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Discussions

Soil organic carbon storage changes in coastal wetlands of the modern Yellow River Delta from 2000 to 2009

J. Yu[1], Y. Wang[1,2], Y. Li[1,2], H. Dong[1,2], D. Zhou[1,2], G. Han[1], H. Wu[1], G. Wang[1,2], P. Mao[1], and Y. Gao[3]

[1]Key Laboratory of Coastal Zone Environmental Processes, Yantai Institute of Coastal Zone Research (YIC), Chinese Academy of Sciences (CAS); Shandong Provincial Key Laboratory of Coastal Zone Environmental Processes, YICCAS, Yantai Shandong 264003, China
[2]Graduate University of Chinese Academy of Sciences, Beijing 100049, China
[3]Department of Geosciences, University of Houston, Houston, TX 77204, USA

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Correspondence to: J. Yu (junbao.yu@gmail.com)

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Abstract

Soil carbon sequestration plays an essential role in mitigating CO_2 increases and the subsequently global greenhouse effect. The storages and dynamics of soil organic carbon (SOC) of 0–30 cm soil depth in different landscape types including beaches, reservoir and pond, reed wetland, forest wetland, bush wetland, farmland, building land, bare land (severe saline land) and salt field in the modern Yellow River Delta (YRD), were studied based on the data of the regional survey and laboratory analysis. The landscape types were classified by the interpretation of remote sensing images of 2000 and 2009, which was calibrated by field survey results. The results revealed an increase of 10.59 km^2 in the modem YRD area from 2000 to 2009. The SOC density varied ranging from 0.73 $kg\,m^{-2}$ to 21.60 $kg\,m^{-2}$ at depth of 30 cm. There were $\sim 3.97 \times 10^6$ t and 3.98×10^6 t SOC stored in the YRD in 2000 and 2009, respectively. The SOC storages changed greatly in beaches, bush wetland, farm land and salt field which were affected dominantly by anthropogenic activities. The area of the YRD increased greatly within 10 yr, however, the small increase of SOC storage in the region was observed due to landscape changes, indicating that the modern YRD was a potential carbon sink and anthropogenic activity was a key factor for SOC change.

1 Introduction

One of the most dramatic changes in the global system resulting from human activity is the rising concentration of the carbon cycling (Ogle et al., 2003; Vitousek et al., 1997). The increase in greenhouse gases related carbon in the atmosphere is presumed to be the basis of current and future climate change (Hansen et al., 2000; Levitus et al., 2001; Schimel et al., 2000; Su et al., 2006). Soil organic carbon (SOC) stock is the largest pool in the terrestrial ecosystem, with a storage of ∼1500 Pg in the top 100 cm depth layer, only a small change in storage has an impact on the level of atmospheric gaseous carbon (Desjardins et al., 2007; Feller and Bernoux, 2008; IPCC, 2001; Janzen, 2004;

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Xu et al., 2011). The organic carbon pool in soils may exceed the amount of carbon (C) in living vegetation by a factor of 2–3 (Lettens et al., 2005; Schlesinger, 1990). Soil carbon sequestration is believed to be one of the cost-effective ways to mitigate CO_2 increase and the global greenhouse effect (Janzen 2004; Xu et al. 2011).

Functioned as the "biological supermarkets" and "kidneys" of the Earth, wetlands provide comprehensive eco-environmental and productive services in terms of large food chain, climate control, pollution prevention, biodiversity maintenance, bio-productivity protection, and rich genetic material (Costanza et al., 1997; William and James, 2000; Woodward and Wui, 2001). Recent reports have indicated that wetland ecosystems especially peat bog have a high carbon storage value (Clark et al., 2007; Mariusz et al., 2008; Mcnamaran et al., 2008). About 20 % ~ 25 % of the global soil organic carbon reserve is stored in wetlands, even though wetland area only accounts for 4 % ~ 6 % the Earth land. As a huge natural carbon storehouse, wetland plays an important role in the global carbon cycle (Parish and Looi, 1999). The organic carbon stocks of wetland soil are determined by the climate, hydrology, topography, vegetation, type of wetland soil and land utilization condition (Liu and Ma, 2008; Post et al., 2001). Thus, it is important to establish the relationships between the geographical distribution of soil carbon and climate, vegetation, human development and other factors as a basis for assessing the influence of changes in any of these factors on the wetland carbon cycle (Post et al., 1982).

The land use change has significantly affected the carbon cycles both regionally and globally (Lal, 2002; Song et al., 2007). It is reported that about one fourth of anthropogenic carbon dioxide emissions are due to land use change, especially deforestation (Barnett et al., 2005; Martin et al., 2010). Long-term experimental studies have confirmed that soil organic carbon is highly sensitive to land use changes from native ecosystems, such as forest or grassland, to agriculture systems, resulting in loss of organic carbon (Jenkinson and Rayner, 1977; Martin et al., 2010; Paul et al., 1997). Approximately, a third carbon emissions brought by land use change caused the reduction of soil organic matter content (OECD, 1996).

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The Yellow River Delta (YRD), which is an area with heavy burden of anthropogenic activities and severe impact of land-ocean interaction among the large river deltas in the world, is the broadest, youngest and most efficiently conserved wetland ecological system in warm temperate zone of China (Han et al., 2006; Xu et al., 2004). Rapid evolution is the typical characteristic of the YRD, because the sediment load delivered into the sea accounts for 6 % of the global rivers sediment load (Milliman and Syvitski, 1992). For the recent years, most of landscape types in the YRD have been changed for seawater intrusion, climate change and anthropogenic activities. To our knowledge, few studies about SOC in the YRD have been reported so far (Wang et al., 2001). In this study, we present SOC storage related to different landscape changes in wetlands of the modern YRD. Our purposes were: (a) to understand the landscape area changes in coastal wetlands of the modern YRD; (b) to illustrate the spatial distribution of SOC density; and (c) to estimate the SOC storage changes related with landscape change in coastal wetlands of the modern YRD from 2000 to 2009.

2 Material and methods

2.1 Study area

The Yellow River Delta locates in the southern coast of the Bohai Gulf and the Western Laizhou Bay (36°55′–38°16′ N, 117°31′–119°18′ E) with an area of approximately 5400 km^2 (Fig. 1a). Based on record of "Outline History of China Water Resources", the Yellow River has changed its major watercourse (about 600 km from the river mouth) 26 times in the last 2200 yr. In this study, the modern YRD (37°26′–38°09′ N, 118°33′–119°18′ E) (Fig. 1b), which was formed since the watercourse of the Yellow River changed in 1855, was selected to evaluate the SOC storage changes because the burden of anthropogenic activities was gradually elevated since then. The climate of study region belongs to warm temperate continental monsoon climate with distinctive

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seasons and a rainy summer. The annual average temperature is 11.7–12.8 °C and the frost-free period lasts 206 days. The annual average rainfall is 530–630 mm, which of 70 % is in the summer, and evaporation is 1900–2400 mm, and the drought index is up to 3.56 (Cui et al., 2009).

The soil is typical saline alluvial soil (Fluvisols, FAO) developed on loess material of the Quaternary period, which was carried by water from the Loess Plateau. The natural vegetation is salt meadow with more than 85 % species are salt tolerant plants and aquatic plants. The predominant species in the region are *Suaeda heteropter Kitag*, *Phragmites australis*, *Tamarix chinensis Lour.*, *Aeluropus sinenis* and *Imperata cylindrica (Linn.) Beauv*, (He et al., 2007).

2.2 Data and methods

Landsat Thematic Mapper (TM) digital images with ground resolution of 30 m of 2000 and 2009 were used to study the landscape change in the study region. All the images were corrected for removing radiometric and atmospheric effects by subtracting the radiance of a "dark pixel" within each band image (Jensen et al., 1993; Lavery et al., 1993), and were geo-referenced and rectified following the procedure by Serra et al. (2003). With the aid of software of EADAS 9.2 (Leica, USA), the field investigation calibration, a classification system was established in this study. The performing classification accuracy was 82.58 % in 2000 and 83.75 % in 2009 and the Kappa statistics was 80.09 % in 2000 and 80.06 % in 2009. With support of the software of ArcGIS 9.3 (ESRI, USA), the indexes of landscape were calculated.

According to grid distribution point method, 252 samples (three replicates) of 0–30 cm soil depth in 84 soil sites were collected in the modern YRD in 2009 (Fig. 1b). The air dry soil samples were kept in sealed plastic bags at 5 °C to limit the microorganism activities until sieved through a 2 mm coarse stainless steel sieve for SOC analysis. Roots and other organic matters were removed before SOC analysis. SOC were determined by Total Organic Carbon Analyzer (TOC-V_{CPH}, Shimadzu, Japan). Cutting

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ring was used to measure soil bulk density. The SOC density and SOC storage was calculated as Eqs. (1) and (2), respectively.

$$\mathrm{SOCD} = \mathrm{SOC} \times \mathrm{BD} \times H \times 0.01 \tag{1}$$

$$\mathrm{SODS} = A \times \mathrm{SOCD} \tag{2}$$

where "SOCD" is soil organic carbon density ($\mathrm{kg\,m^{-2}}$), "SOC" is soil organic carbon content ($\mathrm{g\,kg^{-1}}$), "BD" is soil bulk density ($\mathrm{g\,cm^{-3}}$), H is soil layer height (cm); "SODS" is soil carbon storage (kg), A is the area of different landscape types ($\mathrm{m^2}$). Through RS interpretation, the data of landscape area from TM image were used as well as areas of soil type which were from the second soil census data.

SOC distribution under different landscape was obtained by spatial overlay analysis between field data and RS interpretation images supported by ERDAS 9.2 and ArcGIS 9.3. The field survey of landscapes for the modern YRD was carried out when soil sampled in 2009.

3 Results

3.1 The change of coastal wetland landscapes

The landscapes in the modern YRD were divided to nine types, i.e. beaches, reservoir and pond, reed wetland, forest wetland, bush wetland, farmland, building land, bare land (severe saline land) and salt field (Fig. 2a, b), based on the interpretation results of remote sensing images by our classification system established. The total area of the wetland is about 2113.20 $\mathrm{km^2}$ in 2000 and 2123.79 $\mathrm{km^2}$ in 2009 (Table 1). There was an increase of 0.50 % within 10 yr, at an average of 1.06 $\mathrm{km^2\,yr^{-1}}$. The beaches, reservoir and pond, reed wetland, forest wetland, bush wetland, farm land, building land, bare land, and salt field were about 22.61 %, 5.98 %, 9.88 %, 2.90 %, 23.36 %, 24.02 %, 1.15 %, 7.63 % and 2.47 % of total area in 2000, respectively, and were about

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17.95 %, 6.68 %, 7.63 %, 3.68 %, 12.71 %, 27.83 %, 1.79 %, 11.72 %, and 10.03 % of total area in 2009, respectively (Fig. 3a). The number of landscape patch and total patch perimeter was decreased 37.67 % and 20.95 %, respectively, while the mean patch area and the mean patch perimeter increased about 0.0182 km^2 and 181.02 m from 2000 to 2009 (Table 1). The patch areas of all landscapes except reed wetland, bush wetland and the beaches tended to increase, especially salt field patch area for about 75.49 % increase (Fig. 2).

3.2 The distribution of soil organic carbon density

The soil organic carbon density in 0–30 cm soil layer was calculated from the SOC and soil bulk density (Eq. 1). The distribution of soil organic carbon density in different landscapes of the modern YRD was shown in Fig. 4, which was generated by the application of the Ordinary Kriging interpolation of spatial grid method of ArcGIS 9.3 according to the measuring data of organic carbon concentration and bulk density in soils sampled in 2009. The results indicated that the SOC densities in 0–30 cm soil layer in modern YRD ranged from 0.73 ± 0.95 to 21.60 ± 9.52 kg m^{-2}. There was more than 55.9 % of total study area with SOC density range of 1.43–2.42 kg m^{-2}. Most of them were continuously distributed area of bush wetland, reed wetland, farmland and bare land in region (Fig. 4). The SOC density was ranged from 1.00 to 1.44 kg m^{-2} in separately distributed landscapes of beaches and salt field with an area of ∼648.65 km^2, accounting for about 30.5 % of total study area. The SOC densities in forest wetland, bush wetland and farmland, accounting for 10.5 % of total area of the YRD, which distributed in region of the old river channel in north of the YRD were relatively high (>2.45 kg m^{-2}). While the low values (<0.96 kg m^{-2}) were appeared in bare land and salt field with area of 66.31 km^2 (Figs. 2, 4). The highest SOC density (21.6 kg m^{-2}) was observed in forest wetland and lowest value (0.73 kg m^{-2}) was found in salt field.

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3.3 The change of carbon storage

Based on the data of 84 statistical soil profiles, the 0–30 cm topsoil organic carbon storage of different landscape types in 2009 and 2000 was estimated using Eq. (2) (Fig. 3b). The SOC dynamics during 10 yr in YRD were supported by GIS techniques. The results showed that the region's SOC storages in the 0–30 cm depth in 2009 and 2000 were about 398.45×10^4 t and 397.04×10^4 t, respectively, indicating that the change of carbon reserves was small from 2000 to 2009. The biggest organic carbon bank in landscapes of the modern YRD was bush wetland with 102.74×10^4 t in 2000 and it was changed to farmland with 121.46×10^4 t in 2009. The carbon storage in paddy field was small both in 2000 and 2009. The decreases of carbon storage mainly occurred in beach, reed wetland and bush wetland, while more increases appeared in farmland, bare land and salt field. From 2000 to 2009, more than 50 % carbon storage was lost in bush wetland and about 29.35×10^4 t carbon increased in farmland. There were small carbon storage changes in landscapes of forest wetland, reservoir and pond.

4 Discussions

The land use changes from anthropogenic activities should be responsible for the wetland landscapes changes in the modern YRD. Landscape changes can be distinguished into conversions from one land-cover type into another one and transformations within a given land-cover type (Yue et al., 2003). Based on the remote sensing data of Landsat TM (2000, 2009), the transfer matrix of landscape types in modern YRD were extracted using ArcGIS software (Table 2). From 2000 to 2009, all wetland landscape areas extended except bush wetland, beaches and reed wetland. The largest increase from 2000 to 2009 was salt field, about 75 % of which was changed from bush wetland, beaches and bare land. While the largest decrease was bush wetland, of which about 45 % was changed to farm land, salt field and bare land. The

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lost rate of beaches was similar with bush wetland. The area of reservoir and pond was relatively stable with no more than 10 % change. It is well known that the YRD was formed by functions of sea backwater, rich sediment in river and quick deposit at estuary. The Yellow River is regarded as largest contributor of fluvial sediment load to the ocean in the world (Wang and Aubrey, 1987), thus the quick evolution rate of the YRD is unique. Recent study showed that the average area increase rate of eastern part the modern YRD had decreased to about 3.94 km^2 yr^{-1} in 1996–2008, which was only 24.3 % of that in 1986–1995, because of sharp reductions of runoff and sediment load, of which 84 %–85 % was caused by anthropogenic activities in the river basin (Yu et al., 2011). We calculated that ∼25 km^2 was lost by erosion in northern part of the YRD during studied period. Even though the total extension rate was decreased (∼1.06 km^2 yr^{-1}), the area of the YRD still increased gradually. Therefore it is clear that the most of wetland landscape areas had extended from 2000 to 2009 (Fig. 3). However, our results showed the area of the typical natural wetlands of bush wetland and reed wetland were reduced greatly (Fig. 3) and most of them were changed to farmland and salt land (Table 2), which strongly impacted by human being activities.

Our findings indicated that the change of soil organic carbon reserves in the YRD was mainly caused by anthropogenic activities. The total SOC storage in the modern YRD increased around 1.52×10^4 t with 10.59 km^2 of total area increase during 2000–2009. More than 30 % of total SOC was stored in farmland which increased quickly within the studied period (Fig. 3a, b). The formation history of the modern YRD is no more than 150 yr and the east part was formed since 1976. The tillage period of most of farmland, which mainly changed from suitable farming landscapes of bush wetland, reed wetland and forest wetland, is not over 40 yr. Pervious study found that the potential for different landscape elements to sequester carbon was partly dependent on the changes in SOC stores that occurred since cultivation began (Bedard-Haughn, 2007). We observed that the SOC density farmland with a short-term tillage period was similar with that in reed wetland and bush wetland (Figs. 2 and 4). The conversion of reed wetland and bush wetland to farmland could not change SOC sequestration greatly in

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short period. Meanwhile, with the impact of climate change and increasing intensity of human activities, the wetland in study area has appeared reverse succession. Parts of bush wetland and reed wetland were changed to bare field and salt field besides farmland, and most beaches were changed to bare land. After the degeneration and transformation, the soil water content decreased while soil's air permeability increased. As a result, the function of fixing carbon in soil was weakened (Lili et al., 2009; Liu and Zhang, 2005; Yang et al., 2010). Therefore, it is believed that the declined carbon fixation capacity of coastal wetlands in the modern YRD would be appeared soon under such heavy burden of human activities. On the other hand, the SOC content in coastal wetlands of the modern YRD was much lower than that in Plum Island salt marshes, Louisiana coastal wetlands and Quanzhou Bay coastal wetlands in China (Dodla et al., 2008; Wang et al., 2003, 2007), indicating that the coastal wetlands of the YRD also has a huge carbon fixation potential. The present contribution showed that the overall trend of SOC storage from 2000 to 2009 was increased. The estimation of SOC reserves of 0–30 cm topsoil (397.05×10^4 t) is general consistent with previous result in 0–100 cm soil in 1992 in the YRD (Wang et al., 2001). From the further analysis, we observed that the 0–10 cm SOC content was much higher than that in other soil layer in coastal wetlands of the YRD, because the root of predominant plant was mainly distributed in 0–10 cm soil depth and the litter returned to soil surface directly. It suggested that the topsoil protection was the most important to maintain the stability of the soil carbon pool in coastal wetland of the modern YRD.

5 Conclusion remarks

The Yellow River Delta is one of three big deltas in China. Under heavy burden of human activities including oil exploration (The Shengli oil field which is the second biggest oil field in China locates in the YRD), parts of natural wetlands has changed to farmland, salt field and building land, the natural wetland degradation has been serious and common. Our results showed that only a small increase of SOC storage in coastal wetlands, although the area of the modern YRD extended 10.59 km^2 from 2000 to 2009. It demonstrated that anthropogenic activities played a major role in changing landscapes and carbon storage pattern. However, the coastal wetlands of the YRD have a huge potential for carbon fixation. It suggests that the effective measures of returning farmland to wetland and controlling human disturbance should be carried out as early as possible to maintain coastal wetland SOC pool in the modern YRD.

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Table 1. Comparison of wetland landscapes of 2000 and 2009.

Year	Number of patches	Total area (km^2)	Mean patches area (km^2)	Total perimeter (m)	Mean patches perimeter (m)
2000	71 116	2113.20	0.029714	48 030 899	675.39
2009	44 333	2123.79	0.047905	37 967 376	856.41

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Table 2. The transfer matrix of landscape types from 2000 to 2009 in the modern YRD (km^2) (BW: bush wetland, RP: reservoir and pond, BuL: building land, FW: forest wetland, FL: farm land, Bea: beaches, RW: reed wetland, SF: salt field, BaL: bare land).

2009–2000	BW	RP	BuL	FW	FL	Bea	RW	SF	BaL	Total
BW	131.2	20.0	3.6	7.3	129.2	9.2	55.6	70.1	67.9	494.1
RP	8.4	43.2	2.1	1.9	13.0	20.5	14.3	8.5	9.5	121.4
BuL	1.6	0.0	15.3	0.0	4.0	0.0	2.1	0.0	0.0	23.0
FW	2.5	1.1	0.0	34.2	17.2	0.0	3.9	0.0	2.2	61.1
FL	24.1	13.4	11.0	23.2	367.5	1.7	27.3	2.9	35.2	506.3
Bea	17.8	25.5	0.0	1.4	3.1	258.3	4.7	47.8	69.7	428.3
RW	56.5	21.6	4.6	9.5	40.1	5.1	48.0	10.4	12.3	208.1
SF	0.0	0.0	0.0	0.0	0.8	2.0	0.0	46.5	1.3	50.6
BaL	27.0	12.4	0.8	0.4	16.3	23.3	5.7	26.3	47.5	159.7
Total	269.1	137.2	37.4	77.9	591.2	320.1	161.6	212.5	245.6	2052.6

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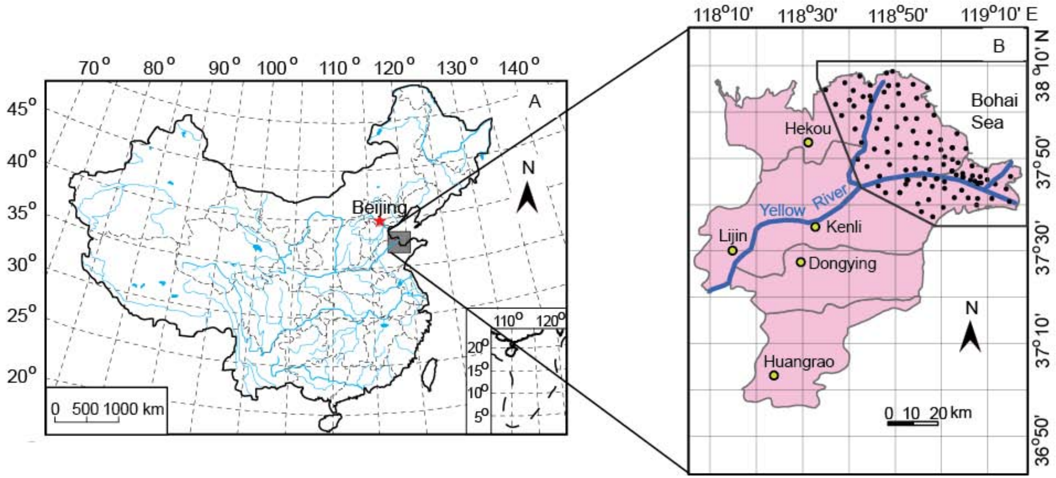

Fig. 1. Location of the modern Yellow River Delta **(A)**, the study region and sample sites **(B)**.

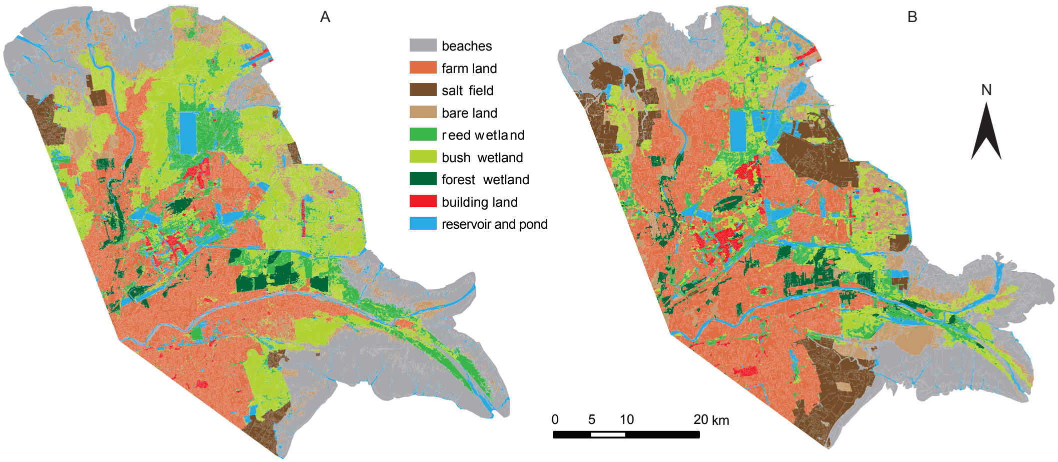

Fig. 2. The landscape types of study area in 2000 **(A)** and 2009 **(B)**.

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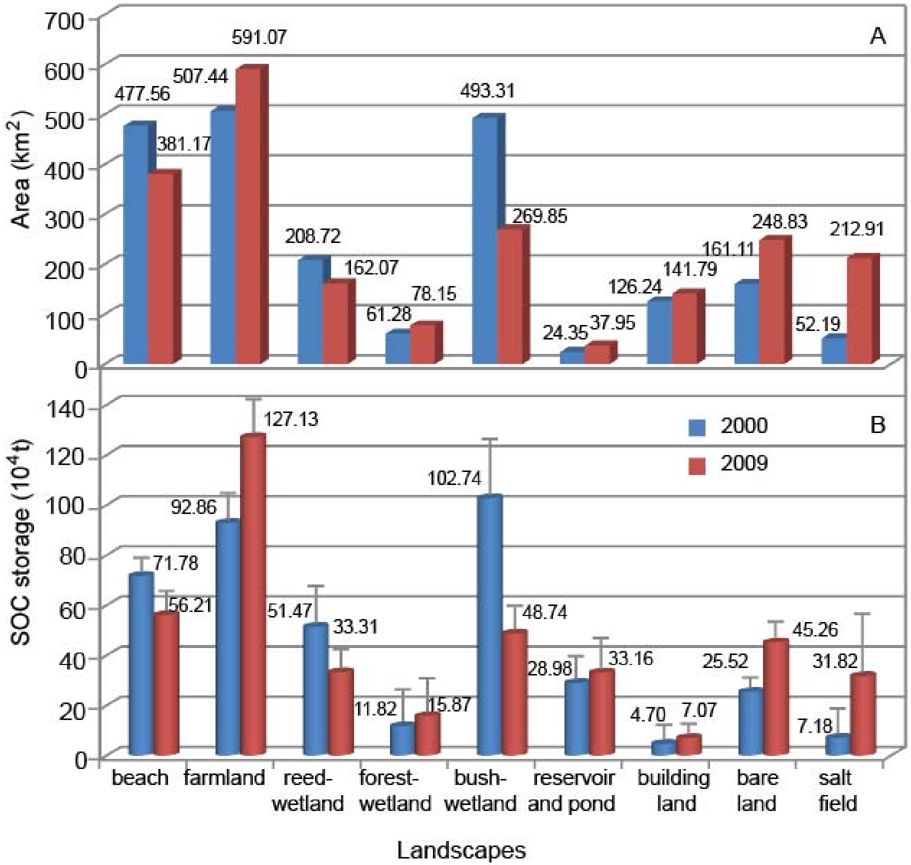

Fig. 3. Comparison of wetland landscape area **(A)** and SOC storage **(B)** in the Yellow River Delta from 2000 to 2009. Vertical bars represent standard error.

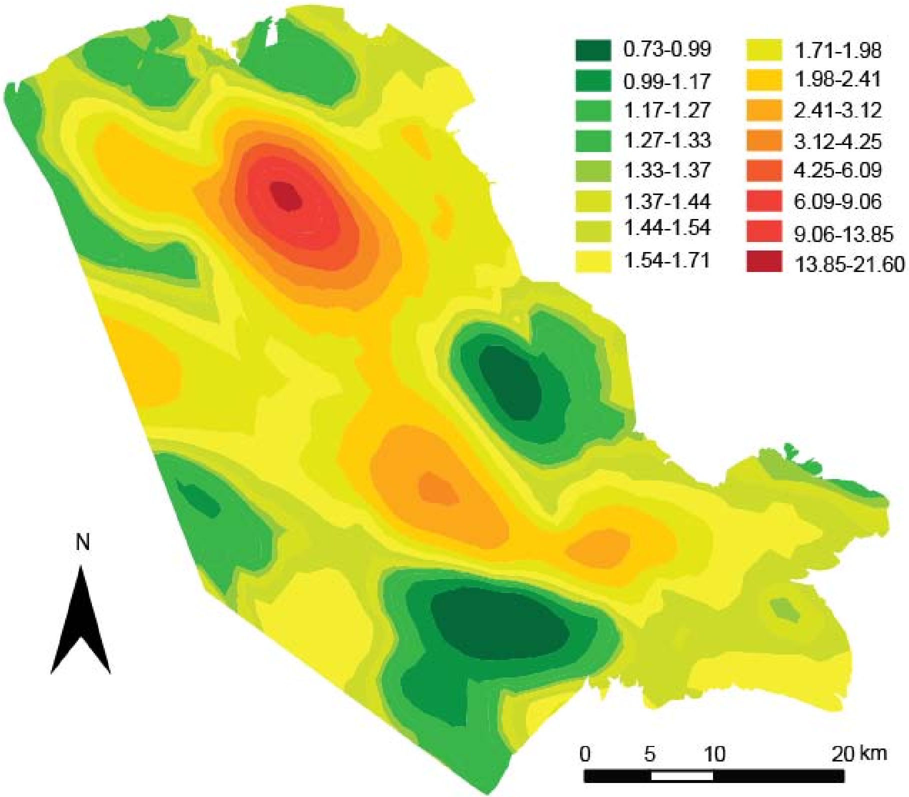

Fig. 4. The distribution of soil organic carbon density in Yellow River Delta.

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