



Soil organic carbon of degraded wetlands treated with freshwater in the Yellow River Delta, China

Hui Wang^{a,b,c,*}, Renqing Wang^{b,**}, Yue Yu^b, Myron J. Mitchell^c, Lianjun Zhang^c

^a School of Resources and Environment, University of Jinan, Jinan, Shandong 250022, PR China

^b College of Life Science, Shandong University, Jinan, Shandong 250100, PR China

^c State University of New York, College of Environmental Science and Forestry, Syracuse, NY 13210, USA

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ABSTRACT

Supplying freshwater is one of the important methods to help restore degraded wetlands. Changes in soil properties and plant community biomass were evaluated by comparing sites with freshwater treatment versus reference sites following freshwater addition to wetlands of the Yellow River Delta for 7 years. The results indicated that soil organic carbon (SOC) was significantly increased in all wetland sites that were treated with freshwater compared to the reference sites. The treatment wetlands had greater total nitrogen (TN), lower pH and electrical conductivity and higher water content in the soil compared to the reference wetlands. In general, the upper soil layer (0–20 cm) had greater SOC than the lower soil layer (20–40 cm). The increase of SOC in the freshwater reintroduction wetlands was higher in the *Suaeda salsa* plant community (mean \pm standard error) (6.89 ± 0.63 g/kg) and *Phragmites communis* plant community (4.11 ± 0.12 g/kg) than in the *Tamarix chinensis* plant community (1.40 ± 0.31 g/kg) in the upper soil layer. The differences were especially marked between the treated and reference wetlands for SOC and TN in the *P. communis* plant communities. The C:N ratio of the soil was significantly greater in the treated compared to the reference wetlands for the *S. salsa* plant community. Although the C:N ratios increased after treatment, they were all <25 suggesting that N availability was not limiting soil organic matter decomposition. Our results indicate that freshwater addition and the concomitant increase in soil moisture content enhances the accumulation of SOC in the Yellow River Delta.

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1. Introduction

Wetland ecosystems constitute a critical component of the global carbon (C) pool and contribute ~ 20 – 25% of the total C stock of soils (Gorham, 1991; Lal, 2004; IPCC, 2007; Zhang et al., 2008). More than half of the total global area of wetlands has been degraded because of anthropogenic disturbances such as peat harvesting, water removal, and converting wetlands to farmlands, forests, and urban areas (Neher et al., 2003; Konisky et al., 2006). These anthropogenic alterations have resulted in substantial losses of C from wetlands (Jenkinson et al., 1991; Larson, 1995; IPCC, 2007).

The addition of freshwater has been shown to be an effective method to help reconstruct degraded estuary wetlands that have been subjected to drainage and saltwater intrusion. Changes in the

* Corresponding author. School of Resources and Environment, University of Jinan, Jinan, Shandong 250022, PR China. Tel.: +86 531 82767237.

** Corresponding author. College of Life Science, Shandong University, Jinan, Shandong 250100, PR China. Tel.: +86 531 88363573.

E-mail addresses: hwang_118@163.com (H. Wang), rqwang@sdu.edu.cn (R.Q. Wang).

hydrological regime of wetlands can have marked effects on soil properties including C accumulation (Craft et al., 2003; Aldous et al., 2007; Craft, 2007; Jordan et al., 2007; Krull and Craft, 2009). Craft (2007) found SOC and N (at 0–30 cm depth) were two times greater in marshes of the freshwater-dominated Altamaha River than in the salt marshes of Doboy Sound and Sapelo River. Fernández et al. (2010) indicated the organic carbon storage capacity was increased by tidal flooding in the salt marshes, caused by land reclamation. However, research on a broader array of wetlands is required to evaluate freshwater treatment effects especially with respect to SOC responses to changes in hydrological regimes (Kempthorne and Myers, 2008). The storage of C in wetlands depends on several factors including the hydrologic regime, topography and landscape pattern, plant community type, temperature, pH and salinity (Collins and Kuehl, 2001). The interactions among these factors affect the storage and change of C during freshwater treatment. Bai et al. (2005) concluded that soil clay content, wetland plant litter inputs, soil moisture and water level greatly affected the spatial distribution of soil organic matter (SOM) and total nitrogen (TN) within riparian wetlands. Leeds et al. (2009) concluded that supplying water to over-drained wetlands

can impact soil nutrients and vegetation, but they did not provide any information of any changes in SOC due to this treatment.

The Yellow River Delta in China (Fig. 1) is one of the most active regions of land–ocean interaction among the large river deltas in the world and is the largest wetland ecosystem in the warm temperate zone of China (Zhao and Song, 1995; Wang, 2007; Cui et al., 2009a;). In the Yellow River, $\sim 10.49 \times 10^{11}$ kg of sediment are transported annually with most sediment being deposited at the river mouth forming new wetlands (Zhao and Song, 1995; Cui et al., 2009a). The hydrological characteristics of these delta wetlands are affected by the interactions between freshwater and seawater, as well as between groundwater and surface water due to much of the wetlands being ~ 10 m below sea level (Xu et al., 2002; Wang et al., 2007).

The wetlands in the Yellow River Delta support a great diversity of plant and animal species. There are 393, 265 and 641 different plant, bird and aquatic animal species, respectively, in National Yellow River Delta Wetland Natural Reserve, which was founded in

1992 to protect wetlands of the Yellow River with particular attention on preserving rare and endangered waterfowl (Zhao and Song, 1995; Wang, 2007). *Suaeda salsa* community (P1), *Tamarix chinensis* community (P2) and *Phragmites communis* community (P3) are dominant plant communities established during the natural vegetation succession. However, degradation of the Yellow River Delta wetlands has continued due to the shortage of the freshwater resulting from hydrological alterations associated with industrial and agricultural developments and tidal intrusion.

The runoff of Yellow River has changed dramatically since 1980s through 1997 with annual discharge fluctuations around ~ 20 billion m^3 with a maximum annual runoff of 49 billion m^3 in 1983. The runoff decreased to less than 10 billion m^3 from 1997 to 2002 with resultant major impacts on wetlands in the Yellow River Delta. Previous research has found that these wetlands were degraded by the decrease in freshwater inputs and as a result of marine tidal intrusions (Tang et al., 2006; Zhang and Li, 2008). Within the Yellow River Wetland Natural Reserve, the area of open water has

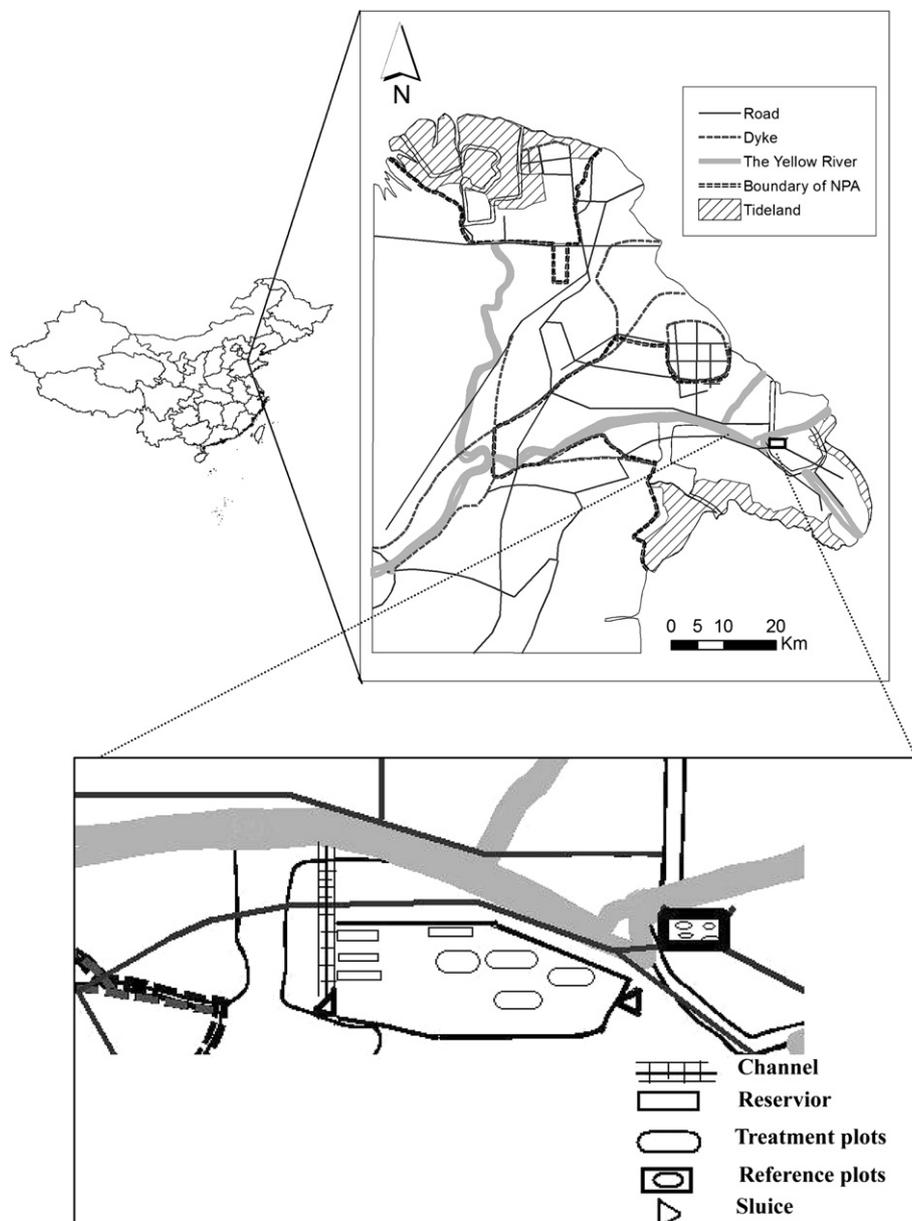


Fig. 1. Location of Yellow River Delta wetlands and sampling plots (the frames mean the research area).

decreased since 1992 by about 10,000 ha, or 25% of the amount found historically in the aquatic areas of the Reserve. Other observed changes in this wetland have included increasing soil salinity and decreasing soil nutrient contents with a concomitant decrease in vegetation biomass (Cui et al., 2009b).

A restoration project was implemented in the Yellow River Delta Nature Reserve in July 2002 to reintroduce freshwater from the river to these degraded wetlands. The goal of this management effort was to reduce the soil salinization, which is the primary threat to the freshwater wetlands, and provide suitable habitats for freshwater vegetation and faunal species, especially waterfowl. The effects of wetland restoration are commonly evaluated by analyzing changes in the hydrology, biological components and the physical and chemical properties of soil (Konisky et al., 2006; Cui et al., 2009b). Within our study, we focused on changes in soil characteristics, especially SOC, that would integrate the effects of both abiotic and biotic processes. We hypothesized that freshwater reintroduction would change the soil characteristics resulting in increased accumulation of soil organic C and N. The specific objectives of the current study were (1) to determine the spatial patterns of SOC in the wetlands associated with different plant communities after increasing the water supply for seven years; and (2) to explore the relationships between SOC and other soil characteristics with particular emphasis on N.

2. Materials and methods

2.1. Study area

The Yellow River Delta wetlands (37°35'N to 38°12'N and 118°33'E to 119°20'E) are located at the mouth of the Yellow River flowing to the sea, on the north border of Shandong Province, China (Fig. 1). This region has a warm temperate continental monsoon climate with distinct seasons including a rainy summer. The annual average temperature is 12.1 °C and annual rainfall is 552 mm. The Yellow River Delta Natural Reserve is divided into three estuary administrative stations: the Yellow River Mouth, the Dawenliu and the Yiqianer. Our study sites were located in the former two units in a test area for the restoration project where a range of experimentally freshwater treated wetlands (T1) and reference wetlands (T2) were available for study. The reference sites were within the degraded wetlands and had high salinity and low biodiversity of plant communities because of the shortage of freshwater and seawater intrusion. These reference sites were established adjacent to the restored sites and were not affected by the freshwater treatment. The restored area was separated from the Yellow River by a road. Four freshwater reservoirs and one channel were constructed to restore the wetland hydrological conditions. A 9 m long, 3.4 m wide and 1.5 m high dike was constructed to prevent seawater from entering the treatment area. A 2.5 km channel was used to divert freshwater from the Yellow River during the flood season from June to July. Freshwater was pumped to the wetlands through this channel. From 2002 through 2008 each year ~3 million m³ of fresh water was pumped into the wetlands (Cui et al., 2009b). One site of the freshwater treated wetlands was identified for each of the three plant communities based upon plant community composition: *S. salsa* community (P1) composed mostly of *S. salsa*, *Aleupus littoralis*, and *Chenopodium album*; *T. chinensis* community (P2) composed mostly of *T. chinensis*, *Suaeda heteroptera*, *Aeluropus littoralis*, *Apocynum venetum*, *C. album* and *Artemisia capillaris*; and, *P. communis* community (P3) dominated by *P. communis*, *Typha* spp., *Limonium sinense* and *Phalaris arundinacea*. During freshwater treatment, the water level fluctuated up to 1.1 m among all wetlands due to the ambient hydrological conditions and

the temporal variation of the amount of diverted freshwater into the treated wetlands. There has been little water in degraded wetlands since the runoff decreased to less 10 billion m³ in 1997. The treated wetlands had substantially greater water levels than the reference wetlands within one year because of the freshwater being supplied annually during the restoration project.

2.2. Soil sample collection and biomass determinations

Five 2 m × 3 m plots were randomly established in each of the twelve (four restored and eight reference) study sites in late April and early May 2009. Soil cores were taken by driving a 3.5 cm-diameter, 40 cm-long auger into the ground after removing any dead plant litter from the surface. Soil cores were collected at two opposite corners and in the middle of the plots. The soil cores were divided into 0–20 cm (D1) and 20–40 cm (D2) depths. The three soil cores from each plot were composited to one soil sample per plot for each depth with a total of five soil samples being collected at the two depths in each of water treatment and reference wetland sites for each type of plant community.

The soil samples were placed in polyethylene bags, kept on ice in the field, and stored at 4 °C (field moist) in the laboratory until subsequent processing. One half of the samples was air-dried for SOC, total nitrogen (TN), pH and electrical conductivity and the other half used to test for the water content.

In order to investigate the biomass of freshwater treated and reference wetlands, five 5 m × 5 m plots were randomly established in September 2008. Multiple sub-plots of 1 m × 1 m were placed at the four corners and the center of each plot. All of the aboveground vegetation was harvested and the visible roots were obtained by digging using the monolith method. The monoliths were flushed with water to remove soil from the roots. Aboveground vegetation and root samples were oven dried at 105 °C for 2 h and then dried at 90 °C to a constant mass for biomass determination. The aboveground and belowground components of *T. chinensis* vegetation were collected in each 5 m × 5 m randomly selected plots. The dry weight of these vegetation samples were determined as described for the other vegetation samples.

2.3. Soil sample analyses

All soil analyses were done using three analytical replicates per sample type. Soil water content was determined by comparing the field moist weight with oven dried samples. The remainder of each soil sample was air-dried until constant weight after which each sample was ground using a mortar and pestle and then passed through a 2-mm mesh sieve before chemical analyses. SOC was determined using potassium dichromate with external heat (Li, 1983). Total N was estimated with the updated Kjeldahl method (Bao, 2000). Soil pH was determined using a 1:2 soil: deionized water slurry. Electrical conductivity (EC, dS/m) was tested using a 1:5 soil: deionized water slurry.

2.4. Statistical data analysis

Analysis of variance (ANOVA) was used to identify statistically significant differences in SOC values among the three plant communities (i.e. *S. salsa*, *T. chinensis* and *P. communis*), restoration condition (i.e., treatment and reference), and two soil depths (0–20 cm and 20–40 cm). When the treatment effects were significant ($p < 0.05$), least significant differences (LSD) were performed to detect the differences between the freshwater treated and reference plots. A pairwise two tail *t*-test was used to test the differences in SOC values between the two soil depths (0–20 cm and 20–40 cm).

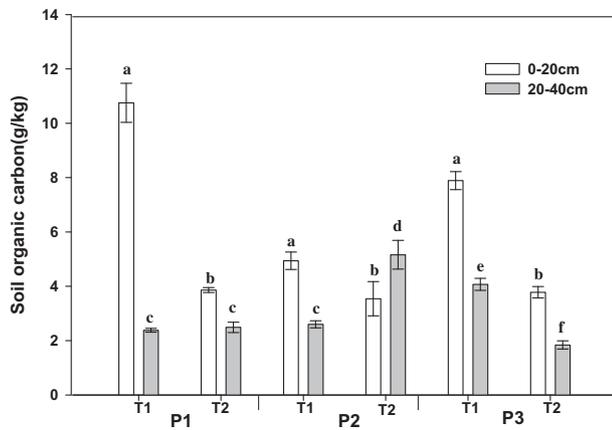


Fig. 2. Soil organic carbon (g/kg) for the two soil depths (0–20 cm and 20–40 cm) within the 3 plant communities and 2 restoration types, where T1 is treated wetlands, T2 is reference wetlands, P1 is *Suaeda salsa* community, P2 is *Tamarix chinensis* community and P3 is *Phragmites communis* community. Error bars are standard errors. The different letters show the significant difference at $p < 0.001$ by t -test within each plant community.

The paired-test was used to test for the differences in SOC, TN, C:N, pH, electrical conductivity, moisture content in the soil, and biomass for the plant communities between water treatment and reference wetlands in the three plant communities. In addition, Spearman rank correlation coefficients were computed to determine the associations between SOC and other soil characteristics including total N, pH, electrical conductivity, and moisture content. All statistical analyses were performed using SAS version 9.1 (SAS Institute Inc. 2004).

3. Results and discussion

3.1. Variation of soil organic carbon

The pairwise two tail t -test indicated that the difference of SOC concentration was highly significant between the freshwater treated and reference wetlands within each plant community (p value < 0.001). The SOC mean concentration was 5.44 ± 0.57 g/kg for the freshwater treated wetlands (T1), and 3.45 ± 0.24 g/kg for the reference wetlands (T2) for the entire 0–40 cm soil depth. Similarly, the difference of SOC concentration was significant between the two soil depths across the plant communities and treatment types (p value < 0.001). For the upper soil depth (0–20 cm), SOC concentrations were 7.86 ± 0.46 g/kg

and 3.73 ± 0.31 g/kg for the freshwater treated and reference wetlands, respectively. The SOC concentration had no significant differences between the treated and reference wetlands (3.02 ± 0.22 g/kg and 3.16 ± 0.42 g/kg, respectively) at the lower soil depth (20–40 cm).

Because all interaction terms of different wetlands sites, different plant communities and different soil depth were statistically significant ($p < 0.001$), the variation of SOC for the two soil depths was compared within the three plant communities and two treatment types of the wetlands (Fig. 2). Generally the upper soil (0–20 cm) had higher concentrations of SOC than the lower soil layer (20–40 cm) in the treated and reference plots except for reference wetlands with *T. chinensis*. The SOC concentration in the reference wetlands (T2) was relatively consistent between the upper soil layers and lower soil layers across the three plant communities (Fig. 2). Hence, freshwater reintroduction significantly increased SOC in the upper soil layers for the *Suaeda* and *Tamarix* communities and in the lower layers for the *Phragmites communis* community. The absence of electron acceptors such as iron oxides and hydroxides under reducing conditions in wetland systems may depress organic matter oxidation and mineralization (Sahrawat, 2003). Our results are consistent with such anaerobic conditions causing slower decomposition and the resultant accumulation of soil organic matter (Bernal and Mitsch, 2008).

3.2. Relationships between SOC and other wetland characteristics

The storage of SOC in wetlands depends on several factors including the topography, landscape pattern, hydrologic regime, plant community, and soil characteristics such as temperature, moisture, pH and salinity (Collins and Kuehl, 2001). The results from our research indicate that sites in which freshwater was reintroduced had more SOC, total N, and soil moisture content, but lower pH and electrical conductivity (Table 1). Spearman rank correlation analysis showed that SOC was positively correlated with TN, and this relationship was much stronger in the freshwater treated sites ($\hat{\rho} = 0.84, p < 0.05$) than in the reference sites ($\hat{\rho} = 0.47, p < 0.05$). A positive correlation was also found between SOC and soil moisture content, while electrical conductivity and pH having negative correlations with SOC in the wetlands with freshwater additions. The differences of SOC between freshwater treated wetlands and reference wetlands were significant for *S. salsa* (P1) and *P. communis* (P3) communities. *S. salsa* is a salt tolerant species (Chinese Academy of Sciences, 1979; Zhang et al., 2003; Chen et al., 2009). The freshwater treatment decreased *S. salsa* biomass while increasing the biomass of those plant species that are better

Table 1

Soil characteristics in the treated and reference wetlands in the three plant communities for the upper soil layers (0–20 cm depth). Values in the parenthesis are the p value for testing the null hypothesis of difference using pairwise comparisons.

| Plant Communities | Restored Wetlands | | | Unrestored Wetlands | | |
|--------------------------------|-----------------------------------|----------------------------------|------------------------------------|----------------------------------|-------------------------------------|---------------------------------------|
| | <i>Suaeda salsa</i> | <i>Tamarix chinensis</i> | <i>Phragmites communis</i> | <i>S. salsa</i> | <i>T. chinensis</i> | <i>P. communis</i> |
| Soil Organic Carbon (g/kg) | 10.75 ± 0.72^a (<0.01) | 4.94 ± 0.32 (0.079) | 7.89 ± 0.33^a (<0.01) | 3.86 ± 0.09^a (<0.01) | 3.54 ± 0.63 (0.079) | 3.78 ± 0.21^a (<0.01) |
| Soil Total Nitrogen (g/kg) | 0.517 ± 0.014 (0.085) | 0.406 ± 0.015 (0.150) | 0.537 ± 0.038^a (<0.01) | 0.482 ± 0.011 (0.085) | 0.375 ± 0.012 (0.015) | 0.276 ± 0.010^a ($p < 0.01$) |
| C:N | 20.79^a (<0.01) | 12.17 (0.054) | 14.69 (0.386) | 8.01^a (<0.01) | 9.44 (0.054) | 13.70 (0.386) |
| pH | 8.34 ± 0.03 (0.305) | 8.30 ± 0.05 (0.072) | 8.25 ± 0.03^a (0.033) | 8.43 ± 0.08 (0.305) | 8.41 ± 0.02 (0.072) | 8.33 ± 0.02^a (0.033) |
| Electrical Conductivity (dS/m) | 1.32 ± 0.03^a (<0.01) | 0.88 ± 0.03^a (<0.01) | 0.44 ± 0.03^a (<0.01) | 5.06 ± 0.08^a (<0.01) | 3.28 ± 0.11^a (<0.01) | 0.97 ± 0.06^a (<0.01) |
| Moisture Content (%) | 23.32 ± 0.12^a (0.045) | 16.97 ± 0.79 (0.548) | 27.44 ± 0.42^a (<0.01) | 23.89 ± 0.21^a (0.045) | 16.72 ± 0.85 ($p = 0.548$) | 23.75 ± 0.18^a (<0.01) |

^a Significant difference between restored wetlands and reference wetlands at $\alpha = 0.05$.

Table 2

Patterns of plant biomass ($\times 10^3$ kg/ha) of aboveground and belowground components between the treated and reference wetlands in three plant communities.

| Plant Communities | Treated Wetlands | Reference Wetlands | <i>p</i> value |
|----------------------------|------------------|--------------------|----------------|
| <i>Suaeda salsa</i> | 31.11 \pm 0.67 | 7.82 \pm 0.40 | <0.01 |
| | 4.09 \pm 0.23 | 1.17 \pm 0.18 | <0.01 |
| <i>Tamarix chinensis</i> | 1.03 \pm 0.07 | 0.43 \pm 0.05 | <0.01 |
| | 3.65 \pm 0.08 | 0.57 \pm 0.06 | <0.01 |
| <i>Phragmites communis</i> | 2.31 \pm 0.09 | 2.21 \pm 0.07 | 0.402 |
| | 2.32 \pm 0.10 | 3.23 \pm 0.08 | <0.01 |

adapted for freshwater conditions. Aboveground and belowground biomass significantly increased after freshwater addition except for the aboveground biomass of *P. communis* community (Table 2). Craft (2007) indicated the rate of root decomposition was positively related to salinity, and decomposition rate was negatively related to soil organic C content and rate of C accumulation. Soil organic matter content and accumulation are mediated by freshwater by affecting organic matter decomposition processes. Crawford et al. (2007) concluded that the soil pH in regenerating wetlands and restored wetlands had a significant negative relationship with root decomposition rate. In our research, all measured pH values were between 8.3–8.4 and there were no significant differences between freshwater treated wetlands and reference wetlands for all plant communities except for *P. communis* (Table 1) suggesting that soil pH was generally not a major factor in affecting our results between treatment and plant communities. Soil moisture content had significant positive correlation with SOC in the treatment plots ($\hat{p} = 0.38$, $p < 0.05$) but not in the reference plots. Various studies (e.g., Eglin et al., 2008; Mitsch and Gosselink, 2000) have found that high moisture conditions may result in the exclusion of oxygen decreasing decomposition rates.

The differences were strongly significant ($p < 0.01$) between the treated and reference sites in 0–20 cm soil layer for both SOC and TN in the plant community of *P. communis*. In contrast, there was no difference in SOC and TN between the treatment and reference sites within the *T. chinensis* community (Table 1). The C:N ratio of the soil tended to increase in all three plant communities after freshwater addition (Table 1), but this increase was strongly significant within the *S. salsa* community, but only moderately significant within the *T. chinensis* community. The C:N ratio of soil is an index of mineralization potential of soil with C:N ratios of soil greater than 25 to 30 associated with soils where N concentrations limit decomposition (Paul and Clark, 1989; Prescott et al., 2000; Xue et al., 2009). Although C:N ratios of soil increased after restoration in our study, they remained <25 suggesting that N concentration was not limiting decomposition in our study.

4. Conclusions

Summer is the period of seasonal flooding for Yellow River. During the same period, however, these degraded wetlands are more likely to be drier and hence affected by saltwater intrusion. To achieve the most benefit from restoration in the degraded wetlands in the Yellow River Delta Natural Reserve, China, freshwater was supplied for seven years during the summer, the seasonal period that also coincided with natural flooding of this region. Restored wetlands had higher SOC concentrations than the reference wetlands in all three plant communities. The influence of the freshwater reintroduction on SOC was most evident in the upper soil layer (0–20 cm) and SOC below the 20 cm soil layer was not as markedly affected after seven years of freshwater reintroduction. The relationships among the soil physical and chemical properties

(e.g., moisture content, pH, electrical conductivity and total N) varied and changed after freshwater treatment and as a function of the three plant community types (*S. salsa*, *T. chinensis* and *P. communis*). There was a close linkage between SOC and total N concentrations. The ratios of C:N of the soil increased after freshwater treatment in three plant communities, but the ratio was not sufficiently large (<25) suggesting that N was not limiting soil decomposition rates. The plant biomass increased in *S. salsa* community and *T. chinensis* community with freshwater reintroduction. These results provide new information on the effects of restoration management in the Yellow River Delta wetlands using the addition of freshwater. After the implementation of the restoration project for seven years, the area of open water has been markedly expanded. The plant species adapted for freshwater reached higher densities and biomass in the freshwater treated wetlands. Our findings suggest that more extensive restoration of the Yellow River Delta wetlands using freshwater will likely result in substantial improvement in soil characteristics and marked changes in the plant communities of this wetland ecosystem. Our results also demonstrate the cumulative impacts of wetland restoration on SOC in estuarine wetlands.

Further studies are needed to determine long-term changes in soil processes and the plant communities within the wetlands in the Yellow River Delta especially to document long-term and large-scale changes in this system. Such studies need to be done in concert with more intensive and extensive efforts that further the restoration of one of the most important arrays of wetland ecosystems in East Asia.

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References

- Aldous, A.R., Craf, C.B., Stevens, C.J., Barry, M.J., Bach, L.B., 2007. Soil phosphorus release from a restoration wetland, Upper Klamath Lake, Oregon. *Wetlands* 27, 1025–1035.
- Bai, J., Ouyang, H., Deng, W., Zhu, Y., Zhang, X., Wang, Q., 2005. Soil distribution characteristics of organic matter and total nitrogen of marsh soil in river marginal wetlands. *Geoderma* 124, 181–192.
- Bao, S., 2000. *Soil Agricultural Chemical Analysis*. China Agriculture Press, Beijing.
- Bernal, B., Mitsch, W.J., 2008. A comparison of soil carbon pools and profiles in wetlands in Costa Rica and Ohio. *Ecol. Eng.* 34, 311–323.
- Chen, M., Yang, Q., Yu, S., Qin, S., 2009. Cloning and analysis of phosphoenolpyruvate carboxylase gene from *Suaeda glauca*. *Mar. Sci.* 33 (6), 67–72.
- Chinese Academy of Sciences, 1979. *Plant Index of China* (Vol. 25, Fascicule 2sec.). Science Press, Beijing.
- Collins, M.E., Kuehl, R.J., 2001. Organic matter accumulation in organic soils. In: Richardson, J.L., Vepraskas, M.J. (Eds.), *Wetland Soils: Genesis, Hydrology, Landscapes, and Classification*. Lewis Publishers, CRC Press, Boca Raton, Florida.
- Craft, C., 2007. Freshwater input structures soil properties, vertical accretion and nutrient accumulation of Georgia and United States tidal marshes. *Limnol. Oceanogr.* 52, 1220–1230.
- Craft, C., Megonigal, P., Broome, S., Stevenson, J., Freese, R., Cornell, J., Zheng, L., Sacco, J., 2003. The pace of ecosystem development of constructed *Spartina alterniflora* marshes. *Ecol. Appl.* 13 (5), 1417–1432.

- Crawford, E.R., Day, F.P., Atkinson, R.B., 2007. Influence of environment and substrate quality on root decomposition in natural regenerating and restored Atlantic white cedar wetlands. *Wetlands* 27 (1), 1–11.
- Cui, B., Tang, N., Zhao, X., Bai, J., 2009a. A management-oriented valuation method to determine ecological water requirement for wetlands in the Yellow River Delta of China. *J. Nat. Conserv.* 17, 129–141.
- Cui, B., Yang, Q., Yang, Z., Zhang, K., 2009b. Evaluating the ecological performance of wetland restoration in the Yellow River Delta, China. *Ecol. Eng.* 35, 1090–1103.
- Eglin, T., Walter, C., Nys, C., Follain, S., Forgeard, F., Legout, A., Squidant, H., 2008. Influence of waterlogging on carbon stock variability at hillslope scale in a beech forest (Fougères forest -West France). *Ann. For. Sci.* 65, 202–211.
- Fernández, S., Santín, C., Marquínez, J., Álvarez, M.A., 2010. Saltmarsh soil evolution after land reclamation in Atlantic estuaries (Bay of Biscay, North coast of Spain). *Geomorphology* 114, 497–507.
- Gorham, E., 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. *Ecol. Appl.* 1, 182–195.
- IPCC., 2007. Chapter 19: Assessing Key Vulnerabilities and the Risk from Climate Change. Cambridge University Press, Cambridge.
- Jenkinson, D.S., Adams, D.E., Wild, A., 1991. Model estimates of CO₂ emissions from soil in response to global warming. *Nature* 351, 304–306.
- Jordan, T.E., Andrews, M.P., Szuch, R.P., Whigham, D.F., Weller, D.E., Jacobs, A.D., 2007. Comparing functional assessments of wetlands to measurements of soil characteristics and nitrogen processing. *Wetlands* 27, 479–497.
- Kemphorne, D., Myers, M.D., 2008. Ecosystem Services Derived from Wetland Conservation Practices in the United States Prairie Pothole Region with an Emphasis on the U.S. Department of Agriculture Conservation Reserve and Wetlands Reserve Programs (U.S. Geological Survey, Reston, Virginia).
- Konisky, R.A., Burdick, D.M., Dionne, M., Neckles, H.A., 2006. A regional assessment of salt marsh restoration and monitoring in the Gulf of Maine. *Restor. Ecol.* 14 (4), 516–525.
- Krull, K., Craft, C.B., 2009. Ecosystem development of a sandbar emergent tidal marsh, Altamaha River estuary, Georgia USA. *Wetlands* 29, 314–322.
- Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304, 1623–1627.
- Larson, D.L., 1995. Effects of climate on numbers of northern prairie wetlands. *Climatic Change* 30, 169–180.
- Leeds, J.A., Garrett, P.B., Newman, J.M., 2009. Assessing impacts of hydroperiod restoration of an overdrained wetland on soil nutrients, vegetation and fire. *Restor. Ecol.* 17, 460–469.
- Li, Y., 1983. *The General Analysis Method of Soil Agricultural Chemistry*. Beijing Science Press, Beijing.
- Mitsch, W.J., Gosselink, J.G., 2000. *Wetlands*. Van Nostrand Reinhold, New York.
- Neher, D.A., Barbercheck, M.E., El-Allaf, S.M., Anasa, O., 2003. Effects of disturbance and ecosystem on decomposition. *Appl. Soil Ecol.* 23, 165–179.
- Paul, F.E., Clark, F.E., 1989. *Soil Microbiology and Biochemistry*. Academic Press, San Diego.
- Prescott, C.E., Chappel, N.H., Vesterda, L., 2000. Nitrogen turnover in forest floors of coastal Douglas fir at sites differing in soil nitrogen capital. *Ecol.* 81, 1878–1886.
- Sahrawat, K.L., 2003. Organic matter accumulation in submerged soils. *Adv. Agron.* 81, 169–201.
- SAS Institute Inc, 2004. *SAS/STAT Users' Manual*. SAS Institute, Inc., Cary.
- Tang, N., Cui, B., Zhao, X., 2006. The restoration of reed (*Phragmites australis*) wetland in the Yellow River Delta. *Acta Ecologica Sinica* 26, 2616–2624.
- Wang, H., Hsieh, Y.P., Harwell, M.A., Huang, W., 2007. Modeling soil electrical conductivity distribution along topographic gradients in tidal salt marshes in Atlantic and Gulf coastal regions. *Ecol. Model.* 3–4, 429–439.
- Wang, Y., 2007. Study on the wetland resource and biodiversity in the Yellow River Delta. *J. Anhui Agr. Sci.* 35 (6), 1745–1746.
- Xu, X., Guo, H., Chen, X., Lin, H., Du, Q., 2002. A multi-scale study on land use and land cover quality change: the case of the Yellow River Delta in China. *Geogr. J.* 3, 177–183.
- Xue, X., Li, Y., Du, M., Liu, A., Zhang, F., Wang, J., 2009. Soil organic matter and total nitrogen changing with altitudes on the southern foot of eastern Qilian Mountains. *J. Glaciol. Geocryol* 31 (4), 642–649.
- Zhang, W., Xiao, H., Tong, C., Su, Y., Xiang, W., Huang, D., Syers, J., Wu, J., 2008. Estimating organic carbon storage in temperate wetland profiles in Northeast China. *Geoderma* 146, 311–316.
- Zhang, X., Li, P., 2008. Coastal erosion and its environmental effect in the Modern Yellow River Delta. *Mar. Environ. Sci.* 27, 475–479.
- Zhang, X., Pang, S., Li, F.Z., 2003. Development and utilization of *Suaeda salsa* in China. *Chin. Wild P. Resour.* 22 (2), 1–3.
- Zhao, T., Song, C., 1995. *Scientific Survey of the Yellow River Delta Nature Reserve*. China Forestry Publishing House, Beijing.