Fractions and spatial distributions of agricultural riparian soil phosphorus in a small river basin of Taihu area, China

Jin Qiana,b, Mengmeng Shen a,b, Peifang Wang a,b, Chao Wang a,b, Kun Li a,b, Jingjing Liu a,b, Xin Tian a,b and Bianhe Lua,b

aKey laboratory of integrated Regulation and Resources Development on Shallow lakes, Ministry of Education, Hohai University, Nanjing, PR China; bCollege of environment, Hohai University, Nanjing, PR China

ABSTRACT

Soil samples were collected from three different ranks riparian soil profiles in a small river basin of Taihu area in China. The method of modified Hedley phosphorus sequential fraction was employed to characterize soil phosphorus fractions. The results showed that the riparian soil total phosphorus (TP) contents, organic phosphorus (OP) and inorganic phosphorus (IP) of the basin ranged from 234.98 to 542.29, 49.76 to 73.81, 161.17 to 492.54 mg kg\(^{-1}\), respectively. HCl-Pi, NaOH-Pi and residual Pi were the major part of IP, accounting for 28, 28 and 26% of IP respectively, but NaHCO\(_3\)-Pi was accounted for 18% of IP. Overall, the various forms of phosphorus, except for Residual P, had a decreasing trend with soils depth. The vertical distributions of TP and IP had same rank order (Riparian Hejiabang > Riparian wuxidang > Riparian Yincungang), while the opposite trend was observed for OP. Surface soils in Riparian Yincungang had lower SOM (soil organic matters):OP ratios than Riparian Wuxidang and Riparian Hejiabang, reflecting the higher probability of OP mineralization in uncultivated soils. Besides, there was significant correlation between phosphorus fractions and SOM, bulk density and capillary porosity.

1. Introduction

Riparian is a complicated ecozone, which has critical environmental effects [1]. The riparian ‘soil – plant – microorganism’ system has physical, chemical and biological functions such as filtering, infiltration, absorption, retention and deposition [2–4], which can remove the non-point pollutants in surface runoff entering receiving water bodies to control pollution, purify water and protect water body [5–8].

Phosphorus has been recognized as one of the most important elements limiting plant growth and water eutrophication [9,10]. It has significant effects on primary production and nutritional status in ecosystem [11]. The riparian soil, as an important source or sink of phosphorus, is a vital place of phosphorus accumulation, transportation and regeneration, with an obvious effect on phosphorus biogeochemistry cycle [12].

The amounts and chemical nature of soil phosphorus are primarily determined by a combination of the major soil forming factors: parent material, climate, topography, soil biota, and time in the riparian ecosystems [13,14]. However, human activities have led to an increase of phosphorus storage in terrestrial and freshwater ecosystems to be at least 75% greater than preindustrial levels of storage [15,16]. The effects of different land-use types on soil phosphorus have been generally well investigated and documented around the world. Agricultural land-uses have accelerated the loss of phosphorus without encouraging its recycling and replacement [17]. Previous studies have found that the type of land use could influence soil phosphorus forms and concentrations [18–20]. Compared to uncultivated soil, arable soil applied with mineral fertilizer and manure generally increased soil phosphorus contents, including total P (TP), inorganic P (IP) and organic P (OP) in grassland, forest or native soils [20]. For different OP forms, Guggenberger et al. [21] found that monoester contents in pasture and woodland soils were higher than those in arable soils.

However, few studies have focused on comparative analysis of fractions and spatial distribution of soil phosphorus aiming to the different ranks riparian zones under various land uses, including cultivated and uncultivated riparian soils. The Taihu area in China is one of the most important agricultural production bases, with its flat topography and interconnected waterways [22]. In this study, we selected the different ranks riparian zones (trench, tributary and stream) in a small river basin of...
Taihu area under various land uses as the research sites. This paper provided a new research perspective angle in exploring the fractions and spatial distribution of riparian soil phosphorus so as to provide the theoretical basis for the water environment comprehensive management in small river basin of Taihu area and the riparian ecological remediation.

2. Materials and methods

2.1. Site description

This study was conducted in the riparian zone of Hejiabang River (trench), Wuxidang River (tributary) and Yincungang River (stream) in a small river basin, respectively. Yincungang River (stream) is an inflowing river of Taihu Lake, which is located in the city of Yixing, Jiangsu Province, China. The study area has a subtropical humid monsoon climate. The temperature in July is about 298 K and the rainfall in July is about 200 mm. At this time of the year, rice cultivation was in Riparian Hejiabang and soluble NPK fertilizer as nutrient sources was applied. The vegetation in Riparian Wuxidang includes Bermudagrass and Zizania with no fertilizer applied. There is no vegetation in Riparian Yincungang and it is a wasteland.

2.2. Soil sampling

All soil samples were collected from three different ranks riparian zones (trench, tributary and stream): Riparian Hejiabang (trench, N 31°27′22″, E 119°59′59″), Riparian Wuxidang (tributary, N 31°27′31″, E 119°59′37″) and Riparian Yincungang (stream, N 31°27′43″, E 119°59′28″) on 28 July 2014. Soil samples were characterized for soil physicochemical properties (described below). Soil samples were sampled at five different depths of the soil cores by collecting samples from the 0–10, 20–30, 50–60, 80–90 and 110–120 cm layers using a spade. Each sample was placed into a pre-labeled zip lock bag and put on ice in a cooler. Soils were transported back the laboratory and were stored at 4 °C until prepared for physicochemical analyses.

2.3. Physicochemical characteristics of soil

The following soil physicochemical parameters were measured on soils: pH, water content, ORP, bulk density, non-capillary porosity, capillary porosity, organic matter (as measured by loss on ignition), TP and different phosphorus fraction. These characteristics could be measured to physically and chemically characterize soils [23]. The pH value of each soil sample was analysed in a 1:10 solid/liquid ratio suspension using a combination pH electrode. A known mass of field moist soil was then dried for 8 h at 105 °C and the net percentage difference between wet and dry weights was quantified as soil moisture content. Soil bulk density was determined using a simplified coring method [24]. Capillary porosity was calculated by the soil bulk density. SOM concentrations were measured by weight loss on ignition to 400 °C [25]. TP was measured by ignition at 550 °C followed by digestion in 6 M HCl [26], with phosphate detection by automated molybdate colorimetry on a Bran + Luebbe Technicon TM Autoanalyzer II.

2.4. Phosphorus fractionation

Phosphorus fractions were sequentially extracted by a modified Hedley fractionation scheme which was proposed by Tiessen and Moir [27]. According to their increasing order of stability in soil, the levels of inorganic and organic phosphorus were extracted by continuous additions of different extraction solvents. (1) The phosphorus, which was extracted by using 0.5 M NaHCO3 represented the freely exchangeable or plant available fraction; (2) The phosphorus, which was extracted by using 0.1 M NaOH, represented the moderately labile pool; (3) The phosphorus, which was extracted by using 1 M HCl, represented Ca-bound portion; (4) Phosphorus remaining in the soil after sequential extraction was determined by digestion with concentrated H2SO4 and H2O2 and is termed residual phosphorus.

2.5. Statistical analyses

This study analysed the whole samples in triplicate to ensure the precision of the experiment results which reported as the average values. Significant differences in soil total concentration and phosphorus sequential fractions among all the sample sites were determined.

3. Results

3.1. Physicochemical characteristics of soil

As illustrated in Table 1, the pH values in the three riparian zones had the same trend that decreased with increasing depth. The soil samples were slightly acidic besides the samples below 80 cm depth in Riparian Yincungang. The soil bulk densities all increased with depth. The difference between water contents for the three riparian zones was significant. The water contents in surface soil were all higher than those in the deep soils. The general vertical distributing pattern at all soil cores was that the water content decreased firstly and then increased with depth. The differences between ORPs for three riparian zones was significant and the rank order was Riparian Wuxidang > Riparian Yincungang > Riparian Hejiabang. The ORP had no significant vertical distributing pattern.

Porosity was composed of capillary porosity and noncapillary porosity, with capillary porosity predominating. The capillary porosity and noncapillary porosity were both in the order of Hejiabang > Wuxidang > Yincungang. The general vertical distributing patterns were
that the capillary porosity and the noncapillary porosity both decreased with the depth increasing in all soil cores. The SOM contents of surface soil in the three riparian zones were all larger. The spatial distributing pattern was Hejiabang > Yincungang > Wuxidang. And the vertical distributing pattern at all soil cores was that the organic matter contents decreased with the depth increasing.

### 3.2. Distribution of phosphorus fractions

#### 3.2.1. TP

The Figure 1 showed that the rank order of TP content was Riparian Hejiabang > Riparian Wuxidang > Riparian Yincungang, which in part reflected a big spatial difference of phosphorus loads.

In Riparian Hejiabang and Riparian Wuxidang, the vertical distributing pattern was that the TP contents decreased sharply with increasing depth in the range of 0–30 cm below soil surface, and 30–120 cm below soil surface followed by a slight increase. In Riparian Yincungang, the TP contents decreased with the depth increasing in the depth of 0–80 cm. However, the TP contents had a slight increase in the depth of 80–120 cm. In the three riparian zones, the TP contents were higher in the surface than subsurface soils.

#### 3.2.2. IP fractionations

IP mainly referred to the phosphorus of different states through a combination of the dissolved inorganic phosphorus and metal ions [28]. In this study, the IP concentration ranged from 161.17 to 492.54 mg kg\(^{-1}\). The mean value of IP was 303.33 mg kg\(^{-1}\) and contributed about 82.21% of TP (Table 2). That is the main factor of TP and its vertical trend was same with TP. In this paper, IP was divided into NaHCO\(_3\)-Pi, NaOH-Pi, HCl-Pi, and Residual Pi (Figure 2).

NaHCO\(_3\)-Pi, NaOH-Pi and HCl-Pi in the riparian zones were all available, ranging from 42.99 to 166.86, 22.53 to 119.32 and 61.64 to 113.98 mg kg\(^{-1}\), respectively. The mean values of NaHCO\(_3\)-Pi, NaOH-Pi and HCl-Pi in three riparian zones are 85.15, 55.06 and 83.92 mg kg\(^{-1}\) and contributed about 28, 18 and 28% of Pi (Table 2), respectively. The spatial distributions of NaHCO\(_3\)-Pi, NaOH-Pi and HCl-Pi were same with TP with the maximum appearing in Riparian Hejiabang. The vertical distributing pattern at all soil cores was that NaHCO\(_3\)-Pi, NaOH-Pi and HCl-Pi decreased sharply with increasing depth in the range of 0–30 cm below soil surface, presenting the characteristic of enrichment in surface soil (Figure 2).

Residual Pi was unavailable, ranging from 27.06 to 111.23 mg kg\(^{-1}\). Its mean value was 76.89 mg kg\(^{-1}\) and contributed about 26% of TP. The rank order of Residual Pi concentration in the three riparian zones was that Riparian Wuxidang > Riparian Hejiabang > Riparian Yincungang. And the concentration increased with the depth increasing on the vertical dimension.

#### 3.2.3. OP fractionations

The soil OP of riparian zone was mainly imported from terrigenous source and itself, and was difficult to be

| Depth (cm) | pH     | Water Content (%) | Bulk density | ORP   | Capillary porosity | Noncapillary porosity | Organic Matter (%) |
|-----------|--------|-------------------|--------------|-------|--------------------|-----------------------|---------------------|
| 0–10      | 6.2 ± 0.8 | 34.10 ± 3.62      | 0.76 ± 0.35  | 705.26 ± 70.43 | 0.769 ± 0.108 | 0.107 ± 0.011 | 12.45 ± 1.65 |
| 20–30     | 6.3 ± 0.5 | 27.23 ± 2.55      | 1.23 ± 0.28  | 900.54 ± 99.64 | 0.523 ± 0.097 | 0.053 ± 0.002 | 10.13 ± 1.63 |
| 50–60     | 6.5 ± 0.7 | 26.42 ± 4.92      | 1.25 ± 0.26  | 672.16 ± 68.43 | 0.752 ± 0.184 | 0.021 ± 0.006 | 7.38 ± 0.93  |
| 80–90     | 7.0 ± 0.4 | 24.16 ± 3.76      | 1.37 ± 0.33  | 752.13 ± 82.45 | 0.546 ± 0.086 | 0.015 ± 0.008 | 8.45 ± 0.59  |
| 110–120   | 6.8 ± 0.5 | 26.72 ± 4.58      | 1.46 ± 0.25  | 710.98 ± 69.43 | 0.495 ± 0.062 | 0.009 ± 0.002 | 7.92 ± 0.96  |
| 0–10      | 5.9 ± 0.5 | 25.55 ± 3.93      | 1.29 ± 0.31  | 2496.45 ± 135.89 | 0.558 ± 0.065 | 0.029 ± 0.003 | 9.74 ± 1.13  |
| 20–30     | 6.2 ± 0.7 | 19.25 ± 2.35      | 1.36 ± 0.51  | 1347.72 ± 175.43 | 0.560 ± 0.101 | 0.028 ± 0.000 | 5.57 ± 1.23  |
| 50–60     | 6.6 ± 0.7 | 23.63 ± 3.58      | 1.27 ± 0.56  | 5277.64 ± 78.43 | 0.582 ± 0.079 | 0.034 ± 0.007 | 8.41 ± 1.67  |
| 80–90     | 6.0 ± 0.3 | 24.92 ± 3.94      | 1.30 ± 0.47  | 2333.81 ± 562.82 | 0.595 ± 0.082 | 0.023 ± 0.005 | 7.27 ± 0.64  |
| 110–120   | 6.5 ± 0.8 | 28.33 ± 5.17      | 1.44 ± 0.59  | 5581.37 ± 400.63 | 0.541 ± 0.114 | 0.014 ± 0.008 | 8.64 ± 0.93  |
| 0–10      | 6.1 ± 0.9 | 30.61 ± 4.52      | 1.21 ± 0.58  | 835.46 ± 100.79 | 0.484 ± 0.093 | 0.028 ± 0.009 | 10.58 ± 1.67 |
| 20–30     | 6.4 ± 0.8 | 25.15 ± 2.99      | 1.36 ± 0.61  | 892.36 ± 89.64  | 0.486 ± 0.096 | 0.022 ± 0.006 | 8.73 ± 0.98  |
| 50–60     | 6.8 ± 0.5 | 23.61 ± 4.85      | 1.53 ± 0.64  | 896.75 ± 74.95  | 0.436 ± 0.094 | 0.015 ± 0.007 | 6.75 ± 1.02  |
| 80–90     | 7.6 ± 0.5 | 28.38 ± 2.73      | 1.39 ± 0.55  | 871.92 ± 84.18  | 0.560 ± 0.108 | 0.020 ± 0.006 | 7.66 ± 1.24  |
| 110–120   | 7.6 ± 0.7 | 33.86 ± 5.58      | 1.42 ± 0.35  | 820.42 ± 82.64  | 0.520 ± 0.121 | 0.012 ± 0.007 | 7.45 ± 0.95  |

**Figure 1.** Distribution of TP in different riparian soils.

Table 1. Characteristics of the soil profile of three different riparian zones. Values are the mean of three replicate samples, each a composite of three replicate cores.

### Annotation:

- RH-Riparian Hejiabang
- RW-Riparian Wuxidang
- Ry-Riparian Yincungang
Maximum of the three OP-fractions all appeared in Riparian Yincungang. In the three riparian zones, the concentrations of NaHCO₃-Pₒ and NaOH-Pₒ decreased with the depth increasing. The Residual Pₒ concentrations of Riparian Yincungang decreased with the depth increasing, but increased in Riparian Hejiabang and Riparian Wuxidang.

The soil OP concentrations of the three riparian zones ranged from 49.76 to 70.34 mg kg⁻¹. The mean value was 62.32 mg kg⁻¹ and contributed about 17% of TP (Table 2), much lower than IP. The OP was divided into NaOH-Pₒ, NaHCO₃-Pₒ and Residual Pₒ. The rank order of OP-fractions extracted was Residual Pₒ > NaOH-Pₒ > NaHCO₃-Pₒ.

Figure 2. Distribution of Pₒ fractions in different riparian soils.
Table 3. Correlation between contents of fractions of phosphorus and soil physicochemical characteristics.

|       | PH     | Water content | Organic matter | Bulk density | ORP    | Capillary porosity | Noncapillary porosity |
|-------|--------|---------------|----------------|--------------|--------|--------------------|-----------------------|
| NaHCO₃-P | −0.184 | 0.342         | 0.662**        | −0.631*      | −0.378 | 0.726**           | 0.508                 |
| NaOH-P | −0.246 | 0.362         | 0.624*         | −0.680*      | −0.343 | 0.753**           | 0.544*                |
| HCl-P  | −0.242 | 0.459         | 0.491          | −0.699*      | −0.159 | 0.741**           | 0.551*                |
| Residual P | −0.081 | −0.003       | 0.098          | 0.071        | 0.523* | 0.167             | −0.072               |
| NaHCO₃-P<sub>2</sub> | −0.350 | 0.061         | 0.627*         | −0.256       | −0.103 | −0.008            | 0.067                 |
| NaOH-P<sub>2</sub> | −0.546* | 0.138        | 0.527*         | −0.373       | 0.266  | 0.101             | 0.164                 |
| Residual P<sub>2</sub> | −0.236 | −0.239        | −0.151         | 0.237        | 0.366  | −0.280            | −0.259               |
| TP    | −0.325 | 0.336         | 0.666**        | −0.653**     | −0.100 | 0.756**           | 0.496                 |

*p < 0.05; **p < 0.01.

3.3. SOM:OP and IP:OP ratios

As shown in Figure 4, the values of SOM:OP ratios ranged from 80 to 461 in the three riparian zones and followed the order of: Riparian Hejiabang > Riparian Wuxidang > Riparian Yincungang in the surface soil. The values of IP:OP ratios varied from 1.3 to 13.8, and they occurred in the following order: Riparian Hejiabang > Riparian Wuxidang > Riparian Yincungang in the top layer. SOM:OP and IP:OP ratios in Riparian Hejiabang and Riparian Wuxidang displayed a decreasing trend with the depth increasing, while they displayed an increasing trend in Riparian Yincungang.

3.4. Relationships between phosphorus fractions extracted and soil physicochemical characteristics

Table 3 shows correlation coefficients among P fractions extracted and soil physicochemical characteristics. The results revealed that there were negative correlations among bulk density and TP, NaHCO₃-P, NaOH-P, HCl-P. And there were positive correlations (p < 0.01) among capillary porosity and TP, NaHCO₃-P, NaOH-P, HCl-P, TP, NaHCO₃-P<sub>2</sub> and NaOH-P<sub>2</sub>. The values of SOM:OP ratios varied from 80 to 461 in the three riparian zones and followed the order of: Riparian Hejiabang > Riparian Wuxidang > Riparian Yincungang in the surface soil. The values of IP:OP ratios varied from 1.3 to 13.8, and they occurred in the following order: Riparian Hejiabang > Riparian Wuxidang > Riparian Yincungang in the top layer. SOM:OP and IP:OP ratios in Riparian Hejiabang and Riparian Wuxidang displayed a decreasing trend with the depth increasing, while they displayed an increasing trend in Riparian Yincungang.

4. Discussion

4.1. Profile changes of TP and all phosphorus fractions

Phosphorus in riparian soils exists in both inorganic and organic forms. The relative proportion of each form depends upon the nature and origin of the soil phosphorus [29]. The soil in Riparian Hejiabang contained more TP (Figure 1) which might have resulted from higher input of phosphorus fertilizers [20] and lower output of phosphorus by plant biomass compared to other soils. In the soil of Riparian Yincungang, lower concentration of TP may be attributed to the lack of input compared to cultivated soils (Riparian Hejiabang). NaHCO₃-P<sub>2</sub> was the primary phosphorus source for plant growth. The concentration of NaHCO₃-P in Riparian Hejiabang was highest among the three riparian zones because of higher phosphorus fertilizer input. NaOH-P<sub>2</sub> and HCl-P<sub>2</sub> were the larger extractable fractions. Their highest concentrations occurred in Riparian Hejiabang and their concentrations in Riparian Wuxidang and Riparian Hejiabang did not differ significantly. Our findings are in line with several studies carried out in Brazil. Pavinato et al. [30] and Rodrigues et al. [31] indicated that phosphorus applied through phosphate fertilization increased the inorganic labile (NaHCO₃-P) and moderately labile phosphorus fractions (NaOH-P<sub>2</sub>, HCl-P<sub>2</sub>). Aguiar et al. [32] reported that higher inorganic labile phosphorus (NaHCO₃-P) levels under agricultural uses (alley cropping) compared to a newly cleared area. In the south eastern Amazon, Riskin et al. [33] also observed that the continuum use of phosphorus fertilizer in soybean fields led to increased inorganic labile phosphorus compared to no vegetation. There was a higher contribution IP in the top soils of Riparian Hejiabang and Riparian Wuxidang accounted for 93.22 and 87.38% of TP (Table 2), higher than that in Riparian Yincungang (65.40%) (Table 2). In the vegetable (Riparian Hejiabang) and grass (Riparian Wuxidang) environment, relatively rapid mineralization of their needles and leaves on the soil surface may lead to a higher percentage of soil phosphorus being held in IP rather than OP. Vincent et al. [34] made a similar observation in a study of lowland forest soil by addition or removal of leaf litter. In addition IP fertilizer was added annually to the vegetable row site, another factor that would lead to a higher percentage of IP. All OP fractions occurred in the following order: Riparian Yincungang > Riparian Wuxidang > Riparian Hejiabang (Figure 3). The supply of phosphorus in forms available to plants depends on mineralization of OP; nevertheless, lower soil biological activity in Riparian Yincungang may result in lower turnover of soil OP, and consequently a higher concentration of OP [35].

4.2. Changes in the SOM:OP and IP:OP ratios

C:P ratios are generally considered to indicate the immobilization, mineralization and loss of phosphorus fertilizer to organic masses and soils [36] and affect the activities of microbes due to variations in these nutrients [37]. Li et al. [38] reported that mineralized carbon had significant and positive relationships with mineralized phosphorus, and microbial biomass carbon and phosphorus were significantly and positively related to soil organic
The lowest SOM:OP ratios occurred in Riparian Yincungang, with no vegetation, showing that OP in Riparian Yincungang has the highest tendency of mineralization. Besides, the values of SOM:OP ratio decreased with depth along soil profiles in Riparian carbon and phosphorus. The complicated variations of SOM:OP ratios along soil profiles in the three riparian zones in this study indicated the complex phosphorus dynamic. The SOM:OP ratios in the top soils of Riparian Hejiabang is higher than that in other two riparian zones (Figure 4). The lowest SOM:OP ratios occurred in Riparian Yincungang, with no vegetation, showing that OP in Riparian Yincungang has the highest tendency of mineralization. Besides, the values of SOM:OP ratio decreased with depth along soil profiles in Riparian
Hejiabang and Riparian Wuxidang may be due to faster soil carbon losses than soil phosphorus [39]. The IP:OP ratios in the three riparian zones has a same tendency with the SOM:OP ratio (Figure 4). The highest IP:OP ratios occurred in the top soil of Riparian Hejiabang and the lowest occurred in the top soil of Riparian Yincungang, which is in agreement with the IP content associated with variations in phosphorus inputs.

4.3. Impact of soil physicochemical characteristics on spatial distribution of phosphorus

Table 3 showed the correlation between phosphorus fractions and soil physicochemical characteristics. The soil TP content was significantly positively related to organic matter content which could increase the resolution of phosphorus (Table 3). That might be chiefly because soil organic colloid could coat iron-aluminium oxides and clay minerals to decrease P immobilization [40]. All the soil phosphorus fractions were influenced in different degree by soil physicochemical characteristics such as pH, water content, SOM, bulk density, ORP, capillary porosity and noncapillary porosity [41,42]. As shown in Table 3, NaHCO$_3$-P$_i$, NaOH-P$_i$, HCl-P$_i$, and TP were positively related to organic matter content and capillary porosity, whereas they were not related to water content. In Riparian Hejiabang and Riparian Wuxidang, the HCl-P$_i$, contents were significantly negatively related to pH, indicating that pH was the major factor of the HCl-P$_i$ content. However, there was significant relationship between the HCl-P$_i$ content and water content in Riparian Yincungang, indicating that water content was the major factor affecting the HCl-P$_i$ content. As shown in Table 3, there were significant positive relationships between NaHCO$_3$-P$_i$, NaOH-P$_i$, and the SOM content. However, there were few relationships between Residual P$_o$ and the SOM content, which indicated that the SOM content was one of the chiefly factors affecting the accumulations and the occurrences of NaHCO$_3$-P$_o$ and NaOH-P$_o$ [43].

NaHCO$_3$-P$_i$, NaOH-P$_i$, HCl-P$_i$, and TP were positively related to capillary porosity and negatively related to bulk density in the three riparian zones of different land use styles. From the above analysis, we could find that the soil machinery composition could affect the distributions of phosphorus fractions from the two aspects of bulk density and porosity. The concentrations of phosphorus fractions were generally negatively related to bulk density. This is mainly because the smaller the bulk density, the looser the soil and the larger the porosity, the stronger the capacities of venting and water-holding. There was a significant positive relationship between TP and porosity. So the larger the porosity, the higher the concentration of TP. Soil could increase the phosphorus immobilization by big porosity and surface area [44]. The rank order of porosity of the riparian zones was Riparian Hejiabang > Riparian Wuxidang > Riparian Yincungang, with the same order of TP. NaHCO$_3$-P$_i$, NaOH-P$_i$ were positively related to SOM, and NaOH-P$_i$ was negatively related to PH. Residual P was positively related to ORP and not related to other environmental factors. Generally, the contents of phosphorus fractions were mainly determined by SOM, bulk density and capillary porosity.

5. Conclusion

The TP concentrations in Riparian Hejiabang, Riparian Wuxidang and Riparian Yincungang were 735, 455 and 335 mg kg$^{-1}$, respectively. IP was accounted for more than 80% of TP. In the soils of different land use styles, the concentrations of HCl-P$_i$, NaHCO$_3$-P$_i$, and NaOH-P$_i$ in Riparian Hejiabang, growing wheat, were all larger than in Riparian Wuxidang and Riparian Yincungang, growing grass or nothing. They all decreased with the depth increasing and had enrichment in surface soil. The lowest SOM:OP ratios occurred in Riparian Yincungang, growing nothing, showing OP there had the highest tendency of mineralization. There was significant difference in physicochemical characteristics of three riparian soil. With the increasing of soil depth, pH and bulk density increased, while porosity decreased. The measures of P contamination control and management are required for protection and future restoration of the agricultural riparian zones of Taihu area.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by National Natural Science Foundation of China [grant number 51379062, 51579073], National Science Funds for Creative Research Groups of China [grant number 51421006], Key Program of National Natural Science Foundation of China [grant number 51647206], National Key Plan for Research and Development of China [grant number 2016YFC0401703], and PAPD.

References

[1] Mander U, Kuusemets V, Krista L, et al. Efficiency and dimensioning of riparian buffer zones in agricultural catchments, Ecol Eng. 1997;8:299–324.
[2] Bottcher AB, Tremwel K, Campbell KL. Best management practices for water quality improvement in the Lake Okeechobee watershed. Ecol Eng. 1995;5:341–356.
[3] McDowell R, Sharpley A, Folmar G. Phosphorus export from an agricultural watershed: linking source and transport mechanisms. J Environ Qual. 2001;30:1587–1595.
[60] Guggenberger G, Christensen BT, Rubaek G, et al. Land-use and nutrient transformation in agricultural areas. Commun Soil Sci Plant Anal. 2003;34:1071–1100.

[5] Ranjith PU, Peter PM. Nitrogen losses in runoff from three adjacent agricultural watersheds with claypan soils. Agric Ecosyst Environ. 2006;117:39–48.

[4] Yang CH, Wu YQ, Zhang F, et al. Pollution characteristics and ecological risk assessment of heavy metals in the surface sediments from a source water reservoir. Chem Spec Bioavailab. 2016;28:1–4.

[3] Ogunbanjo O, Onawumi O, Gbadamosi M, et al. Chemical speciation of some heavy metals and human health risk assessment in soil around two municipal dumpsites in Sagamu, Ogun state, Nigeria. Chem Spec Bioavailab. 2016;28:1–4.

[2] Soltani SM, Hanafi MM, Wahid SA, et al. Zinc fractionation of tropical paddy soils and their relationships with selected soil properties. Chem Spec Bioavailab. 2015;27(2):53–61.

[1] Kaiserli A, Voutsa D, Samara C. Phosphorus fractionation in lake sediments—Lakes Volvi and Koronia, N. Greece. Chemosphere. 2002;46:1147–1155.

[0] Zhang TX, Wang XR, Jin XC. Variations of alkaline phosphatase activity and P fractions in sediments of a shallow Chinese eutrophic lake (Lake Taihu). Environ Pollut. 2007;150:288–294.

[10] Ruttengen KC. Development of a sequential extract ion method for different forms of phosphorus in marine sediment. Limnol Oceanogr. 1992;37:1460–1482.

[9] McDowell R, Sharpley A, Withers P. Indicator to predict the movement of phosphorus from soil to subsurface flow. Environ Sci Technol. 2002;36:1505–1509.

[8] Letkeman LP, Tiessen H, Campbell CA. Phosphorus transformations and redistribution during pedogenesis of western Canadian soils. Geoderma. 1996;71:201–218.

[7] Magid J, Tiessen H, Condron LM. Dynamics of organic phosphorus in soil under natural and agricultural ecosystems. In: Piccolo A, editor. Humic substances in terrestrial ecosystems. Amsterdam: Elsevier Science; 1996. p. 429–466.

[6] Bennett EM, Carpenter SR, Caraco NF. Human impact on erodable phosphorus and eutrophication: a global perspective. BioScience. 2001;51:227–234.

[5] Bulu YI, Adewole MB. Organic fertilizer applications influence on the shoot and root biomass production and plant nutrient of Calopogonium mucunoides from crude oil-contaminated soils. Chem Spec Bioavailab. 2015;27(2):7–12.

[4] Brady NC, Weil RR. Nature and properties of soils. 14th ed. Upper Saddle River (NJ): Prentice Hall; 2008.

[3] McDowell RW, Stewart I. The phosphorus composition of contrasting soils in pastoral, native and forest management in Otago, New Zealand: sequential extraction and 31P NMR. Geoderma. 2006;130:176–189.

[2] Soimne H, Uusitalo R, Sarvi M, et al. Characterization of soil phosphorus in differently managed clay soil by chemical extraction methods and 31P NMR spectroscopy. Commun Soil Sci Plant Anal. 2011;42:1995–2011.

[1] Troitzho F, GileStotres F, Leirös MC, et al. Effect of land use on some soil properties related to the risk of loss of soil phosphorus. Land Degrad Dev. 2008;19:21–35.

[0] Guggenberger G, Christensen BT, Rubæk G, et al. Land-use and fertilizer effects on P forms in two European soils: resin extraction and 31P-NMR analysis. Eur J Soil Sci. 1996;47:605–614.
[41] Kehl M, Everding C, Botschek J, et al. Erosion processes and erodibility of cultivated soils in North Rhine-Westphalia under artificial rain. I: Site characteristics and results of laboratory experiments. J Plant Nutr Soil Sc. 2005;168(1):34–44.

[42] Moore A, Reddy K. Role of Eh and pH on phosphorus geochemistry in sediments of Lake Okeechobee, Florida. J Environ Qual. 1994;23(5):955–964.

[43] Crews TE, Brookes PC. Changes in soil phosphorus forms through time in perennial versus annual agroecosystems. Agric Ecosyst Environ. 2005;184(2):168–181.

[44] Verma S, Subehia SK, Sharma SP. Phosphorus fractions in an acid soil continuously fertilized with mineral and organic fertilizers. Biol Fert Soils. 2005;41(4):295–300.