



Comparison of phosphorus sorption characteristics in the soils of riparian buffer strips with different land use patterns and distances from the shoreline around Lake Chaohu

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Abstract

Purpose The construction of riparian buffer strips has become increasingly important due to the effective phosphorus (P) retention of the strips, thus preventing eutrophication in freshwater ecosystems. The key mechanism is P sorption in soils. To provide some suggestions for increasing the sorption ability of P, the relationships between P sorption behavior and both land use patterns and distance from the shoreline were determined.

Materials and methods In April, July, and October 2013, field investigations were carried out along the shoreline of Lake Chaohu. Eleven sections, including 36 sampling sites at different distances from the shoreline, were chosen, and these sections contained different types of riparian buffer strips, such as grassland, farmland, forest, wetland, and forest/grassland. The P species, sorption parameters, and dominant vegetation species were analyzed.

Results and discussion The total P (TP) and P sorption maximum (Q_{\max}) showed no recognizable seasonal variation and were closely correlated with the distance from the shoreline. The further the distance from the shoreline, the higher the TP and Q_{\max} values, suggesting that soil traits could determine the P sorption extent. However, the Olsen-P content and equilibrium P concentration (EPC_0) fluctuated greatly, with the peak occurring in spring and the minimum occurring in summer in the majority of the sampling sites. In addition, positive relationships existed between the TP content and the Q_{\max} value as well as the Olsen-P content and the EPC_0 value. Canonical correlation analysis (CCA) further showed that the Olsen-P content and EPC_0 values were closely related to the dominant vegetation species, indicating that land use patterns played a decisive role in regulating the P sorption strength and the level of available P.

Conclusions To effectively adsorb P (increase Q_{\max}) and prevent P leaching (reduce the EPC_0), we recommend changing the land use patterns (more constructed wetlands and forests with grass) in riparian buffers.

Keywords Lake Chaohu · Phosphorus sorption · Phosphorus species · Riparian buffer strips

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1 Introduction

Riparian buffer strips, the interface between land and freshwater ecosystems, have been considered the last line of defense and play a pivotal role in nutrient removal from nonpoint source pollution through soil adsorption, microbial immobilization, and vegetation utilization, which could effectively alleviate freshwater eutrophication (Syversen 2005; Stutter et al. 2009). Phosphorus (P) has been identified as the first limiting factor for phytoplankton growth and eutrophication in freshwater ecosystems (Shen et al. 2018). Therefore, P removal efficiency in riparian buffer strips has become increasingly vital and has been considered a priority for designing riparian

buffer restoration or protection by watershed managers and planners (Brian et al. 2004; Weissteiner et al. 2013). The establishment of buffer strips has been adopted in riparian areas to target the main transport pathways of P, including P retention (Kronvang et al. 2005).

P retention in riparian buffer zones is controlled by a range of physical, geochemical, and biological processes, including sediment deposition, sorption and precipitation, reduction and oxidation processes, plant uptake, and biological mineralization-immobilization dynamics (Hoffmann et al. 2009). P sorption has been considered the most important long-term P sequestration mechanism (Zhang et al. 2010a), which is mainly associated with iron and aluminum oxides as well as the organic matter in soils (Subramaniam and Singh 1997; Giesler et al. 2005; Li et al. 2007).

Moreover, land use patterns determine soil traits, which further influence P sorption and retention ability. Riparian soils can be statistically separated by habitat type, providing evidence that they deliver ecosystem services to differing extents (De et al. 2018). Grass, woody vegetation, and forests have been considered effective measures for nitrate and phosphate reduction from highly polluted subsurface flow (Kyehan et al. 2000; Zhang et al. 2010b; Izydorczyk et al. 2018). Additionally, the recognizable difference in the P retention efficiency in riparian buffer strips with different land use patterns indicates the different optimal width demand when establishing buffer zones, which has been reported and

reviewed (Hoffmann et al. 2009; Weissteiner et al. 2013). As a consequence, the functions of soil in riparian buffer strips as a sink or source of phosphorus must be greatly affected by land use patterns along the shoreline, which could be estimated by P sorption parameters, e.g., equilibrium P concentration (EPC_0) and P sorption maximum (Q_{max}).

An integrated riparian buffer zone may be a valuable modification of dry buffer strips to mitigate the adverse impacts of high nutrient loading from agricultural fields to the aquatic environment (Zak et al. 2018), indicating that the distance from the shoreline could influence P retention. However, little research has focused on the difference in P sorption characteristics in the soils of riparian buffer strips with different distances from the shoreline, and the relative mechanisms and explanations are scarce.

In this study, spatial and seasonal samples were taken from soils representing different patterns of land use and different distances from the shoreline around a Chinese large shallow lake (Lake Chaohu). The different P species and P sorption behaviors in the soils were analyzed. The aims of this study were to (1) examine the seasonal and spatial variation trends in the P species and P sorption behaviors; (2) test whether the distance from the shoreline could influence the P sorption behaviors and further determine the phosphorus forms, determining the mechanisms; and (3) provide suggestions for restoring or modifying riparian buffer strips to greatly improve the P retention efficiency.

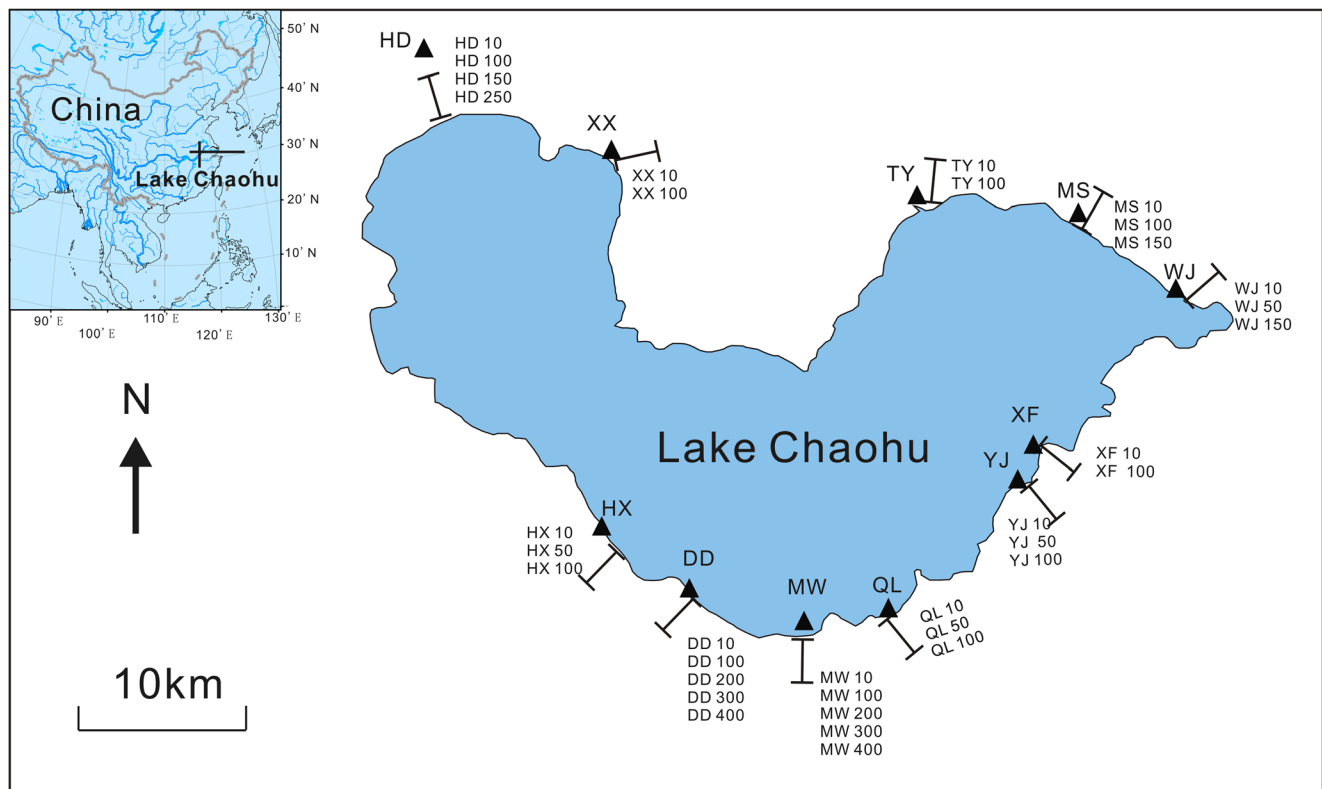


Fig. 1 The map showing the sampling sites in the riparian buffer strips with different distances from the shoreline around Lake Chaohu

Table 1 The type and dominant species in the riparian buffer strips around Lake Chaohu (the number behind the sampling site name refers to the distance from the shoreline)

Sampling site	Type of buffer strips	Dominant vegetation species
HD10	Wetland	<i>Phalaris arundinacea</i> , <i>Carex tristachya</i>
HD100	Wetland	<i>Typha orientalis</i> , <i>Carex tristachya</i>
HD150	Grassland	<i>Imperata cylindrical</i> , <i>Solidago virgaurea</i> var. <i>coreana</i>
HD250	Forest	<i>Populus</i> L.
XH10	Wetland	<i>Phragmites australis</i> , <i>Phalaris arundinacea</i>
XH50	Grassland	<i>Roegneria kamoji</i> , <i>Rumex dentatus</i>
XH100	Wetland	<i>Zizania latifolia</i>
DD10	Grassland	<i>Cerastium arvense</i> , <i>Erigeron annuus</i>
DD100	Farmland	<i>Brassica napus</i>
DD200	Farmland	<i>Triticum aestivum</i>
DD300	Farmland	<i>Triticum aestivum</i>
DD400	Forest	<i>Populus</i> L.
XX10	Grassland	<i>Arundinella Raddi</i> , <i>Galium asperuloides</i>
XX100	Grassland	<i>Imperata cylindrical</i> , <i>Vicia sepium</i>
XF10	Grassland	<i>Cynodon dactylon</i> , <i>Carex tristachya</i>
XF100	Grassland	<i>Cynodon dactylon</i> , <i>Medicago sativa</i>
MW10	Wetland	<i>Phragmites australis</i> , <i>Artemisia</i>
MW100	Wetland	<i>Phragmites australis</i> , <i>Typha orientalis</i>
MW200	Forest + grassland	<i>Salix babylonica</i> , <i>Phragmites australis</i> , <i>Typha orientalis</i>
MW300	Forest + grassland	<i>Salix babylonica</i> , <i>Phragmites australis</i> , <i>Phalaris arundinacea</i>
MW400	Forest + grassland	<i>Salix babylonica</i> , <i>Broussonetia papyrifera</i> , <i>Carex tristachya</i>
MS10	Wetland	<i>Cynodon dactylon</i> , <i>Carex tristachya</i>
MS100	Grassland	<i>Carex tristachya</i> , <i>Cynodon dactylon</i>
MS150	Grassland	<i>Eremochloa ophiuroides</i> , <i>Cynodon dactylon</i>
MS200	Grassland	<i>Eremochloa ophiuroides</i> , <i>Cynodon dactylon</i>
QL10	Wetland	<i>Carex tristachya</i> , <i>Cynodon dactylon</i>
QL50	Grassland	<i>Cynodon dactylon</i> , <i>Medicago Sativa</i>
QL100	Grassland	<i>Cynodon dactylon</i> , <i>Arundinella Raddi</i>
TY10	Wetland	<i>Carex tristachya</i> , <i>Cynodon dactylon</i>
TY100	Wetland	<i>Phragmites australis</i> , <i>Phalaris arundinacea</i>
YJ10	Grassland	<i>Cynodon dactylon</i>
YJ50	Grassland	<i>Hemarthria sibirica</i> , <i>Cynodon dactylon</i>
YJ100	Grassland	<i>Cynodon dactylon</i>
WJ10	Forest + grassland	<i>Salix babylonica</i> , <i>Paspalum distichum</i>
WJ50	Forest + grassland	<i>Salix babylonica</i> , <i>Carex tristachya</i>
WJ150	Forest + grassland	<i>Salix babylonica</i> , <i>Cynodon dactylon</i>

2 Materials and methods

2.1 Study area description

Lake Chaohu (117° 16' 54"–117° 51' 46" E and 31° 25' 28"–31° 43' 28" N), one of the five largest freshwater lakes in China, is located in the Yangtze-Huaihe region, central to Anhui Province. Its surface area is approximately 780 km², the total drainage area is 13,486 km², and the shoreline length around the whole lake is 184.66 km. The basic limnological data were provided by Xu et al. (2005). The main types of land use in the Lake Chaohu watershed can be roughly classified into six classes: abandoned field, shrubbery, artificial *Pinus massoniana* forest, grassland, secondary *Pinus massoniana* forest, and cultivated land. The soil type of the former five is Ochrept, and the nutrient contents in the surface soil of the abandoned field were significantly higher than those of the other land use types. The total organic carbon, total nitrogen, total phosphorus, and available nitrogen in the surface soil of the secondary *Pinus massoniana* forest were higher than those of the shrubbery and grasslands (Wang et al. 2011). The soil

types of the cultivated land are mainly Uderts (85%), Ochrept (9%), and Aquept (4.4%) (Ding et al. 2011).

In recent decades, due to agricultural development and road construction around the lake, the ability to remove nutrients and intercept riparian buffer strips has become weak, causing eutrophication to become increasingly serious (Shang and Shang 2005). At present, the types of riparian buffer strips around Lake Chaohu are mainly farmland, grassland, wetland, and forest, and the width of the riparian buffer strips has become narrow.

2.2 Sample collection

In April, July, and October 2013, field investigations were carried out along the shoreline of Lake Chaohu. Eleven sections, including 36 sampling sites with different distances from the shoreline, were chosen, which contained different types of riparian buffer strips, such as grassland, farmland, forest, wetland, and forest/grassland. The number of grassland, farmland, forest, wetland, and forest/grassland sampling sites was 15, 3, 2, 10, and 6, respectively. The interval between the sampling sites in the same section was approximately 50–100 m. The

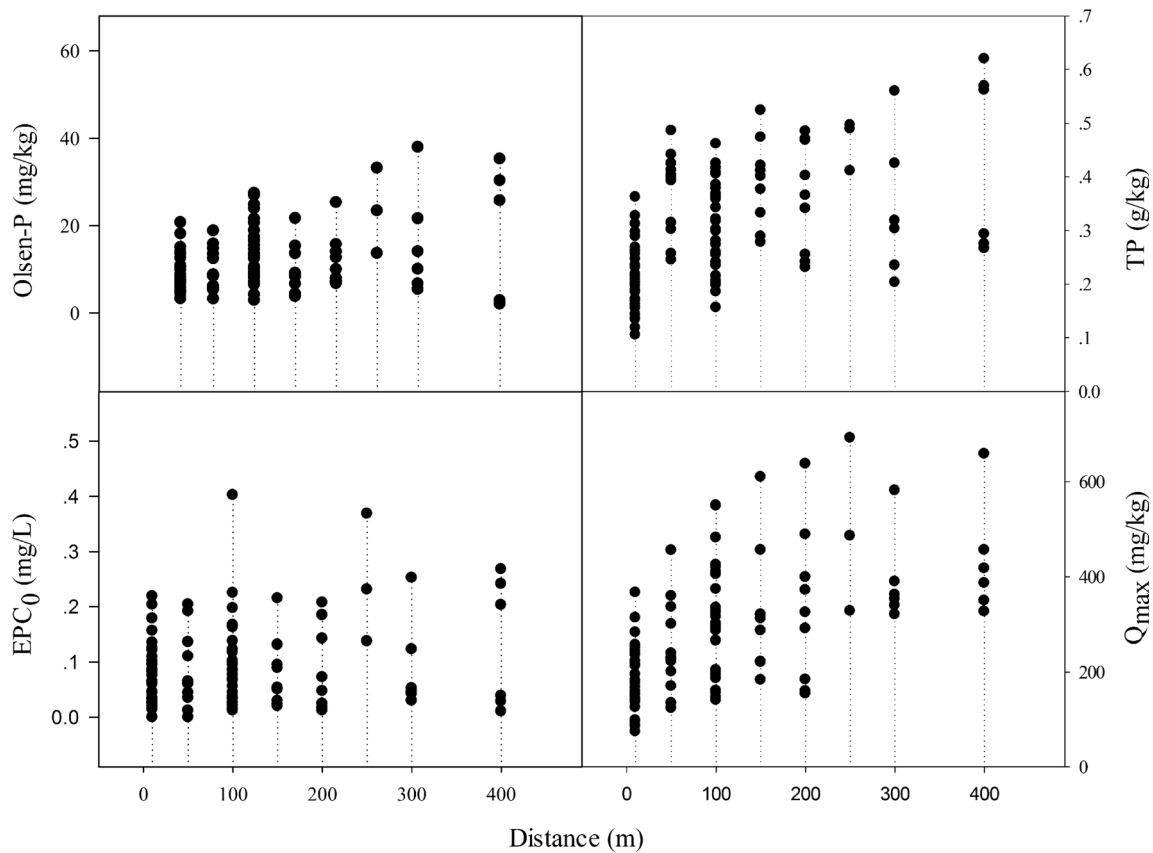


Fig. 2 The seasonal variations in the Olsen-P, total phosphorus (TP), equilibrium P concentration (EPC_0), and phosphorus sorption maximum (Q_{max}) in the soils of different sampling sites around Lake Chaohu

positions and types as well as the dominant vegetable species of the sampling sites are shown in Fig. 1 and Table 1. Soil samples were collected for the analysis of the P species, including Olsen-P and total P (TP), and the P adsorption under the surface of the vegetation at 10–20-cm soil depth at each site. The vegetation analysis was conducted in the field.

2.3 Chemical analysis

The soil samples were air-dried, sieved to < 2 mm, and analyzed for the following parameters.

The Olsen-P was determined by 0.5 M $NaHCO_3$ solution (pH 8.5) in an air-dried sample to extract a solution ratio of 1:20 (Olsen et al. 1954).

The total P (TP) was determined as the difference between ignited and nonignited soils extracted with 0.1 M H_2SO_4 (Saunders and Williams 1955).

Batch P sorption isotherm experiments were conducted in triplicate for the soil samples under reducing conditions using 0.01 mol L^{-1} KCl solution containing 0, 0.1, 0.2, 1, 2, 5, 8, 10, 15, 20, 30, 40, 50, and 100 mg P L^{-1} KH_2PO_4 as sorption solution matrices (modified by Istvanovics 1994). The sealed centrifuge tubes with the mixed solution were shaken on a reciprocal shaker at a speed of $200\text{ cycles min}^{-1}$ for 24 h at

$25 \pm 3\text{ }^\circ\text{C}$. The suspension was centrifuged at 3500 rpm for 20 min. The supernatants were filtered through a $0.22\text{-}\mu\text{m}$ mixed cellulose ester membrane for determining the soluble reactive phosphorus. The sorption parameters were calculated using the following equations:

Linear equation:

$$Q = KC - Q_0$$

Langmuir equation:

$$C/Q = C/Q_{max} + 1/K Q_{max}$$

C The P concentration in the solution after 24-h equilibrium (mg L^{-1}).

Q The amount of P sorbed by the solid phase (mg kg^{-1}).

The EPC_0 was measured by the linear equation, where no P sorption or desorption occurs and is equal to the value of C when Q is 0. Q_{max} was measured by the Langmuir equation (Xiao et al. 2012).

2.4 Biological analysis

The vegetation species composition, relative cover degree, abundance degree, and growing stage were investigated and recorded

in the field. Three survey quadrats were randomly chosen for each sampling site, and the areas of each quadrat were 1 m × 1 m, 5 m × 5 m, and 10 m × 10 m for the herbaceous vegetation, shrubs, and forest, respectively.

2.5 Statistical analysis

The Pearson correlation coefficients were determined, and a log-normal regression analysis was performed using SigmaPlot 2000 and SPSS 13.0 for windows. Pearson's test was performed using the SPSS 18.0 package (SPSS, Chicago, IL), with a value of 0.05 selected for significance. Canonical correlation analysis (CCA) was used to identify the key factors regulating the community structure of the vegetation species with the software CANOCO for Windows, version 4.5 (Ter Braak and Šmilauer 2002).

3 Results and discussion

In all the studied types of riparian buffer strips, the TP content and Q_{\max} value showed a close relationship with the distance from the shoreline, while the Olsen-P content and EPC_0 value did not (Fig. 2). In addition, positive relationships existed between the TP content and the Q_{\max} value as well as the Olsen-P content and the EPC_0 value (Fig. 3). All these variations could be explained in terms of land use patterns and relevant soil properties. The Olsen-P content and EPC_0 value were more affected by the vegetation growing stage with apparent seasonality. Significantly and positively related to the Olsen-P content, the EPC_0 value varied greatly after the rainy season in the sediment along the shoreline of Lake Chaohu (Zhou et al. 2011). Furthermore, laboratory experiments demonstrated that vegetative treatment areas generally had elevated EPC_0 values, indicating an inevitable fluctuation of available P (Andersen et al. 2015), which provided solid evidence explaining the differences in the seasonal variation modes of the studied variables (Fig. 4).

The CCA analysis, reflecting the relationship between the dominant vegetation species and the environmental variables, showed that the Olsen-P and the EPC_0 were closely related to the dominant vegetation species, especially *Populus L.*, *Zizania latifolia*, and *Triticum aestivum* (Fig. 5). Different dominant vegetation species could produce different effects on the P sorption behavior in soil. First, decaying vegetation residue was considered an important factor affecting P sorption. Using a radioactive phosphate tracer and laboratory incubations, it was demonstrated that litter inputs, as both long-term inputs and short-term leachate pulses, can decrease the quantity and strength of phosphate sorption, which may increase the biological availability of this key nutrient (Schreeg et al. 2013). As an important soil organic matter (SOM) source, decaying vegetation residue plays a major role in sorption processes. SOM affects P sorption in soils, but P

sorption also depends on specific soil properties that are often related to land use (Wang et al. 2013). An increase in P desorption observed after SOM removal indicated that SOM was a potential soil constituent, which increased P binding and limited P leaching from soils (Debicka et al. 2016). Second, vegetation root exudates, to a certain degree, could also influence the P sorption process in soils. The exudation of organic acid has been proposed to be involved in many processes operating in the rhizosphere (Jones 1998). It has been indicated that organic acids, especially low-molecular-weight organic acid, decrease the amount of sorbed P and other sorption parameters, such as the extent of sorption, the energy of sorption, the equilibrium buffering capacity, and the EPC_0 in soils (Moradi et al. 2012; Wang et al. 2016). Hence, the decay of vegetation residue and root exudates results in the alteration of P sorption properties, which eventually influences the availability of P in soils.

TP contents and Q_{\max} values are also affected by the land use patterns, such as vegetation coverage. It is well known that the efficiency of nutrient reduction by riparian buffer strips is

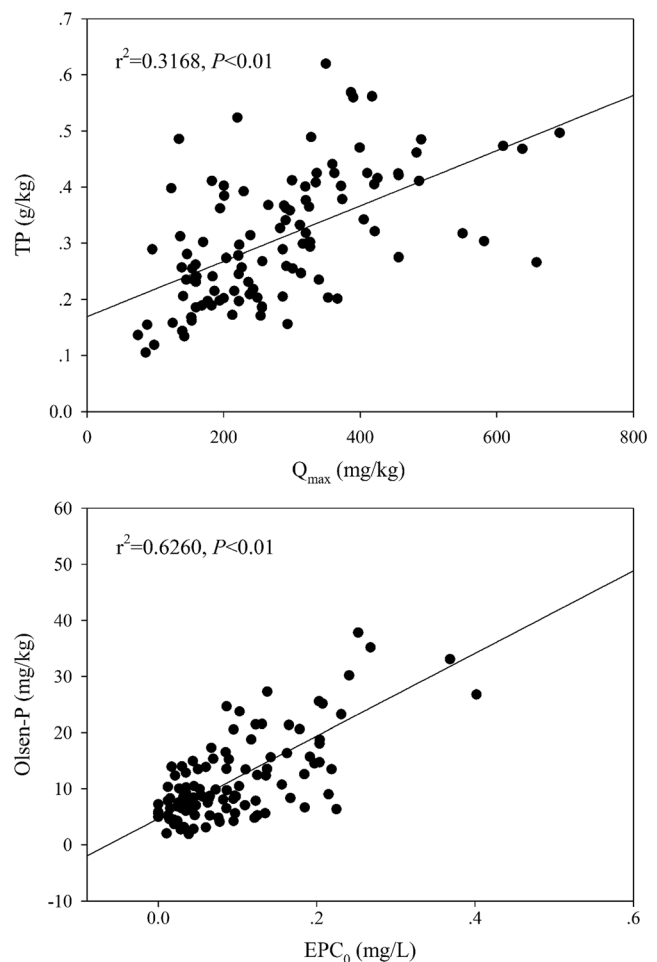


Fig. 3 The relationship between total phosphorus (TP) and phosphorus sorption maximum (Q_{\max}) and between the Olsen-P and the equilibrium P concentration (EPC_0) in the soils of riparian buffer strips around Lake Chaohu

greatly influenced by the width of the riparian buffer (Moon et al. 2013; Weissteiner et al. 2013), and most available nutrients can be preferentially accumulated and utilized by organisms in riparian buffer strips distant from the shoreline, resulting in a higher TP content in the relevant soils. In addition, in riparian buffer strips distant from the shoreline, woody species and terrestrial vegetation with high densities combined with periodic biomass harvests have great potential to reduce P movement to riparian buffer strips close to the shoreline (Kaoru and Yasuo 1998; Kelly et al. 2007). Adequate infiltration resulting from soil properties and vegetation type at riparian buffer strips distant from the shoreline further facilitated P accumulation (Mankin et al. 2007). All these factors facilitate riparian buffer strips distant from the shoreline to retain a large amount of P, which would be effectively utilized by the organisms in those areas. In addition, the SOM derived from

these vegetation types also resulted in a linear increase in the Q_{max} values of the sediment along the shoreline of Lake Chaohu (Zhou et al. 2011).

Furthermore, the TP contents and Q_{max} values were largely dependent on the soil properties, which remained unchanged on a seasonal scale (Fig. 4) and had some links with locality in relation to the shoreline (Fig. 2). As a key parameter determining soil properties, the pH value has an important impact on the P sorption characteristics of soils. For example, the pH value of the vegetation-covered land around Lake Chaohu ranged from 7.6 to 8.3, while that of the cultivated land varied between 5.9 and 6.7, with the value of the polder areas that were closer to the shoreline being the lowest (Wang et al. 2011; Ding et al. 2011). Moreover, in our results, soils distant from the shoreline were mainly mineral soils, while those close to the shoreline were mainly peat soils. Peat soils in general have extremely low pH values (Zhou

Fig. 4 The comparison of the Olsen-P, total phosphorus (TP), equilibrium P concentration (EPC_0), and phosphorus sorption maximum (Q_{max}) in soils at different distances from the shoreline around Lake Chaohu

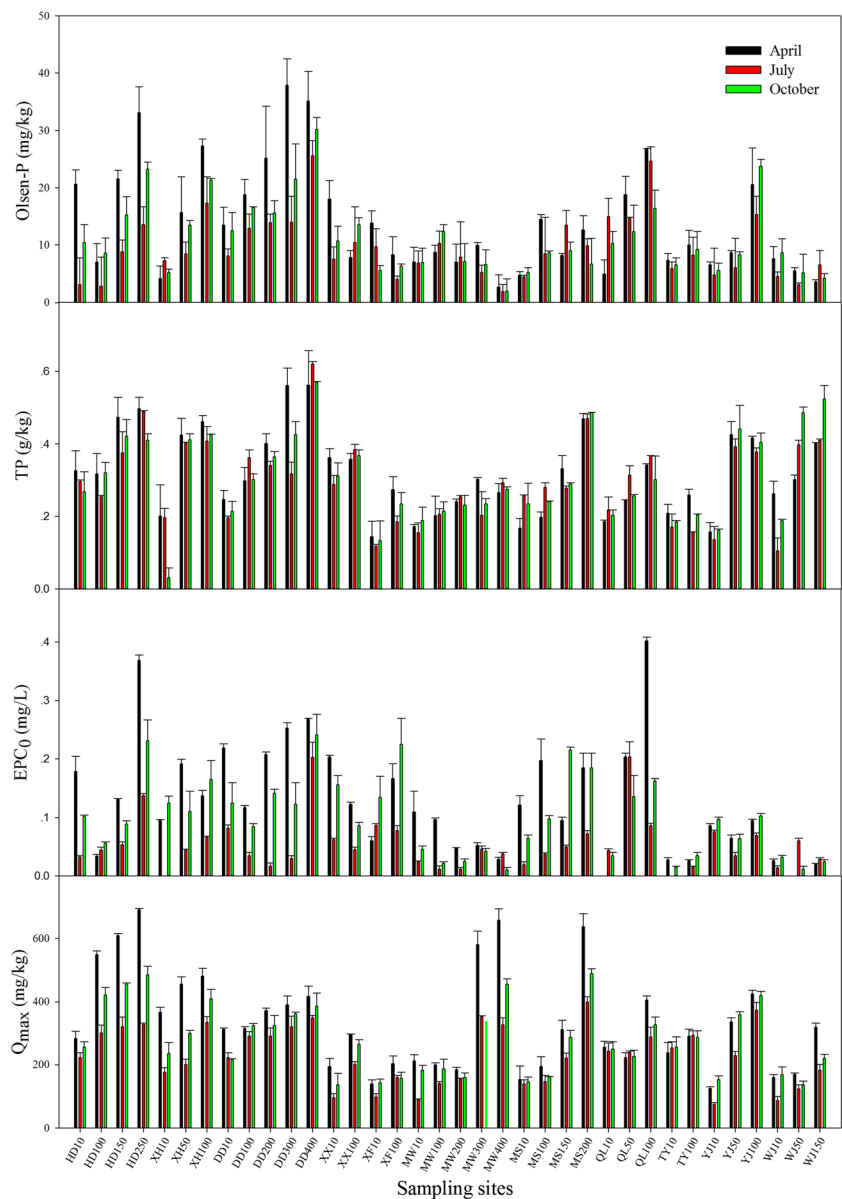
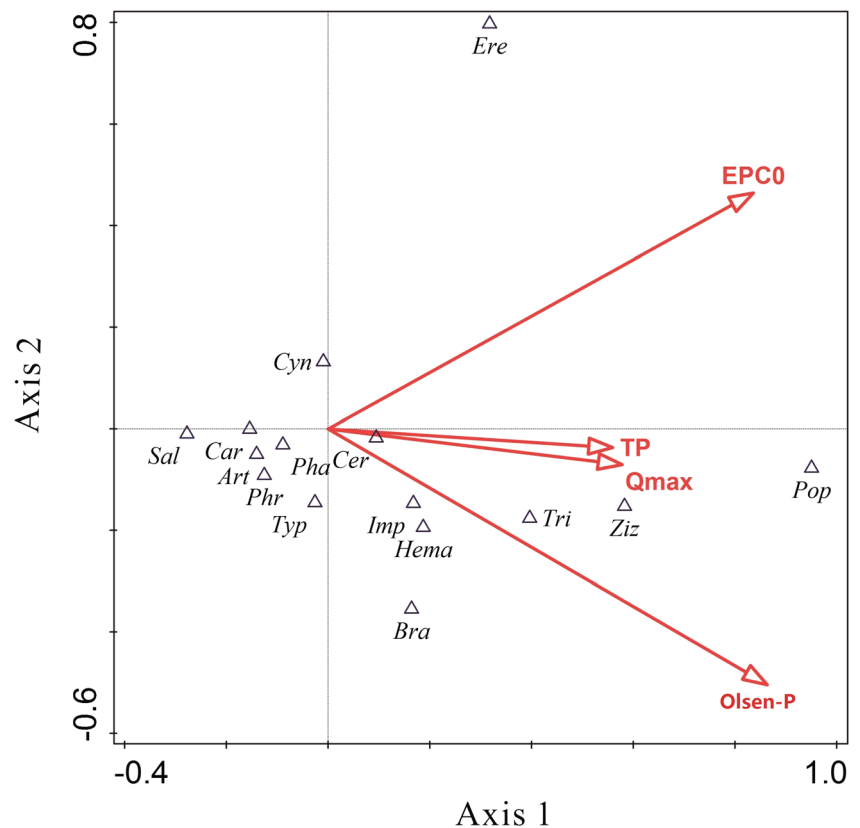


Fig. 5 Canonical correlation analysis (CCA) based on the dominant vegetation species distributions and environmental parameters in soils with different land use patterns (TP, total phosphorus; EPC_0 , equilibrium P concentration; Q_{max} , phosphorus sorption maximum; *Phr*, *Phragmites australis*; *Typ*, *Typha orientalis*; *Pha*, *Phalaris arundinacea*; *Car*, *Carex tristachya*; *Cyn*, *Cynodon dactylon*; *Imp*, *Imperata cylindrical*; *Pop*, *Populus L.*; *Art*, *Artemisia*; *Ziz*, *Zizania latifolia*; *Cer*, *Cerastium arvense*; *Bra*, *Brassica napus*; *Tri*, *Triticum aestivum*; *Sal*, *Salix babylonica*; *Ere*, *Eremochloa ophiuroides*; and *Hema*, *Hemarthria sibirica*)



and Li 2002). In short, alterations in land use patterns affect the soil pH value, electrical conductivity, and available N and P as well as the organic carbon content in soils. In turn, these changes in soil properties influence the P sorption capacity, such as Q_{max} (Yang et al. 2014). Finally, based on data about texture and organic matter, a key parameter representing soil erodibility was given, which was inversely related to the P sorption index (PSI) in the Lake Chaohu watershed (Zhou and Gao 2011). Interestingly, in the sediment along the shoreline of Lake Chaohu, a significantly positive relationship was found between the PSI and the Q_{max} value (Zhou et al. 2011). Thus, the Q_{max} value in our results might not only indicate the capacity of soil to buffer dissolved phosphorus in runoff but also reflect erodibility, which is largely dependent on soil texture, thereby implying a risk of particulate P discharge into Lake Chaohu through soil erosion.

4 Conclusions

The TP content and Q_{max} value had similar variation trends, both of which were closely correlated with the distance from the shoreline. However, the Olsen-P content and EPC_0 value were mainly regulated by the land use pattern (vegetation species in particular). All these facts could be indirectly indicated by the positive relationship between the TP content and the Q_{max} value as well as the Olsen-P content and the EPC_0 value. These

changes could be attributed to land use patterns, resulting in the alteration of the soil pH value, electrical conductivity, available N and P, organic carbon content, and the erodibility in the soils. These results provide insight into the prevention of P leaching through changes in land use patterns in riparian buffer strips. Wetlands and forests with grass are recommended as the main land use patterns for adjusting the EPC_0 value and minimizing P leaching from soils.

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