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Carbon, Nitrogen and Phosphorus Contents of Wetland Soils in Relation to Environment Factors in Northeast China

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Abstract Soil organic carbon (OC) is sensitive to climatic change, and it can be expected to manifest measurable responses to global warming. Globally, nitrogen (N) and phosphorus (P) are the most common nutrients limiting plant growth and soil carbon storage. We collected soil samples at 17 marsh sites in August 2012 across Northeast China. These samples were analysed for variations in soil organic carbon (OC), total nitrogen (TN) and total phosphorus (TP) levels, and multiple controlling of environmental and biotic factors. Results showed the means to be as follows: 16,850.7 mmol kg^{-1} (OC), 540.5 mmol kg^{-1} (TN), 30.0 mmol kg^{-1} (TP), 29.9 (C:N), 516.5 (C:P) and 16.8 (N:P). The OC, TN, TP and C:N:P ratios decreased with increases in the mean annual temperature (MAT) and flooding depth, whereas the C:N ratio did not change significantly with the flooding depth. Quadratic relationships were observed between the OC, TN and TP and soil pH. Linear mixed-effect models showed that climate exerted great influences on soil nutrients. These results will improve our understanding of the ecological patterns of nutrient fluxes and the biogeochemical mechanisms of the response of vegetation to climate changes.

Keywords Soil nutrient traits · Marsh · Climate · Flooding depth · Soil pH · Community type

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Introduction

From cellular metabolism to ecosystem structure, carbon (C), nitrogen (N) and phosphorus (P) are biologically coupled through their influences on the biochemical reactions that control photosynthesis, respiration and decomposition in terrestrial ecosystems (Sterner and Elser 2002; Vitousek et al. 2010; Finzi et al. 2011; Melillo et al. 2011; Schlesinger et al. 2011; Peñuelas et al. 2012; Rivas-Ubach et al. 2012; Penuelas et al. 2013). Soil organic carbon (OC) is sensitive to climatic change, and it can be expected to manifest measurable responses to global warming (Xiao 1999). Globally, nitrogen (N) and phosphorus (P) are the most common nutrients limiting plant growth and soil carbon storage (Vitousek and Howarth 1991; Aerts and Chapin 2000). These elements are required in strict proportions for living organisms, in order to synthesize essential compounds with specific ratios of C:N:P (Sterner and Elser 2002; Finzi et al. 2011). Hence, a better knowledge of the soil C, N, and P ecological stoichiometries would enable predictions of how the terrestrial ecosystems would respond to future climate change.

Soil nutrient traits have received considerable attention in the past decade. However, in terrestrial systems, as soil has high spatial heterogeneity caused by both local-scale (e.g., fires, landslides and land use change) and regional-scale factors (e.g., glacial history, climate, topography, and biotic diversity) (Jenny 1941; McGroddy et al. 2004), there are large differences in research outcomes (Cleveland and Liptzin 2007; Tian et al. 2010; Bui and Henderson 2013; Qu et al. 2014). Therefore, studies at different scales are needed to understand the spatial heterogeneity of the soil.

Wetlands can be sources or sinks of C, N and P (Reddy et al. 1995; Mitsch and Gosselink 2007; Ramsar 2013) and are very sensitive to environmental change. Some environmental factors have been confirmed or assumed to be critical drivers, such as climate change (Yang et al. 2005; Novak et al. 2008), flooding regimes (Steinman et al. 2012; Wang et al. 2015), soil pH (Craft et al. 1988; Guo et al. 2008), and community type (Shang et al. 2013). However, most of these studies deal with the relationship between soil elements and environmental variables, especially at a small region. Little effort has been invested in seeking multivariable controlling of climate, flooding regime, soil pH and community type on soil chemical traits due to the high spatial heterogeneity in soil properties.

Northeast China has a large area of wetlands of around 1.02×10^5 km^2, which accounts for 26.5% of the natural wetland area in China (Liu 2005). The wetlands are mostly located adjacent to the rivers and noteworthy for their rich biodiversity, however, they are suffering from a decline in area and deterioration in quality due to changes in climate and land use over recent decades. Although concern about global climate change is increasing, few studies of wetlands in Northeast China have paid attention to the impacts of these climatic factors on soil nutrient traits and C:N:P ratios (Zhang et al. 2012, 2013; Xiao et al. 2014).

Therefore the objective of this study was to explore the responses of OC, TN, TP and C:N:P ratios in Northeast China to the environmental factors in riverine wetlands. Specifically, the purposes of this study were to: 1) characterize the patterns of OC, TN, TP and C:N:P ratios across Northeast China, 2) evaluate variations in the patterns of soil element content along environmental gradient and 3) reveal how the environmental and biotic factors are associated with these patterns.

Materials and Methods

Study Area

The study area, located in Northeast China, is a broad plain bordered on three sides by mountains with the Bohai Sea to the south (Fig. 1). Mean annual precipitation (MAP) varies from 59 mm in the west to 1090 mm in the east, and mean annual temperature (MAT) ranges from −4 °C to more than 11 °C. Winter is typically long and cold with predominantly northwest winds, whereas the summer is short, warm and wet with predominantly southeast

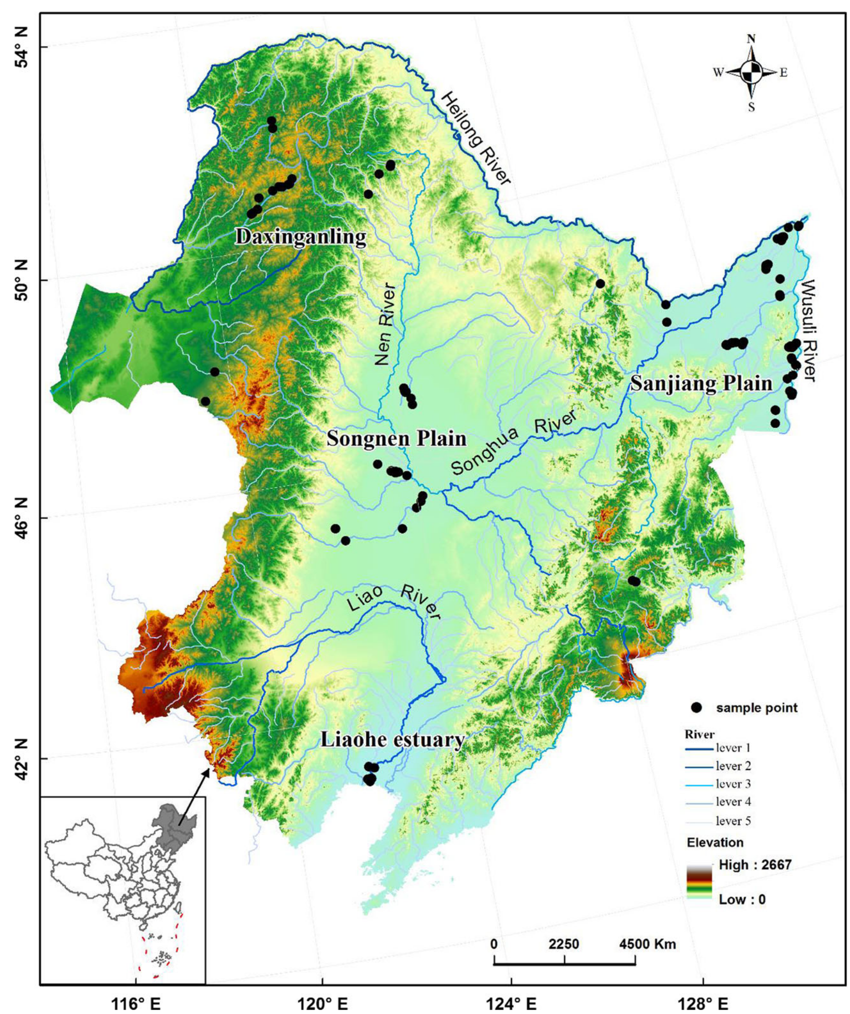


Fig. 1 Distribution map of plots used in this study

winds (Lu 2008). Many rivers and streams run across the plain, including the Heilong River, Songhua River, Liao River, Ussuri River, Razdolnaya River, and Tumen River. The dominant soil types of the study region are azonal soils such as meadow soil, boggy soil and albic bleached soil. The typical marsh plants are species of the genera *Carex*, *Glyceria*, *Deyeuxia*, *Phragmites*, *Cyperus* and *Echinochloa*.

Soil Sampling and Measurements

A total of 127 soil samples were collected across 17 marsh sites (Table 1) in August 2012. We selected large wetlands with minimal anthropogenic disturbances. At each wetland, at least three samples were collected using a metal auger to a depth of 10 cm. The samples were stored in polyethylene plastic bags. The soil was air-dried and then finely ground to pass through 1 mm nylon screens prior to chemical analysis.

OC concentrations were measured by the $K_2Cr_2O_7$-H_2SO_4 oxidation method. TN and TP concentrations were measured by the Kjeldahl and molybdenum-antimony anti-spectrophotometric methods (Sparks et al. 1996), with a continuous flow analyzer (SKALAR San++, Netherlands) after pretreatment. Soil pH was determined by a Leici pH meter (PHS-3C, Shanghai).

Table 1 Detail information of the seventeen wetlands. Longitude and latitude, area and main soil type were taken from Zhao (1999) and Liu (2005). Dominant species and Flooding depth were collected by the authors in August 2012

Study area	Longitude and latitude	Area (km^2)	Main soil type	Dominant species	Flooding depth (cm)	Plot number
Shuangtai Estuary	121°30′ ~ 122°00′E 40°45′ ~ 41°10′N	801	coastal saline-alkali soil	*Phragmites*	20	9
Keerqin	121°40′ ~ 122°14′E 44°51′ ~ 45°17′N	76	saline-alkali soil	*Phragmites*, *Echinochloa*	11	3
Zhalong	123°47′ ~ 124°37’E 46°52′ ~ 47°32’N	1218	alkali soil	*Phragmites*	28	7
Momoge	123°27′ ~ 124°04’E 45°42′ ~ 46°18’N	950	saline-alkali soil	*Phragmites*, *Cyperus*	15	18
Nanweng River	125°08′ ~ 125°50’E 51°05′ ~ 51°39’N	809	peat mire soil	*Carex*, *Glyceria*	6	5
Gen Rever	121°34′-122°41’E 50°48′-51°13’N	1260	peat mire soil	*Carex*, *Deyeuxia*	0	15
Hailae	120°40′ ~ 122°30’E 49°20′ ~ 50°15’N	27	humus fen soil meadow bog soil	*Carex*, *Glyceria*	5	2
Changbaishan	128°17′ ~ 128°40’E 43°41′ ~ 43°54’N	101	peat soil	*Carex*, *Glyceria*	9	3
Dulu Rever	130°38′ ~ 131°07’E 47°17′ ~ 47°23’N	105	humus fen soil	*Carex*, *Glyceria*, *Deyeuxia*	12	3
Dongsheng	132°34′ ~ 132°46’E 46°30′ ~ 46°45’N	162	humus fen soil meadow bog soil	*Carex*, *Glyceria*, *Deyeuxia*	-2	7
Dongfanghong	130°34′ ~ 130°56’E 46°12′ ~ 46°28’N	466	humus fen soil meadow bog soil	*Carex*, *Glyceria*, *Deyeuxia*	1	11
Hong Rever	133°34′ ~ 133°46’E 47°42′ ~ 47°52’N	218	humus fen soil meadow bog soil	*Deyeuxia*	1	3
Sanjiang	133°43′ ~ 134°46’E 47°26′ ~ 48°23’N	1980	humus fen soil meadow bog soil	*Deyeuxia*	-2	10
Naoli Rever	132°12′ ~ 132°31’E 45°03′ ~ 47°12’N	252	humus fen soil meadow bog soil	*Carex*, *Deyeuxia*	-2	5
Qixing River	132°05′ ~ 132°26’E 46°40′ ~ 46°52’N	913	humus fen soil meadow bog soil	*Phragmites*, *Glyceria*	0	14
Xingkai Lake	131°58′ ~ 133°07’E 45°04′ ~ 45°13’N	170	humus fen soil meadow bog soil	*Carex*, *Glyceria*, *Deyeuxia*	4	6
Zhenbaodao	133°28′ ~ 133°48’E 45°52′ ~ 46°17’N	444	humus fen soil meadow bog soil	*Carex*, *Glyceria*, *Deyeuxia*	4	6

Climate Data Collection

MAT and MAP estimates were derived using spatial interpolation with a resolution of 10 × 10 km in the ESRI ArcGIS 9.3 software package. Data for the estimates were obtained from 95 climate stations in Northeast China (from 1983 to 2012), which was sourced from China meteorological data sharing service system (cdc.cma.gov.cn/home.do).

Statistical Analyses

A square-root-transformed (sqrt) was first applied to the contents of OC, TN and TP and C:N:P ratios in order to improve the normality of the data for later statistical analyses. All means and standard errors were then transformed back into the original units. An analysis of the Spearman linear correlation coefficients was provided to reflect the relationship between soil stoichiometry and environmental factors. Analysis-of-variance followed by Student–Newman–Keuls (S–N–K) post hoc tests were used to examine potential differences in the means of sqrt(OC), sqrt(TN), sqrt(TP), sqrt(C:N), sqrt(N:P), sqrt(C:P) and sqrt(C:N:P) ratios for different regions and community types.

Linear mixed-effects models (LMMs) were used to calculated the variance explained by fixed effects only (marginal R^2) and the variance explained by both fixed and random effects (conditional R^2; Nakagawa and Schielzeth 2013). Climate, soil pH, flooding depth and community type were treated as fixed factors and site was treated as random factor. Akaike information criterion (AIC) was used to select competing models: model with the lowest AIC valuewas chosen as the final model. All the above-mentioned analyses were carried out using SPSS 18.0, 2010 and R 3.3.1 (R Development Core Team 2016).

Results

Statistics of Soil OC, TN, TP

Across all data, the OC contents varied from 111.9 mmol kg^{-1} to 51,390.5 mmol kg^{-1}, and the highest coefficient of variation was approximately 84%. The TN values ranged from 11.6 mmol kg^{-1} to 1809.1 mmol kg^{-1}, and the TP values varied from 2.5 mmol kg^{-1} to 115.7 mmol kg^{-1}. The soil C:N ratio varied between 9.3 and 72.4, and the soil N:P ratio ranged from a low of 2.7 to a high of 52.0. The observed soil C:P ratio exhibited the widest range (from 26.5 to 2102.1) and the highest coefficient of variation of 67% (Table 2).

The Spearman linear correlation indicated that the results were significant, positive associations among the OC, TN and TP concentrations (overall, $P < 0.01$ for all models; Fig. 2). The strength of the relationship varied between elements, although the R^2-values ranged from 0.688 (soil C:P) to 0.899 (soil C:N; Fig. 2).

Table 2 Descriptive statistics of OC, TN, TP and C:N:P ratios in wetland soil, Northeast China. SE, standard error; CV, coefficient of variation

	Mean	SE	Maximum	Minimum	CV (%)
C(mmol kg^{-1})	16,850.7	1251.8	51,390.5	111.9	84
N(mmol kg^{-1})	540.5	36.3	1809.1	11.6	76
P(mmol kg^{-1})	30.0	1.7	115.7	2.5	64
C:N	29.9	0.8	72.4	9.3	30
C:P	516.5	30.1	2102.1	26.5	67
N:P	16.8	0.8	52.0	1.9	55

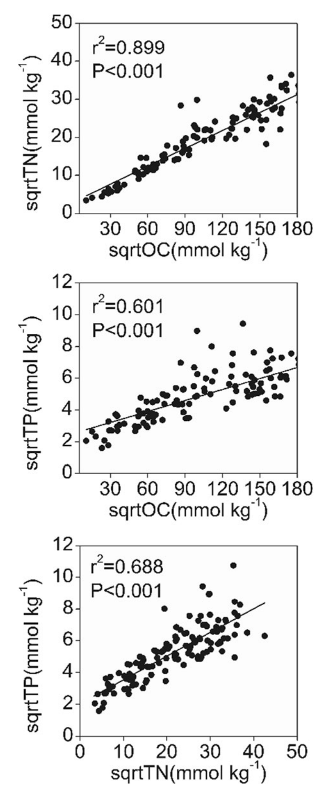
Variations of Soil OC, TN and TP along Environmental Gradients

Negative linear correlations were found between the OC, TN, TP and C:N:P ratios and environmental variables including MAT and flooding depth, where only the C:N ratio did not significantly differ with flooding depth (Figs. 3a–f and 4a–f). Soil pH showed negative linear correlations with C:N, C:P and N:P, while quadratic regression relationships with OC, TN and TP (Fig. 4g–l). As to MAP, soil elements exhibited no significant correlations with it (Fig. 3g–l).

Variation among Community Types

Large differences in the soil nutrient concentrations were found among community types($p < 0.05$). The OC, TN and

Fig. 2 Relationships among the SOC, TN and TP contents in wetland soils of Northeast China



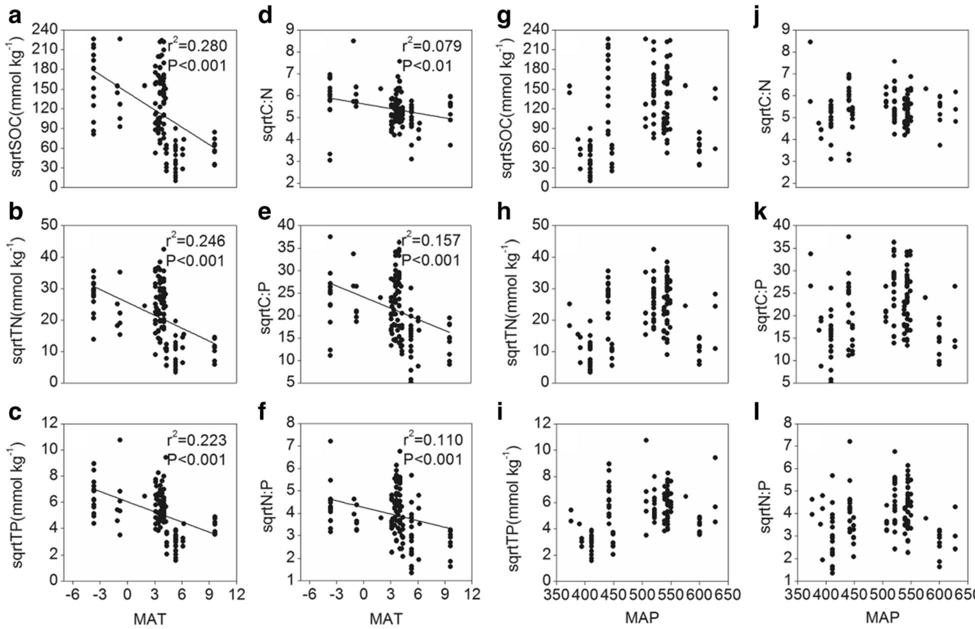


Fig. 3 Relationships between soil stoichiometry and MAT and MAP in wetland soils of Northeast China

TP of *Carex*, *Glyceria*, and *Deyeuxia* were markedly higher than that of *the others*. The C:N of *Echinochloa* and C:P of *Cyperus* were significantly lower than that of *Carex* and *Glyceria*. The N:P of *Cyperus* were significantly lower than that of the other communities (Table 5).

Multivariate Relationships of Soil OC, TN and TP versus Environmental and Biotic Factors

The LMMs analysis showed that for soil OC, TN and TP, the best model included MAT, MAP and site as predictors, with a marginal R^2 of 0.31, 0.28 and 0.45 and conditional R^2 of 0.45, 0.45 and 0.45, respectively (Table 3). For C:N and C:P, MAT and site were included in the final model, with a marginal R^2 of 0.13 and 0.13 and conditional R^2 of 0.24 and 0.33, respectively (Table 3). The best model included site for N:P (Table 3), with a conditional R^2 of 0.27.

Discussion

The spatial distributions of soil C, N and P are important for understanding the underlying patterns of nutrient fluxes along with the biogeochemical mechanisms of the response of

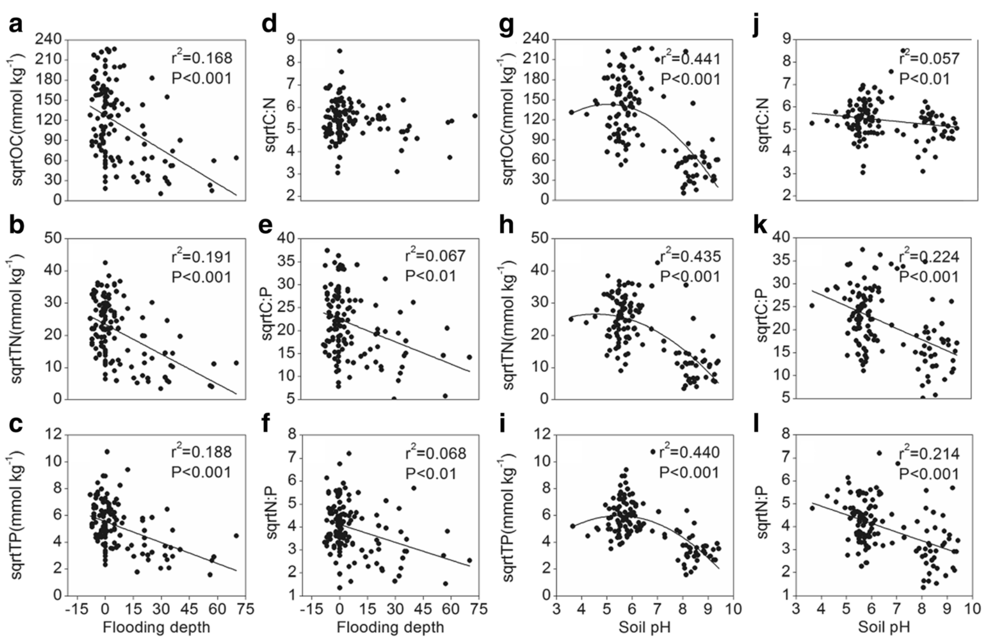


Fig. 4 Relationships between soil stoichiometry and flooding depth and soil pH in wetland soils of Northeast China

Table 3 Summary of linear mixed-effect models for OC, TN, TP and C:N:P ratios

Dependent variable	Final model	R^2_m	R^2_c
OC	MAT + MAP + site	0.31	0.45
TN	MAT + MAP + site	0.28	0.45
TP	MAT + MAP + site	0.45	0.45
CN	MAT + site	0.13	0.24
CP	MAT + site	0.13	0.33
NP	site	-	0.27

Abbreviations: R^2_m marginal R^2, R^2_c conditional R^2, *CT* community type, *MAT* mean annual temperature, *MAP* mean annual precipitation, *SpH* soil pH, *FD* flooding depth

vegetation to climate change. Quantifying the response of environmental and biotic factors to soil nutrient traits is important for ecologists to understand the driving mechanism of these patterns. This study is the first description of wetland soil C, N and P in Northeast China, and will provide the scientific base for management of this region.

Variation of Soil C, N and P

Our analysis showed that the contents of OC, TN, and TP in the wetland soils were higher than values reported from those in grasslands and forests (Table 4). Similar results have also been demonstrated by the other studies (Jiao et al. 2013; Shang et al. 2013; Gao et al. 2014; Fan et al. 2015). This may be related to the anaerobic condition in wetlands, which inhibits litter decomposition. To a certain degree, this explains the fact that wetland ecosystems, which occupy a relatively small land surface area, play an important role in the global storage capacity of C, N and P.

Our results also demonstrated that OC and P contents in wetland soils of Northeast China were higher and lower, respectively, when compared to those in other regions of China (Table 4). Meanwhile, the two elements in grasslands and forests of Northeast China were also higher and lower than those in other regions of China (Wang 2007; Wang et al. 2014; Zhao et al. 2014; Fan et al. 2015). This may be due to the unique climate and geologic parent material in our research area. Consequently, this finding indicates that we should pay more attention to the research on the interaction between soil OC, P content and plants in this region in the near future.

Cleveland and Liptzin (2007) observed that in the soil, similar to marine ecosystems, the atomic C:N:P ratios are constrained and suggested that close interactions between organisms and the environment drive the observed similarities in their element ratios. Although the concentrations of soil elements were highly variable (Fig. 2), our analysis suggests a similar pattern in the wetland soils of the study region. The C:N, C:P and N:P ratios were well-constrained throughout the dataset, as demonstrated by the relatively high correlation coefficients among the OC, TN and TP concentrations, where R^2 = 0.899, 0.601, 0.688, respectively (Fig. 2). This might indicate that the soil C:N:P ratio was remarkably well-constrained, at a value of approximately 517:17:1. However, since this value is different to the 186:13:1 value reported in Cleveland and Liptzin (2007), this demonstrates that the C:N:P ratio might change with variations in environmental factors.

Influence of Environment Factors on C, N and P

We observed a negative association between spatial distributions of soil nutrients and MAT (Fig. 3a–f). This pattern agreed with the observations found by previous studies in

Table 4 Means of mass OC, TN, TP and C:N:P ratios in Northeast China compared with other regions. The different letters indicate significant difference among different regions ($p < 0.05$)

Study area	OC (g kg^{-1})	TN (g kg^{-1})	TP (g kg^{-1})	C:N	C:P	N:P	Types	Reference
Daxinganling	307.9[a]	10.4[a]	1.4[a]	30.3[a]	245.5[a]	8.0[a]	Peatland	This study
Sanjiang Plain	255.3[a]	9.9[a]	1.1[a]	25.7[ab]	243.6[a]	9.3[a]	Freshwater Marsh	This study
Songnen Plain	30. 1[b]	1.0[b]	0.3[c]	20.1[b]	95.9[b]	4.7[b]	Saline-alkaline Marsh	This study
Liaohe Estuary	45.3[b]	1.9[b]	0.5[b]	22.7[ab]	86.1[b]	3.5[b]	Estuarine Marsh	This study
Tibetan Plateau	252.5	20.8	0.9	12.2	280.6	23.1	Peatland	Shang et al. 2013
Tibetan Plateau	173.9	12.6	2.1	13.8	82.8	6.0	Freshwater Marsh	Gao et al. 2014
Minjiang Estuary	36.0	1.7	0.7	21.2	54.6	2.6	Estuarine Marsh	Wang et al. 2015
Tianma National Forestry Farm	20.3	2.0	0.2	9.9	85.0	8.6	Forest	Fan et al. 2015
Loess Plateau	3.9	0.4	0.5	9.3	7.2	0.8	Grassland	Jiao et al. 2013
China's soil	24.6	1.9	0.8	13.1	31.7	2.4	Overall	Tian et al. 2010

China (Zhao et al. 2005; Yang et al. 2010). Temperature influences the accumulation and mineralization of organic matter by controlling the activity of soil microbes (Craft et al. 1988; Ajwa et al. 1998). Paul (2014) reported that a C:$N > 25$ on a mass basis implies that organic matter accumulation is occurring faster than decomposition and a C:$P < 200$ implies net mineralization. In our research, the C:N ratio was greater than 25 in Sanjiang Plain and Daxinganling where the MAT was relatively low, indicating net immobilization; in contrast, the C:P ratio was less than 200 in Liaohe Estuary and Songnen Plain where the MAT was relatively high, thus indicating net mineralization (Fig. 1, Table 4). Hence, this demonstrates that the OC, TN and TP contents decreased with increasing temperature.

Flooding depth is the most significant factor that controls production and turnover of organic matter in wetlands (Brinson et al. 1984; Sun and Liu 2007). Our results showed that the flooding depth clearly decreased the SOC, TN and TP concentrations. These decreasing concentrations were consistent with those observed in previous studies (Guo et al. 2008; Zhao et al. 2014). Low microbial activity due to the low oxygen levels in persistently flooded systems inhibited decomposition, which tended to produce low-nutrient soil conditions (Crawford et al. 2007; Guo et al. 2008). Furthermore, high water levels make litter not easily returned to the soil directly, which reduces the input of OC, N and P (van Oorschot et al. 2000; Bai et al. 2005; Zhao et al. 2014) that cause strongly anaerobic conditions in surficial soils, which could induce the release of phosphorus (Patrick and Khalid 1974). When soluble phosphorus is released into a flooded wetland it may flow out of the wetland.

Soil pH is an important chemical factor that directly affects the existing forms, bioavailability and migration of various elements (Yu et al. 2002). Our results showed that the OC, TN and TP had quadratic relationships with the soil pH. Similar trends were found in other wetlands (Bai et al. 2003; Gao et al. 2008). Perhaps it could be attributed to bacterial diversity, richness and activity which were highly inhibited in acid or alkaline environments (Huang 1994; Li et al. 2001; Fierer and Jackson 2006). Hence, when microorganisms decompose less litter, lower levers of OC, TN and TP exist in the soils.

Plant production inputs are the major source of carbon and nitrogen in wetland soils (Gorham 1991; Updegraff et al. 1995; Bridgham et al. 1998). We found significant changes in OC, TN and TP among community types (Table 5), which can partly be explained by higher relative belowground biomass for *Carex*, *Glyceria*, and *Deyeuxia* than for *Phragmites*, *Cyperus* and *Echinochloa* (He 2003; Jia et al. 2006; Qin et al. 2006; Zhang et al. 2006). Below-ground plant residues can be decomposed easier, however wetlands are covered by water, so litter is not easily returned to the soil.

Multivariate Relationships of Soil C, N and P versus Flooding Depth, Vegetation Type and Climate

The LMMs analysis showed that climate was the major environmental factor influencing soil nutrients, which was in accordance with previous studies (Jobbágy and Jackson 2000; Xu et al. 2013). Climate explained large proportions of variance in soil OC, TN and TP (31, 28 and 45%, respectively, Table 3), indicating that soil elements may decrease in response to future increases in temperature. In addition, climate had stronger influences on soil TP than on soil OC and TN, which can be explained by the stronger response of P cycling induced by climate (Elser et al. 2010). In contrast to the adequate C and N mainly deriving from plants, soil P is mainly derived from primary rock minerals which are strongly influenced by shifts in climate (Chadwick et al. 1999; Aerts and Chapin 2000). Therefore, soil P is more sensitive to climate.

In the final LMMs, site explained large proportions of variation in OC, TN and C:N:P ratios (Table 3). The variation represented the among-site variability that had not been captured by the selected environmental factors. Unexplained variances may be due to various other factors we did not measure, such as micro-environment, geologic parent material and topography (Jenny 1941; Xu et al. 2013).

Conclusions

Our findings showed that soil C, N, P and C:N:P ratios were highly sensitive to environmental change, especially climate. This should encourage increased efforts to utilize the potential

Table 5 Means of atomic OC, TN, TP and C:N:P ratios in Northeast China among different community types. The different letters indicate significant difference among different regions ($p < 0.05$)

Community type	OC(mmol kg^{-1})	N(mmol kg^{-1})	P(mmol kg^{-1})	C:N	C:P	N:P
Carex	24976.3^{a}	765.2^{a}	42.5^{a}	33.7^{a}	652.8^{a}	19.3^{a}
Glyceria	21810.6^{a}	643.95^{a}	33.4^{a}	33.5^{a}	652.8^{a}	19.3^{a}
Deyeuxia	19578.9^{a}	648.2^{a}	36.1^{a}	29.1^{a}	526.1^{a}	17.5^{a}
Phragmites	8386.7^{b}	298.1^{b}	15.9^{b}	27.4^{ab}	403.3^{ab}	14.6^{a}
Echinochloa	3780.2^{b}	191.9^{b}	11.8^{b}	19.6^{b}	338.0^{ab}	17.8^{a}
Cyperus	1868.3^{b}	74.6^{b}	9.0^{b}	24.3^{ab}	170.8^{b}	6.9^{b}

capacity of wetland ecosystems to fix carbon and decrease the emission of greenhouse gases. Our results suggest that there may be a single Redfield-like ratio in the wetland soils of Northeast China of approximately 566:18:1. However, further research is needed with even larger sample sizes to cover all the wetlands in the region.

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