Chin. Geogra. Sci. 2020 Vol. 30 No. 5 pp. 934–946
https://doi.org/10.1007/s11769-020-1155-7

Springer Science Press
www.springerlink.com/content/1002-0063

Soil Carbon, Nitrogen and Phosphorus Concentrations and Stoichiometries Across a Chronosequence of Restored Inland Soda Saline-Alkali Wetlands, Western Songnen Plain, Northeast China

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Abstract: Soil carbon (C), nitrogen (N) and phosphorus (P) concentrations and stoichiometries can be used to evaluate the success indicators to the effects of wetland restoration and reflect ecosystem function. Restoration of inland soda saline-alkali wetlands is widespread, however, the soil nutrition changes that follow restoration are unclear. We quantified the recovery trajectories of soil physicochemical properties, including soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) pools, for a chronosequence of three restored wetlands (7 yr, 12 yr and 21 yr) and compared these properties to those of degraded and natural wetlands in the western Songnen Plain, Northeast China. Wetland degradation lead to the loss of soil nutrients. Relative to natural wetlands, the mean reductions of in SOC, TN, and TP concentrations were 89.6%, 65.5% and 52.5%, respectively. Nutrients recovered as years passed after restoration. The SOC, TN, and TP concentrations increased by 2.36 times, 1.15 times, and 0.83 times, respectively in degraded wetlands that had been restored for 21 yr, but remained 29.2%, 17.3%, and 12.8% lower, respectively, than those in natural wetlands. The soil C∶N (R_{CN}), C∶P (R_{CP}), and N∶P (R_{NP}) ratios increased from 5.92 to 8.81, 45.36 to 79.19, and 7.67 to 8.71, respectively in the wetland that had been restored for 12 yr. These results were similar to those from the natural wetland and the wetland that had been restored for 21 yr ($P > 0.05$). Soil nutrients changes occurred mainly in the upper layers (≤ 30 cm), and no significant differences were found in deeper soils (> 30 cm). Based on this, we inferred that it would take at least 34 yr for SOC, TN, and TP concentrations and 12 yr for R_{CN}, R_{CP}, and R_{NP} in the top soils of degraded wetlands to recover to levels of natural wetlands. Soil salinity negatively influenced SOC ($r = -0.704$, $P < 0.01$), TN ($r = -0.722$, $P < 0.01$), and TP ($r = -0.882$, $P < 0.01$) concentrations during wetland restoration, which indicates that reducing salinity is beneficial to SOC, TN, and TP recovery. Moreover, plants were an important source of soil nutrients and vegetation restoration was conducive to soil nutrient accumulation. In brief, wetland restoration increased the accumulation of soil biogenic elements, which indicated that positive ecosystem functions changes had occurred.

Keywords: inland soda saline-alkali wetland; wetland degradation and restoration; soil nutrients; ecological stoichiometry; *Phragmites australis*

Citation: YANG Yanli, MOU Xiaojie, WEN Bolong, LIU Xingtu, 2020. Soil Carbon, Nitrogen and Phosphorus Concentrations and Stoichiometries Across a Chronosequence of Restored Inland Soda Saline-Alkali Wetlands, Western Songnen Plain, Northeast China. *Chinese Geographical Science*, 30(5): 934–946. https://doi.org/10.1007/s11769-020-1155-7

1 Introduction

Soil organic carbon (SOC) is an important soil component that greatly influences terrestrial ecosystems productivity and global climate change (Rawls et al., 2003; Stockmann et al., 2013, Shen et al., 2020). Like SOC,

Received date: 2020-02-21; accepted date: 2020-04-28

Foundation item: Under the auspices of National Key Research and Development Program of China (No. 2016YFC05004), National Project of China (No. 41971140), Science Foundation for Excellent Youth Scholars of Jilin Province (No. 20180520097JH)

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soil nitrogen (N) and phosphorus (P) are essential mineral nutrients and key limiting elements for plant growth. They have significant impacts on global biogeochemical cycles (Wang et al., 2009). Moreover, SOC, N, and P are closely related, and their interaction in soil plays a crucial role in maintaining ecosystem balance (Sterner and Elser, 2002; Michaels, 2003; Elser et al., 2007; Urbina et al., 2017). Ecological stoichiometry can reflect the balances of energy and chemical elements (e.g., C, N, and P) in ecosystems, and serve an important role in driving understanding of biogeochemistry, and ecosystem processes at the individual and ecosystem levels (Elser et al., 2000; 2007; Michaels, 2003; Hu et al., 2018). Soil C, N, and P ratios directly reflect the state of soil fertility. Different soil C, N, and P ratios occur in different ecosystems (Vinton and Burke, 1995; Lawrence and Zedler, 2013; Bai et al., 2016). For example, the C∶N∶P ratio is 169∶12.3∶1 in grassland soil and 212∶14.6∶1 in forest soil worldwide (Cleveland and Liptzin, 2007). Thus far, stoichiometrics characteristics have been studied broadly in lake, forest, grassland, farmland, and wetland ecosystems (Barbhuiya et al., 2004; Liu et al., 2017; Hu et al., 2018).

Wetland ecosystems are multi-functional terrestrial ecosystems. They are important sources, sinks, and converters of nutrient elements (Mitsch et al., 2013). The globally rare inland soda alkaline wetland ecosystem is distributed mainly in the soda saline soil distribution area, where it maintains the ecological balance of the area (Li et al., 2017). China is one of three soda alkaline land distribution areas in the world (Sumner and Naidu, 1998). There are extensive inland soda alkaline wetlands in the western Songnen Plain of Northeast China (Guan et al., 2001; Li et al., 2013). However, the saline alkaline land area in the Songnen Plain increased to 2.57 million ha in 2001 because of the drought, lack of rain, and sandstorms (Liu, 2001). In contrast, the wetland area decreased by 74% (Wang et al., 2011; Wen et al., 2012). Wetland restoration as attracted extensive attention and become an important part of ecological restoration since the 1990s (Thormann and Bayley, 1997; Visser et al., 1999; Zedler and Kercher, 2005). Various researchers have performed wetland restoration in the inland soda saline-alkali wetlands via vegetation restoration, hydrological regulation, and *Phragmites australis* field fish farming, as well as by constructing a complex *Phragmites australis*-crab/fish-rice ecological system (Wen et al., 2012).

Changes in wetland soil nutrition following degradation into restoration are well documented in the inland freshwater, coastal, and estuarine wetlands (Craft, 2007; Meyer et al., 2008; Zou et al., 2014; An et al., 2018; Wang et al., 2019a). Haywood et al. (2020) held that degradation enhances decomposition, decreasing storage of soil nutrients. Wetland restoration is an effective way to regain soil nutrient elements (Meyer et al., 2008; Gao et al., 2014; Wang et al., 2019b). Even though restoration is increasingly used to assist recovery of degraded wetlands, this can require considerable time (Xu, et al., 2019). Meyer et al. (2008) inferred that the total carbon would reach levels found in natural wetlands after just 25 yr of restoration in the Platte River Valley. Even so, nutrient elements (i.e., SOC, TN, and TP) in the soil can be used as success indicators to assess the level of degraded wetland recovery (Salmo III et al.; 2013). Substantial effort has gone into restoration of inland soda saline-alkali wetlands, but the effects of wetland restoration on soil nutrients (SOC, TN, and TP) characteristic are still unclear. Therefore, we focus on soil carbon, nitrogen, and phosphorus concentrations and stoichiometries across a chronosequence of restored inland soda saline-alkali wetlands in the western part of the Songnen Plain, Northeast China. The objectives are: 1) to characterize the SOC, TN, and TP concentrations and stoichiometries distribution patterns in the soil profiles of natural, degraded, and restored inland soda alkali wetlands; 2) to discuss the effects of wetland restoration on soil nutrient element concentrations and ratio and infer the time required for SOC, TN, and TP concentrations to recover to the levels observed in natural wetlands; and 3) to illustrate the main factors that affect the SOC, TN, and TP contents and ratios in inland soda saline wetland.

2 Methods and Materials

2.1 Study area

The Niuxintaobao *Phragmites australis* wetlands (45°13′N–45°16′N, 123°15′E −123°21′E) are located in the western Songnen Plain of Northeast China (Fig. 1). They are extensive saline-alkali *Phragmites australis* wetlands that cover over approximately 5000 ha. The region is characterized by a semi-arid continental monsoon climate in the middle temperate zone. The mean annual temperature is 4.3℃ with frost-free periods of approximately 137 d. The annual precipitation and evaporation are 412.7 mm and 1817.3 mm, respectively (Wen et al., 2012). The soil types in the region are dominated by $NaHCO_3$ saline marsh soil and alkaline soil, which are characterized by high bulk densities and poor permeabilities. The soil pH ranges between 8.0 and 10.5, and the salinity varies from 0.1% to 1.6% (Li et al., 2017). Modern swamp plant cover on is dominated by *Phragmites australis* accompanied by *Leymus chinensis*, *Stargrass*, *Cattail*, *Suaeda salsa,* and other sedges.

In study area, natural wetlands were permanent flooding and present only in undisturbed core areas, and about 80% of wetlands were degraded to varying degrees in the 1990s (Wen et al., 2012). Wetland restoration began in 1995. Large areas were restored in 2004 and 2009, respectively. Prior to restoration, restored sites were used to cultivate corn for more than 20 yr and degenerated into alkali patches due to lack of water. Restoration sites were transplanted with *Phragmites australis* from natural wetlands and then reasonable irrigation and drainage were performed. The irrigation and drainage sequence is as follows: spring irrigation 5–8 cm in April, first drainage in early May, summer irrigation 10–15 cm from late May to early August, and second drainage in late August (Wen et al., 2012). Thus far, nearly 4000 ha of degraded wetlands have been restored.

2.2 Sample collection

In this study, five sampling sites were prepared during October 15–21, 2017 and shown in the Fig. 1. These sites included *Phragmites australis* wetlands restored for 21 yr (RW_{21a}, restoration in 1995), 12 yr (RW_{12a}, restoration in 2004), and 7 yr (RW_{7a}, restoration in 2009), as well as degraded wetland (DW) and natural wetland (NW). Wetland restoration was performed via a combination of hydrological management and vegetation transplantation. At each site, six duplications were set for each sample plot. Soil was randomly sampled at depths of 0–10 cm, 10–20 cm, 20–30 cm, 30–50 cm, 50–70 cm, and 70–100 cm. A total of 180 composite soil samples (5 sites × 6 depth layers × 6 profiles) were collected and transported to the laboratory. At each wetland site, aboveground biomass of *Phragmites australis* was measured by clipping six randomly selected 1 m × 1 m quadrats.

2.3 Laboratory analysis and statistical analysis

Soil samples were air-dried and ground to 100 mesh after removal of impurities. They were then subjected to physicochemical analysis. Plants were washed with distilled water and dried at 70℃ for 48 h. SOC and plant organic carbon (POC) were measured according to the H_2SO_4-$K_2Cr_2O_7$ oxidation method, while soil and plant total nitrogen (STN and PTN, respectively) and total phosphate (STP and PTP, respectively) were determined using a SAN^{++} continuous flow chemical analyzer (SKALAR Analytical Instruments, Netherlands). The

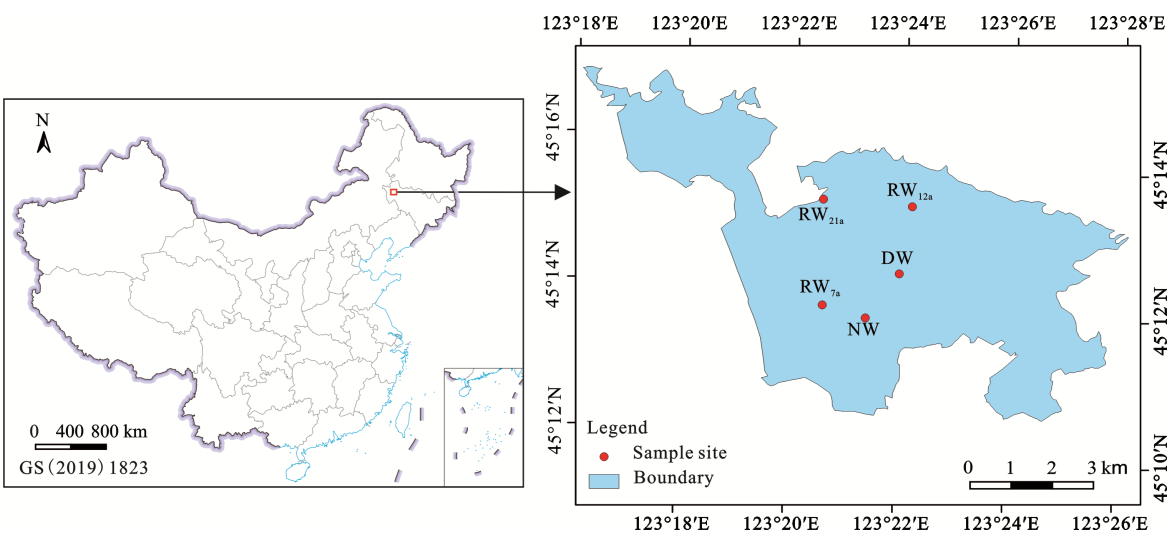

Fig. 1 Location of sites in the inland soda alkali wetlands within the western Songnen Plain of Northeast China. DW, degraded wetland; RW_{7a}, wetland restored for 7 yr; RW_{12a}, wetland restored for 12 yr; RW_{21a}, wetland restored for 21 yr; NW, natural wetland

weight method was adopted for soil moisture, bulk density, and biomass determinations. The soil pH and electrical conductivity (EC) were determined using a volumetric ratio of 1∶5 (weight/volume) with water. Measurements were performed using a FE38 pH meter (Mettler Toledo, Switzerland) and DDS-307 EC meter (Rex, China), respectively. The salinity was expressed as the sum of K^+, Na^+, Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^-, Cl^-, and SO_4^{2-} (Lu, 1999). All laboratory works were conducted in the Analysis and Test Center of the Northeast Institute of Geography and Agroecology, Chinese Academy of Sciences.

Statistical analyses were performed using SPSS 22.0 and OriginPro 2018 for Windows. The results were presented as a mean of replicates alongside the standard error. In our study, SOC, TN, and TP ratios were expressed as molar ratios. Pearson's correlation coefficients were used to test for relationships among SOC, TN, and TP concentrations, their ratios, and the measured environmental variables. We used analysis of variance (two-way ANOVA) followed by the Tukey test ($P < 0.5$) to evaluate the effects of the wetland type, soil depth, and their interactions on the soil characteristics. We used a typical linear model to fit changes in nutrient elements vs. years since restoration. In all tests, differences were considered significant only if $P < 0.05$.

3 Results and Analysis

3.1 SOC, TN, and TP concentrations in degraded, restored, and natural wetland soils

Wetland degradation resulted in the loss of soil nutrient elements, but restoration recovered the lost nutrients (Table 1). In DW, the average SOC, TN, and TP concentration was 2.03 g/kg, 0.40 g/kg, and 0.112 g/kg, respectively. The mean reductions in the SOC, TN, and TP concentrations are 89.6%, 65.5%, and 52.5%, respectively, relative to the concentrations in NW. After restoration of a degraded wetland, the SOC, TN, and TP concentrations in the restoration wetland (RW) soil samples increase significantly. However, the aforementioned concentrations remain lower than those in NW samples even 21 yr after DW restoration. The SOC, TN, and TP concentrations are 29.2%, 17.3%, and 12.8%, respectively, lower in RW_{21a} than in NW.

In the five wetland soil profiles, SOC, TN, and TP concentrations decrease with the soil depth (Fig. 2). The five wetlands have significantly different ($P < 0.05$) SOC, TN, and TP concentrations in the upper 30 cm soil. The concentrations follow the order DW < RW < NW. Few changes are noted in deeper layers ($P > 0.05$). SOC, TN, and TP concentrations in the upper 30 cm soil are linearly increasing with number of years since restoration (Fig. 3). The increase rates of SOC, TN, and TP concentrations in the surface 10 cm are higher than 10–20 cm and 20–30 cm. According to the linear fitting results, in the 0–10 cm degraded wetland soil layer, it would take just over 34 yr for SOC, 29 yr for TN, and 34 yr for TP levels to recover to the level of a natural wetland. The SOC, TN, and TP concentrations in the 10–20 cm and 20–30 cm soil layers would recover in a relatively short time.

3.2 Soil C∶N, C∶P and N∶P ratios

Significantly lower C∶N, C∶P, and N∶P ratios occur in degraded wetland soil profiles ($P < 0.05$, Table 1) than in those of natural wetlands. The soil C∶N, C∶P, and N∶P ratios increase with the time since restoration in restored wetlands ($P < 0.05$). Overall, the soil C∶N, C∶P, and N∶P ratios in the restored wetlands are lower than those in natural wetland, but no significant differences are found between natural wetland and RW_{12a}, and RW_{21a} ($P > 0.05$).

Table 1 The mean values of soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) concentrations and stoichiometries in 1 m of inland soda saline-alkali wetland soil in the western Songnen Plain, Northeast China

Wetlands	SOC (g/kg)	TN (g/kg)	TP (g/kg)	R_{CN}	R_{CP}	R_{NP}
DW	2.03±0.57a	0.40±0.044a	0.112±0.015a	5.92±1.07a	45.36±3.82a	7.67±0.37a
RW_{7a}	3.14±0.45b	0.50±0.052b	0.128±0.015a	7.20±0.91b	61.98±3.58b	8.32±0.27b
RW_{12a}	6.16±0.84c	0.75±0.108c	0.177±0.016b	8.81±1.21c	79.19±8.54c	8.71±0.60b
RW_{21a}	6.82±1.06c	0.86±0.044c	0.205±0.019c	8.69±1.27c	74.69±6.84c	8.37±0.34b
NW	9.63±0.67d	1.04±0.052d	0.235±0.023d	9.55±1.06c	85.27±8.30c	8.55±0.24b

Notes: Different letters within the same column indicate significant differences between types ($P< 0.05$); R_{CN} indicates soil C∶N ratios, R_{CP} indicates soil C∶P ratios, and R_{NP} indicates soil N∶P ratios; DW, degraded wetland, RW_{7a}, wetland restored for 7 yr, RW_{12a}, wetland restored for 12 yr, RW_{21a}, wetland restored for 21 yr, NW, natural wetland

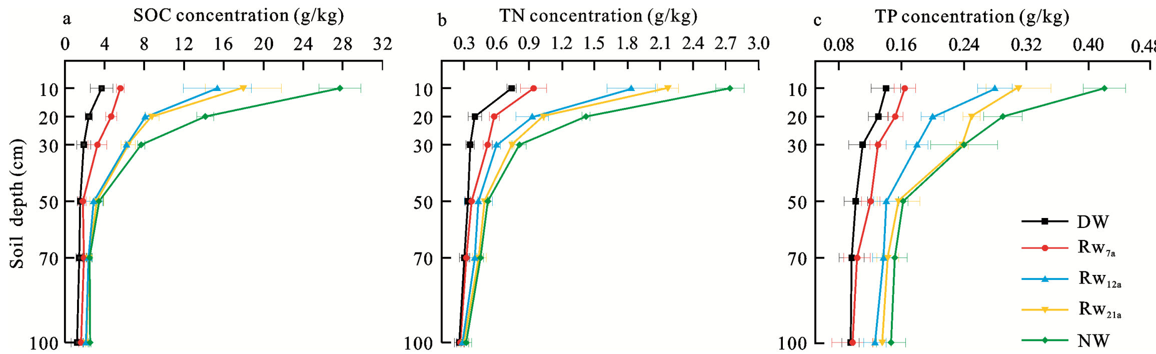

Fig. 2 Vertical distributions of (a) soil organic carbon (SOC), (b) total nitrogen (TN), and (c) total phosphorus (TP) concentrations in degraded wetland (DW), wetland restored for 7 yr (RW_{7a}), wetland restored for 12 yr (RW_{12a}), wetland restored for 21 yr (RW_{21a}), and natural wetland (NW) samples in the inland soda saline-alkali wetlands in the western Songnen Plain, Northeast China

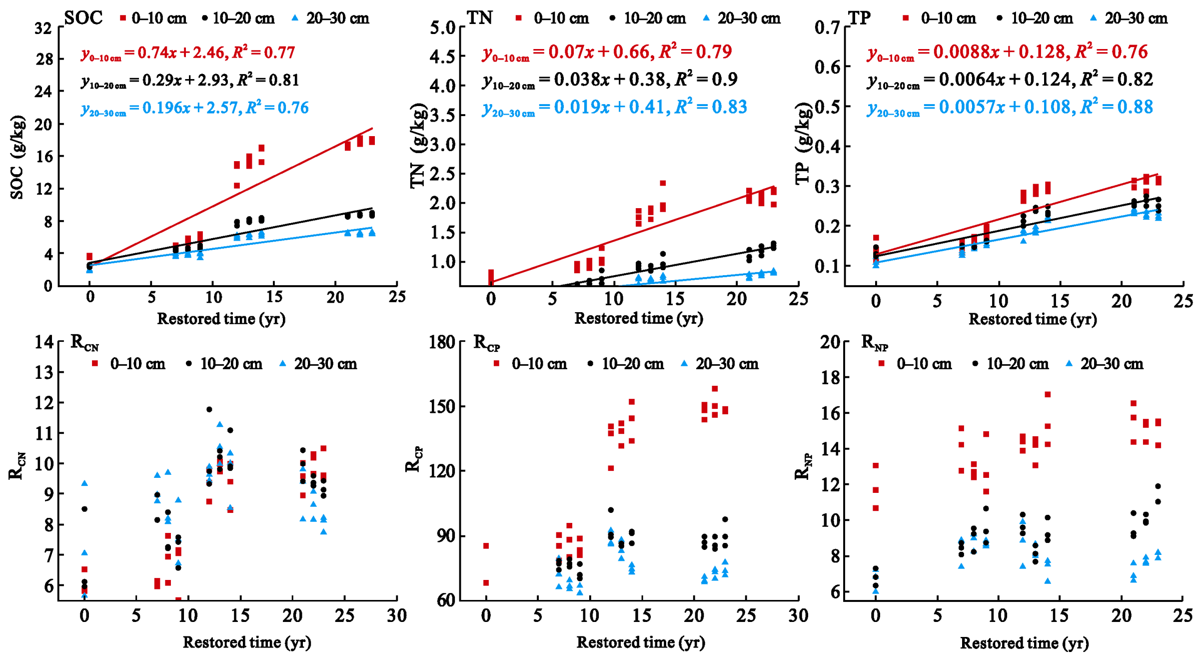

Fig. 3 Soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) concentrations and stoichiometris in the top 30 cm of restored wetland soil in the inland soda saline-alkali wetlands in the western Songnen Plain, Northeast China. Regression lines indicate significant changes with years since restoration; R_{CN}, soil C∶N ratios; R_{CP}, soil C∶P ratios; R_{NP}, soil N∶P ratios

Soil C∶N ratios decrease with the soil depths in degraded wetland, but fluctuate widely in natural and restored wetlands (Fig. 4a). In all five wetlands, the C∶P, and N∶P ratios decrease with the soil depth (Figs. 4b and c). In the upper 30 cm of soil, the C∶N, C∶P, and N∶P ratios are significantly different among the five wetlands (P < 0.01), but no obvious differences are present in deeper soil samples (> 30 cm) (P > 0.05). Soil C∶N, C∶P, and N∶P ratios in the wetland restored 12 yr in the 0–30 cm are similar to those in NW (Fig. 3).

3.3 SOC, TN and TP stocks in wetland soils

Wetland degradation significantly decreases SOC, TN, and TP stocks (Fig. 5). The mean reductions in SOC, TN and TP stocks in 1 m of degraded wetland soil are 69.3%, 47.5%, and 41.2%, respectively. Thus, the related stocks are much lower than in natural wetland soil (P < 0.01). Restoration recovers the SOC, TN, and TP stocks, which increase with the number of years since restoration. The SOC, TN, and TP stocks in 1 m of restored wetland soil increase from 3.8 kg/m^2 to 7.4 kg/m^2, from 0.62 kg/m^2 to 0.98 kg/m^2, and from 0.176 to

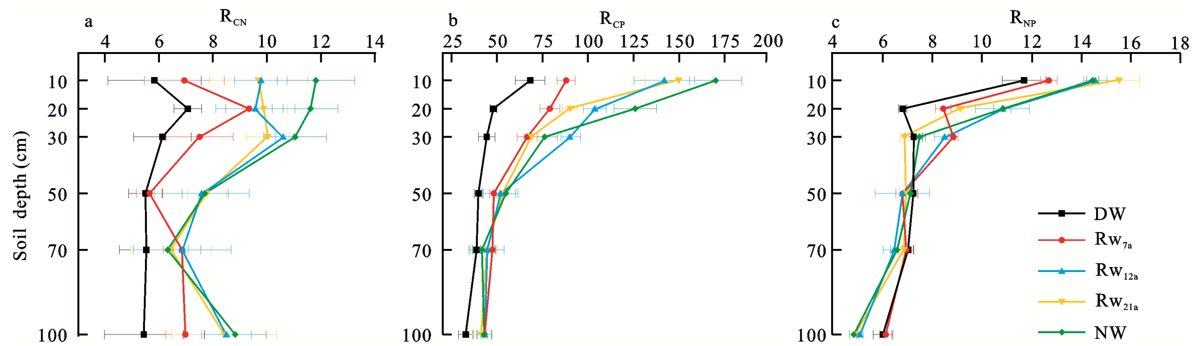

Fig. 4 The distributions of (a) soil C : N ratios (R_{CN}), (b) soil C : P ratios (R_{CP}), and (c) soil N : P ratios (R_{NP}) in degraded wetland (DW), wetland restored for 7 yr (RW_{7a}), wetland restored for 12 yr (RW_{12a}), wetland restored for 21 yr (RW_{21a}), and natural wetland (NW) samples in the inland soda saline-alkali wetlands in the western Songnen Plain, Northeast China

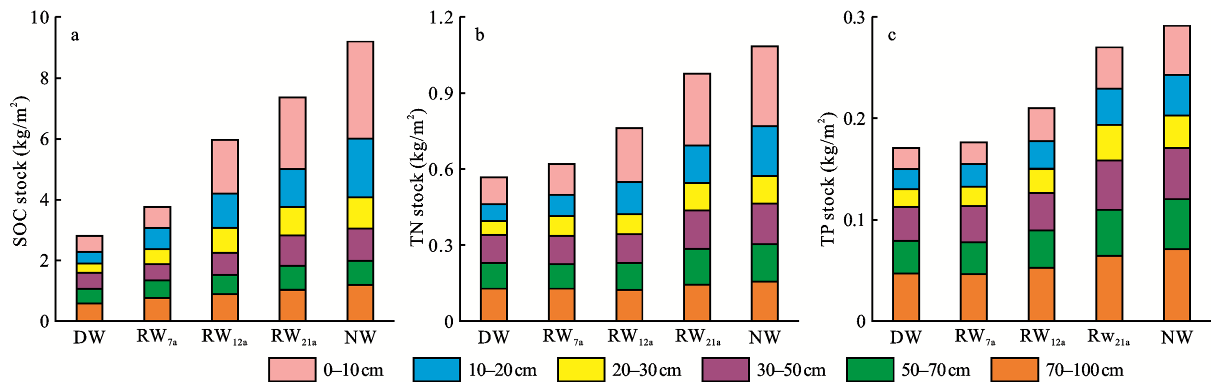

Fig. 5 Soil organic carbon (SOC, a), total nitrogen (TN, b), and total phosphorus (TP, c) stocks in the top 1 m soils of degraded wetland (DW), wetland restored for 7 yr (RW_{7a}), wetland restored for 12 yr (RW_{12a}), wetland restored for 21 yr (RW_{21a}), and natural wetland (NW) in the inland soda saline-alkali wetlands in the western Songnen Plain, Northeast China

0.270 kg/m^2, respectively, but remain lower than those in natural wetland ($P < 0.05$).

3.4 Soil physicochemical property and nutrients correlation analysis

The soil bulk density, pH, and salinity decreased significantly with the number of years since degraded wetland restoration ($P < 0.05$, Table 2). No obvious bulk density, pH, EC, or salinity differences are found among NW, RW_{12a}, and RW_{21a} ($P > 0.05$).

The wetland sample type (degraded, restored, or natural), soil depth, and their interactions each have significant effects on all selected response variables ($P < 0.01$), except the TP concentration ($P > 0.05$, Table 3).

Table 2 Physical and chemical properties of wetland soil in the degraded wetland (DW), wetland restored for 7 yr (RW_{7a}), wetland restored for 12 yr (RW_{12a}), wetland restored for 21 yr (RW_{21a}), and natural wetland (NW) in the inland soda saline-alkali wetlands in the western Songnen Plain, Northeast China

Types	Bulk density (g/cm^3)	pH	EC (μS/cm)	Salinity (‰)	CO_3^{2-}+HCO_3^- (g/kg)
DW	1.48±0.08a	10.5±0.02a	1166±41.58a	15.8±1.32a	3.60±0.55a
RW_{7a}	1.38±0.04ab	8.63±0.18b	407±28.18b	4.3±0.79b	1.16±0.18b
RW_{12a}	1.24±0.12b	8.28±0.21bc	226±44.98c	2.4±0.67c	0.73±0.14c
RW_{21a}	1.16±0.05bc	7.89±0.15c	237±40.50c	2.5±0.31c	0.86±0.26bc
NW	1.15±0.08c	7.74±0.16c	280±21.32c	2.67±0.28c	0.94±0.21bc

Notes: Different letters within the same column indicate significant differences between sites ($P < 0.05$); EC, electrical conductivity; DW, degraded wetland, RW_{7a}, wetland restored for 7 yr, RW_{12a}, wetland restored for 12 yr, RW_{21a}, wetland restored for 21 yr, NW, natural wetland

Table 3 Results of two-way ANOVA for effects of the sampling type, soil depth, and their interactions on soil factors in the inland soda saline-alkali wetlands in the western Songnen Plain, Northeast China

Index	Variables	SOC	TN	TP	R_{CN}	R_{CP}	R_{NP}	BD	pH	EC	Sal
F	Types	5099	454	1.10	1130	5295	195	109	7252	23223	1043
	Depth	10148	1468	1.01	712	18427	8993	104	956	783	69
	T × D	1219	104	1.00	64	1083	229	8	203	1430	27
P-value	Site	< 0.01	< 0.01	0.382	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	Depth	< 0.01	< 0.01	0.418	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	T × D	< 0.01	< 0.01	0.471	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01

Notes: T, Types; D, Depth; SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; R_{CN}, soil C∶N ratios; R_{CP}, soil C∶P ratios; R_{NP}, soil N∶P ratios; BD, bulk density; EC, electrical conductivity; Sal, salinity

In the inland soda saline wetland, the soil salinity is significantly negatively correlated with the SOC, TN, and TP concentrations ($P < 0.01$) but, positively correlated with R_{CN} ($P < 0.05$, Table 4). Moreover, the pH is negatively correlated with the TP concentration ($P < 0.01$) and the bulk density is negatively correlated with R_{NP} ($P < 0.05$).

Significant correlations are found between SOC, TN, and TP concentrations and stoichiometries in our study (Table 5). SOC and TN concentrations are significantly positively correlated with R_{CN}, R_{CP}, and R_{NP} ($P < 0.01$), TP concentrations is significantly positively correlated with R_{CN} ($P < 0.05$).

3.5 Correlation analysis of nutrients in wetland soils and *Phragmites australis*

In DW sites, the *Phragmites australis* aboveground biomass, organic carbon, TN are 72.76%, 12.37%, 52.00%, and TP 68.35% lower, respectively, than in NW site (Table 6). The aboveground biomass and concentrations of organic carbon, TN, and TP increase with restoration. The highest biomass, organic carbon, TN, and TP concentrations are present in NW. However, the concentrations of organic carbon and total nitrogen in RW_{12a} and RW_{21a} are similar to those in NW ($P > 0.05$), total phosphorus concentration was significantly lower than that in the NW ($P < 0.05$). Plant C∶N, C∶P, and N∶P

Table 4 Correlation coefficients of soil properties, as well assoil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) concentrations and stoichiometries in the inland soda saline-alkali wetlands in the western Songnen Plain, Northeast China

Parameter	SOC	TN	TP	R_{CN}	R_{CP}	R_{NP}
Moisture	0.034	0.059	−0.400	0.066	0.336	0.590*
Bulk density	−0.065	−0.180	0.268	0.019	−0.209	−0.511*
pH	−0.353	−0.429	−0.782**	0.248	−0.004	−0.319
EC	−0.563*	−0.631**	−0.887**	0.413	0.178	−0.185
Salinity	−0.704**	−0.722**	−0.882**	0.566*	0.371	−0.055

Notes: ** Correlation is significant at the 0.01 level; * Correlation is significant at the 0.05 level; R_{CN}, soil C∶N ratios; R_{CP}, soil C∶P ratios; R_{NP}, soil N∶P ratios

Table 5 Correlation coefficients of soil properties and soil organic carbon (SOC), total nitrogen (TN), and total phosphorus (TP) concentrations and stoichiometries in the inland soda saline-alkali wetlands in the western Songnen Plain, Northeast China

Parameter	SOC	TN	TP	R_{CN}	R_{CP}	R_{NP}
SOC	1					
TN	0.902**	1				
TP	0.736**	0.760**	1			
R_{CN}	0.897**	0.675**	0.556*	1		
R_{CP}	0.832**	0.697**	− 0.287	0.886**	1	
R_{NP}	0.731**	0.656**	− 0.204	0.270	0.667**	1

Notes: ** Correlation is significant at the 0.01 level; * Correlation is significant at the 0.05 level; R_{CN}, soil C∶N ratios; R_{CP}, soil C∶P ratios; R_{NP}, soil N∶P ratios

Table 6 Plant organic carbon (C), total nitrogen (TN),and total phosphorus (TP)concentrations and stoichiometries in the degraded wetland (DW), wetland restored for 7 yr (RW_{7a}), wetland restored for 12 yr (RW_{12a}), wetland restored for 21 yr (RW_{21a}), and natural wetland (NW) in the inland soda saline-alkali wetlands in the western Songnen Plain, Northeast China

Type	Biomass (kg/m^2)	Plant organic C (g/kg)	Plant TN (g/kg)	Plant TP (g/kg)	C∶N	C∶P	N∶P
DW	0.60±0.22a	432.40±4.61a	10.30±0.34a	0.94±0.03a	48.90±1.48a	1192±36a	24.40±0.74a
RW_{7a}	1.14±0.35b	449.10±10.54b	12.20±0.80b	1.15±0.11b	43.20±2.90b	1019±106a	23.60±1.6b
RW_{12a}	1.80±0.40c	461.90±5.74bc	17.30±0.93c	1.90±0.15c	31.20±1.80c	632±46b	20.30±0.73c
RW_{21a}	1.66±0.53c	485.60±15.30c	20.80±1.40c	2.63±0.17c	27.40±2.50c	479±18c	17.50±0.25d
NW	2.20±0.26c	493.40±7.83c	21.50±0.86c	2.97±0.09d	26.80±0.70c	430±8c	16.10±0.44d

Notes: Different letters within the same column indicate significant differences between different sites (P< 0.05); C∶N, plant C∶N ratios; C∶P, plant C∶P ratios; N∶P, plant N∶P ratios

ratios decrease with years since restoration. No significant differences are found between the RW_{21a} and NW (P > 0.05).

Plant biomass is significantly positively correlated with soil SOC, TN, and TP concentrations, as well as R_{CN} and R_{CP} (P < 0.01). It is positively correlated with R_{NP} (P < 0.05, Table 7). Plant organic carbon and TN concentrations are positively correlated with soil SOC, TN, and TP concentrations, as well as R_{CN} and R_{CP} (P < 0.05). Plant TP concentrations are positively correlated with soil SOC, TN, and TP concentrations and R_{CN} (P < 0.05). Plant C∶N ratios are negatively correlated with soil SOC, TN, and TP concentrations (P < 0.05), while C∶P ratios are negatively correlated with soil SOC and TP concentrations (P < 0.05). N∶P ratios are negatively correlated with soil TP concentrations (P < 0.05).

4 Discussion

4.1 Changes in soil SOC, TN, and TP concentrations following wetland restoration

The soil SOC, TN, and TP concentrations increased with recovery time after the degraded inland soda saline-alkali wetlands were restored. This result is in line with those of previous studies (Meyer et al., 2008; Xu et al., 2019). Hydrological conditions may have been a direct cause of the differences between the nutrient element contents of degraded and restored wetlands (Yang et al., 2020). In our study, nutrient elements recovered in degraded wetland soil after restoration of hydrological conditions, in other words, wetland degradation caused by lack of water resulted in nutrient loss. Increased aridity in the degraded wetlands altered the soil structure (Zhao et al., 2018), reducing biological activity (Delgado-Baquerizo et al., 2013) and therefore nutrient availability. For example, drought and water shortages increased soil aeration, promoted soil respiration, and accelerated SOC decomposition (Delgado-Baquerizo et al., 2013). The lower TN concentrations observed in degraded wetland soils were probably derived from higher soil erosion and reduced plant cover, which inhibit nitrogen mineralization. This may lead to a positive feedback loop that affects nutrient availability (Schimel and Bennett, 2004). In addition, degradation reduced

Table 7 Correlation coefficients of soil and plant organic carbon, total nitrogen (TN), and total phosphorus (TP) concentrations and stoichiometries in the inland soda saline-alkali wetlands in the western Songnen Plain, Northeast China

Parameter	SOC	Soil TN	Soil TP	R_{CN}	R_{CP}	R_{NP}
Biomass	0.965**	0.957**	0.943**	0.995**	0.993**	0.884*
Plant organic C	0.956**	0.976**	0.981**	0.925*	0.891*	0.687
Plant TN	0.960**	0.981**	0.987**	0.946*	0.911*	0.732
Plant TP	0.971**	0.988**	0.994**	0.918*	0.877	0.716
Plant C∶N	−0.922**	−0.613*	−0.774*	−0.342	−0.423	−0.313
Plant C∶P	−0.817**	−0.557	−0.638*	−0.446	0.009	−0.201
Plant N∶P	−0.233	0.299	−0.804*	−0.379	−0.611	−0.673

Notes: ** Correlation is significant at the 0.01 level, * Correlation is significant at the 0.05 level; SOC, soil organic carbon; TN, total nitrogen; TP, total phosphorus; R_{CN}, soil C∶N ratios; R_{CP}, soil C∶P ratios; R_{NP}, soil N∶P ratios microbial activity by limiting the mobility of extracellular enzymes and the ability of microorganisms to obtain nutrients (Borken and Matzner, 2009). Nutrient element concentrations increased after sufficient water was supplied to the degraded wetland. On the one hand, water supplied some N and P to the wetlands (Bai et al., 2007). On the other hand, flooding created an anaerobic environment that inhibited microbial activity, decreased SOC decomposition (Zhao et al., 2018), and was unfavorable to organic nitrogen mineralization (Amdor et al., 2005) and well as P accumulation (Gao et al., 2014). Hence, we hold that water supplementation may be a good approach to SOC, TN, and TP recovery during the inland soda alkaline wetland restoration.

The SOC, TN, and TP concentrations in the inland soda alkaline wetland soil were affected not only by the hydrological conditions, but also by plants and soil properties. In this study, lower SOC, TN, and TP concentrations in degraded wetlands and younger restored sites were related to higher salinity. This result is consistent with those of some previous studies (Qadir et al., 2000; Wong et al., 2010, Zhao et al., 2018). It indicated that salinity inhibit soil carbon, nitrogen, and phosphorus sequestration. High salinity reduced microbial activity and soil respiration (Rousk et al., 2009; Setia et al., 2011) by causing flocculation or dispersion of soil particles (Wong et al., 2010; Zhao et al., 2018), increased osmotic potential, and a decline in soil structure, there by changing soil organic matters solubility and nitrogen mineralization rate (Gao et al., 2014). Zeng et al. (2013) found that rates of nitrification and denitrification decreased when the soil salinity exceeded 0.67 dS/m. In our study, the degraded wetland soil salinity was 1.16 dS/m, indicating the lowest nutrient availability (Wieski et al., 2010; Freitas and Costa, 2014; Estrelles et al., 2015). Besides, salinity caused differences in vegetation ecological characteristics, influencing the inputs to and storage of soil nutrients (Belleveau et al., 2015). Lower nutrient inputs into the soil most affected by salt would be caused by increased osmotic potential and ionic toxicity to vegetation. Salinity decreases caused by wetland restoration lead to soil nutrient accumulation. Hence, reducing salinity during wetland restoration may be conducive to the recovery of soil SOC, TN, and TP in degraded inland soda saline-alkali wetlands. Furthermore, we found that plants had positive effects on SOC, TN, and TP concentrations. Biomass was expected to control the profile distributions of C and N by contributing to their respective accumulations in surface soils. Delgado-Baquerizo et al. (2013) held that degradation reduced plant activity and nutrient uptake by reducing vegetation cover, resulting in nitrogen loss and higher phosphorus availability. The lack of soil nutrients promoted the secretion of organic acids by plant roots, more sugars were supplied to soil microorganisms, and more extracellular enzymes entered the soil to aid nutrient absorption (Qin et al., 2016). The soil nutrient content gradually increased with vegetation restoration, decreasing the degree to which nutrients limited vegetation growth. In addition, some studies found that plant litter was another important contributor to SOC, TN, and TP accumulation in the soil (Cross et al., 2005). Litter nutrient elements that returned to the soil after decomposition could improve soil fertility (Ren et al., 2016). The litter yield was significantly lower in degraded wetlands than in restored and natural wetlands. This was one of the reasons for decreased degraded wetland soil nutrients. We believe that vegetation restoration is an effective way to recover soil nutrients in degraded wetlands.

In our study, the soil SOC, TN, and TP concentrations were higher in the surface (≤ 30 cm) soil layers than in the deep layers (> 30 cm). This result is similar to those observed in previous studies (Bai et al., 2007; Hu et al, 2018a; Wan et al., 2020). Some studies have suggested that the surface soil layer has the most plant roots and strong microbial activity that promotes plant litters decomposition (Jobbágy and Jackson et al., 2002; Fröberg et al., 2007). Nutrients reach deep soil mainly primarily via physical or biological migration from upper soil (Bai et al., 2016). In our study area, most plant roots were distributed in 0–30 cm soil layer. Plant litter decomposition occurred in surface soil with high biological activity, giving it higher nutrient concentrations than deep soil.

Although wetland restoration improved their nutritional statuses, the SOC, TN, and TP concentrations in the three restored wetlands clearly remained lower than in natural inland soda saline-alkaline wetlands. Our results showed that it would take just over 29 yr for SOC, TN, and TP levels in the 0–10 cm degraded wetland soil layer to recover to the level of a natural wetland. Hydrological restoration improved soil texture, reduced soil salinity, and was suitable for plant growth (Meyer et al., 2008), resulting in acceleration of organic residue decomposition and nutrient accumulation (Li et al., 2016). Increases in SOC, TN, and TP in the restored wetlands indicated that positive to ecosystem functions occurred (Meyer et al., 2008). Inland soda saline-alkali wetlands require more time for soil nutrient recovery than inland freshwater (Confer and Niering, 1992; Meyer et al., 2008), and coastal, or estuarine wetlands (Craft et al., 1999). Hence, we must pay attention to protection of this special wetland type.

4.2 Variation in nutrient element stoichiometry with years since restoration

The C∶N ratio (R_{CN}) is an index used to measure the soil N mineralization ability. According to Tisdale et al. (1985), a soil R_{CN} larger than 20 indicates microbial immobilization of available soil N, whereas a R_{CN} of less than 20 indicates that sufficient N is available for plant uptake. Our results showed R_{CN} values of natural inland soda alkali wetlands soils ranged from 8.82 to 11.79 with the soil profile. The average value was 9.5, suggests sufficient N available for plant uptake. These values were within the average range for China (Tian et al., 2010). The R_{CN} was positively correlated with SOC and TN concentrations. The degraded wetland exhibited a lower R_{CN} because soil SOC and TN concentrations were lower than in the restored and natural wetlands. Wetland degradation decreased TN concentrations due to increased mineralization rates, as well as leaching or volatilization of inorganic N (Meyer et al., 2008). The R_{CN} ranged from 7.2 to 8.8 in the restored wetlands and increased with time. It became similar to that observed in natural wetland after more than 12 yr of restoration. During wetland restoration, the SOC accumulation rate exceeded that of TN. This could be because wetland restoration increased the soil N supply capacity, resulting in potential C sequestration improvement (Li et al., 2016). In inland soda saline-alkali wetland restoration, R_{CN} recovery reflected the restoration of wetland function.

In our study, we found that C∶P ratio (R_{CP}) declined faster than R_{CN} with soil profiles and were significantly affected by SOC. This is in line with results from other researchers (Tian et al., 2010; Bui and Henderson, 2013; Jiang and Guo, 2019). These relationships resulted primarily from the fact that P could be more stable in the soil profile than SOC (Tian et al., 2010). Black and Goring (1953) found that an R_{CP} of < 200 could contribute to a net accumulation of P. In natural inland soda alkali wetlands, the R_{CP} value in the surface soil was 170.4. This reflects the potential of wetlands as P sinks. Degradation resulted in lower productivity as well as lower SOC and TP concentrations. Recovery increased SOC and TP accumulation. R_{CP} increases in the restored wetland were driven primarily by SOC concentration increases. Lajtha and Schlesinger (1988) found that parent material provided the major source of soil P. This was followed by litter decomposition. Even though biomass increases with restoration time led to increased TP concentrations, low TP accumulation rate and high SOC accumulation rate resulted in high R_{CP} values.

Soil R_{NP} is one of the most important indexes used to evaluate N and P limitations. It has used to determine nutrient limitation thresholds (Güsewell et al., 2003; Morse et al., 2004). Verhoeven et al. (1996) pointed out that soil R_{NP} values larger than 30 or 35 could indicate P limitations, while values of less than 30 or 35 could indicate of N limitations. Others held that R_{NP} values lower than 14 could result in soil N deficiencies and thereby limit of plant growth (Koerselman and Meuleman, 1996; Aerts and Chapin III, 1999; Townsend et al., 2007). The R_{NP} (14.44) in our study region was slightly higher than 14 and less than 30, indicating that the N and P in the soil were sufficient for plant growth in natural inland soda saline-alkali wetlands. The R_{NP} was lowest in the degraded wetland and increased with restoration time. Low values in the degraded and younger restored wetland soils indicated "N limitations". The R_{NP} recovered to the level of a natural wetland after 12 yr of restoration. As with R_{CN} and R_{CP}, R_{NP} was mainly affected by SOC and TN concentrations.

5 Conclusions

In this study, we compared soil physical and chemical properties, as well as SOC, TN, and TP concentrations and stoichiometries in degraded, restored, and natural wetlands in order to evaluate the effects of wetland restoration. The implementation of restoration measures could contribute to higher SOC, TN, and TP concentrations and stoichiometris, which resulted in nutrient storage that increased with the wetland restoration time. Increases of SOC, TN, and TP concentrations and stoichiometries indicated positive changes to wetland ecosystem function. Given current restoration measures, we inferred that at least 34 yr would be required for soil SOC, TN, and TP levels to reach those of natural wetland. The SOC, TN, and TP ratios indicated that it would take more than 12 yr for the soil to reach stoichiometric balance after degraded wetland restoration. Our results demonstrated that the soil N concentration was sufficient for plant growth when the inland soda saline-alkali wetlands had been restored for over 12 yr. Salinity and plants played important roles in wetland restoration. Reducing salinity and performing vegetation restoration were conducive to the accumulation of SOC, TN, and TP.

Acknowledgments

We gratefully acknowledge the staff at Niuxintaobao National Wetland Park for field work in the form of investigation and sampling. We also thank the Analysis and Test Center of the Northeast Institute of Geography and Agroecology, Chinese Academy of Science, for sample analysis.

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