Soil quality assessment of coastal wetlands in the Yellow River Delta of China based on the minimum data set

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Abstract: Little information is available to assess the dynamic changes in wetland soil quality in coastal regions, though it is essential for wetland conservation and management. Soil samples were collected in *Suaeda salsa* wetlands (SWs), *Tamarix chinensis* wetlands (TWs), *Suaeda salsa-Tamarix chinensis* wetlands (STWs), freshwater *Phragmites australis* wetlands (FPWs) and saltwater *Phragmites australis* wetlands (SPWs) in three sampling periods (i.e., summer and autumn of 2007 and spring of 2008). According to the flooding characteristics of these wetlands, the study area could be grouped into three sub-regions: short-term flooding region (STFR), seasonal flooding region (SFR) and tidal flooding region (TFR). Soil quality was evaluated using the soil quality index (SQI), which was calculated using the selected minimum data set (MDS) based on principal components analysis (PCA). Our results showed that soil salt content (SSC), total carbon (TC), magnesium (Mg), nitrate nitrogen (NO_3^- -N) and total sulfur (TS) consisted of a MDS among 13 soil properties. The SQI values varied from 0.18 to 0.66 for all soil samples, of which the highest and lowest SQI values were observed in TFR. The average SQI values were significantly higher in summer (0.50 ± 0.13) than in spring (0.37 ± 0.13) and autumn (0.36 ± 0.11) in the whole study area ($p < 0.05$). The average SQI values followed the order STFR (0.44 ± 0.12) >

TFR (0.41 ± 0.15) > SFR (0.35 ± 0.09) although no significant differences were observed among the three regions ($p > 0.05$). SPWs and SWs soils showed higher SQI values (0.50 ± 0.10 and 0.47 ± 0.15 , respectively) than TWs (0.30 ± 0.08) soils ($p < 0.05$). The SSC was the dominant factor of soil quality with its proportion of 34.1% contributing to the SQI values, followed by TC (24.5%) and Mg (24.1%). Correlation analysis also showed that SQI values were significantly negatively correlated with SSC. SSC might be a characteristic indicator of wetland soil quality assessment in coastal regions. The findings of this study showed that the SQI based on MDS is a powerful tool for wetland soil quality assessment.

Key words: Soil quality assessment; Minimum data set; Principal components analysis; Soil quality index; Coastal wetlands.

1. Introduction

The soil quality of wetlands is significantly influenced by many critical environmental processes including sediment deposition, freshwater–saltwater interaction, delta accretion and material-energy exchanges (Bai et al., 2012). Bai et al. (2012) demonstrated that flow-sediment regulation has increased sediment and chemical matter input to the Yellow River Delta during the period from late June to early July since 2002. Additionally, previous studies focused on the effects of different management types on farmland soil quality (Nakajima et al., 2015; Armenise et al., 2013; Nesbitt et al., 2014), soil quality assessment of forestland (Zornoza et al., 2007; Ngo-Mbogba et al., 2015) and grassland (Navas et al., 2011; Askari et al., 2014) under different land covers. However, little information is available on the comprehensive soil quality assessment in coastal wetlands with high hydrological fluctuations. Therefore, a better understanding of

wetland soil quality and its spatio-temporal dynamic characteristics is needed for sustainable management and conservation of coastal wetlands.

After the concept of integrative indices was applied to soil ecosystems by Larson and Pierce (1991), many methods, such as soil quality cards and test kits (Ditzler and Tugel, 2002), soil quality index (SQI) methods (Doran and Parkin, 1994; Andrews et al., 2002), fuzzy association rules (Xue et al., 2010), dynamic soil quality models (Larson and Pierce, 1994) and the soil management assessment framework (Andrews et al., 2004; Karlen et al., 2008), have been established for soil quality assessment and soil management of farmlands. Comparatively, the SQI method has been widely applied (Andrews et al., 2002) due to its simplicity and quantitative flexibility (Chen et al., 2013). The SQI method involves three main steps (Andrews et al. 2002): (1) choosing appropriate indicators for a minimum data set (MDS); (2) transforming indicator scores; and (3) combining the indicator scores into the index. A large number of soil parameters (e.g., soil physical, chemical and biochemical properties) are needed to make the assessment result more accurate (Marzaioli et al. 2010; Bonanomi et al. 2011). However, there was no consensus on a definitive set of soil properties for soil quality assessment because soil quality is very complex (Liu et al., 2014a). Many researchers have agreed to establish a minimum data set (MDS) adequately representing the total data set (TDS) to reduce the cost of soil quality assessment (Glover et al. 2000; Rezaei et al. 2006; Qi et al. 2009).

The identification of the MDS can be conducted using methods such as linear and multiple regression analysis, factor analysis, discriminant analysis and scoring functions (Yao et al., 2013). Factor analysis is widely used to identify the MDS because it can reduce redundant information in the original data set (Yao et al., 2013). The process of establishing a MDS is not standardized as

the indicators vary significantly, and it depends on practical research. Chen et al. (2013) selected sand, clay, cation exchange capacity, TP, AP, exchangeable Mg, available Fe and available boron as the MDS to assess soil quality in farmlands of Northeast China. Liu et al. (2014b) assessed paddy soil quality using an MDS including TN, pH, available Si, available Zn and microbial biomass carbon from twenty soil variables. Gong et al. (2015) selected total salt content, TN, pH and soil water content as the final indicators to calculate SQIs of farmlands, natural forestland, saline and alkaline land, desert and sand land. Armenise et al. (2013) assessed soil quality of croplands under different managements using the MDS including clay, SOM, exchangeable K^+ , plant available water and AP. Therefore, MDS indicators and scoring functions might be associated with soil types and land-use types or even with time due to varying soil properties,(Andrews and Carroll, 2011).

The Yellow River Delta is one of the largest deltas in China, and the high sediment load has made this delta one of the richest sediment supplies in the world (Bai et al., 2015) despite the declining trend of sediment load from 1950 to 2007 (Peng et al., 2010). The amount of sand and soil carried and deposited per year is very high in the delta due to serious soil erosion in the Loess Plateau region (Zhao et al., 2004; Xu et al., 2002). Meanwhile, massive sediment transport brings a large amount of nutrients from the Loess Plateau and the upstream agricultural irrigation regions to the Yellow River Delta (Wang et al., 2000); thus, the nutrients in the transported sediments and developed wetland soils are essential in sustaining estuarine ecosystem health in this region (Peng et al., 2010).

The primary objectives of this study were (1) to establish a minimum data set (MDS) of wetland soil quality in the Yellow River Delta; (2) to compare the soil qualities among different

wetlands in three sampling seasons and analyze the spatio-temporal soil quality dynamics; and (3) to determine the dominant factors influencing soil quality of coastal wetlands in the Yellow River Delta.

2. Materials and methods

2.1. Study area

The study area is located in the Yellow River Delta (37°40'–37°50' N and 118°57'–119°20' E, Fig. 1), Shandong province, China. It has a warm-temperate and continental monsoon climate, with annual mean precipitation of 640 mm and annual mean evaporation of 1962 mm. The annual mean air temperature is 11.9 °C, with 196 frostless days (Bai et al, 2015). The soil type in this region is mainly coastal saline soil, derived from the sediment and the parent materials of loess soil (Huang et al., 2012). The dominant vegetation includes *Phragmites australis*, *Suaeda salsa* and *Tamarix chinensis*.

According to the flooding characteristics of the wetlands, the area could be grouped into three sub-regions: short-term flooding region (STFR), seasonal flooding region (SFR) and tidal flooding region (TFR) (Fig. 1). The flooding duration of the STFR lasted less than one month, beginning from the water and sediment regulation project in the summer. The flooding of the SFR lasted three or four months due to its low elevation. The TFR was obviously affected by tidal flooding twice a day. Each region could also be divided into three kinds of wetlands based on the dominant species. The STFR and SFR mainly include *Suaeda salsa*-*Tamarix chinensis* wetlands (STWs), *Suaeda salsa* wetlands (SWs) and freshwater *Phragmites australis* wetlands (FPWs). The TFR can be divided into *Suaeda salsa* wetlands (SWs), *Tamarix chinensis* wetlands (TWs) and

saltwater *Phragmites australis* wetlands (SPWs). Overall, there were five types of wetlands (i.e., SWs, TWs, STWs, FPWs and SPWs) based on vegetation covers in this study area.

2.2. Soil collection and analysis

Surface soil (0–20 cm) samples were collected from three sampling regions including the STFR, SFR and TFR in summer (August) and autumn (November) of 2007 and spring (April) of 2008. STFR soils with 5-6 replicates and TFR soils with 13 replicates in three sampling seasons, and SFR soils with 4 replicates in autumn and spring were sampled. SFR soils were not collected in summer due to difficult sampling. In total, 63 surface soil samples were obtained and used for the determination of 13 soil physico-chemical properties. All soil samples were then placed in polyethylene bags, and transported to the laboratory. All soil samples were air dried at room temperature for three weeks and sieved through a 2-mm nylon sieve to remove coarse debris. All the air-dried soil samples were then ground with a pestle and mortar until all particles passed a 0.149-mm nylon sieve. Additionally, a single 4.8-cm diameter soil core was collected from each site for the determination of bulk density (BD) and soil water content (SWC).

Soil samples were digested using a mixture of HClO_4 , HNO_3 and HF in Teflon tubes for analysis of total phosphorus (TP), total potassium (TK), total magnesium (Mg) and total sulfur (TS). The digested sample solutions were analyzed using inductively coupled plasma atomic emission spectrometry (ICP/AES). The total carbon (TC) and total nitrogen (TN) contents were measured using an Elemental Analyzer (CHOS Elemental Analyzer, Vario EL, Germany). Available phosphorus (AP) was determined using the Mo-Sb colorimetric method. Nitrate nitrogen (NO_3^- -N) was measured using an Ion Chromatograph (Dionex-300). TK and Mg were determined using the flame photometer method.

Soil organic matter (SOM) was measured using the dichromate oxidation method (Nelson and Sommers, 1982). Soil pH was measured using a Hach pH meter (Hach Company, Loveland, CO, USA) (soil: water = 1:5). Soil salt content (SSC) was determined in the supernatant of 1:5 soil–water mixtures using a salinity meter (VWR Scientific, West Chester, PA, USA). The soils were oven dried at 105°C for 24 h and weighed for the determination of BD and SWC.

2.3. Soil quality assessment method

The first step for soil quality assessment is to select soil quality indicators that can influence the capacity of a soil to perform and are sensitive to the final outcome (Nakajima et al., 2015). Those selected indicators compose the MDS. We employed Principal Component Analysis (PCA) as a data reduction tool in combining the norm values to establish the MDS for the study area. Secondly, each indicator from the MDS was transformed into a unitless score ranging from 0 to 1. Scoring functions were used to score soil indicators. The actual shape of indicators were either a sigmoid curve with an upper asymptote, a sigmoid curve with a lower asymptote, or some variation on a bell-shaped curve (Andrews and Carroll, 2011). Generally, the indicators' scoring functions follow “more is better”, “less is better” or “optimum” scoring curve trends. We used “more-is-better” functions for soil nutrients, and “Less-is-better” functions for BD due to the inhibitory effect of high bulk density on root growth and soil porosity (Andrews et al., 2003). Soil pH was evaluated using an “optimum” curve, but we applied a “less is better” relationship for scoring pH in this study because the soil is weakly alkaline in the study area. In this study, the selected indicators were scored using a linear technique (Diack and Stott, 2001).

Eqs. (1) and (2) were used for linear scoring of “more is better” and “less is better” curves, respectively:

$$S_i = (x - L) / (H - L) \quad (1)$$

$$S_i = 1 - (x - L) / (H - L) \quad (2)$$

S_i is the linear score of soil variable (0-1), x is the soil variable value, L is the minimum value and H is the maximum value of a soil variable (Masto et al., 2008).

Finally, indicator scores were integrated into an additive index (Andrews et al., 2002) which was calculated by Eq. (3):

$$SQI = \sum_{i=1}^n W_i S_i \quad (3)$$

S_i is the indicator score; n is the number of variables integrated in the index; W_i is the weighing value of indicators. SQI values ranged from 0 to 1. High SQI values indicate better soil quality (Ngo-Mbogba et al., 2015). The weights of indicators can be determined by the communality of PCA, as the communality describes the proportion of variance in each soil property explained by the PCA model. A high communality indicates that a high proportion of an indicator's variance can be explained by the factors (Brejda et al., 2000; Chen et al., 2013).

2.4. Statistical analysis

Pearson correlation analysis was performed to reveal the relationships between the measured soil properties. One-way analysis of variance (ANOVA) was performed to test the significant differences in individual soil properties among the different lands in three sampling seasons. Differences were considered to be significant if $p < 0.05$. The separation of means among the different regions and different sampling seasons were made using the least significant difference (LSD) test at 0.05 probability. PCA was used to select the most appropriate soil quality indicators (Ngo-Mbogba et al., 2015). Statistical analysis was performed using SPSS17.0 Windows software package.

3. Results and discussion

3.1. Soil characterization

Table 1 summarizes the characterization of 13 variables of the studied soils. The soil pH values ranged from 7.63 to 8.95, with the lowest coefficient of variation of 3.7% compared with other variables, indicating the weakly alkaline soil environment in the study area. The mean value of bulk density (BD) is 1.70 g/cm^3 , which belongs to the “solid” grade according to the 2nd Chinese national soil census (Table 2). High BD might be attributed to serious compaction and breakdown of soil structure in coastal areas (Whitbread, 1995).

Higher coefficients of variation of NO_3^- -N (68.0%) and SSC (66%) were observed among 13 soil properties. Generally, NO_3^- -N contents were relatively lower in this area, ranging from <1 to 7.4 mg/kg. Soil salt contents ranged from 0.1‰ to 4.5‰ in these wetlands, indicating the strong interactions of freshwater and saltwater in this area. With the exception of pH and TK, all other properties exhibited moderate variability ($10\% < \text{CV} < 100\%$) (Hu et al., 2008). SOM is often considered to be the soil attribute with the greatest effect on soil quality (Shukla et al. 2006), however, the SOM content was very low in the study area, ranging from 1.38 to 12.48 g/kg (Table 1). Soil nutrients such as SOM, AP and TN were very low, whereas TK, Mg and TS were relatively abundant based on the classification standard (Table 2). Overall, the soil quality is poor in study area because soil nutrients, especially SOM, TN and AP were at lower levels compared with farmlands (Liu et al., 2014a; Mohammad and Nicholas, 2015).

3.2. Spatial and seasonal variations in soil properties

We observed significantly higher average levels of SWC, BD, TP and Mg in summer than those in spring (Table 3, $p < 0.05$), whereas no significant differences in the average levels of TP

and Mg between autumn and spring ($p>0.05$). This was associated with the nutrient and sediment inputs as affected by the flow-sediment regulation of the upstream Xiaolangdi reservoir in summer (Bai et al., 2012) and plant uptake in the growing season. Comparatively, much lower SSC and TS levels were observed in summer than those in spring ($p<0.05$), and they had no significant differences in autumn compared with summer or spring ($p>0.05$). This indicated that the flow-sediment regulation regime in summer significantly decreased soil salt and TS contents. Both NO_3^- -N and TN showed significantly higher average levels in spring than in autumn ($p<0.05$) and slightly lower levels in summer ($p>0.05$). Higher dry nitrogen deposition in the Yellow River Delta in spring could contribute to elevating N levels in the top 10 cm soils (Yu et al., 2014), and higher wet nitrogen deposition in summer could offset some soil nitrogen loss due to plant assimilation in summer and autumn. Additionally, no significant differences in pH, SOM, AP, TC and TK were observed among the three sampling seasons ($p>0.05$), suggesting these indicators had no significant seasonal variations in this region. Compared with TFR soils, the average contents of SWC, TK and TS were significantly lower in STFR soils (Table 3, $p<0.05$) and slightly lower in SFR soils ($p>0.05$), which could be attributed to tidal flooding of sea water twice a day in the TFR. Both pH and SSC were considerably higher in SFR and TFR soils than in STFR soils ($p<0.05$), whereas no significant differences were observed between SFR and TFR soils ($p>0.05$). This indicates higher risks of salinization and alkalization in the SFR and TFR soils. In contrast, STFR soils contained significantly higher NO_3^- -N contents than TFR soils ($p<0.05$) and slightly higher contents than SFR soils ($p>0.05$), which might be associated with higher nitrification potential in STFR soils due to lower salinity (Table 3). TC contents were significantly higher in TFR soils than in SFR soils ($p<0.05$) and slightly higher than in STFR soils ($p>0.05$).

However, there were no significant differences in BD, SOM, AP, TP, TN and Mg among the three wetland soils ($p>0.05$). This suggests that these indicators showed lower spatial variability and had similar effects on wetland plants.

The vegetation type can affect soil formation and erosion (Ngo-Mbogba et al., 2015) and potentially reflect soil quality. The study area was divided into SWs, TWs, STWs, FPWs and SPWs according to different land cover types. As shown in Table 4, SPWs had the highest SWC and pH values compared with other wetlands, which indicates the strong effect of tidal flooding on TFRs, but no significant differences in BD and TS were observed among the five wetland types ($p>0.05$). The SSC of the five wetlands followed the order of TWs>STWs>SWs>FPWs>SPWs, demonstrating the adaptation of wetland plants to salt content. However, the SSC in SPWs was slightly lower than that in FPWs, which was possibly attributed to serious seawater intrusion and soil salinization in FPWs. Additionally, the highest values of SOM, AP, TN and TC were observed in SPWs, which might be associated with frequent flooding deposits and weak microbial decomposition.

3.3. Indicator selection for the MDS

The indicators were screened for the MDS using principal component analysis (PCA) (Andrews et al., 2002; Ngo-Mbogba et al., 2015). Only soil properties with large differences can be selected for PCA (Liu et al., 2014b). The spatial and seasonal dynamics of 13 soil properties showed higher spatio-temporal variabilities (Tables 3 and 4), thus all these indicators were selected to conduct the PCA analysis.

As shown in Table 5, the first four PCs had eigenvalues > 1 , each explaining at least 5% of the data variation and accounting for 70.94% of the total variance. The first PC explained 33.16%

of the variation, and PC2 and PC3 explained more than 10% of the variation. The PC4 accounted for 8.01% of the variation. Communalities for the soil properties indicated that the four components explained > 90% of the variance in TC; >80% of variance in TP, TN and Mg; >70% of variance in SWC, SSC and TK; >60% of variance in SOM, AP, NO₃⁻-N and TS. However, the four components explained <60% of the variance in pH and BD, which indicates that most of variance of these two indicators remained unexplained. Thus, both pH and BD were considered to be the least important variables for soil quality evaluation due to the low communality estimates (Yao et al., 2013).

All these soil properties were grouped into four PCs according to the factor loadings (≥ 0.50) in each PC. Group 1 contained SWC, SOM, AP, TN, TC and TK. Group 2 was comprised of BD, TP and Mg. Group 3 consisted of pH and NO₃⁻-N. The rest entered into Group 4. Andrews and Carroll (2001) suggested that indicators with weighted absolute values within 10% of the highest indicator value for each PC were selected for the MDS, but the single value in each PC cannot reflect the information of multi-dimensional space (Yemefack et al., 2006). Therefore, the norm value was introduced to solve this problem.

The norm values were calculated by Eq. 4 (Chen et al., 2013):

$$N_{ik} = \sqrt{\sum_1^k (U_{ik}^2 \cdot \lambda_k)} \quad (4)$$

where N_{ik} is the comprehensive loading of soil variable i in the first k PCs, λ_k is the eigenvalue of the PC, and U_{ik} is the loading of soil variable i in PC k . Indicators receiving N_{ik} within 10% of the highest norm values were selected for the MDS.

Pearson correlation analysis was used to examine the relationships among these indicators to reduce redundancy (Table 6). In Group 1, we observed that TC had the highest norm value (1.969), and only TN had a norm value falling within the scope of 10% of the highest value. Because TC and TN were significantly correlated with each other (Table 6), TC was maintained in the MDS. Similarly, Mg had the highest norm value (0.820) in Group 2, and Mg was retained due to the significant correlation between Mg and TP (Table 6). Although pH and NO_3^- -N were not well correlated with each other in Group 3, the coefficient of variation of pH was 3.7% in the study area, which was less than the threshold of sensitivity at 10% (Xu et al., 2005), so pH was eliminated and NO_3^- -N was kept in the MDS. The norm value of SSC was higher than TS in Group 4, and both indicators entered into the MDS together due to less significant correlation between them. Therefore, the final MDS included the following screened indicators: TC, Mg, NO_3^- -N, SSC and TS, which were all seldom selected for other ecosystems in previous studies (Nakajima et al., 2015; Gong et al., 2015; Liu et al., 2014b; Chen et al., 2013; Armenise et al., 2013).

3.4. Soil quality assessment using SQI

Selection of soil quality indicators and the integration of such indicators into a single index could provide information about soil quality change (Chen et al., 2013) and provide a better indication of soil evolution than individual properties. These screened indicators, including SSC, NO_3^- -N, TC, Mg and TS, were scored using a linear scoring function with Eqs. (1) or (2) according to their soil functions. The weights of these indicators based on their communalities are shown in Table 7.

SQI could be calculated using Eq. (3) once the MDS indicators were weighted and scored. The SQI values for 63 soil samples varied from 0.18 to 0.66. The highest and lowest SQI values were observed in the TFR. The average SQI values of this study area were higher in summer (0.50 ± 0.13) than those in spring (0.37 ± 0.13) and autumn (0.36 ± 0.11) ($p < 0.05$; Fig.2, a). The soil quality of the three sampling regions followed the order of STFR (0.44 ± 0.12) > TFR (0.41 ± 0.15) > SFR (0.35 ± 0.09) although no significant difference were observed between three regions ($p > 0.05$; Fig.2, b).

In summer, the SQI value of the TFR (0.53 ± 0.12) was slightly higher than the STFR (0.42 ± 0.10), but no significant difference was observed between the two regions ($p > 0.05$; Fig. 2, c). However, TFR soils showed lower SQI values than STFR soils in autumn ($p < 0.05$). It is obvious that low-quality soils always have high SSC. Similarly, the SQI values for the SFR were slightly lower compared with the STFR in autumn and spring, despite no significant differences between them ($p > 0.05$), which might be caused by different flooding conditions.

No significant seasonal variations in the SQI values were observed in the STFR and SFR ($p > 0.05$; Fig. 2, c), indicating the duration of flooding did not obviously alter the soil quality in these wetlands, which might be due to wetland adaptation to high soil water content. The SQI values for the TFR were significantly higher in summer than in autumn and spring ($p < 0.05$). This was associated with higher nutrient inputs in river runoff and freshwater dilution of seawater in the intertidal region due to increasing precipitation in summer (Zhang et al., 2011). In general, the SQI values can be used to monitor trends in soil properties and functions over time (Karlen et al., 2003), indicating an overall trend among numerous potentially conflicting indicator results (Andrews et al., 2003).

Vegetation plays an important role in controlling soil quality through influencing soil organic matter quality, the availability of nutrients, bulk density, etc. (Gao et al., 2014; Ngo-Mbogba et al., 2015). Figure 3 illustrates the SQIs for five wetlands with different vegetation cover. Generally, the soil quality varied from five vegetation types. The SQI values for TWs were significantly lower than those for SWs and SPWs ($p < 0.05$), and no significant difference in SQI values were observed among the other wetlands ($p > 0.05$). The highest contribution of TC to the SQI value for SPWs might be caused by sediment and carbon deposition in the TFR. Soil quality could be reflected by the vegetation zonation, which could be influenced by the complex environmental variables such as soil moisture (Bornman et al., 2008), salinity (Silvestri et al., 2005), water table depth (Bornman et al., 2004), elevation (Song et al., 2009), and distance from the estuary (Funk et al., 2004) in the coastal zone.

3.5. Dominating factor analysis

The relative contribution ratio of each indicator to the SQI value is shown in Fig. 3. SSC had the highest contribution ratio (34.1%) among the indicators, followed by TC (24.5%) and Mg (24.1%), whereas the lower contribution ratios were observed for TS (9.4%) and NO_3^- -N (7.9%). Among these selected indicators, the SQI value only exhibited a strong correlation (-0.581^{**}) with SSC (Fig. 4), showing a significant decrease with increasing soil salinity. This indicated that SSC was the dominating factor of wetland soil quality in the Yellow River Delta. Zhang et al. (2011) and Liu and Qi (2011) observed that soil salinization was severe in this region due to the low and flat terrain, high groundwater table, high degree of mineralization of groundwater, poor drainage conditions and infiltration of seawater. Shi and Zhang (2003) presented that the wetland soils in the delta were highly affected by salinity, and approximately 70% of the delta is considered to be

saline soils. Liu et al. (2012) observed that soil salinity significantly influenced the changes in TN and TP contents in surface soils under different water levels.

Soil organic matter (SOM) is often considered as the largest contributor to soil quality (Shukla et al. 2006; Abid and Lal, 2008), and thus it has been included in MDS by almost all previous literatures (Yao et al.,2013), whereas it was not selected as an indicator in the MDS due to the lack of SOM in the study area. To test the accuracy of the MDS indicators for wetland soil assessment, we replaced TC with SOM in the MDS, and TS was excluded due to its significant correlation with SOM (Table 6). Thus, there were only four indicators (SOM, SSC, Mg and NO_3^- -N) in the MDS for SQL_4 . We calculated SQL_4 and SQL_{13} (based on TDS) using Eq. (3) according to their scoring functions and communalities. As shown in Figure 5, the SQL_4 and SQL_{13} values showed strong linear relationships with the SQI values (based on MDS), which suggests the established MDS was suitable for assessing the wetland soil quality of the Yellow River Delta.

4. Conclusions

The soil quality of the study area is poor with low SOM, TN, AP and high bulk density. Thirteen soil properties exhibited significant spatio-temporal variation. The SQI based on MDS could be a useful tool to comprehensively assess the soil quality of coastal wetlands. Five soil variables (TC, Mg, NO_3^- -N, SSC and TS) among 13 soil properties were retained in the MDS based on the PCA analysis and norm values. Soil salt content was the limiting factor of soil quality due to its high contribution ratio to the SQI value, showing a strong correlation with SQI. Soil organic matter (SOM) was not selected as an MDS indicator despite its important role in soil. However, the calculated SQI of our study based on the MDS has generally proved suitable for assessing wetland soil quality, and the findings can provide integrated information of soil for

wetland soil quality management in the Yellow River Delta and contribute to improving wetland primary productivity through improving soil quality.

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References

- Abid, M., Lal, R., 2008. Tillage and drainage impact on soil quality-I. Aggregate stability, carbon and nitrogen pools. *Soil Till. Res.* 100, 89–98.
- Askari, M.S., Holden, N.M., 2014. Indices for quantitative evaluation of soil quality under grassland management. *Geoderma* 230–231, 131–142.
- Askari, M.S., Cui, J.F., O'Rourke, S.M., Holden, N.M., 2015. Evaluation of soil structural quality using VIS–NIR spectra. *Soil Till. Res.* 146, 108–117.
- Andrews, S.S., Carroll, C.R., 2001. Designing a soil quality assessment tool for sustainable agroecosystem management. *Ecol. Appl.* 11(6), 1573–1585.
- Andrews, S.S., Flora, C.B., Mitchell, J.P., Karlen, D.L., 2003. Growers' perceptions and acceptance of soil quality indices. *Geoderma* 114, 187–213.

370 Andrews, S.S., Karlen, D.L., Cambardella, C.A., 2004. The soil management assessment
 371 framework: A quantitative soil quality evaluation method. *Soil Sci. Soc. Am. J.* 68,
 372 1945–1962.

373 Andrews, S.S., Karlen, D.L., Mitchell, J.P., 2002. A comparison of soil quality indexing methods
 374 for vegetable production systems in northern California. *Agr. Ecosyst. Environ.* 90, 25–45.

375 Armenise, E., Redmile-Gordon, M.A., Stellacci, A.M., Ciccicarese, A., Rubino, P., 2013.
 376 Developing a soil quality index to compare soil fitness for agricultural use under different
 377 managements in the Mediterranean environment. *Soil Till. Res.* 130, 91–98.

378 Bai, J.H., Xiao, R., Zhang, K.J., Gao, H.F., 2012. Arsenic and heavy metal pollution in wetland
 379 soils from tidal freshwater and salt marshes before and after the flow-sediment regulation
 380 regime in the Yellow River Delta, China. *J. Hydrol.* 450-451, 244-253.

381 Bai, J.H., Zhao, Q.Q., Lu, Q.Q., Wang, J.J., Reddy, K.R., 2015. Effects of freshwater input on
 382 trace element pollution in salt marsh soils of a typical coastal estuary, China. *J. Hydrol.* 520,
 383 186–192.

384 Bastida, F., Zsolnay, A., Hernández, T., García, C., 2008. Past, present and future of soil quality
 385 indices: a biological perspective. *Geoderma* 147, 159–171.

386 Bonanomi, G., D'Ascoli, R., Antignani, V., Capodilupo, M., Cozzolino, L., Marzaioli, R., Puopolo,
 387 G., Rutigliano, F.A., Scelza, R., Scotti, R., Rao, M.A., Zoina, A., 2011. Assessing soil quality
 388 under intensive cultivation and tree orchards in Southern Italy. *Appl. Soil Ecol.* 47,
 389 184-194.

390 Bornman, T.G., Adams, J.B., Bate, G.C., 2004. The influence of floodplain geohydrology on the
 391 distribution of *Sarcocornia pillansii* in the Olifants Estuary on the West Coast, South Africa. J.
 392 Arid Environ. 56, 603–625.

393 Bornman, T.G., Adams, J.B., Bate, G.C., 2008. Environmental factors controlling the vegetation
 394 zonation patterns and distribution of vegetation types in the Olifants Estuary, South Africa. S.
 395 Afr. J. Bot. 74, 685–695.

396 Brejda, J.J., Karlen, D.L., Smith, J.L., Allan, D.L., 2000. Identification of regional soil quality
 397 factors and indicators: II. Northern mississippi loess hills and palouse prairie. Soil Sci. Soc.
 398 Am. J. 64, 2125–2135.

399 Chen, Y.D., Wang, H.Y., Zhou, J.M., Xing, L., Zhu, B.S., Zhao, Y.C., Chen, X.Q., 2013. Minimum
 400 Data Set for Assessing Soil Quality in Farmland of Northeast China. Pedosphere 23(5),
 401 564–576.

402 Craswell, E.T., Lefroy, R.D.B., 2001. The role and function of organic matter in tropical soils.
 403 Nutr. Cycl. Agroecosys. 61, 7–18.

404 Diack, M., Stott, D.E., 2001. Development of a soil quality index for the chalmers silty clay loam
 405 from the midwest USA. In Stott, D. E., Mohtar, R. H. and Steinhardt, G.C. (eds.) The Global
 406 Farm. Selected papers from the 10th International Soil Conservation Meeting held on May
 407 24–29,1999 at Purdue University and the USDA-ARS National Soil Erosion Research
 408 Laboratory. USA. pp. 550–555.

409 Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. In Doran, J.W., Coleman,
 410 D.C., Bezdicsek, D.F. and Stewart, B.A. (eds.) Defining Soil Quality for a Sustainable

411 Environment. SSSA Special Publication 35. Soil Science Society of America Inc., Madison.
 412 pp. 3–21.

413 Funk, D.W., Noel, L.E., Freedman, A.H., 2004. Environmental gradients, plant distribution, and
 414 species richness in arctic salt marsh near Prudhoe Bay, Alaska. *Wetl. Ecol. Manag.* 12(3),
 415 215-233.

416 Gao, H.F., Bai, J.H., Wang, Q.G., Huang, L.B., Xiao, R., 2010. Profile distribution of soil nutrients
 417 in unrestored and restored wetlands of the Yellow River Delta, China. *Procedia Environ. Sci.*
 418 2, 1652–1661.

419 Gao, H.F., Bai, J.H., Xiao, R., Yan, D.H., Huang, L.B., Huang, C., 2012. Soil Net Nitrogen
 420 Mineralization in Salt Marshes with Different Flooding Periods in the Yellow River Delta,
 421 China. *Clean Soil Air Water*, 40 (10), 1111–1117.

422 Gao, X., Wu, P., Zhao, X., Wang, J., Shi, Y., 2014. Effects of land use on soil moisture variations
 423 in semi-arid catchment: implications for land and agricultural water management. *Land*
 424 *Degrad. Dev.* 25, 163–172.

425 Glover, J.D., Reganold, J.P., Andrews, P.K., 2000. Systematic method for rating soil quality of
 426 conventional, organic, and integrated apple orchards in Washington State. *Agr. Ecosyst.*
 427 *Environ.* 80, 29-45.

428 Gong, L., Ran, Q.Y., He, G.X., Tiyp, T., 2015. A soil quality assessment under different land use
 429 types in Keriya river basin, Southern Xinjiang, China. *Soil Till. Res.* 146, 223–229.

430 Hu, W., Shao, M.A., Wang, Q.J., Fan, J., Reichardt, K., 2008. Spatial variability of soil hydraulic
 431 properties on a steep slope in the Loess Plateau of China. *Sci. Agr.* 65(3), 268-276.

432 Huang, L.B., Bai, J.H., Chen, B., Zhang, K.J., Huang, C., Liu, P.P., 2012. Two-decade wetland
 433 cultivation and its effects on soil properties in salt marshes in the Yellow River Delta, China.
 434 Ecol. Inform. 10, 49-55.

435 Huang, Y.N., Lu, F.X., 1988. A study on the sulfur chemistry of acid sulfate paddy soils of
 436 Guangdong province. Acta Pedologica Sinica 25, 101-109. (in Chinese)

437 Karlen, D.L., Ditzler, C.A., Andrews, S.S., 2003. Soil quality: why and how? Geoderma 114,
 438 145–156.

439 Karlen, D.L., Tomer, M.D., Neppel, J., Cambardella, C.A., 2008. A preliminary watershed scale
 440 soil quality assessment in north central Iowa, USA. Soil Till. Res. 99, 291–299.

441 Karr, J.R., 1981. Assessment of biotic integrity using fish communities. Fisheries 6, 21–27.

442 Li, Z., Wang, H., Liu, S., 2006. Analysis about the biodiversity of Yellow River Delta. Ecol. Envir.
 443 15, 577-82.

444 Larson, W.E., Pierce, F.J., 1991. Conservation and enhancement of soil quality. Pages 175–203 in J.
 445 Dumanski, E. Pushparajah, M. Latham, and R. Myers, editors. Evaluation for sustainable land
 446 management in the developing world. IBSRAM Proceedings number 12. Volume 2. Technical
 447 papers. Proceedings of international workshop, 15–21 September 1991, Chiang Rai, Thailand.
 448 International Board for Soil Research and Management, Bangkok, Thailand.

449 Larson, W.E., Pierce, F.J., 1994. The dynamics of soil quality as a measure of sustainable
 450 management. In Doran, J.W., Coleman, D.C., Bezdicek, D.F. and Stewart, B.A.(eds.)
 451 Defining Soil Quality for A Sustainable Environment. Soil Science Society of America Inc.,
 452 Madison, USA. pp. 37–51.

453 Liu, P.P., Bai, J.H., Ding, Q.Y., Shao, H.B., Gao, H.F., Xiao, R., 2012. Effects of Water Level and
 454 Salinity on TN and TP Contents in Marsh Soils of the Yellow River Delta, China. *Clean Soil*
 455 *Air Water* 40 (10), 1118–1124.

456 Liu, X.Z., Qi, S.Z., 2011. Wetlands environmental degradation in the Yellow River Delta,
 457 Shandong Province of China. *Procedia Environ. Sci.* 11, 701-705.

458 Liu, Z.J., Zhou, W., Shen, J.B., Li, S.T., He, P., Liang, G.Q., 2014a. Soil quality assessment of
 459 Albic soils with different productivities for eastern China. *Soil Till. Res.* 140, 74–81.

460 Liu, Z.J., Zhou, W., Shen, J.B., Li, S.T., Liang, G.Q., Wang, X.B., Sun, J.W., Ai, C., 2014b. Soil
 461 quality assessment of acid sulfate paddy soils with different productivities in Guangdong
 462 Province, China. *J. Integ. Agric.* 13(1), 177-186 (in Chinese).

463 Luo, Q., 1994. Soil S and its analytical methods. *Acta Agric. Jiangxi* 6(2), 135-143. (in Chinese)

464 Mandernack, K.W., Lynch, L., Morgan, M.D., 2000. Sulfur cycling in wetland peat of the New
 465 Jersey Pinelands and its effect on stream water chemistry. *Geochim. Cosmochim. Ac.* 64 (23),
 466 3949–3964.

467 Marzaioli, R., D’Ascoli, R., de Pascale, R.A., Rutigliano, F.A., 2010. Soil quality in a
 468 Mediterranean area of Southern Italy as related to different land use types. *Appl. Soil Ecol.*
 469 44, 205-212.

470 Masto, R., Chhonkar, P., Singh, D., Patra, A., 2008. Alternative soil quality indices for evaluating
 471 the effect of intensive cropping, fertilisation and manuring for 31 years in the semi-arid soils
 472 of India. *Environ. Monit. Assess.* 136, 419–435.

473 Moeskops, B., Buchan, D., Sukristiyonubowo Neve, S.D., Gusseme, B.D., Widowati, L.R.,
 474 Setyorini, D., Sleutel, S., 2012. Soil quality indicators for intensive vegetable production
 475 systems in Java, Indonesia. *Ecol. Indic.* 18, 218–226.

476 Mohammad, S.A., Nicholas, M.H., 2015. Quantitative soil quality indexing of temperate arable
 477 management systems. *Soil Till. Res.* 150, 57–67.

478 Mou, X.J., Sun, Z.G., Wang, L.L., Wang, C.Y., 2011. Nitrogen cycle of a typical *Suaeda salsa*
 479 marsh ecosystem in the Yellow River estuary. *J. Environ. Sci.* 23(6), 958–967.

480 Nakajima, T., Lal, R., Jiang, S.G., 2015. Soil quality index of a crosby silt loam in central Ohio.
 481 *Soil Till. Res.* 146, 323–328.

482 Navasa, M., Benitoa, M., Rodríguez, I., Masaguera, A., 2011. Effect of five forage legume covers
 483 on soil quality at the Eastern plains of Venezuela. *Appl. Soil Ecol.* 49, 242– 249.

484 Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon, and organic matter. In: Page,
 485 A.L., Miller, R.H., Keeney, D.R. (Eds.), *Methods of Soil Analysis*. American Society of
 486 Agronomy, Wisconsin, pp. 539–579.

487 Nesbitt, J.E., Adl, S.M., 2014. Differences in soil quality indicators between organic and
 488 sustainably managed potato fields in Eastern Canada. *Ecol Indic.* 37, 119– 130.

489 Ngo-Mbogba, M., Yemefack, M., Nyeck, B., 2015. Assessing soil q.uality under different land
 490 cover types within shifting agriculture in South Cameroon. *Soil Till. Res.* 150, 124–131.

491 Peng, J., Chen, S.L., Dong, P., 2010. Temporal variation of sediment load in the Yellow River
 492 basin, China, and its impacts on the lower reaches and the river delta. *Catena* 83, 135–147.

493 Qi, Y.B., Darilek, J.L., Huang, B., Zhao, Y.C., Sun, W.X., Gu, Z.Q., 2009. Evaluating soil quality
 494 indices in an agricultural region of Jiangsu Province, China. *Geoderma* 149, 325–334.

495 Rezaei, S.A., Gilkes, R.J., Andrews, S.S., 2006. A minimum data set for assessing soil quality in
 496 rangelands. *Geoderma* 136, 229-234.

497 Shi, C., Zhang, D., 2003. Processes and mechanisms of dynamic channel adjustment to delta
 498 progradation: the case of the mouth channel of the Yellow River, China. *Earth Surf. Proc.*
 499 *Land*. 28(6), 609-624.

500 Shukla, M.K., Lal, R., Ebinger, M., 2006. Determining soil quality indicators by factor analysis.
 501 *Soil Till. Res.* 87, 194-204.

502 Silvestri, S., Defina, A., Marani, M., 2005. Tidal regime, salinity and salt marsh plant zonation.
 503 *Estuar. Coast. Shelf S.* 62, 119–130.

504 Song, C.Y., Liu, G.H., Liu, Q.S., 2009. Spatial and environmental effects on plant communities
 505 in the Yellow River Delta, Eastern China. *J. Forest. Res.* 20(2), 117-122 (in Chinese).

506 Sun, Z.G., Mou, X.J., Song, H.L., Jiang, H.H., 2013. Sulfur biological cycle of the different
 507 *Suaeda salsa* marshes in the intertidal zone of the Yellow River estuary, China. *Ecol. Eng.* 53,
 508 153–164.

509 Sun, Z.G., Mou, X.J., Tong, C., Wang, C.Y., Xie, Z.L., Song, H.L., Sun, W.G., Lv, Y.C., 2015.
 510 Spatial variations and bioaccumulation of heavy metals in intertidal zone of the Yellow River
 511 estuary, China. *Catena* 126,43–52.

512 Tesfahunegn, G.B., Tamene, L., Vlek, P.L.G., 2011. Evaluation of soil quality identified by local
 513 farmers in Mai-Negus catchment, northern Ethiopia. *Geoderma* 163, 209–218.

514 Wang, D.D., Chakraborty, S., Weindorf, D.C., Li, B., Sharma, A., Paul, S., Ali, M.N., 2015.
 515 Synthesized use of VisNIR DRS and PXRF for soil characterization: Total carbon and total
 516 nitrogen. *Geoderma* 243–244, 157–167.

517 Wang, H., 1997. A review of soil Mg. *Soil Fertility* (1),9-13 (in Chinese)

518 Wang, H., Wang, R.Q., Yu, Y., Mitchell, M.J., Zhang, L.J., 2011. Soil organic carbon of degraded
519 wetlands treated with freshwater in the Yellow River Delta, China. *J. Environ. Management*
520 92, 2628-2633.

521 Wang, Z., Liang, Z., 2000. Dynamic characteristics of the Yellow River mouth. *Earth Surf. Proc.*
522 *Land*. 25, 765-82.

523 Whitbread, A.M., 1995. Soil organic matter: its fractionation and role in soil structure. In: Lefroy,
524 R.D.B., Blair, G., Craswell, E.T. (Eds.), *Soil Organic Matter Management for Sustainable*
525 *Agriculture*. pp. 124–130.

526 Xi, M., Kong, F.L., Lyu, X.G., Jiang, M., Li, Y., 2015. Spatial variation of dissolved organic
527 carbon in soils of riparian wetlands and responses to hydro-geomorphologic changes in
528 Sanjiang Plain, China. *Chinese Geogr. Sci* 25(2), 174–183.

529 Xu, X.G., Guo, H.H., Chen, X.L., Lin, H.P., Du, Q.L., 2002. A multi-scale study on land use and
530 land cover quality change: the case of the Yellow River Delta in China. *GeoJournal* 3,
531 177–183.

532 Xu, M.X., Liu, G.B., Zhao, Y.G., 2005. Assessment indicators of soil quality in hilly Loess Plateau.
533 *Chinese J. Appl. Ecol.* 16, 1843–1848(in Chinese).

534 Xue, Y.J., Liu, S.G., Hu, Y.M., Yang, J.F., 2010. Soil quality assessment using weighted fuzzy
535 association rules. *Pedosphere* 20, 334–341.

536 Yao, R.J., Yang, J.S., Gao, P., Zhang, J.B., Jin, W.H., 2013. Determining minimum data set for soil
537 quality assessment of typical salt-affected farmland in the coastal reclamation area. *Soil Till.*
538 *Res.* 128, 137–148.

539 Yemefaek, M., Jet'ten, V.G., Rossiter, D.G., 2006. Developing a minimum data set for
540 characterizing soil dynamics in shifting cultivation systems. *Soil Till. Res.* 86, 84–98.

541 Yu, J.B., Ning, K., Li, Y.Z., Du, S.Y., Han, G.X., Xing, Q.H., Wu, H.F., Wang, G.M., Gao, Y.J.,
542 2014. Wet and dry atmospheric depositions of inorganic nitrogen during plant growing
543 season in the coastal zone of Yellow River Delta. *Sci. World J.* 3, 435-444.

544 Zhang, P., Zou, L., Yao, X., Guo, X., Gao, H., Yamaguchih, I., 2011. Transportation fluxes of
545 nutrients in intertidal area of Yellow River Delta. *Mar. Environ. Sci.* 30(1), 76-80.

546 Zhang, T.T., Zeng, S.L., Gao, Y., Ouyang, Z.T., Li, B., Fang, C.M., Zhao, B., 2011. Using
547 hyperspectral vegetation indices as a proxy to monitor soil salinity. *Ecol. Indic.* 11,
548 1552–1562.

549 Zhao, G.X., Lin, G., Warner, T., 2004. Using Thematic Mapper data for change detection and
550 sustainable use of cultivated land: a case study in the Yellow River delta, China. *Int. J.*
551 *Remote Sens.* 25 (13), 2509–2522.

552 Zornoza, R., Mataix-Solera, J., Guerrero, C., Arcenegui, V., Mayoral, A.M., Morales, J.,
553 Mataix-Beneyto, J., 2007. Soil properties under natural forest in the Alicante Province of
554 Spain. *Geoderma* 142, 334–341.

Table 1 Descriptive statistics of the 13 soil variables (n=63)

Soil property	Minimum	Maximum	Mean	Standard error	Coefficient of variation (%)
SWC (g/g)	0.21	0.35	0.2543	0.03187	12.5
BD(g/cm ³)	1.32	1.97	1.7048	0.17682	10.4
pH	7.63	8.95	8.3448	0.31115	3.7
SSC (‰)	0.10	4.50	1.5112	0.99669	66.0
SOM(g/kg)	1.38	12.49	6.0258	2.01509	33.4
AP(mg/kg)	0.49	10.69	4.8368	2.43471	50.3
NO ₃ ⁻ -N(mg/kg)	0.95	7.40	1.9724	1.34037	68.0
TP(mg/kg)	445.66	798.44	626.6764	66.62644	10.6
TN(g/kg)	0.05	0.45	0.2053	0.09087	44.3
TC(g/kg)	12.29	24.30	17.9313	3.45624	19.3
TK(g/kg)	15.09	24.73	20.29	1.95	9.6
Mg(g/kg)	5.51	19.17	11.46	3.56	31.1
TS(mg/kg)	287.08	1582.69	593.741	181.914	30.6

Table 2 The classification standards for some soil properties based on the 2nd national soil census of China and other previous studies.

Property	SOM (g/kg)	TN (g/kg)	AP (mg/k g)	TK (g/kg)	TP (mg/kg)	TS ^a (mg/k g)	Mg ^b (g/kg)	Bulk Density (g/cm ³)	pH		
Class I	>40	>2	>40	>25	>1000	>500	>30	Loose	<1.00	Strong acid	<4.5
Class II	30-40	1.5-2	20-40	20-25	800-1000	350-500	20-30	Suitable	1.00-1.25	Acid	4.5-5.5
Class III	20-30	1-1.5	10-20	15-20	600-800	250-350	10-20	A little tight	1.25-1.35	Weak acid	5.5-6.5
Class IV	10-20	0.75-1	5-10	10-15	400-600	150-250	5-10	Tight	1.35-1.45	Neutral	6.5-7.5
Class V	6-10	0.5-0.75	3-5	5-10	200-400	50-150	0.48-5	Too tight	1.45-1.55	alkaline	>7.5
Class VI	<6	<0.5	<3	<5	<200	<50	<0.48	Solid	>1.55	-	-

a Classification refers to agriculture soil S content in China (50-500 mg/kg) (Luo, 1994).

b Classification refers to soil Mg contents in China (0.48-30 g/kg) (Wang, 1997).

Table 3 The average values of each soil property during the three sampling seasons and the mean levels of 13 soil properties in three regions with different flooding periods (Data are shown as the mean $\pm$ SD).

Property	Summer (n=21)	Autumn (n=22)	Spring (n=20)	STFR (n=16)	SFR (n=8)	TFR (n=39)
SWC(g/g)	0.27 $\pm$ 0.04a	0.25 $\pm$ 0.02b	0.25 $\pm$ 0.03b	0.24 $\pm$ 0.02A	0.24 $\pm$ 0.02AB	0.26 $\pm$ 0.04B
BD(g/cm ³)	1.79 $\pm$ 0.07a	1.83 $\pm$ 0.06a	1.47 $\pm$ 0.07b	1.72 $\pm$ 0.19A	1.64 $\pm$ 0.15A	1.71 $\pm$ 0.18A
pH	8.33 $\pm$ 0.35a	8.38 $\pm$ 0.37a	8.33 $\pm$ 0.19a	8.11 $\pm$ 0.30A	8.16 $\pm$ 0.26B	8.48 $\pm$ 0.25B
SSC(‰)	1.17 $\pm$ 0.94a	1.51 $\pm$ 0.81ab	1.87 $\pm$ 1.15b	0.91 $\pm$ 0.58A	1.74 $\pm$ 0.51B	1.71 $\pm$ 1.11B
SOM(g/kg)	5.75 $\pm$ 1.54a	6.29 $\pm$ 2.31a	6.02 $\pm$ 2.16a	5.82 $\pm$ 2.64A	4.99 $\pm$ 1.81A	6.32 $\pm$ 1.71A
AP (mg/kg)	5.05 $\pm$ 3.13a	4.67 $\pm$ 1.80a	4.80 $\pm$ 2.31a	4.33 $\pm$ 2.44A	5.03 $\pm$ 1.32A	5.00 $\pm$ 2.62A
NO ₃ ⁻ -N (mg/kg)	1.77 $\pm$ 1.06ab	1.68 $\pm$ 0.93b	2.50 $\pm$ 1.81a	2.59 $\pm$ 2.05A	2.09 $\pm$ 0.92AB	1.69 $\pm$ 0.93B
TP (mg/kg)	681.9 $\pm$ 58.9a	607.2 $\pm$ 40.6b	590.0 $\pm$ 61.5b	645.9 $\pm$ 1.9A	637.8 $\pm$ 25.7A	616.5 $\pm$ 72.9A
TN (g/kg)	0.20 $\pm$ 0.09ab	0.18 $\pm$ 0.08b	0.24 $\pm$ 0.10a	0.23 $\pm$ 0.12A	0.18 $\pm$ 0.06A	0.20 $\pm$ 0.08A
TC (g/kg)	19.13 $\pm$ 3.88a	17.33 $\pm$ 2.64a	17.34 $\pm$ 3.62a	16.99 $\pm$ 3.26AB	15.32 $\pm$ 2.97A	18.85 $\pm$ 3.32B
TK (g/kg)	20.82 $\pm$ 2.36a	20.04 $\pm$ 0.99a	20.02 $\pm$ 2.24a	19.51 $\pm$ 1.67A	20.01 $\pm$ 1.21AB	20.67 $\pm$ 2.10B
Mg (g/kg)	15.33 $\pm$ 1.72a	9.52 $\pm$ 2.44b	9.54 $\pm$ 2.65b	12.18 $\pm$ 3.41A	11.23 $\pm$ 3.16A	11.21 $\pm$ 3.74A
TS (mg/kg)	540.3 $\pm$ 129.1a	582.3 $\pm$ 86.7ab	662.5 $\pm$ 271.8b	515.8 $\pm$ 152.1A	602.7 $\pm$ 146.3AB	623.9 $\pm$ 193.4B

^{ab} Values in each row with different letters represent significant differences between different sampling seasons ($p<0.05$).

^{AB} Values in each row with the same letter are not significantly (LSD) different between different season ($p<0.05$).

Table 4 The mean levels of 13 soil properties in five wetlands with different vegetation types (Data are shown as the mean $\pm$ SD) .

Property	SWs (n=21)	TWs (n=16)	STWs (n=7)	FPWs (n=8)	SPWs (n=11)
SWC(g/g)	0.25 $\pm$ 0.03a	0.24 $\pm$ 0.02a	0.24 $\pm$ 0.01a	0.25 $\pm$ 0.03a	0.29 $\pm$ 0.03b
BD(g/cm ³)	1.69 $\pm$ 0.17a	1.74 $\pm$ 0.19a	1.75 $\pm$ 0.17a	1.59 $\pm$ 0.14a	1.68 $\pm$ 0.19a
pH	8.41 $\pm$ 0.36a	8.36 $\pm$ 0.27a	8.01 $\pm$ 0.33b	8.17 $\pm$ 0.20ab	8.47 $\pm$ 0.13a
SSC(‰)	1.38 $\pm$ 0.81a	2.56 $\pm$ 0.95b	1.58 $\pm$ 0.51a	1.18 $\pm$ 0.32a	1.10 $\pm$ 0.47a
SOM(g/kg)	6.26 $\pm$ 1.69ab	5.77 $\pm$ 1.91ab	5.22 $\pm$ 2.56a	5.69 $\pm$ 1.85ab	7.23 $\pm$ 1.85b
AP (mg/kg)	4.84 $\pm$ 2.59a	3.48 $\pm$ 1.21a	4.42 $\pm$ 2.18a	5.72 $\pm$ 0.81ab	7.44 $\pm$ 1.93b
NO ₃ ⁻ -N (mg/kg)	2.23 $\pm$ 1.79a	2.01 $\pm$ 1.31a	2.36 $\pm$ 1.23a	2.36 $\pm$ 1.40a	1.47 $\pm$ 0.45b
TP (mg/kg)	659.6 $\pm$ 57.5a	576.8 $\pm$ 66.4b	645.7 $\pm$ 36.2a	619.1 $\pm$ 22.9ab	617.7 $\pm$ 56.4ab
TN (g/kg)	0.23 $\pm$ 0.11a	0.15 $\pm$ 0.07b	0.20 $\pm$ 0.12ab	0.21 $\pm$ 0.02ab	0.24 $\pm$ 0.05a
TC (g/kg)	19.07 $\pm$ 3.64a	16.17 $\pm$ 1.52b	15.83 $\pm$ 3.86b	16.33 $\pm$ 3.94ab	21.34 $\pm$ 1.69c
TK (g/kg)	21.41 $\pm$ 1.65a	19.76 $\pm$ 1.99b	19.50 $\pm$ 1.33b	20.05 $\pm$ 1.06ab	20.38 $\pm$ 2.00ab
Mg (g/kg)	12.57 $\pm$ 3.50a	10.06 $\pm$ 3.43b	11.55 $\pm$ 3.78ab	10.77 $\pm$ 3.16ab	11.59 $\pm$ 3.92ab
TS (mg/kg)	664.0 $\pm$ 233.2a	551.6 $\pm$ 122.1a	629.3 $\pm$ 206.2a	544.1 $\pm$ 12.7a	600.7 $\pm$ 105.2a

^{ab} Values in each row with the same letter are not significantly (LSD) different between different season ($p<0.05$) .

Table 5 Results of principal component analysis of 13 soil properties and their

norm values and groups.

Property	PC1	PC2	PC3	PC4	Norm value	Communality	Group
SWC(g/g)	0.764	0.087	-0.403	-0.075	1.668	0.760	1
BD(g/cm ³)	-0.122	0.618	-0.062	0.215	1.013	0.447	2
pH	0.246	0.000	-0.620	0.315	0.968	0.544	3
SSC(‰)	-0.458	-0.411	0.263	0.537	1.307	0.736	4
SOM(g/kg)	0.685	-0.393	0.065	0.030	1.548	0.629	1
AP(mg/kg)	0.760	-0.129	-0.208	-0.118	1.615	0.652	1
NO ₃ ⁻ -N(mg/kg)	0.166	-0.343	0.693	-0.202	1.076	0.666	3
TP(mg/kg)	0.373	0.767	0.286	0.102	1.460	0.819	2
TN(g/kg)	0.814	-0.317	0.242	-0.240	1.801	0.880	1
TC(g/kg)	0.947	-0.033	-0.072	0.035	1.969	0.904	1
TK(g/kg)	0.605	0.221	0.312	0.479	1.441	0.741	1
Mg(g/kg)	0.394	0.753	0.312	-0.001	1.471	0.820	2
TS(mg/kg)	0.382	-0.474	0.067	0.500	1.195	0.623	4
Eigenvalues	4.310	2.378	1.492	1.041			
% of variance	33.16%	18.29%	11.48%	8.01%			
Cumulative variance (%)	33.16%	51.45%	62.93%	70.94%			

(Significant factor loading (≥ 0.5) are shown in bold)

Table 6 Correlation coefficients matrix among 13 soil properties

Property	SWC	BD	pH	SSC	SOM	AP	NO ₃ ⁻ -N	TP	TN	TC	TK	Mg	TS
SWC	1	-0.062	0.297*	-0.437**	0.402**	0.621**	-0.157	0.181	0.457**	0.752**	0.332**	0.271*	0.175
BD		1	-0.032	-0.120	-0.094	-0.119	-0.212	0.317*	-0.377**	-0.069	0.045	0.261*	-0.234
pH			1	-0.138	0.064	0.183	-0.174	-0.033	0.015	0.300*	0.176	-0.082	0.025
SSC				1	-0.061	-0.332**	0.108	-0.364**	-0.330**	-0.364**	-0.116	-0.306*	0.137
SOM					1	0.524**	0.223	-0.074	0.660**	0.692**	0.290*	-0.012	0.349**
AP						1	0.052	0.143	0.549**	0.668**	0.255*	0.144	0.312*
NO ₃ ⁻ -N							1	-0.063	0.402**	0.119	0.184	-0.024	0.065
TP								1	0.127	0.288*	0.444**	0.778**	-0.059
TN									1	0.776**	0.382**	0.141	0.367**
TC										1	0.514**	0.335**	0.334**
TK											1	0.439**	0.259*
Mg												1	-0.202
TS													1

*Significant correlation at $p < 0.05$. ** Significant correlation at $p < 0.01$.

Table 7 Communality and weight of soil quality indicators in the MDS.

MDS indicators	Communality	Weight
SSC	0.736	0.196
NO ₃ ⁻ -N	0.666	0.178
TC	0.904	0.241
Mg	0.820	0.219
TS	0.623	0.166

Figure captions

Figure 1 Location map of the study area and soil sampling regions. A, B and C represent short-term flooding region, seasonal flooding region and tidal flooding region, respectively.

Figure 2 The mean SQI values among summer, autumn and spring in the whole study area (a).

The mean SQI values for STFR, SFR and TFR in the whole studied period (b). The mean SQI vales for STFR, SFR and TFR in each of three sampling seasons (c).

^{ab} different letters represent significant difference among different sampling seasons in the same flooding region ($p < 0.05$). ^{AB} different letters represent significant difference among different flooding region in the same season ($p < 0.05$).

Figure 3 Soil quality index (SQI) values of five wetlands with different vegetation cover and the individual contribution of each MDS indicator. Values with the same letter are not significantly different ($p < 0.05$).

Figure 4 The relationship between SQI and soil salt content(SSC).

Figure 5 The linear relationships between the SQI (based on the MDS), SQI₄ (based on the indicators of SOM, SSC, Mg and NO₃⁻-N) and SQI₁₃ (based on TDS).

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5