

Soil Organic Carbon Storage Changes in Coastal Wetlands of the Modern Yellow River Delta from 2000 to 2009

Junbao Yu^{1,*}, Yongli Wang^{1,2}, Yunzhao Li^{1,2}, Hongfang Dong^{1,2}, Di Zhou^{1,2},
Guangxuan Han¹, Huifeng Wu¹, Guangmei Wang^{1,2}, Peili Mao¹, Yongjun Gao³

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, P. R. China

² Graduate University of Chinese Academy of Sciences, Beijing 100049, China

³ Department of Geosciences, University of Houston, Houston, TX 77204, USA.

* Author for correspondence: Prof. Dr. Junbao Yu, 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, P. R. China.

Phone Number: +86 535 2109113, Fax: +86 535 2109000, E-mail:
junbao.yu@gmail.com; jbyu@yic.ac.cn

Abstract

Soil carbon sequestration plays an essential role in mitigating atmospheric CO₂ 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 km² in the modern YRD area from 2000 to 2009. The SOC density varied ranging from 0.73 kg m⁻² to 4.25 kg m⁻² at depth of 30 cm. There were *approx.* 3.559×10⁶ t and 3.545×10⁶ 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 years, 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.

Keywords: landscape types; soil organic carbon; Coastal wetland; Modern Yellow

River Delta

1. Introduction

One of the most dramatic changes in the global system resulting from human activity is the rising greenhouse gases (Ogle et al. 2003; Vitousek et al. 1997). The increase in carbon-containing greenhouse gases 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 *approx.* 1,500 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; 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 CO₂ 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 bogs 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, 45 vegetation, type of wetland soil and land utilization condition (Liu and Ma 2008; Post et al. 2001; Song et al. 2011). 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).

50 **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; Ding et al. 2004; Martin et al. 2010). Long-term experimental studies have confirmed that soil organic carbon is highly sensitive to 55 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).

The Yellow River Delta (YRD), which is an area with heavy burden of 60 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

65 (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
70 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

75 2.1 Study area

The Yellow River Delta locates in the southern coast of the Bohai Gulf and the
western Laizhou Bay ($36^{\circ}55'-38^{\circ}16'N, 117^{\circ}31'-119^{\circ}18'E$) with an area of
approximately 5400 km² (Fig. 1A). Based on record of “Outline History of China
Water Resources”, the Yellow River has changed its major watercourse (about 600
80 km from the river mouth) 26 times in the last 2200 years. In this study, the modern
YRD ($37^{\circ}26'-38^{\circ}09'N, 118^{\circ}33'-119^{\circ}18'E$) (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
85 monsoon climate with distinctive 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
90 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 sinensis* and *Imperata cylindrica (Linn.) Beauv* (He et al. 2007).

95 **2.2 Data and methods**

Landsat Thematic Mapper (TM) digital images with ground resolution of 30 meters 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;
100 Lavery et al. 1993), and were geo-referenced and rectified following the procedure by Serra et al (Serra et al. 2003). With the aid of software of [ERDAS 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
105 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
110 SOC analysis. Roots and other organic matters were removed before SOC analysis.
SOC was determined by Total Organic Carbon Analyzer (TOC-V_{CPH}, Shimadzu,
Japan). Cutting ring was used to measure soil bulk density. The SOC density and SOC
storage was calculated as Equation 1 and Equations 2, respectively.

$$SOCD = SOC \times BD \times H \times 0.01 \quad (1)$$

115 $SODS = A \times SOCD \quad (2)$

Where *SOCD* is soil organic carbon density (kg m⁻²), *SOC* is soil organic carbon
content (g kg⁻¹), *BD* is soil bulk density (g cm⁻³), *H* is soil layer height (cm);
SODS is soil carbon storage (kg), *A* is the area of different landscape types (m²).
Through RS interpretation, the data of landscape area from TM image were used as
120 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.

125 **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
130 interpretation results of remote sensing images by our classification system

established. The total area of the wetland is about 2113.20 km² in 2000 and 2123.79 km² in 2009 (Table 1). There was an increase of 0.50% within 10 years, at an average of 1.06 km² per year. 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 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 km² 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 (Equation 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 3.52 ± 0.68 kg m⁻². There was more than 57.2% of total study area with SOC density range of 1.44 - 2.41 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 0.99 to 1.44 kg m⁻² in separately distributed landscapes of beaches and salt field with an area of ~690.15 km², accounting for about 32.3% of total study area. The SOC densities in forest wetland, bush wetland and farmland, accounting for 7.4% of total area of the YRD, which distributed in region of the old river channel in north of the YRD were relatively high (>2.41 kg m⁻²). While the low values (<0.99 kg m⁻²) were appeared in bare land and salt field with area of 66.31km² (Figs. 2, 4). The highest SOC density (3.52 kg m⁻²) was observed in forest wetland and lowest value (0.73 kg m⁻²) was found in salt field.

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 Equation 2 (Fig. 3B). The SOC dynamics during 10 years 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 355.88×10⁴ t and 354.51×10⁴ t, respectively, indicating that the change of carbon reserves was small from 2000 to 2009. The biggest organic carbon banks in landscapes of the modern YRD were both farmland with 90.06×10⁴ t in 2000 and 94.85×10⁴ 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 70% carbon storage was lost in bush wetland and about 9.48×10⁴ t carbon increased in farmland. There were small

175 [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
180 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
185 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 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
190 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 km² year⁻¹ in 1996-2008, which was only 24.3% of that in 1986-1995, because of sharp
195 reductions of runoff and sediment load, of which 84%-85% was caused by anthropogenic activities of the construction of reservoirs and dams in the river basin](#)

(Yu et al. 2011). We calculated that $\sim 25 \text{ km}^2$ was lost by erosion in northern part of the YRD during studied period. Even though the total extension rate was decreased ($\sim 1.06 \text{ km}^2$ per year), 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).

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 $1.38 \times 10^4 \text{ t}$ with 10.59 km^2 of total area increase during 2000-2009. More than 25% 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 years and the east part were 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 years. 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 2006). 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 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
220 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
225 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. 2007; Wang et al. 2003), indicating
that the coastal wetlands of the YRD also has a huge carbon fixation potential. The
230 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 \(\$354.51 \times 10^4\$ t\) 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
235 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

240 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 km² 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.

Acknowledgments

We are grateful for support from the Knowledge Innovation Program of the CAS (kzcx2-YW-223), National Natural Science Foundation for Distinguished Young Scholar of Shandong Province (No. JQ201114), Project of National Science & Technology Pillar Program in “12th Five Year” period (2011BAC02B01) and the CAS/SAFEA international partnership program for creation research team. We thank Yellow River Delta Ecology Research Station of Coastal Wetland, CAS, with the help of field work.

References

260

Barnett, T. P., Adam, J. C. and Lettenmaier, D. P.: Potential impacts of a warming climate on water availability in snow-dominated regions, *Nature*, 438, 303-309, 2005.

265

Bedard-Haughn, A.: The effects of erosional and management history on soil organic carbon stores in ephemeral wetlands of hummocky agricultural landscapes (vol 135, pg 296, 2006), *Geoderma*, 138, 272-272, 2007.

Clark, J. M., Lane, S. N., Chapman, P. J. and Adamson, J. K.: Export of dissolved organic carbon from an upland peatland during storm events: Implications for flux estimates, *J. Hydrol.* 347, 438-447, 2007.

270

Costanza, R., d'Arge, R., deGroot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. V., Paruelo, J., Raskin, R. G., Sutton, P. and vandenBelt, M.: The value of the world's ecosystem services and natural capital, *Nature*, 387, 253-260, 1997.

275

Cui, B. S., Yang, Q. C., Yang, Z. F. and Zhang, K. J.: Evaluating the ecological performance of wetland restoration in the Yellow River Delta, China, *Ecol. Eng.*, 35, 1090-1103, 2009.

[Ding, W. X., Cai, Z. C. and Wang, D. X.: Preliminary budget of methane emissions from natural wetlands in China, *Atmos. Environ.*, 38, 751-759, 2004.](#)

280

Desjardins, R. L., Hutchinson, J. J. and Campbell, C. A.: Some perspectives on carbon sequestration in agriculture, *Agr. Forest Meteorol.*, 142, 288-302, 2007.

Dodla, S. K., Wang, J. J., DeLaune, D. R. and Cook, R.: Denitrification potential and

- its relation to organic carbon quality in three coastal wetland soils, *Sci. Total Environ.* 407: 407, 471-480, 2008.
- Feller, C. and Bernoux, M.: Historical advances in the study of global terrestrial soil organic carbon sequestration, *Waste Manage.*, 28, 734-740, 2008.
- Han, M., Zhang, X. and Liu, L.: Research progress on wetland of the Yellow River Delta, *Ecol. Environ.*, 15, 872-875, 2006.
- Hansen, J., Sato, M., Ruedy, R., Lacis, A. and Oinas, V.: Global warming in the twenty-first century:an alternative scenario., *Proceedings of the National Academy of Sciences of the United States of America*, 97, 9875-9880, 2000.
- He, Q., Cui, B., Zhao, X., Fu, H., Xiong, X. and Feng, G.: Vegetation distribution patterns to the gradients of water depth and soil salinity in wetlands of Yellow River delta, china, *Wetland Sci.*, 5, 208-214, 2007.
- IPCC. 2001. *Climate change: the scientific basisi*. Cambridge University Press, Cambridge.
- Janzen, H. H.: Carbon cycling in earth systems - a soil science perspective, *Agr. Ecosyst. Environ.*, 104, 399-417, 2004.
- Jenkinson, D. S. and Rayner, J. H.: Turnover of Soil Organic-Matter in Some of Rothamsted Classical Experiments, *Soil Sci.*, 123, 298-305, 1977.
- Jensen, J. R., Narumalani, S., Weatherbee, O. and Mackey, H. E.: Measurement of Seasonal and Yearly Cattail and Waterlily Changes Using Multidate Spot Panchromatic Data, *Photogramm. Eng. Rem. S.*, 59, 519-525, 1993.
- Lal, R.: Soil carbon dynamics in cropland and rangeland, *Environ. Pollut.*, 116,

353-362, 2002.

305 Lavery, P., Pattiaratchi, C., Wyllie, A. and Hick, P.: Water-Quality Monitoring in
Estuarine Waters Using the Landsat Thematic Mapper, *Remote Sens. Environ.*, 46,
268-280, 1993.

Letten, S., van Orshoven, J., van Wesemael, B., Muys, B. and Perrin, D.: Soil organic
carbon changes in landscape units of Belgium between 1960 and 2000 with
310 reference to 1990, *Glob. Change Biol.*, 11, 2128-2140, 2005.

Levitus, S. J., Antonov, I., Wang, J., Delworth, T. L., Dixon, K. W. and Baldocchi, A.
J.: Anthropogenic warming of the earth's climate system., *Science*, 292, 267-270,
2001.

Lili, W., Changchun, S., Ruijuan, G., YanYu, S. and DeYan, L.: Soil organic carbon
315 storage under different land-use types in Sanjiang Plain, *China Environ. Sci.*, 29,
656-660, 2009.(In chinese)

Liu, Z. and Zhang, K.: Wetland soils carbon stock in the Sanjiang Plain,
Journal-Tsinghua University, 45, 788, 2005.(In chinese)

Liu, Z. G. and Ma, X. H. 2008. *Overview of Wetlands in China*. China forestry
320 publishing house, Beijing. (In chinese)

Mariusz, L., Milena, O. and Edward, A. D.: Autogenic succession, land use change,
and climatic influences on the Holocene development of a kettle-hole mire in
Northern Poland, *Rev. Palaeobot. Palyno.*, 151, 21-40, 2008.

Martin, D., Lal, T., Sachdev, C. B. and Sharma, J. P.: Soil organic carbon storage
325 changes with climate change, landform and land use conditions in Garhwal hills

of the Indian Himalayan mountains, *Agr. Ecosyst. Environ.*, 138, 64-73, 2010.

Mcnamaran, P., Plant, T. and Oakley, S.: Gully hotspot contribution to landscape methane (CH₄) and carbon dioxide (CO₂) fluxes in a northern peatland, *Sci. Total Environ.*, 354-360, 2008.

330 Milliman, J. D. and Syvitski, J. P. M.: Geomorphic Tectonic Control of Sediment Discharge to the Ocean - the Importance of Small Mountainous Rivers, *J. Geol.*, 100, 525-544, 1992.

OECD. 1996. *Guidelines for aid agencies for improved conservation and sustainable use of tropical and subtropical wetlands*. Organization for Economic
335 Co-operation and Development, Paris, France.

Ogle, S. M., Breidt, F. J., Eve, M. D. and Paustian, K.: Uncertainty in estimating land use and management impacts on soil organic carbon storage for US agricultural lands between 1982 and 1997, *Glob. Change Biol.*, 9, 1521-1542, 2003.

Parish, F. and Looi, C. C. 1999. *Wetlands, biodiversity and climate change options and needs for enhanced linkage between the Ramsar conventions on wetland.*,
340 Tokio.

Paul, E. A., Follett, R. F., Leavitt, S. W., Halvorson, A., Peterson, G. A. and Lyon, D. J.: Radiocarbon dating for determination of soil organic matter pool sizes and dynamics, *Soil Sci. Soc. Am. J.*, 61, 1058-1067, 1997.

345 Post, W. M., Emanuel, W. R., Zinke, P. J. and Stangenberger, A. G.: Soil Carbon Pools and World Life Zones, *Nature*, 298, 156-159, 1982.

Post, W. M., Izaurralde, R. C., Mann, L. K. and Bliss, N.: Monitoring and verifying

changes of organic carbon in soil, *Climatic Change*, 51, 73-99, 2001.

Schimel, D., Melillo, J., Tian, H. Q., McGuire, A. D., Kicklighter, D., Kittel, T.,
350 Rosenbloom, N., Running, S., Thornton, P., Ojima, D., Parton, W., Kelly, R.,
Sykes, M., Neilson, R. and Rizzo, B.: Contribution of increasing CO₂ and climate
to carbon storage by ecosystems in the United States, *Science*, 287, 2004-2006,
2000.

Schlesinger, W. H.: Evidence from Chronosequence Studies for a Low
355 Carbon-Storage Potential of Soils, *Nature*, 348, 232-234, 1990.

Serra, P., Pons, X. and Sauri, D.: Post-classification change detection with data from
different sensors: some accuracy considerations, *Int. J. Remote Sens.*, 24,
3311-3340, 2003.

Song, C. C., Wang, L. L., Guo, Y. D., Song, Y. Y., Yang, G. S. and Li, Y. C.: Impacts of
360 natural wetland degradation on dissolved carbon dynamics in the Sanjiang Plain,
Northeastern China, *J. Hydrol.*, 398, 26-32, 2011.

Song, C. C., Zhang, J. B. and Wang, S. M.: Dynamics of soil organic carbon and its
fractions after abandonment of cultivated wetlands in northeast China, *Soil Till.
Res.*, 96, 350-360, 2007.

365 Su, Z. Y., Xiong, Y. M. and Zhu, J. Y.: Soil Organic Carbon Content and Distribution
in a Small Landscape of Dongguan, South China, *Pedosphere*, 10-17, 2006.

Vitousek, P. M., Mooney, H. A., Lubchenco, J. and Melillo, J. M.: Human domination
of Earth's ecosystems, *Science*, 277, 494-499, 1997.

Wang, A., Chen, J., Li, D. and Zhou, Z.: Spatial Variations of Carbon and Nitrogen in

- 370 Coastal Wetland Sediments of Quanzhou Bay in China, *Environ. Sci.*, 28,
2361-2368, 2007. (In chinese)
- Wang, S., Xu, J. and Zhou, C.: The Effect of Land Cover Change on Carbon Cycle: A
case study in the Estuary of Yellow River Delta, *J. Remote Sens.*, 5, 142-146,
2001.
- 375 Wang, X. C., Chen, R. and Berry, A.: Sources and preservation of organic matter in
Plum Island salt marsh sediments (MA, USA): long-chain n-alkanes and stable
carbon isotope compositions, *Estuar. Coast. Shelf S.*, 58, 917-928, 2003.
- Wang, Y. and Aubrey, D. G.: The Characteristics of the China Coastline, *Continental
Shelf Res.*, 7, 329-349, 1987. (In chinese)
- 380 William, J. and James, G. G. 2000. *Wetlands*. John Wiley, New York.
- Woodward, R. T. and Wui, Y. S.: The economic value of wetland services: a
meta-analysis, *Ecol. Econ.*, 37, 257-270, 2001.
- Xu, N. Z., Zhang, T. L., Wang, X. X. and Liu, H. Y.: Soil organic carbon storage
changes in Yangtze Delta region, China, *Environ. Earth Sci.*, 63, 1021-1028, 2011.
- 385 (In chinese)
- Xu, X. G., Lin, H. P. and Fu, Z. Y.: Probe into the method of regional ecological risk
assessment - a case study of wetland in the Yellow River Delta in China, *J.
Environ. Manage.*, 70, 253-262, 2004. (In chinese)
- Yang, Y. H., Chen, Y. N., Li, W. H. and Chen, Y. P.: Distribution of soil organic carbon
390 under different vegetation zones in the Ili River Valley, Xinjiang, *J. Geogr. Sci.*,
20, 729-740, 2010. (In chinese)

Yu, J., Fu, Y., Li, Y., Guan, B., Han, G., Wang, Y., Zhou, D., Sun, W., Gao, Y. and
Meixner, X. F.: Effects of water discharge and sediment load on evolution of
modern Yellow River Delta, China, over the period from 1976 to 2009,
395 Biogeosciences, 8, 2427-2435, 2011.

Yue, T. X., Liu, J. Y., Jorgensen, S. E. and Ye, Q. H.: Landscape change detection of
the newly created wetland in Yellow River Delta, Ecol. Model., 164, 21-31, 2003.

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	71116	2113.20	0.029714	48030899	675.39
2009	44333	2123.79	0.047905	37967376	856.41

400 Table 2 the transfer matrix of landscape types from 2000 to 2009 in the modern YRD (km²) (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	BW	RP	BuL	FW	FL	Bea	RW	SF	BaL	Total
2000										
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

405 **Figure captions**

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)

410

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