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Research Article

The Accumulation and Seasonal Dynamic of the Soil Organic Carbon in Wetland of the Yellow River Estuary, China

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The wetland of the Yellow River estuary is a typical new coastal wetland in northern China. It is essential to study the carbon pool and its variations for evaluating the carbon cycle process. The study results regarding the temporal-spatial distribution and influential factors of soil organic carbon in four typical wetlands belonging to the Yellow River estuary showed that there was no significant difference in the contents of the surface soil TOC to the same season among the four types of wetlands. For each type of wetlands, the TOC content in surface soils was significantly higher in October than that in both May and August. On the whole, the obvious differences in DOC contents in surface soils were not observed in the different wetland types and seasons. The peak of TOC appeared at 0–10 cm in the soil profiles. The contents of TOC and DOC were significantly higher in salsa than those in reed, suggesting that the rhizosphere effect of organic carbon in salsa was more obvious than that in reed. The results of the principal component analysis showed that the nitrogen content, salinity, bulk density, and water content were dominant influential factors for organic carbon accumulation and seasonal variation.

1. Introduction

The accumulation and decomposition of soil organic carbon in wetlands influence the stability of soil pools and CO_2 emission, which plays an important role in the global terrestrial carbon cycle and climate change. Meanwhile, maintaining the stability of carbon pools and the function of high carbon sinks is significant in mitigating concentrations of CO_2 in the atmosphere and increasing the wetlands' primary productivity [1, 2].

Estuary wetland ecosystems, especially, are ecotones located between terrestrial areas and marine areas with high net primary productivity and carbon sequestration, playing an important role in alleviating coastal eutrophication and reducing CO_2 emissions [3–5]. Soil total organic carbon (TOC) and dissolved organic carbon (DOC) in wetlands can sensitively reflect dynamics of soil pools, which play an important role in assessing accurately the process of carbon cycling and the potential of carbon sequestration [6, 7]. As we know, the accumulation and distribution characteristics of organic carbon in wetland soils are mainly influenced by the vegetation, litter decomposition, and climate conditions. On one hand, different types of plant communities and difference of vegetation development will have obvious influence on soil organic carbon contents, and soils with high primary productivity have high organic carbon storage [8]. Soil mechanical composition, bulk density, salinity, and nutritional status will influence the capacity of vegetation directly and affect the input and output of soil carbon [9]. Meanwhile, the plants in growth process affect the soil organic carbon content and distribution through changing the surrounding environment, especially the rhizosphere microenvironment (such as soil salinity, pH value, water, etc.) [2].

Currently, regional carbon cycle research is focused on the estimation of the distribution of soil stocks, carbon sequestration, and CO_2 emission reduction potential. To determine the uncertainty of the temporal and spatial distribution in regional carbon sources and sinks is of great importance for accurate decisions and a comprehensive understanding of the intensity, process, and mechanism of global carbon cycle [10].

The wetland of the Yellow River estuary, as a new ecosystem, is a typical coastal wetland in north China. The accumulation and decomposition of soil organic carbon in wetlands directly affect the primary productivity and the regional carbon balance; the dynamics of the soil carbon pool are essential to accurately evaluate the process of carbon cycling and the potential of carbon sequestration [11, 12]. The Yellow River estuary has four typical types of wetlands, including bare soil without vegetation, salsa (*Suaeda prostrata* Pall.), tamarix (*Tamarix chinensis* Lour.), and reed (*Phragmites australis*).

The aims of this study include three aspects as follows:

(1) to determine the temporal and spatial distribution characteristics of total organic carbon (TOC) and dissolved organic carbon (DOC) in the Yellow River delta wetlands with different plant communities;

(2) to compare the soil organic carbon distribution and rhizosphere effects between rhizosphere soil and nonrhizosphere soil that cover different typical plants, including reed and salsa;

(3) to discuss the relationship among soil organic carbon, soil texture, bulk density, water content, pH, total nitrogen, and inorganic nitrogen content.

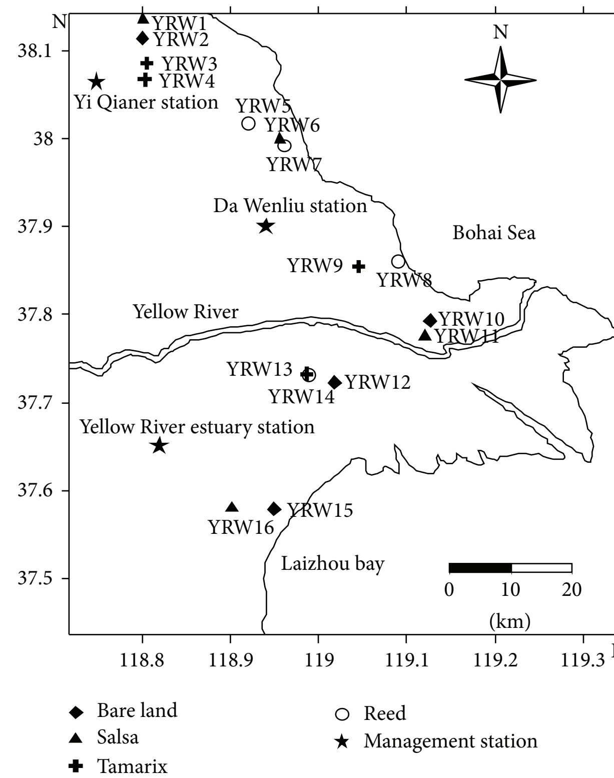


Figure 1: Location of studied region and sampling sites.

2. Materials and Methods

2.1. Study Areas. The Yellow River delta estuary wetlands (118°48′–119°08′E; 37°34′–38°09′N) are located in Dongying city in the Shandong province of China. The climate is a temperate humid northern continental monsoon climate with four distinct seasons, and the seasons alternate significantly. The mean temperature is 12.1°C and the evaporation capacity is 1962 mm. The average annual rainfall is 551.6 mm with rain and heat over the same period. With the uneven distribution of precipitation and the large evaporation capacity, the drought index reached 3.56 [13]. The typical soil types are alluvial soil and saline soil.

The predominant natural wetland vegetation is reed, tamarix, and salsa, of which distribution is mainly restricted by soil salinity, groundwater level, salinity, topography type, and human activities. Due to the impact of human activities, such as agricultural reclamation and artificial breeding, the salinization of wetlands was aggravated and the natural wetland was severely reduced and degenerated [14]. In 1992, to protect the estuarine ecosystems, the State Council approved a measure to establish the Yellow River Delta National Nature Reserve.

2.2. Soil Sampling. The four typical wetlands of bare soil (without vegetation, salsa wetland, tamarix wetland, and reed wetland) were chosen in the offshore estuary of the Yellow River delta. The four sampling points were selected in each type, with 16 total sites. There were 48 surface layer (0–20 cm) samples collected in October 2008, May 2009, and August 2009. There was one soil profile (YRW5, YRW9, YRW11, and YRW12) with a sampling depth of 60 cm in each type of wetland, and one sample was collected in 10 cm intervals. In the four soil profiles from the three seasons, 72 total samples were taken.

To discuss the rhizosphere effect of the plants on the accumulation of soil organic carbon, the typical reed and salsa communities were chosen and 11 (R1–R11) soil samples were collected from each rhizosphere and nonrhizosphere of reed soil (Figure 1). At the same time, eight (S1–S8) soil samples were collected from each rhizosphere and nonrhizosphere of salsa soil in August 2010.

2.3. Soil Analysis

2.3.1. Soil Carbon Analysis. The soil samples were naturally air-dried and hand-picked to remove obvious plant debris and roots, sieved (<2 mm) in the laboratory, and subsequently the soil was analysed. The total organic carbon was determined using an automated carbon analyzer (EA2000 elementary analyzer, Germany). The quality control used the standard soil samples GBW07403 as internal control samples, and the recovery was controlled at 98%–104% [15]. Then, 20% samples were randomly chosen as the duplicate samples to analyze, and all of the RSD measurements were less than 4%.

The 10 g fresh soil was taken and extracted in 50 mL distilled water, and then it was shocked continuously for 5 h at normal temperature (25°C). Next, it was centrifuged at high speed for 5 min. The supernatant was filtered from the 0.45 μm microfiltration. At last, the soil DOC was determined by using the TOC-V_{CPH} analysis meter [16]. Finally, 20% samples were randomly chosen as the duplicate samples to to analyze, and all of the RSD measurements were less than 5%.

2.3.2. Soil Physic-Chemical Properties Analysis. The soil moisture was determined by the oven-drying method. The bulk density was determined by the cutting ring method and the pH was determined by the potentiometry method in situ. After air drying and fully mixing, the soil particle size was measured by the hydrometer sieve analysis method. The total nitrogen (TN) was determined by the selenium-copper-sulfate-acid-digestion method [17], and the total phosphorus (TP) was determined by using the acid soluble-molybdenum antimony colorimetric method [17]. The standard samples GBW07403 were used as the internal samples, and the recovery rate was controlled 97%–100% and 90%–100%, respectively. The presence of ammonia (NH_4-N) was determined by using the indophenol blue colorimetric method [17] and the recovery rate was controlled 90%–104%. The level of nitrate (NO_3-N) was determined by using the phenoldisulfonic acid method [18] and the recovery rate was controlled 100%–105%. Throughout the experiments, 20% samples were chosen for parallel measurements, and all of the RSD measurements of the determined results were less than 4%.

2.4. Data Analysis. The statistics analysis and disposal of data were conducted by Suffer 8.0, Origin 8.5, and SPSS19.0. Significant differences in soil DOC and TOC were examined using one-way ANOVA at the 5% level of significance. To test effects of the soil physic-chemical properties on soil carbon principal components 1 (PC1) and 2 (PC2) of PCA, PCA was performed by SPSS19.0.

3. Results and Discussion

3.1. Dynamics of Organic Carbon in the Surface Soil. Figure 2 illustrated the distribution characteristics of the TOC contents in surface soils of four typical wetlands (bare soil, salsa, tamarix, and reed) in May, August, and October. In the studied areas, the TOC content amplitude of the surface soils was 1.12–6.41 mg g^{-1} and the mean value was 2.99 mg g^{-1} in May. The TOC content amplitude of the surface soils was 1.50–5.31 mg g^{-1} and the mean value was 2.41 mg g^{-1} in August. The TOC content amplitude of the surface soils was 6.97–18.24 mg g^{-1} with a mean value of 9.62 mg g^{-1} in October. The TOC content of Liaohe estuarine wetlands in surface soils was considerably higher than the Yellow River estuary wetlands' [15]. On the whole, the TOC content of surface soils in October was much higher than that in both May and August, and the difference was significant ($P < 0.05$). The same results were reported in Liaohe estuarine wetlands [15].

The TOC contents of the other three types of wetlands in May were slightly more than that in August, except for the bare soil without vegetation. When the wetland vegetation comes to mature period in October, the vegetation root system can fix more carbon. In addition, the amount of litter decomposition return made the organic carbon accumulated in autumn [19]. In May, the vegetation in the Yellow River estuary enters the growing season gradually, and the soil organic carbon mainly comes from the accumulation from the last year.

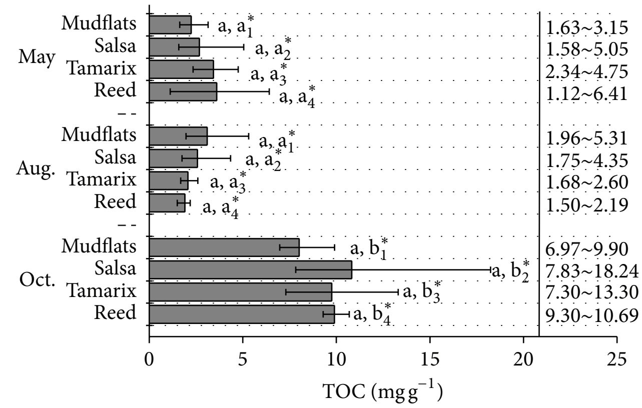


Figure 2: Soil TOC content in the four types of Yellow River estuary wetlands. The columns represent the average content of soil TOC, while the lines represent the variation range. The number at the right part is the range of TOC and the letters represent the difference of soil TOC in the different types of wetlands in the same season. The ∗ means the significant difference at the 0.05 level.

Through the long process of soil freezing in the winter, the decomposition and mineralization interaction of the organic fragment leads to the decomposition of soil carbon exceeding its accumulation [20]. Therefore, the soil carbon content in May was much lower than that in October. In August, it is hot and rainy in the area of the Yellow River estuary, providing the proper conditions for organic carbon mineralization and decomposition, and, thus, the content of soil organic carbon reduced slightly in August compared with that in May.

In October and May, the mean TOC contents of the surface soils for the salsa, tamarix, and reed wetlands were slightly higher than that in the bare soil without vegetation, because soils with vegetation could fix more carbon and make the accumulation of organic matter through the return of litter [21]. In August, the TOC content of the bare soil in the surface soils took advantage of that in vegetation communities, because the severe microbial mediation aggravated the mineralization and decomposition of the soil organic matter in the vegetation communities. But during the same month, the differences of TOC contents in the surface wetlands soils of the four types (bare soil, salsa, tamarix, and reed) were not significant ($P > 0.05$).

Figure 3 showed the distribution characteristics of DOC contents in surface soils in the four typical types of Yellow River estuary wetlands in May, August, and October. The DOC contents were 15.75–151.64 mg kg^{-1}, 10.59–46.69 mg kg^{-1}, and 15.06–100.28 mg kg^{-1}, and the average contents were 57.05 mg kg^{-1}, 21.43 mg kg^{-1}, and 42.58 mg kg^{-1}, respectively. The DOC contents of the different soil types (bare soil, salsa, tamarix, and reed) that accounted for the TOC contents in May were 1.60%, 2.22%, 1.65%, and 2.12%, respectively; 0.55%, 0.69%, 0.93%, and 1.66% in August, respectively; and 0.56%, 0.35%, 0.43%, and 0.47% in October, respectively. In total, among the surface soil DOC contents over the three months, May occupied first place, October came second, and August was the least. The DOC content of Liaohe estuarine wetlands in surface soils was about 7.55 mg/L, and

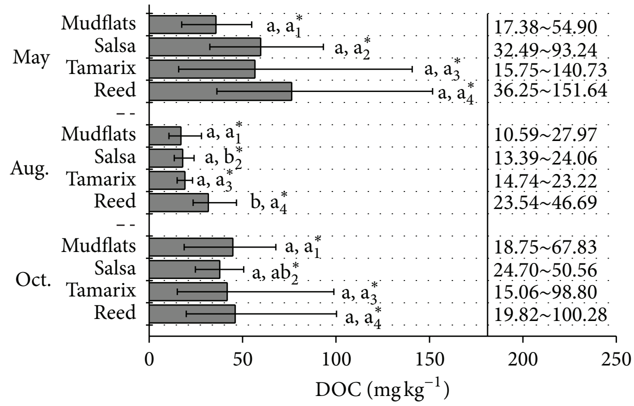


Figure 3: Soil DOC content in four types of Yellow River estuary wetlands. The columns represent the average content of soil TOC, the lines represent the variation range, the number at the right part is the range of TOC, the letters represent the difference of soil DOC in different types of wetlands in the same season, and $*$ means the significant difference at the 0.05 level.

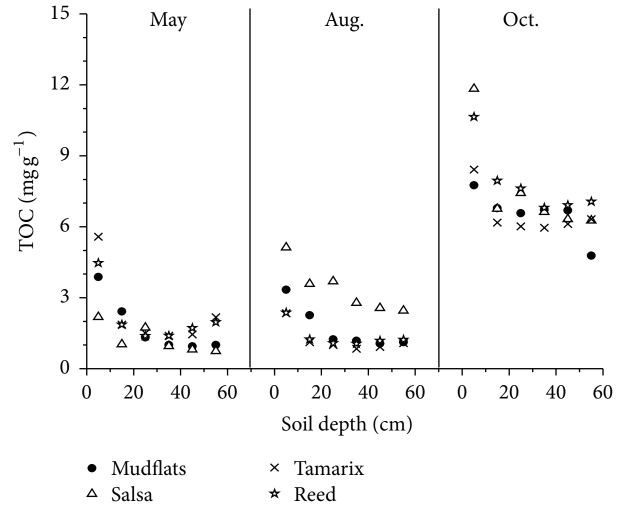


Figure 4: TOC contents in the soil profile of the Yellow River estuary wetland.

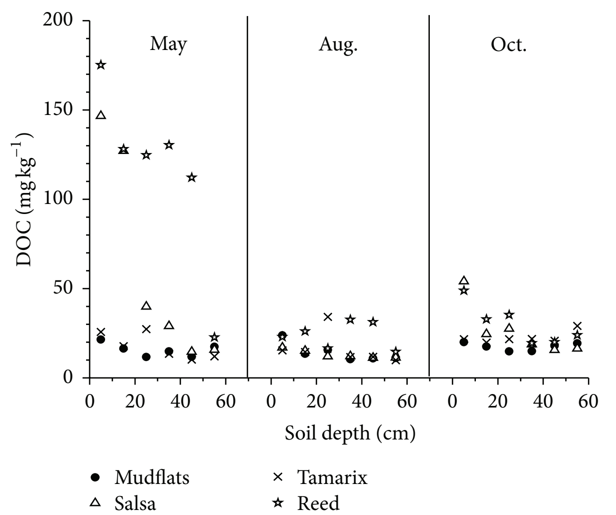


Figure 5: DOC contents in the soil profile of the Yellow River estuary wetland.

the seasonal variation was consistent with the Yellow River estuary wetlands'. The similar results in Liaohe estuarine wetlands were reported [22]. In spring, soil microbial activity has been gradually increased with much more metabolic products [22]. Therefore, the DOC contents in May were higher than other months. The DOC content in May shared 1.91% of the TOC content, about 1% higher than that in the general wetlands [23, 24]. As such, it revealed that the Yellow River estuary wetland in May had a high potential of degradation, matching the comparison of the TOC contents, which was significantly lower in May than that in October.

Compared with the different months in the same type of wetlands, the differences of DOC contents in the surface soils of bare soil, tamarix, and reed were not significant in May, August, and October; the differences of DOC contents in the surface soils of salsa were significant ($P < 0.05$) between in May and August. The DOC in May was significantly higher than that in August. Compared with the different types of wetlands in the same month, the differences of DOC contents in the surface soils of the four types of wetlands were not significant in May and October. In August, the differences of the DOC contents in the surface soils of the reed wetland and the other three types of wetlands were significant. Furthermore, the DOC content in the reed wetland was obviously higher than that in the other three types of wetlands.

3.2. The Dynamics of Soil Organic Carbon in Soil Profile. Figures 4 and 5 showed the distribution of TOC and DOC contents in the soil profile of the four typical types of Yellow River estuary wetlands. The results showed that the vertical distribution characteristics of TOC contents in the soil profile for the four types of wetlands were concentrated near the surface in May, August, and October. The peak of TOC contents was observed in 0–10 cm. The TOC content demonstrated very few changes in the soil profiles and the values remained low 20 cm below the surface of the soil. The plant root distribution in the study area was shallow and declined from surface towards the deep layers. The same vertical distribution characteristics of TOC contents in the soil profile were also reported in the Yellow River estuary tidal flat wetlands concentrated near the surface in Liaohe estuarine wetlands [25].

That form of root distribution determined the high organic material in the surface soil [25, 26], and the decomposition and half-decomposition products were mainly retained in the surface soil. The seasonal difference of the TOC contents in the soil profile was similar with the changes in the surface soil. The TOC contents in all of the studied wetlands were higher in October than that in both May and August.

Figure 5 showed that the DOC contents of the salsa and reed in the surface (0–10 cm) soil were much higher than they were below the surface soil in May and October. The DOC content was also higher than that in the surface of the bare soil and the tamarix. The surface soil DOC content was high, because the high degradation potential of the surface soil organic carbon from herbaceous plants occurred easily under high humification. The DOC contents of mudflats and tamarix in the soil profile underwent little change in May and October. The DOC contents of the four types of wetlands in the soil profile also underwent little change in August.

3.3. Dynamics of Organic Carbon in the Rhizosphere and Nonrhizosphere Soils. Rhizosphere is the interaction center of plants, soil, and microorganisms. The rhizosphere processes can induce change, through plant roots, in the physical structure of the surrounding soil. The release of root exudates and rhizosphere microorganisms can significantly influence the rhizosphere soil nutrients [27]. The reed and salsa plants in the wetlands of the Yellow River estuary were selected to compare the difference of soil organic carbon accumulation between the rhizosphere and the nonrhizosphere soil.

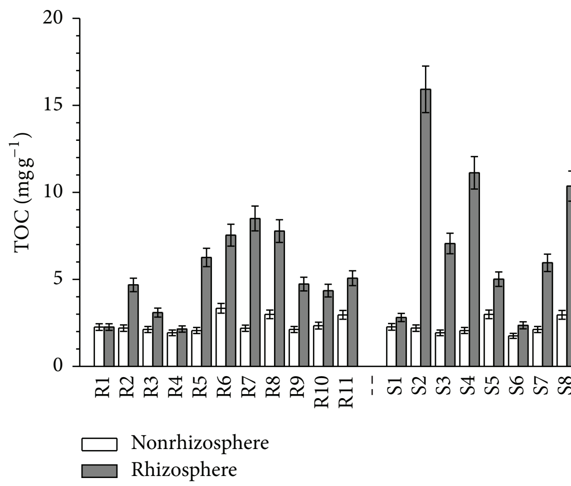
Figures 6 and 7 showed the TOC and DOC contents in the rhizosphere and nonrhizosphere soil of reed and salsa in August 2010. The TOC contents in the rhizosphere soil of reed and salsa were higher than in the nonrhizosphere, and the difference was significant ($P < 0.05$) (Figure 6). The mean value of the TOC content in the rhizosphere soil of reed was up to 5.13 mg g^{-1}, about 2.13 times as much as in the nonrhizosphere soil. The mean value of the TOC content in the rhizosphere soil of salsa was up to 7.57 mg g^{-1}, about 3.31 times as much as in the nonrhizosphere soil. Root exudates or plant precipitates could lead to a priming effect in the rhizosphere environment, and the carbon allocation in the subsurface promotes the growth of roots. Then, the roots exudates could support the growth of microorganisms and increase the SOM decomposition [28].

The mean value of the DOC content in the rhizosphere soil of reed was up to 21.22 mg kg^{-1}, slightly higher than that in nonrhizosphere soil (Figure 7). The mean value of the DOC content in the rhizosphere soil of salsa was up to 30.76 mg kg^{-1}, obviously higher than that in the nonrhizosphere soil ($P < 0.05$). The rhizosphere effect of dissolved carbon in salsa wetland soil was especially obvious.

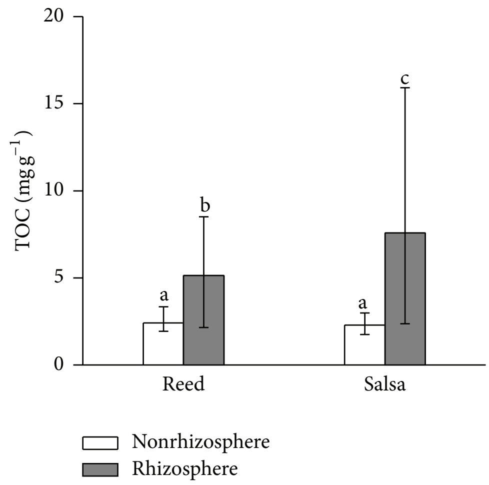
The difference of TOC and DOC contents in the nonrhizosphere soil of reed and salsa was not obvious, but the TOC and DOC contents in the salsa rhizosphere soil were obviously higher than those in the reed rhizosphere soil (Figures 6 and 7). The difference of TOC contents in the two plants rhizosphere soils was especially significant. The salsa rhizosphere effect of organic carbon was more obvious than that in the reed. Because salsa was better-adapted than the other halophytic vegetation such as *Kalidium foliatum* (Pall.) Moq. and *Nitraria sibirica* Pall. in the environment, studies showed that, around salsa root system, the salinity reduced significantly, and the microbial amounts and microbial activity increased more obviously [29].

3.4. The Relationship between Soil Physic-Chemical Properties and Organic Carbon. The close relationships between the soil organic carbon of the wetlands and the soil physic-chemical properties were observed in this study. The results of the principal component analysis (PCA) showed that the accumulative percentage of the three principal components reached 70.71%, and the eigenvalue of each component was more than 1.

All of the above could objectively reflect the main control factors of organic carbon in the Yellow River estuary. The eigenvalue of PC1 was 1.93. The DIN and TON, with larger load values, were 0.85 and 0.81, respectively. This principal component for soil organic carbon was a dominant influencing factor, with a contribution rate of 27.49%. The eigenvalue of PC2 was 1.58. Salt (S) and bulk density (B) with larger load values were 0.78 and 0.72, respectively. The eigenvalue of PC3 was 1.45. The moisture content with larger load value was −0.74. Therefore, nitrogen content, salinity, bulk density, and water content are dominant influencing factors of organic carbon [12].



(a)



(b)

Figure 6: TOC contents in rhizosphere and nonrhizosphere soils of reed and salsa. The columns represent the average contents and the error bars in left part represent the uncertainty U of TOC contents and in the right part represent the variation range. The letters represent the differences of soil TOC contents at the 0.05 level.

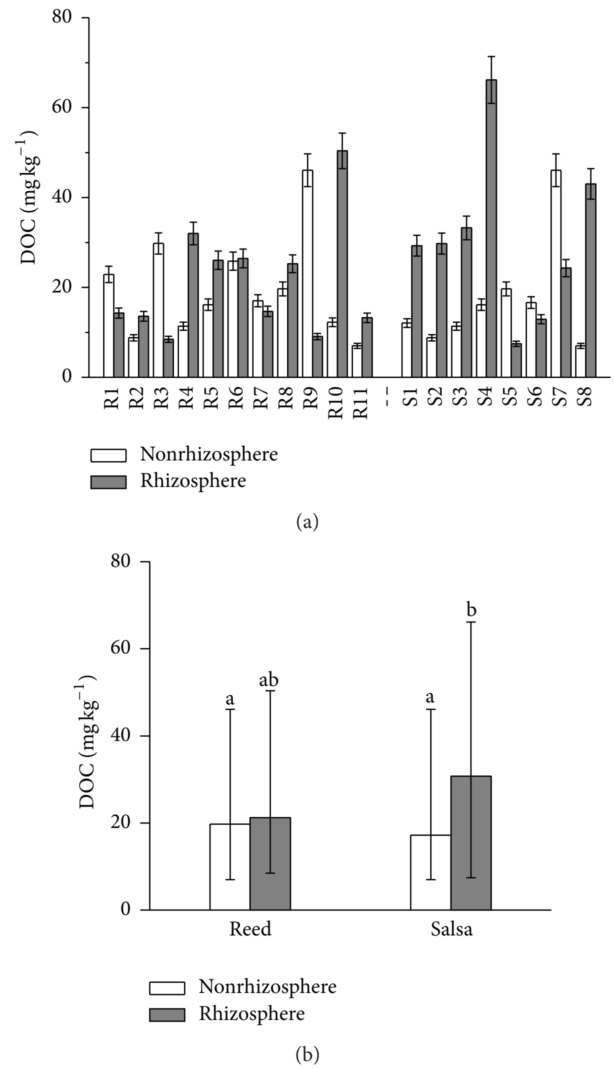


Figure 7: DOC contents in rhizosphere and nonrhizosphere soils of reed and salsa. The columns represent the average contents and the error bars in left part represent the uncertainty U of TOC contents and in the right part represent the variation range. The letters represent the differences of soil TOC contents at the 0.05 level.

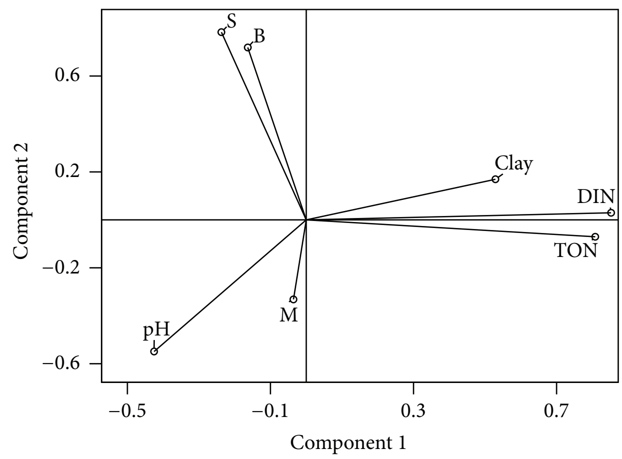


Figure 8: The principal component analysis for soil properties, S-salt, B-bulk density, M-moisture content, clay (the content of grain with diameter <0.063 μm), DIN-inorganic nitrogen, ammonia and nitrates, and TON-organic nitrogen.

The results of the principal component analysis showed that the DIN content was the main influencing factor of the organic pool in Yellow River estuary wetlands (Figure 8). According to the correlation analysis, the TOC and DOC contents in the surface soils of the Yellow River estuary wetlands exhibited a significant positive relationship with inorganic nitrogen content (ammonia and nitrates) ($r = 0.46$, $n = 48$, and $P < 0.01$ and $r = 0.29$, $n = 48$, and $P < 0.05$, resp.). The DOC content in the surface soils of the Yellow River estuary wetlands exhibited a significant positive relationship with organic nitrogen content ($r = 0.39$, $n = 48$, and $P < 0.01$).

On one hand, the increase of nitrogen elements in wetland soils, especially the increase of inorganic nitrogen content, can be used directly by vegetation and can help plants to flourish. The high organic carbon storage was observed in the soil with high primary productivity [8]. On the other hand, the decomposition of organic carbon can promote the release of inorganic nitrogen to the wetland soils. There was a close intercoupling relationship between them. Then, the high soil salinization on the wetland plants' growth would be a negative effect. The decrease of soil bulk density suggested that the soil became much looser, along with developing better permeability, stronger water-holding, and a higher storage capacity. This favored the accumulation of nutrient elements, as well as the increase of accumulation of soil organic carbon and dissolved organic carbon [30].

Furthermore, the TOC content in surface soils exhibited a significant positive relationship with water content ($r = 0.67$ and $P < 0.01$). The results suggest that bulk density, water content, and nitrogen content, which are significantly influenced by vegetation types and microtopography, are dominant factors of soil organic carbon accumulation.

4. Conclusions

On the whole, the TOC content of surface soils in October was much higher than that in May and August, and the difference was significant ($P < 0.05$). But during the same month, the differences of TOC contents in the surface wetlands soils of the four types (bare soil, salsa, tamarix, and reed) were not significant ($P > 0.05$). Among the surface soil DOC contents over the three months, May occupied first place, October came second, and August was the least. It revealed that the Yellow River estuary wetland in May had a high potential of degradation, matching the comparison of the TOC contents.

The vertical distribution: TOC contents of soil profile presented near-surface characteristic (peaked at 0–10 cm soil layer). The TOC content changes little in soil profiles and remained low at a soil depth of below 20 cm. The TOC contents in the soil profile were higher in October than in both May and August. The DOC contents of salsa and reed in surface (0–10 cm) soil were higher than that in the soil beneath the surface in May and October. The slight changes of the DOC content were observed in bare soil and in the tamarix soil profile.

The TOC contents of the two plants (reed and salsa) in the rhizosphere soil were significantly higher than that of the nonrhizosphere soil ($P < 0.05$). The DOC content in the rhizosphere soil of the reed was slightly higher than that in nonrhizosphere soil. The DOC content in the salsa rhizosphere soil was obviously higher than that in the reed rhizosphere soil ($P < 0.05$). The TOC and DOC contents in the salsa rhizosphere soil were obviously higher than that in the reed rhizosphere soil.

The results of the principal component analysis showed that the nitrogen content, salinity, bulk density, and water content were dominant influencing factors of organic carbon. It suggests that bulk density, water content, and nitrogen content, which are significantly influenced by vegetation types and microtopography, were dominant factors of organic carbon accumulation.

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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