (Fig. 3b). ReRP presented the highest CO_2 emission (2.24–2.31 kg CO_2 m^{-2} $year^{-1}$), followed by ECS (1.27–1.37 kg CO_2 m^{-2} $year^{-1}$), ECP (1.21–1.29 kg CO_2 m^{-2} $year^{-1}$), SCS (0.78–0.83 kg CO_2 m^{-2} $year^{-1}$), and RRP (0.52–0.56 kg CO_2 m^{-2} $year^{-1}$). As the weak alkalinity (Li et al., 1999; Li, 2022) of the tide could dissolve CO_2 and prevent its release into the atmosphere, the effect of waterlogging time on the amount of CO_2 emission per unit area (including waterlogging time) was determined for each zone based on the corresponding average waterlogging time (Table 3). As indicated in Fig. 3b, ReRP exhibited the highest CO_2 emission (2.24–2.31 kg CO_2 m^{-2} $year^{-1}$), followed by ECP (0.94–1.01 kg CO_2 m^{-2} $year^{-1}$), ECS (0.89–0.96 kg CO_2 m^{-2} $year^{-1}$), SCS (0.50–0.53 kg CO_2 m^{-2} $year^{-1}$), and RRP (0.29–0.32 kg CO_2 m^{-2} $year^{-1}$). For each zone, the CO_2 emission calculated considering the waterlogging time was lower than that determined excluding the waterlogging time, with the decrease ratio being low for high tidal flat and high for low tidal flat.

The carbon budget was ascertained based on plant carbon fixation and soil CO_2 emission in the five typical zones. It can be observed from Fig. 4 that all the five typical modified tidal wetlands were net carbon sinks. When excluding waterlogging time, SCS (8.06–8.22 kg CO_2 m^{-2} $year^{-1}$) presented the highest carbon budget, which reached the level of natural estuary wetland (Qian 2019). When waterlogging time was taken into consideration, SCS (8.34–8.52 kg m^{-2} $year^{-1}$ CO_2) still exhibited the highest carbon budget, whereas ECS (1.24–1.86 kg m^{-2} $year^{-1}$ CO_2) had the lowest carbon budget. Moreover, the carbon budget of ECP (2.56–3.37 kg m^{-2} $year^{-1}$ CO_2) was higher than that of ECS (2.35–3.24 kg m^{-2} $year^{-1}$ CO_2).

The soil organic carbon content was 2.750.14, 8.350.2, 15.740.51, 14.070.36, and 17.400.58 g C kg^{-1} in ECS, ECP, SCS, RRP, and ReRP, respectively. The bulk density of the five wetlands ranged between 1.05 and 1.60 g cm^{-3} (Fig. 5a). Based on the soil organic carbon content and bulk density (Fig. 5a), soil organic carbon density was calculated (Fig. 5b). SCS (24.57–28.6 kg CO_2 m^{-2}) and ReRP (26.89–27.69 kg CO_2 m^{-2}) exhibited higher soil organic carbon density, when compared with the other modified tidal wetlands (0–40 cm), indicating that SCS and ReRP had higher carbon storage. Interestingly, although

carbon storage is theoretically proportional to carbon sink capacity (Abbott et al., 2019; Qian et al., 2019), ReRP presented the highest carbon storage despite its carbon sink capacity not being the highest, and this phenomenon deserves further investigation.

Discussion

Main factors that affect plant carbon fixation efficiency of the five modified tidal wetlands

Carbon budget determines the carbon sink capacity of an ecosystem, and the annual plant biomass and plant carbon fixation are the main contributors to carbon income (Potter, 2010). The major factors that affect plant biomass and carbon fixation include plant types, the growth attributes of plants, and external environmental factors. The plant biomass and plant carbon fixation in SCS were the highest (6.59 ± 0.25 kg m^{-2} $year^{-1}$ and 8.84–9.05 kg CO_2 m^{-2} $year^{-1}$, respectively), whereas those in ECS were the lowest (1.91 ± 0.24 kg m^{-2} $year^{-1}$ and 2.20–2.75 kg CO_2 m^{-2} $year^{-1}$, respectively) (Fig. 2a, 2b). Although both SCS and ECS are coastal wetlands with *S. alterniflora* as the dominant plant species and high tidal salinity (6.9–16.6 and 26.1–30.8 psu, respectively), the average elevation of SCS (3.57 m) was lower than that of ECS (3.89 m), which resulted in longer average waterlogging time in SCS than that in ECS. These findings suggested that wetlands with high salinity and low elevation are more suitable for *S. alterniflora* growth. Similar findings have also been reported by (Yuan et al., 2021), who found that the strong salt tolerance of *S. alterniflora* is an excellent adaptation of plants in coastal wetlands to salinity environment.

Numerous studies have shown that the biomass of *P. communis* is slightly lower than that of *S. alterniflora* (Medeiros et al., 2013; Theuerkauf et al., 2015; Theuerkauf et al., 2017; Yan et al., 2018). However, in the present study, the biomass of *P. communis* (2.91 ± 0.19 kg m^{-2} $year^{-1}$) was significantly higher in ECP than that of *S. alterniflora* (1.91 ± 0.24 kg m^{-2} $year^{-1}$) in ECS, which is different from those observed in Jiuduansha wetlands (Qian et al., 2019). These contradictory findings may be owing to the high elevation of the enclosure coastal wetland examined in the present study, which was unsuitable for *S. alterniflora* growth, but conducive to *P. communis* growth. Similar results have also been reported by Packer et al. (2017) and Chen et al. (2005), who indicated that the best elevation for *P. communis* is about 4 m, while that for *S. alterniflora* is about 2.5 m.

As shown in Fig. 2a and 2b, the biomass and carbon fixation of *P. communis* in ECP, RRP, and ReRP were different. ReRP exhibited the highest plant biomass and carbon fixation (3.87 ± 0.10 kg m^{-2} $year^{-1}$ and 4.92–5.46 kg CO_2 m^{-2} $year^{-1}$, respectively), while ECP (2.91 ± 0.19 kg m^{-2} $year^{-1}$) and RRP (2.63 ± 0.10 kg m^{-2} $year^{-1}$) presented similar plant biomass. It must be noted that ECP had high tidal salt content (26.1–30.8 psu), RRP had low tidal salt content (≈ 0 psu), and ReRP had no tidal input because of the lake reclamation measures (Table 3). However, as the elevation of ReRP (3.95 m) was higher than that of RRP (3.39 m), it could be speculated that elevation had a greater effect on *P. communis* growth, because longer waterlogging time may not be conducive to *P. communis* growth. Furthermore, comparison of

plant biomass between ReRP and ECP revealed that low salinity may be more suitable for *P. communis* growth, similar to that reported by (Medeiros et al., 2013).

Therefore, *S. alterniflora* was noted to be more suitable for carbon fixation in wetlands with high salinity and low elevation, whereas *P. communis* was found to be suitable for carbon fixation in wetlands with high elevation, short waterlogging period, and lower salinity. Moreover, the effects of elevation on plant growth were observed to be higher than those of salinity.

Main factors that affect soil respiration intensity of the five modified tidal wetlands

Soil respiration is the main contributor to CO_2 emissions in tidal wetlands. From the perspective of carbon budget, effective improvement of plant carbon fixation and reduction of soil respiration can significantly enhance the carbon sink capacity of tidal wetlands (B. Wang et al., 2021).

In the present study, the average soil respiration of SCS (0.58 ± 0.02 μmol m^{-2} s^{-1}) was significantly lower than that of ECS (0.95 ± 0.04 μmol m^{-2} s^{-1}). As shown in Table 3, the average elevation of SCS and ECS was 3.57 and 3.89 m, respectively, and the main plant was *S. alterniflora*. SCS is a siltation-promoting zone, and the silt-promoting dam built at − 1.5 m may effectively reduce the elevation of the wetland, which could decrease soil respiration of the wetland.

The average soil respiration of RRP (0.39 ± 0.02 μmol m^{-2} s^{-1}) was significantly lower than that of ReRP (1.64 ± 0.03 μmol m^{-2} s^{-1}) (Fig. 3b). As shown in Table 3, the average elevation of RRP and ReRP was 3.39 and 3.95 m, respectively, and the main plant was *P. communis*. The ReRP was completely isolated from the tide after reclamation, resulting in higher average altitude and irregular flooding, leading to highest soil respiration (1.64 ± 0.03 μmol m^{-2} s^{-1}).

These results suggest that the elevation of wetlands may be an important factor affecting soil respiration, with lower elevation leading to longer waterlogging time, which can ensure anaerobic environment in soil, thereby reducing heterotrophic decomposition activity of soil microorganisms and significantly decreasing CO_2 emission. Similar findings have also been reported by Lewis et al. (2014), who found that the changes in elevation affect waterlogging time, which in turn can influence the soil carbon mineralization rate and CO_2 efflux rate.

In theory, the elevation of ECP (4.26 m) was higher than that of ECS (3.89 m), which must result in higher soil respiration of ECP; however, the soil respiration of ECP (0.90 ± 0.03 μmol m^{-2} s^{-1}) was slightly lower than that of ECS (0.95 ± 0.04 μmol m^{-2} s^{-1}). This result may be owing to the fact that *S. alterniflora* litter is easily degradable than *P. communis* litter, which could have promoted soil respiration. In a previous study, Yan et al. (2020) compared the changes in soil respiration before and after returning *S. alterniflora* and *P. communis*, and confirmed that *S. alterniflora* had higher biodegradability.

Thus, elevation, waterlogging period, and plant types are important factors affecting soil respiration. In particular, reclamation increases elevation and blocks tidal input to promote soil respiration, and the easy

biodegradability of *S. alterniflora*, when compared with that of *P. communis*, can also enhance soil respiration.

Relationship between carbon sink capacity and carbon storage of the five modified tidal wetlands

As shown in Fig. 5a, the soil organic carbon density in ReRP (26.89–27.69 kg CO_2 m^{-2}) was the highest, followed by SCS (24.57–28.6 kg CO_2 m^{-2}), RRP (22.52–24.97 kg CO_2 m^{-2}), ECP (16.14–18.18 kg CO_2 m^{-2}), and ECS (5.74–6.70 kg CO_2 m^{-2}). In theory, carbon storage is determined by carbon budget, and carbon budget is proportional to carbon sink capacity (Gao et al., 2021). Although ReRP exhibited weak carbon sink capacity, its carbon storage was the highest, which may be owing to the fact that ReRP was reclaimed without tidal input and no significant increase in elevation. Consequently, plant litter has remained buried in the surface soil for the past 15–20 years, resulting in the highest soil organic carbon content (17.40 ± 0.58 g kg^{-1}) above 40 cm of the surface layer. In contrast, the other modified wetlands had tidal input, which led to new deposition every year, with 5–10 years of deposition in the surface layer of 0–40 cm; thus, only 5–10 years of plant input formed the organic carbon in the surface soil, which was much briefer than that in ReRP.

The soil organic carbon density in SCS was also high (24.57–28.60 kg CO_2 m^{-2}), it was similar to that in ReRP. The reason may be owing to the low elevation of SCS, thus longer waterlogging time and low soil respiration, which is conducive to improving carbon sink capacity. In addition, there are factors of more tidal organic carbon input due to long waterlogging time. Consequently, SCS exhibited high soil organic carbon density and carbon storage.

In summary, elevation of tidal wetland is an important factor that affects soil respiration intensity by reducing heterotrophic decomposition activity of soil microorganisms. Higher soil organic carbon density can induce higher soil respiration, which is not conducive to subsequent carbon sequestration. When the beach develops to the elevation where plants can grow, the elevation of nascent tidal flat will continue to increase under the action of continuous deposition. While the soil organic carbon content in nascent sediments is low, the carbon sink potential of the vegetation coverage area is higher (reflected in the lower soil organic carbon content, higher plant carbon fixation, and lower soil respiration). Once the flat develops into land, the soil organic carbon content will gradually get saturated with the input of plant litter over the years, owing to the lack of new sediment sources, and will promote soil microbial heterotrophic respiration, which is not conducive to subsequent continuous carbon sequestration. Owing to the continuous deposition of sediment with low organic carbon content in siltation-promoting wetland, the surface soil organic carbon content and soil respiration remain low, resulting in significant carbon accumulation potential. However, when the wetland is reclaimed, it can quickly develop into land, coupled with no tidal input and no new deposition, causing saturation, which could reduce the carbon accumulation potential.

Conclusion

Based on the results of the present study, the following conclusions could be drawn:

(1) SCS had the highest carbon sink capacity, and SCS and ReRP had the highest carbon storage. (2) *S. alterniflora* is more suitable for carbon fixation in wetlands with high salinity and low elevation, whereas *P. communis* is suitable for carbon fixation in wetlands with high elevation, short waterlogging time, and lower salinity. The effect of elevation on plant growth is greater than that of salinity.

(3) Elevation and waterlogging period are important factors affecting soil respiration. Reclamation increases elevation and blocks tidal input to promote soil respiration. Besides, the easy biodegradability of *S. alterniflora*, when compared with that of *P. communis*, can also enhance soil respiration.

(4) Owing to no new siltation in reclamation wetlands, soil organics saturation and soil respiration increase, which is not favorable for continuous carbon accumulation. Thus, promotion of siltation and expansion of low-elevation beach wetlands are beneficial to carbon accumulation.

Declarations

Author Contributions Statement

Zhang Jialu processed the data and wrote the main manuscript text. **Dong Haoyu** took samples and investigation. **Wang Lupei** took charge of measurement. **Qian Liwei** took samples and provided the method. **Lv Daming** provided resources. **Tao Weiguo** was responsible for project management. **Qian Xiaofeng** was responsible for project management. **Fu Xiaohua** provided resources. **Wang Lei** designed the experiment and revised the manuscript. All authors reviewed the manuscript.

Declaration of competing interest

the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper

Data Availability statement

the results/data/figures in this manuscript have not been published elsewhere, nor are they under consideration by another publisher

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Figures

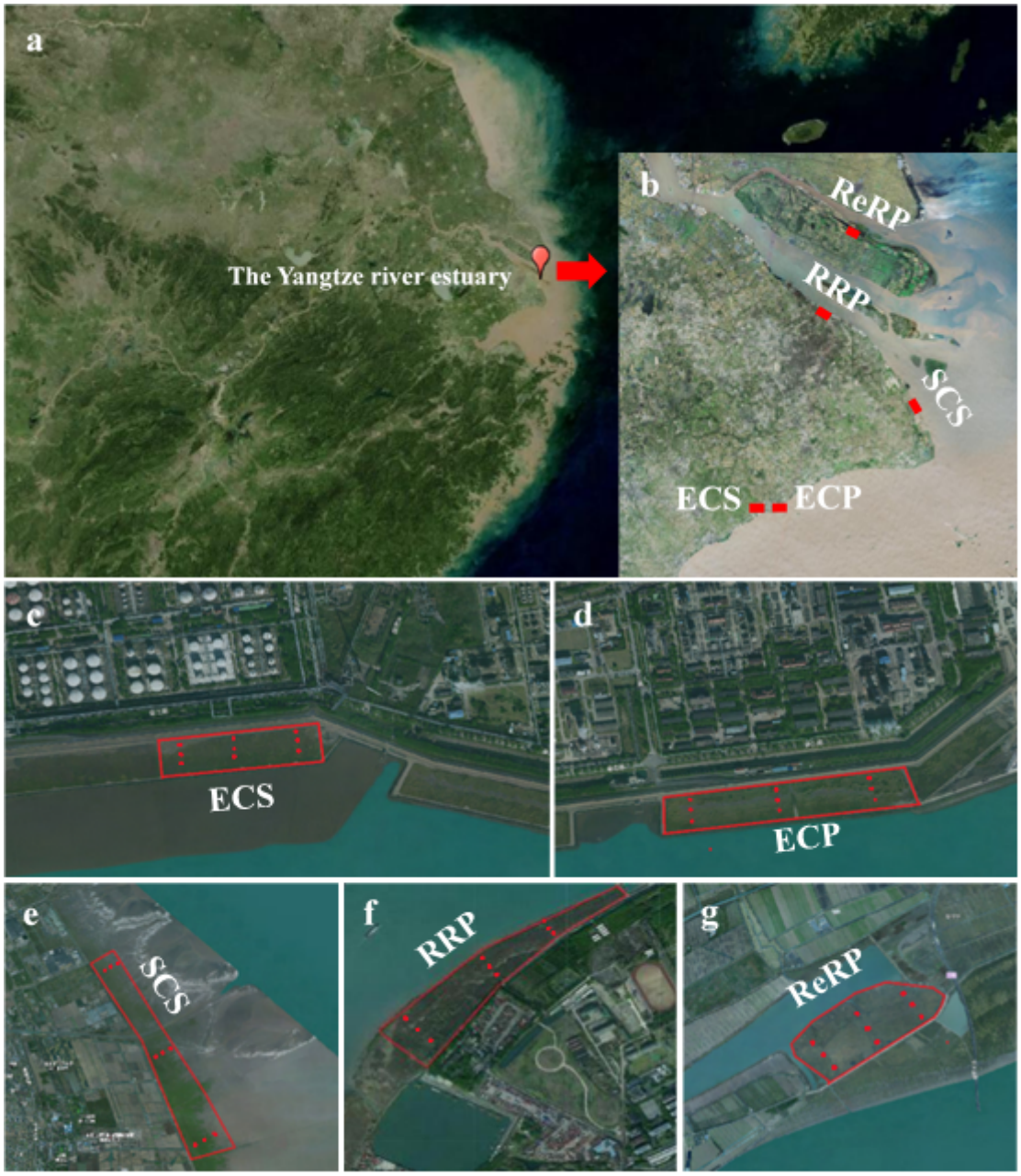


Figure 1

Map of the studied zone of five types of wetland in the Yangtze river estuary and three belt transects from high to low elevation in each zone. Each belt transect was equidistance selected three parts of the soil. Abbreviations represent: an enclosed coastal wetland with *S. alterniflora* (ECS), an enclosed coastal wetland with *P. communis* (ECP), Siltation coastal wetland with *S. alterniflora*(SCS), Rock rip-rap riverside wetland with *P. communis* (RRP), and Reclamation riverside wetland with *P. communis* (ReRP).

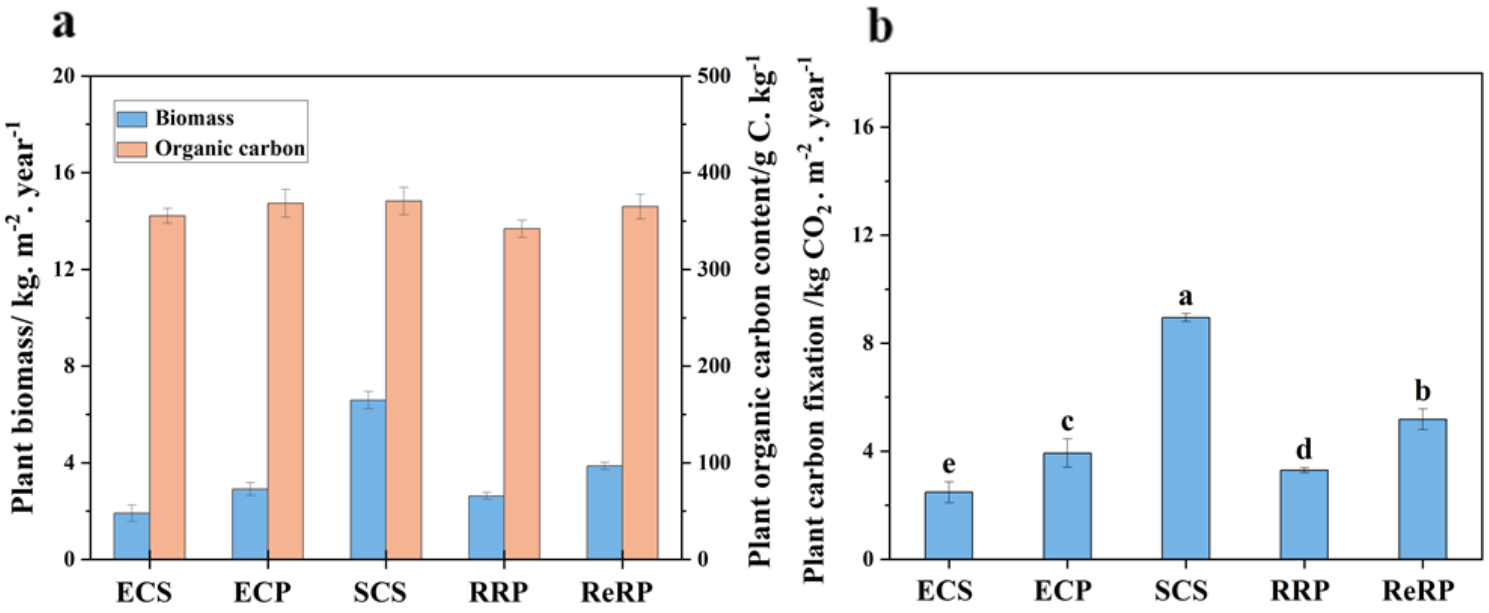


Figure 2

Plant biomass (means ± SD), plant organic carbon content (means ± SD), and plant carbon fixation of ECS, ECP, SCS, RRP, ReRP (a plant biomass and plant organic carbon content; b plant carbon fixation). a, b, c, d, e means that five zones were significantly different at the 0.05 level from high to low.

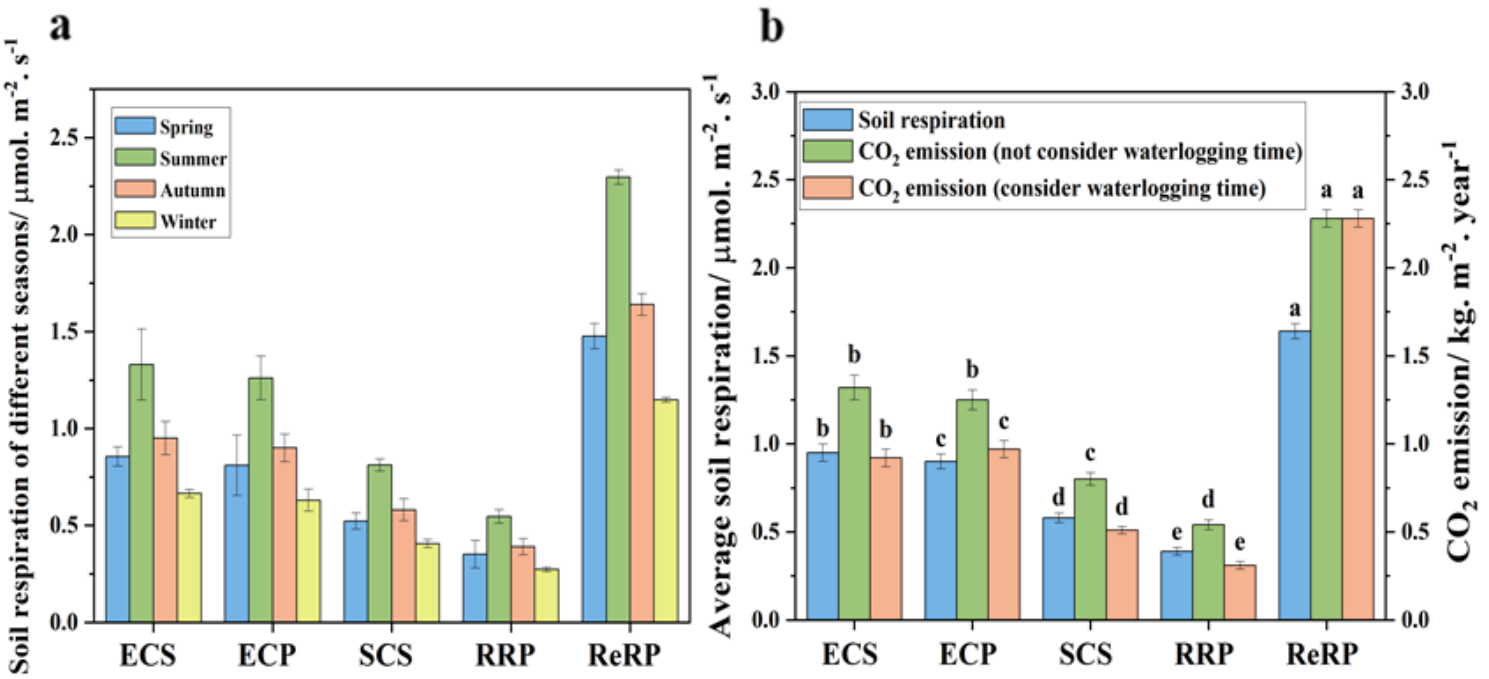


Figure 3

Soil respiration of different seasons (means ± SD), average soil respiration, CO_2 emission of ECS, ECP, SCS, RRP, ReRP (Panel a soil repiration of different seasons; panel b average soil respiration and CO_2 emission). a, b, c, d, e means that five zones were significantly different at the 0.05 level from high to low.

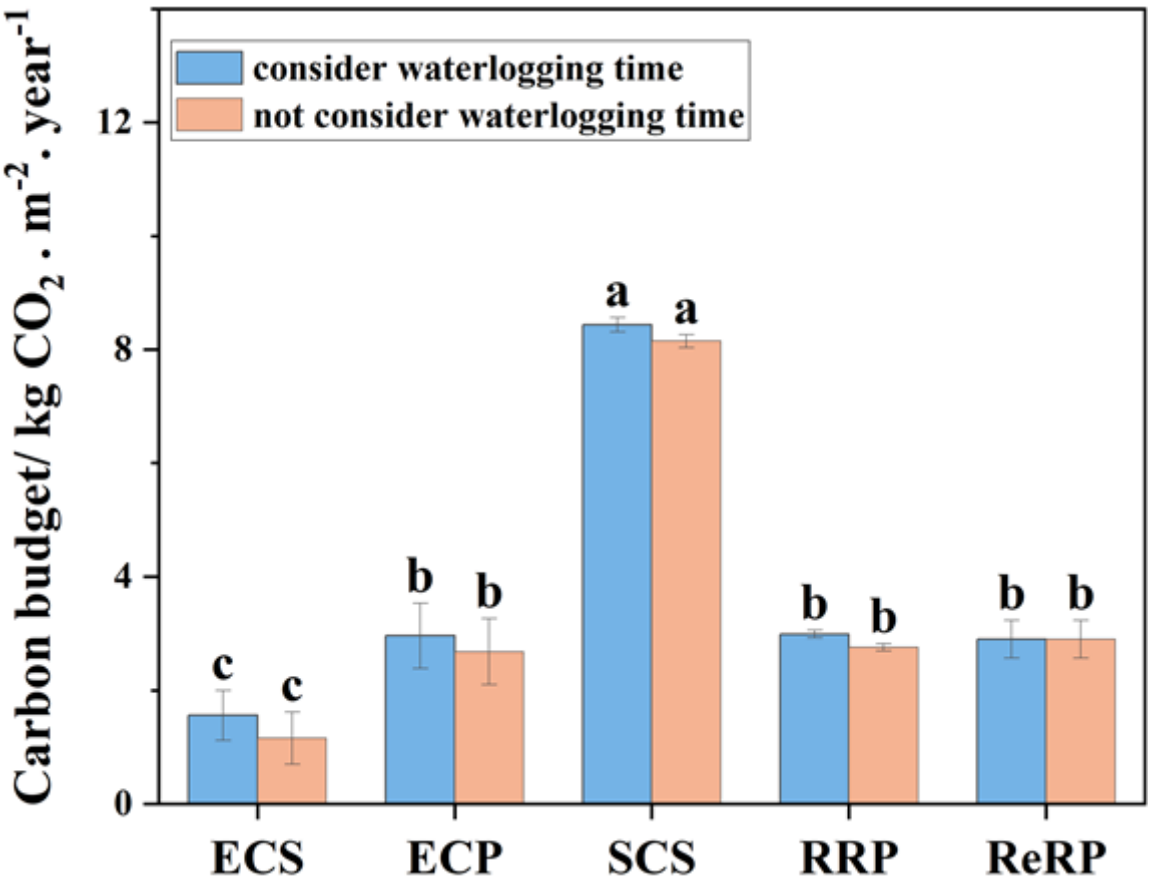


Figure 4

Carbon budget of ECS, ECP, SCS, RRP, ReRP (consider waterlogging time and not consider waterlogging time). a, b, c, d, e means that the five zones were significantly different at the 0.05 level from high carbon budget to low carbon budget.

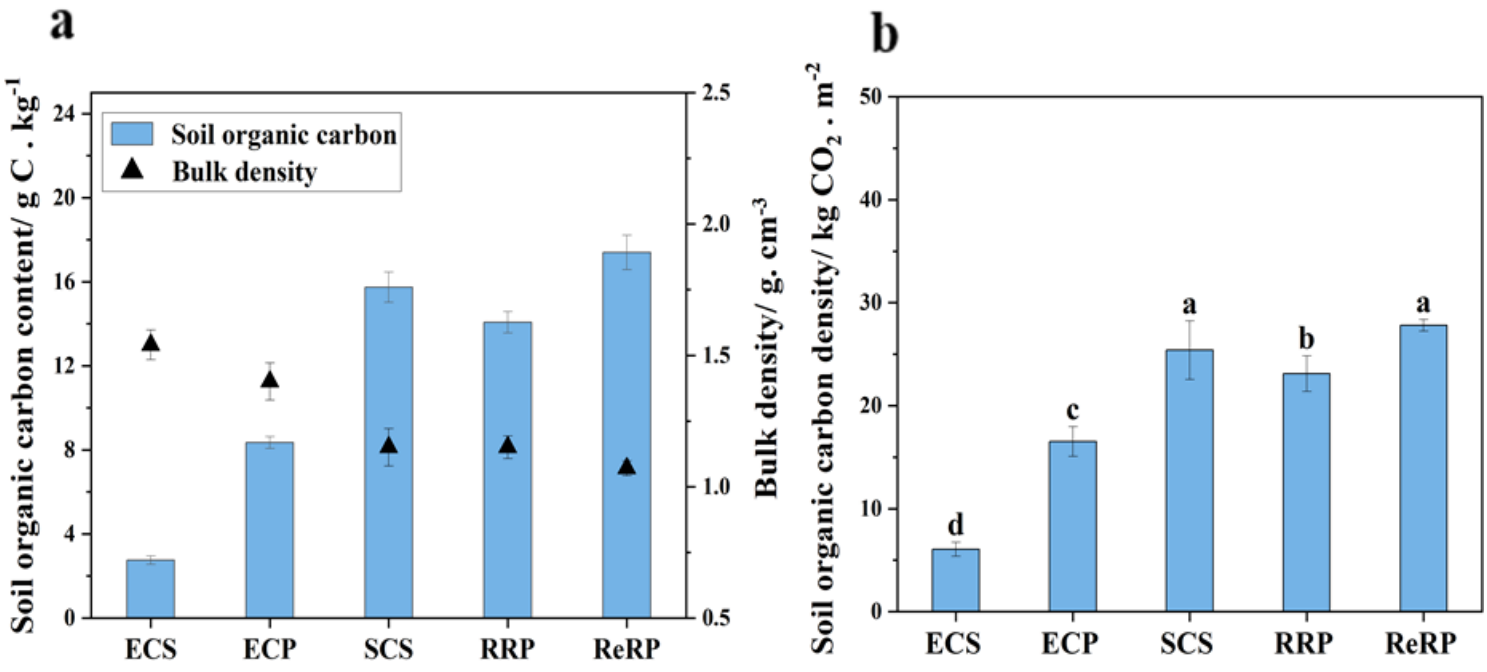


Figure 5

Soil organic carbon content (means ± SD), bulk density (means ± SD), and soil organic carbon density of ECS, ECP, SCS, RRP, ReRP (a soil organic carbon content and bulk density; b soil organic carbon density). a, b, c, d, e means that five zones were significantly different at the 0.05 level from high to low.