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Original article

Ecological stoichiometric characteristics of soil SOC, TN, and TP under different restoration methods in QiXing river wetland

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ABSTRACT

Objectives: Different recovery methods, (1) Return farmland to wetland (RFW), (2) Return Farmland to Forest (RFF) areas are located in QiXing River Wetland National Natural Reserves. The purpose of this study was to analyze the impacts of different wetland restoration on the soil elements.
Methods: From three regions that RFW, RFF, and NW (Natural Wetland for reference) in QiXing river wetland, the soil samples were collected for soil SOC, TN, TP, NO_3^--N, NH_4^+-N, and SAP contents determination. C:N:P ratios were calculated in the spring, summer, and autumn of 2018.
Results: In this study, soil SOC, TN contents reached Ⅰ standard of China, TP was in medium above to excellent, the soil C:N:P ratios of RFW, RFF, and NW were 138:7.8:1, 131:5.4:1, 145:7.6:1 (molar ratios, the same is as follows), in QiXing river wetland, closed to on China's soils. And the SOC, TN, NO_3^--N, and C:N:P ratios of RFW higher than of RFF, and C:N of RFF more than RFW, indicating that soil SOC were rich in QiXing river wetland, the RFF was more beneficial to available phosphorus release and by N restriction. As elements of plant growth that NH_4^+-N, TP shown as spring and summer were inferior to autumn, owing to demand of elements in the flourishing period more than in the mature period.
Conclusions: The C:N:P ratios of RFW higher than of RFF, indicating that soil SOC were rich in QiXing river wetland, the RFF was more beneficial to available phosphorus release and by N restriction. While RFW was more beneficial to promotes plants growth and restoration, and soil carbon and nitrogen metabolism and balance.

1. Introduction

Ecological stoichiometry focuses on the mass balance of multiple nutrient elements by the study of the changes of those and their ratios (Rong et al., 2015). Carbon (C), nitrogen (N), and phosphorus (P) are the most important nutrient of soil, which ecological stoichiometric characteristics play a critical role in exploring the material cycle, multi-element balance, and nutrient limit of the ecosystem (Michaels et al., 2001). The stoichiometric characteristics of soil C, N, and Pon cycles influence by climate conditions, hydrological regimes, and biological, directly or indirectly, leading to more complexity (Xu et al., 2019). Therefore, the stoichiometric characteristics of soil C, N and P have a good sign effect, such as C:N and C:Preflect the growth of plants, N:P restricts plant growth (Luo et al., 2012; Qian et al., 2018). Wetlands that transitional region between terrestrial and aquatic ecosystems play an important role in storing carbon and nitrogen, protecting species diversity and keeping regional ecological security (Hefting et al., 2013). Hence, the restoration and protection of wetlands is still an important task and have a hot topic (Yepsen et al., 2014). The ecological stoichiometric characteristics of wetland soil not only reflect the cycling status of nutrients and affect of soil quality, but also have an important significance to reveal the productivity, stability, and restoration effect of the wetland ecosystem (Yanf, 2002). Cui et al. (2009) reported the soil SOC and TP content were higher in the cultivated poplar to wetland compared with natural restoration wetland in Lake. However, Li et al. (2016) researched the soil organic matter, available nitrogen, available phosphorus, and available potassium of natural restoration wetland were higher than that of artificial restoration method, indicated that natural restoration wetland more significant affect on soil improvement in WuYu

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river wetland. Zhou et al. (2020) showed the soil total phosphorus, available phosphorus, and available nitrogen of natural restoration in the middle-reaches of Heihe River were superior to restoration protection, the organic carbon and total nitrogen were the highest by built trestles and regular mowing. The Yellow River delta wetland after the artificial restoration found the soil C:N was lower than 25, the SOC and TN were higher than the unrecovered area, which proved to decompose organic matter was not restricted by N and promoted to the release of nutrients (Dong et al., 2011; Shugart and Botkin, 1981; Su et al., 2018). Therefore, it is important to choose a reasonable restoration method to promote the restoration and protection of wetlands in China.

QiXing wetland national nature reserve is a representative and typical wetland in Sanjiang plain of northeast China, located in the north of Baoqing county, Heilongjiang province. The topography of the QiXing wetland is a typical low plain and floodplain of the valley, formed the hilt-land that is suitable for reclamation and cultivation in the wetland. Since the 1950s, the QiXing wetland had been mainly used for agricultural cultivation. With the development of agriculture, the corridor connectivity of the QiXing river was damaged, by 2000, which reduced by 51%, and the landscape index and species diversity decreased (Liu et al., 2004). Until 2002, according to the wetland different terrain, flooding, and other, the QiXing river adopted two major projects of returning farmland to the wetland.1. For the areas with intermittent flooding, the natural restoration wetland without human interference was selected return farmland to wetland (RFW), 2. For the hilt-land with less flooding, the cultivated *populous L* with human interference was selected return farmland to the forest (RFF). Much researches in QiXing wetland mainly includes the area decrease analysis, the characteristics of climate change, the breeding behavior of Chlidonias hybridus, the diversity and abundance of invertebrates, and Ammonia-Oxidizing Archaea and other aspects (Yu et al., 2014). The objectives of this study were to examine (1) the stoichiometric characteristics of soil SOC, TN, TP, NO_3^--N, NH_4^+-N, and SAP under different restoration methods wet land (2) the equilibrium mechanism of interaction of soil nutrient elements under different restoration methods wetland (3) the effects of soil carbon, nitrogen, and phosphorus after different restoration methods in QiXing wetland.

2. Materials and methods

2.1. Study sites

The QiXing wetland (132° 5′–132° 26′ E, 46° 40′–46° 52′ N) for this study is located in China's a humid and sub-humid continental monsoon climate zone. The region is characterized by quickly rises temperature spring, warm and humid summer, sharply drops temperature autumn, and cold and long winter, with mean annual precipitation, which confined mainly to April to September, and annual temperatures, annual relative humidity are shown in Table S1. Gramineae are natural plants such as *Calamagrostis angustifolia*, *Phragmites australis*, and *Carex*, are widely distributed in QiXing wetland. In the meantime, *Artemisia atrovirens* and other plants are associated in high floodplain or hilt-land. The study sites were established on QiXing river wetland national nature reserve in the experimental area (Fig. S1).

2.2. Sample collection

In 2018, most soil samples were collected in spring, summer, and autumn, respectively (Table S2). Three plots were selected for each research areas, and the distance between each plot not <100 m. Three subplots were arranged in each plot, a total of 27, and the distance between each subplot not <50 m, within each subplot soil samples according to the three points method. Sample was air-dried and sieved (0.25 mm), divided into 3 equal parts and put into sealing bags for the analysis of ammonium nitrogen (NH_4^+-N), nitrate-nitrogen (NO_3^--N) and available phosphorus (SAP) contents.

2.3. Sample analysis

The soil SOC, TN, and TP were determined via point analysis with EDAX energy spectrometer ((HITACHI)S-4800, Japan). Soil samples were subjected to scanning electron microscopy (SEM) analysis. The soil NO_3^--N, and NH_4^+-N were determined.

2.4. Data analysis

Two-way ANOVA with SPSS 19.0 software was used to analyze the variation of soil properties. And Pearson correlation analysis was used to study the elements.

3. Results

3.1. Soil SOC, TN and TP and their variability

The different restoration methods and seasons displayed that soil SOC content (44.72 g·kg^{-1}–54.72 g·kg^{-1}, all data) was not significantly different (Fig. 1A), and was consistent with TN (2.61 g·kg^{-1}–2.79 g·kg^{-1}) in spring (Fig. 1B), and TP (0.81 g·kg^{-1}–1.52 g·kg^{-1}) in spring and summer (Fig. 1C). Soil TN content showed as summer higher and autumn than spring in RFW; TP content was better autumn than spring and summer in different wetlands. The average variation coefficient of soil SOC was demonstrated as spring > summer, and > autumn in different restoration methods, consistent with TN and TP, generally, whereas the TN of RFW and TP of RFF were spring > autumn, and > summer (Table 1).

Different capital letters represent significant differences between different restoration methods and different little letters represent significant differences between different seasons (P < 0.05). Value = M ± S.D. RFW: Return Farmland to Wetland; RFF: Return Farmland to Forest; NW: Natural Wetland.

3.2. The stoichiometric ratios of soil SOC, TN and TP and their variability

The soil C:N (17.38–18.93), C:P (55.39–60.47), and N:P (2.93–3.54) ratios of different wetlands were not significantly different in spring (Fig. 2). In other seasons, the C:N (12.58–24.49), C:P (36.63–71.47), and N:P (1.29–4.96) showed the difference. The soil C:P and N:P ratios were varied widely in autumns > spring and summer (Table 2).

3.3. Soil NO_3^--N, NH_4^+-N, and SAP in wetland

The different restoration methods displayed that soil NO_3^--N (0.86 mg·kg^{-1}-–1.43 mg·kg^{-1}), NH_4^+-N (129.6 mg·kg^{-1}–285.6 mg·kg^{-1}), and SAP (0.93 mg·kg^{-1}–1.12 mg·kg^{-1}) contents (Fig. 3). The soil NO_3^--N, SAP contents were stable, except NO_3^--N of NW was autumn < spring and summer, same as NH_4^+-N (Table 3).

3.4. The characteristics of soil SOC, TN and TP contents in different wetlands

In this study, the average soil SOC content was erage (44.72 g·kg^{-1}–54.72 g·kg^{-1}) of RFW, RFF, and NWreachedI standard. According to the classification standard of soil SOC is superior

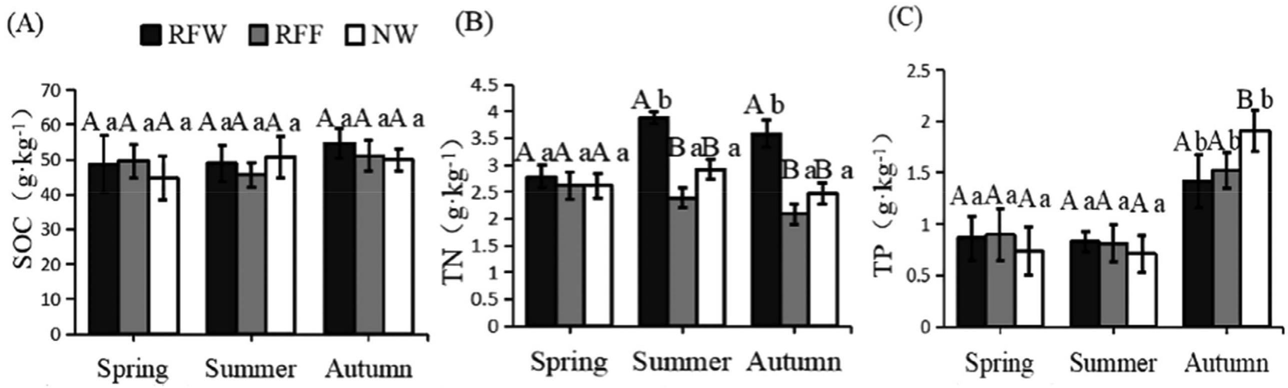

Fig. 1. Contents of SOC, TN, and TP under different restoration methods in QiXing River wetland.

Table 1
The variability of SOC, TN, and TP contents under different restoration methods in QiXing River wetland.

Element	Restoration method	Min (g·kg^{-1})			Max (g·kg^{-1})			C.V. (%)			Average C.V.(%)
		Spring	Summer	Autumn	Spring	Summer	Autumn	Spring	Summer	Autumn	
SOC	RFW	40.00	41.20	44.70	56.60	55.80	61.10	8.80	8.10	7.60	8.17
	RFF	33.50	31.10	47.90	62.90	52.20	59.80	13.60	11.80	6.80	10.73
	NW	27.20	31.20	43.30	60.30	58.20	58.80	18.40	10.10	8.50	12.33
TN	RFW	8.16	15.80	22.90	19.60 20.20 20.30	29.80	38.80	25.30	14.00	15.60	18.30
	RFF	4.73	6.056.05	19.20		11.90	34.30	37.60	20.30	20.20	26.03
	NW	3.35		10.20		19.10	33.80	49.60	30.10	22.60	34.10
TP	RFW	0.45	0.84	1.20	1.90	3.07	2.30	35.90	20.40	18.30	24.87
	RFF	0.32	0.88	1.40	2.10	2.20	2.40	40.70	21.50	27.84	30.01
	NW	0.27	0.99	1.20	1.60	2.10	2.80	35.30	17.10	10.22	20.87

RFW: Return Farmland to Wetland; RFF: Return Farmland to Forest; NW: Natural Wetland.

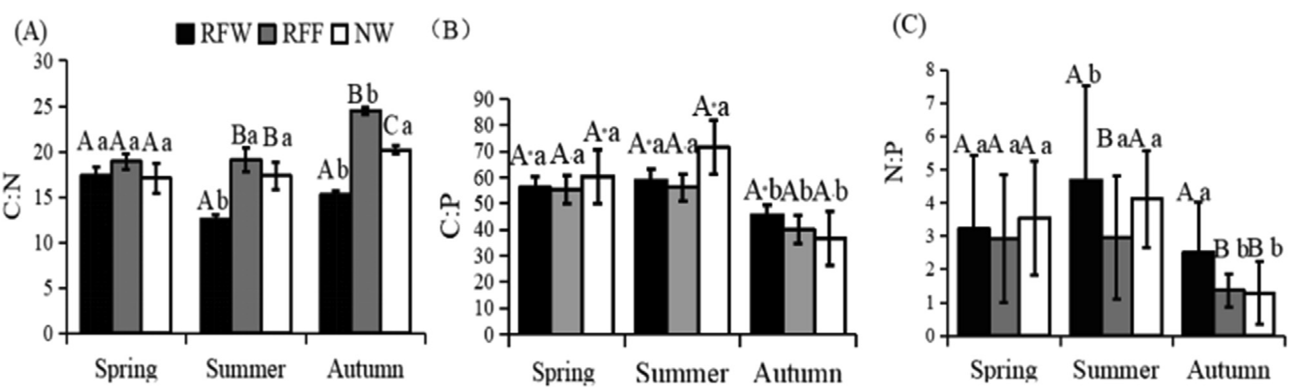

Fig. 2. Contents of C:N, C:P, and N:P under different restoration methods in QiXing River wetland.

Table 2
The variability of SOC, TN, and TP stoichiometric ratio under different restoration methods in QiXing River wetland.

Stoichiometric ratio	Restoration method	Min			Max			C.V. (%)			Average C.V.(%)
		Spring	Summer	Autumn	Spring	Summer	Autumn	Spring	Summer	Autumn	
C:N	RFW	2.90	1.30	1.50	35.70	23.10	22.60	5.20	3.14	2.22	3.52
	RFF	2.80	2.20	1.30	28.20	27.50	33.20	4.45	7.08	1.90	4.47
	NW	2.30	2.50	1.40	32.90	28.13	35.50	9.05	8.50	2.46	6.67
C:P	RFW	61.90	31.30	47.10	141.0	158.3	91.00	6.77	6.71	8.35	7.27
	RFF	77.90	74.80	48.80	211.0	159.4	88.30	5.38	9.10	11.14	8.54
	NW	43.00	59.50	25.00	99.00	147.4	66.50	9.46	8.35	14.59	10.80
N:P	RFW	0.80	1.30	1.00	11.00	12.00	10.50	59.05	57.91	71.19	62.72
	RFF	1.19	1.80	0.20	10.00	9.10	7.70	84.42	83.84	36.59	68.28
	NW	1.10	1.09	0.80	12.00	12.70	6.40	45.96	31.23	49.87	42.34

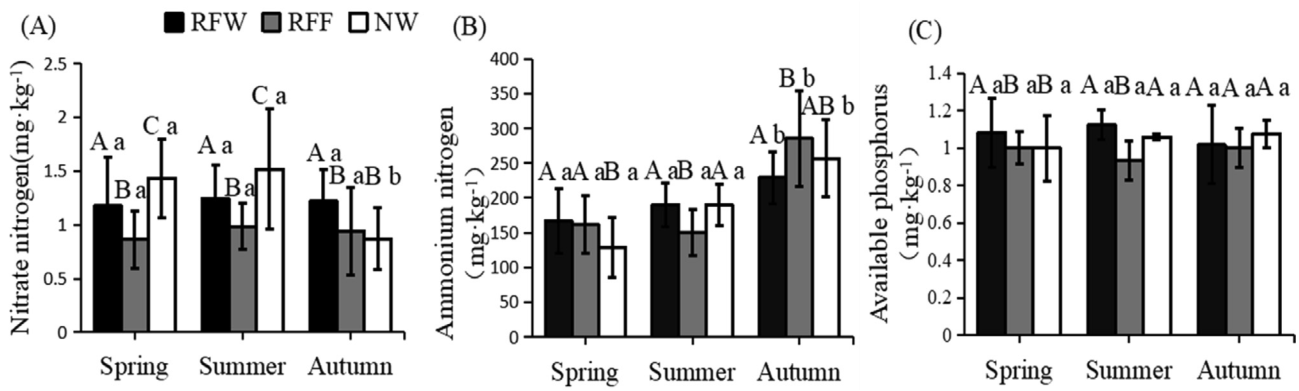

Fig. 3. Contents of nitrate nitrogen, ammonium nitrogen, and available phosphorus contents under different restoration methods in QiXing River wetland.

Table 3
The variability of nitrate nitrogen, ammonium nitrogen, and available phosphorus contents under different restoration methods in QiXing River wetland.

Element		Min ($mg·kg^{-1}$)			Max ($mg·kg^{-1}$)			C.V. (%)			Average C.V.(%)
Restoration method		Spring	Summer	Autumn	Spring	Summer	Autumn	Spring	Summer	Autumn	
NO_3^--N	RFW	0.50	0.60	0.60	2.20	2.20	2.80	38.30	25.70	24.30	29.43
	RFF	0.60	0.60	0.30	1.80	1.10	2.03	30.30	21.70	42.90	31.63
	NW	0.90	0.70	0.20	2.40	2.70	2.40	25.20	36.70	63.10	41.66
NH_4^+-N	RFW	70.00	133.0	203.0	238.0	252.0	329.0	46.70	31.80	37.70	38.73
	RFF	98.00	77.00	168.0	259.0	203.0	476.0	41.90	32.70	68.20	47.60
	NW	133.0	84.00	245.0	357.0	182.0	483.0	43.00	30.20	55.60	42.93
SAP	RFW	0.10	0.18	0.90	1.20	1.30	1.70	17.05	7.15	20.06	14.75
	RFF	0.96	0.90	0.90	1.06	1.40	1.60	8.64	11.40	10.56	9.20
	NW	0.92	0.90	0.90	1.10	1.10	2.70	17.10	6.60	7.10	10.27

to the 23.20 $g·kg^{-1}$ for Ⅰ level in China. The standard classification of carbon, nitrogen, and phosphorus content of classification in China was described in Table S3. The soil SOC and TN were significant positive correlated ($P < 0.01$), which reflects this synergistic relationship (Table 4). In wetland restoration, TN and TP were positively correlated ($P < 0.05$), while TN and SAP was a negative linear correlation indicating that there was also a synergistic relationship between TN and TP in wetland restoration. The stoichiometric ratios correlation between RFF and NW was generally higher than that of RFW (Table 5). A linear regression was used to distinguish seasons and soil nutrient elements, and stoichiometric ratios and nutrients and SAP, and seasons. A linear regression analyses between soil nutrient elements and seasons were tested and the results were tabulated ($R^2 = 0.68$) (Table 6).

4. Discussion

The soil SOC content is an important index to measure soil quality and has important significance for soil stability and biodiversity. Our results indicated that the soil SOC nutrient was rich in the different wetlands, promoting the plant's restoration and the growth of native plants. Generally, the SOC content of the restored

Table 4
The relationship of soil carbon, nitrogen, and phosphorus contents under different restoration methods in QiXing River wetland.

Restoration method	Element	SOC	TN	TP	NO_3^--N	NH_4^+-N	SAP
RFW	SOC	1.000	0.310**	−0.267*	0.061	0.128	0.058
	TN		1.000	0.148*	0.009	−0.097	−0.273*
	TP			1.000	0.052	0.182	−0.163
	NO_3^--N				1.000	−0.07	0.127
	NH_4^+-N					1.000	0.095
	SAP						1.000
RFF	SOC	1	0.368**	−0.432**	0.039	0.321**	0.241*
	TN		1.000	0.126*	−0.046	−0.121	−0.036
	TP			1.000	0.006	−0.238*	−0.231*
	NO_3^--N				1.000	0.132	−0.04
	NH_4^+-N					1.000	0.457**
	SAP						1.000
NW	SOC	1	0.263*	−0.549**	0.195	−0.271*	0.079
	TN		1.000	−0.027	0.138	0.162	−0.221*
	TP			1.000	−0.179	0.317**	0.078
	NO_3^--N				1.000	−0.263*	−0.295**
	NH_4^+-N					1.000	0.108
	SAP						1.000

SOC: Soil organic carbon; TN: Total nitrogen, TP: Total phosphorus; NO_3^--N:Nitrate nitrogen; NH_4^+-N: Ammonium nitrogen; SAP: Soil available phosphorus; RFW: Return Farmland to Wetland; RFF: Return Farmland to Forest; NW: Natural Wetland. * represents significant correlation at 0.05 levels, while ** represents significant correlation at 0.01 levels. The same is as follows.

Table 5
The relationship of stoichiometric ratio of soil carbon, nitrogen, and phosphorus under different restoration methods in QiXing River wetland.

Restoration method	stoichiometry	C:N	C:P	N:P	C:NO_3^--N	C:NH_4^+-N	C:SAP
RFW	C:N	1.000	−0.057	−0.065	0.051	−0.220*	−0.178
	C:P		1.000	0.996**	0.025	0.041	−0.064
	N:P			1.000	−0.003	0.008	−0.103
	C:NO_3^--N				1.000	0.133	0.511**
	C:NH_4^+-N					1.000	0.382**
	C:SAP						1.000
RFF	C:N	1.000	−0.045	−0.074	−0.125	−0.17	−0.098
	C:P		1.000	0.953**	0.145	0.303**	0.464**
	N:P			1.000	0.056	0.237*	0.327**
	C:NO_3^--N				1.000	0.381**	0.621**
	C:NH_4^+-N					1.000	0.536**
	C:SAP						1.000
NW	C:N	1.000	−0.179	−0.228*	−0.065	0.355**	0.072
	C:P		1.000	0.992**	0.016	−0.021	0.426**
	N:P			1.000	0.016	−0.051	0.402**
	C:NO_3^--N				1.000	−0.005	0.341**
	C:NH_4^+-N					1.000	0.08
	C:SAP						1.000

Table 6
A linear regression analyses of the soil nutrient elements and seasons.

Y	Equations					
	RFW	R^2	RFF	R^2	NW	R^2
SOC	y = 2.5678x + 43.283	0.6347	y = 0.7559x + 47.31	0.0702	y = 3.0782x + 44.579	0.7903
TN	y = 0.395x + 2.6312	0.4903	y = −0.2663x + 2.9002	0.994	y = −0.0737x + 2.8187	0.1029
TP	y = 0.2777x + 0.4816	0.7021	y = 0.3135x + 0.4499	0.6964	y = 0.5837x − 0.0489	0.7303
C:N	y = 0.175x + 15.877	0.0037	y = 0.035x + 19.207	0.3372	y = 0.575x + 16.947	0.7175
C:P	y = −5.31x + 64.25	0.5614	y = −7.62x + 65.847	0.7063	y = −11.92x + 80.03	0.4479
N:P	y = −0.825x + 5.21	0.3391	y = −0.465x + 2.8733	0.7902	y = −0.925x + 5.28	0.422
NO_3^-−N	y = 0.0218x + 1.1686	0.423	y = 0.0391x + 0.8493	0.4005	y = −0.2807x + 1.8347	0.638
NH_4^+-N	y = 31.13x + 132.89	0.9782	y = 62.056x + 74.95	0.6812	y = 64x + 63.926	0.999
SAP	y = −0.0332x + 1.1416	0.3884	y = −0.0101x + 0.9786	0.2623	y = 0.0378x + 0.97	0.8985

R2: square of the total correlation coefficients (n = 81); X: the seasons.

wetlands (RFW, RFF) in this paper was higher than that of the natural wetland (NW), which is similar to the research results of Wang. The soil nitrogen is mainly obtained from the residues of plants and animals, biological nitrogen fixation, atmospheric deposition, and others in the wetland ecosystem (Sun et al., 2015). According to the classification, soil nitrogen content increased to 2.00 g·kg^{-1} for the first level in China. TN (2.08 g·kg^{-1}–3.88 g·kg^{-1}) was in excellent condition, and TN of restored wetlands was generally better than of NW, related with the residual nitrogen caused by the used of fertilizers before the restored wetland and the longer time of soil nitrogen metabolism. The soil TN composition and transformation can be influenced by microorganism, including bacteria, fungi and actinomycetes which were dominant in microorganisms in QiXing river wetland. This was also one of the factors that the TN content of RFW was higher than that of RFF. As available nitrogen not only reflect the nutrient supply and availability of wetland soil, but also affect the growth of vegetation and the stability of wetland system (Shugart and Botkin, 1981). In this study, the NO_3^--N content of RFF was generally lower than that of RFW and NW, because of the above-ground biomass of the main vegetation of RFF was large. The change of soil NO_3^--N content not only the related to plant absorption, also closely related with moisture conditions (Wang et al., 2015). In this study, the contents of soil NO_3^--N and NO_3^--N in different wetlands were shown similar trend, increased NH_4^+-N, while decreased NO_3^--N with the seasons, generally. The NH_4^+-N was higher than NO_3^--N indicated the importance of soil NH_4^+-N as nitrogen that can be directly used by plants for growth in QiXing river wetland. TP ranging from 0.71 g·kg^{-1} to 1.91 g·kg^{-1}, was in the medium above to excellent condition. Soil TP content is related to some factors including, vegetation, precipitation (Xiao et al., 2017). The C:N ratio is negatively correlated with the mineralization rate of soil N and positively correlated with the fixed rate of N. High C:N ratio is conducive to the accumulation of soil organic matter, while low C:N ratio is conducive to the release, leading to the high soil mineralization, and increasing the soil available nitrogen.

5. Conclusions

The soil C:N ratios of RFW, RFF, and NW were 17.69 (molar ratios), 24.59, 19.07, and C:N:P ratios were 138:7.8:1, 131:5.4:1, 145:7.6:1, respectively. The mean value was 138:6.9:1, were closed to China's scale in QiXing river different wetland, resulting to that the soils organic carbon were rich, the availability of phosphorus was released to outward, and the growth of the native plants was restored. The plant's growth restricted by N, the RFF was highest in terms of available phosphorus release and N restriction. The SOC, TN, and NO_3^-N of RFW was higher than RFF, indicated that the metabolism and balance of soil SOC and TN of RFW that was beneficial to plant growth and promoted vegetation restoration. Particularly, in the flourishing period, resulting to NH_4^+-N, TP of spring and summer were inferior to autumn. The variation and correlation of soil SOC, TN, and TP contents and ratios and NO_3^--N, NH_4^+-N, and SAP of NW lower to RFW and RFF indicated good stability.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jksus.2021.101407.

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