

Characteristics of organic phosphorus fractions in different trophic sediments of lakes from the middle and lower reaches of Yangtze River region and Southwestern Plateau, China

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Organic phosphorus fractions in sediments from 6 different trophic Chinese lakes were characterized using an improved fractionation scheme.

Abstract

In this study, the characteristics of organic phosphorus (P_o) fractions in sediments of six lakes from the middle and lower reaches of Yangtze River region and Southwestern China Plateau, China were investigated using a soil P_o fractionation scheme, and the relationships between P_o , inorganic phosphorus (P_i) and pollution status were also discussed. The results show that the rank order of P_o fractions was: residual $P_o > \text{HCl-}P_o > \text{fulvic acid-P} > \text{humic acid-P} > \text{NaHCO}_3\text{-}P_o$, with their average relative proportion 8.7:4.6:3.2:2.1:1.0. P_o fractions, especially nonlabile P_o , were significantly correlated with organic matter, P_o and $\text{NaOH-}P_i$. Different distribution patterns of P fractions were observed in those two different regions. P_o fractions in the heavily polluted sediments were higher than those in moderately and no polluted sediments, it is suggested that P_o should be paid more attention in the lake eutrophication investigation.

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1. Introduction

Phosphorus (P) is an essential nutrient in aquatic environments and is one of the limiting nutrients for the primary production in lakes (Kaiserli et al., 2002; Ahlgren et al., 2005). Efforts have been made in recent years to investigate the biogeochemical cycling of P in lake ecosystems (Jin et al., 1995, 2006; Havens et al., 2001). The release of P from the sediments is an important source for the overlying water and may result in continuous eutrophication in eutrophic lakes even after the reduction of external loading (Ramm and Scheps, 1997; Xie et al., 2003). Therefore, P transformation,

bioavailability and exchange between sediment and the overlying water have been extensively studied (Zhou et al., 2001; Søndergaard et al., 2003; Jin et al., 2006). Sequential extraction procedures were developed to elucidate the chemical nature of P in sediments (Hupfer et al., 1995; Ruban et al., 2001; Fytianos and Kotzakioti, 2005), and they generally isolated P into two fractions: inorganic P (P_i) and organic P (P_o) (Barbanti et al., 1994). P_i consisted of P associated to Fe, Al and Ca oxides and hydroxides or clay minerals (Hieltjes and Lijklema, 1980), and P_o represented various P_o compounds and associated to organisms (Carman et al., 2000). However, most of those previous studies mainly focused on P_i fractions and their bioavailability (Zhou et al., 2001; Kaiserli et al., 2002). In fact, P_o was a major chemical component in sediments (Pettersson, 2001) and was usually treated as a residue

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or a refractory fraction in P fractionation studies (Ruttenberg, 1992; Graca and Bolalek, 1998).

Previous studies demonstrated that P_o played a vital role in lake sediments, and provided a nutrient source for phytoplankton uptake followed by phosphatase hydrolysis, bacterial decomposition and photolysis of P_o compounds (Jansson et al., 1988; Ahlgren et al., 2005). However, concentrations, fractions, and dynamics of P_o in sediments are poorly understood since there were no appropriate fractionation and characterization approaches. Bowman and Cole (1978) developed a scheme separating soil P_o into four distinct fractions: labile P_o , moderately labile P_o , moderately resistant P_o and highly resistant P_o . But phytate added to the soils was not recovered in any fractions (Bowman and Cole, 1978). In fact, higher concentrations of phytate occurred in most soils and sediments (Golterman et al., 1998; Turner et al., 2002). Oluyedun et al. (1991) have reported that P_o in the lake sediments was recovered incompletely with Bowman and Cole's method. The fractionation scheme was further improved later on (Sharpley and Smith, 1985; Ivanoff et al., 1998; Fan et al., 1999). For example, Ivanoff et al. (1998) proposed a comprehensive scheme to fractionate soil P_o and greatly improved P_o recovery by using additional step to analyze biomass and residual P_o . Currently there are no systemic fractionation studies on P_o in sediments (Sommer's et al., 1972; Oluyedun et al., 1991; Golterman, 1998).

Eutrophication is a serious environmental problem in China, and had imposed as a threat to water resource, human health and social sustainable development (Yu, 2000). More than 66% of lakes and reservoirs were under eutrophic conditions and 22% of the total water bodies were in hypereutrophication in China (Huang, 2001). Lakes from the middle and lower reaches of Yangtze River region and Southwestern China Plateau were the most seriously polluted waters in China (Wang, 2001). Hence, it is essential to investigate the chemical forms and biogeochemical cycling of P in the sediments. The objectives of this study were to (1) investigate the characteristics of P_o fractions in the surface sediments of lakes from the middle and lower reaches of Yangtze River region and Southwestern China Plateau, and (2) discuss the relationships between P_o and P_i fractions and lake eutrophication.

2. Materials and methods

2.1. Study areas

In this study, six lakes were chosen based on different trophic status in the Yangtze River region and Southwestern China Plateau. The middle and lower

reaches of Yangtze River region are central areas of freshwater shallow lakes in China. There are 651 lakes with areas larger than 1 km² and there are 18 lakes with areas larger than 100 km² in this region (Jin et al., 1995). Lake Taihu (30°56'–31°33' N, 119°54'–126°36' E), one of the five biggest freshwater lakes in China, is located in the South Yangtze River Delta with a total water surface area of 2338.11 km², and an average depth of 1.89 m (Chen, 2001). Lake Meiliang and Lake Yuantouzhu are two of the most seriously eutrophic lakes in China, located at the Lake Taihu's northwestern tip (Shen et al., 2001; Geng et al., 2006). Those two lakes serve as the principal water resource for Wuxi City, Jiangsu Province and also receive industrial wastewater and sewage from the city. In addition, Lake Yuantouzhu is an important entertainment and tourist attraction. Lake Gonghu is located at the northeast part of Lake Taihu, with a vast water surface, good fluidity and a high capacity of oxygen restoration. Abundant submerged plants were found and the water quality remained good and was in mesotrophication (Fan et al., 1997). Southwestern China Plateau is a large karst area in China. There are more than 30 lakes with a water depth from 10 to 50 m in this area. According to previous lake chemistry surveys (Wang, 2001; Wu et al., 2001), one slightly polluted lake (Lake Erhai) and two heavily polluted lakes (Lake Hongfeng and Baihua) were selected in this area. Lake Erhai is the largest fault lake in this region. Lakes Hongfeng and Baihua are located in the suburbs of Guiyang City, Guizhou, China and are the main artificial drinking-water reservoirs. These six lakes represent major lake types in two regions and were chosen in this study. Their geographic and limnological features are shown in Table 1.

2.2. Sediment sampling and analyses

Sediment core samples (0–10 cm) were obtained from the six lakes in the two regions in May 2005. The core sampler with 30 cm length, 5 cm diameter Plexiglas cylinder tube was used. The sediment samples were taken to the laboratory in sealed plastic bags that were put in iceboxes (<4 °C), and freeze-dried. They were then ground and sieved with a standard 100-mesh sieve for experiments.

Total P (TP) was measured by treating at 500 °C (2 h), followed by HCl extraction. P_i was determined by direct extraction with 1 M HCl (16 h). P_o concentrations in sediments were calculated as the difference between TP and P_i (Aspila et al., 1976). Organic matter (OM) in sediments was analyzed as the loss of ignition at 500 °C for 2 h (Jensen et al., 1992).

2.3. P_o fractionation

P_o fractionation procedure was primarily based on Ivanoff et al. (1998) scheme, and was presented in Fig. 1. This scheme originally for soils was used because the fractions were consistent with well-known operationally defined sediment components. P_o in lake sediments was classified into labile, moderately labile and nonlabile fractions. Labile P_o was initially extracted with 0.5 M NaHCO₃ at pH 8.5. The extracted P_o was mainly referred to the loosely sorbed P_o on sediment colloids. Moderately labile P_o was extracted with 1.0 M HCl, followed by 0.5 M NaOH. The NaOH extract was acidified with concentrated HCl until pH 0.2 to separate the nonlabile fraction (humic acid-P) from the moderately labile fraction (fulvic acid-P). Finally, the highly resistant and nonlabile fraction was determined by ashing the residue from the NaOH extraction at 550 °C for 1 h, followed by dissolution in 1 M H₂SO₄. The P concentration in all extracts was estimated colorimetrically according to a reported method by Murphy and Riley (1962). Acid or alkaline extracts were neutralized

Table 1
Geographic and limnological features of the studied lakes

Parameters	Yangtze River region			Southwestern China Plateau		
	Lake Meiliang	Lake Yuantouzhu	Lake Gonghu	Lake Hongfeng	Lake Baihua	Lake Erhai
Positions	31°25' N, 120°10' E	31°31' N, 120°12' E	31°24' N, 120°15' E	26°25'–34' N, 106°20'–28' E	26°35'–42' N, 106°27'–34' E	25°35'–58' N, 100°05'–17' E
Surface area (km ²)	123.8	3.0	147	57.2	14.5	249.8
Mean depth (m)	2	1.1	2	9.3	13.0	10.5
Trophic status	Hypereutrophication	Eutrophication	Mesotrophication	Eutrophication	Eutrophication	Mesotrophication
References	Shen et al., 2001	Geng et al., 2006	Fan et al., 1997	Wang, 2001	Wang, 2001	Jin et al., 1995

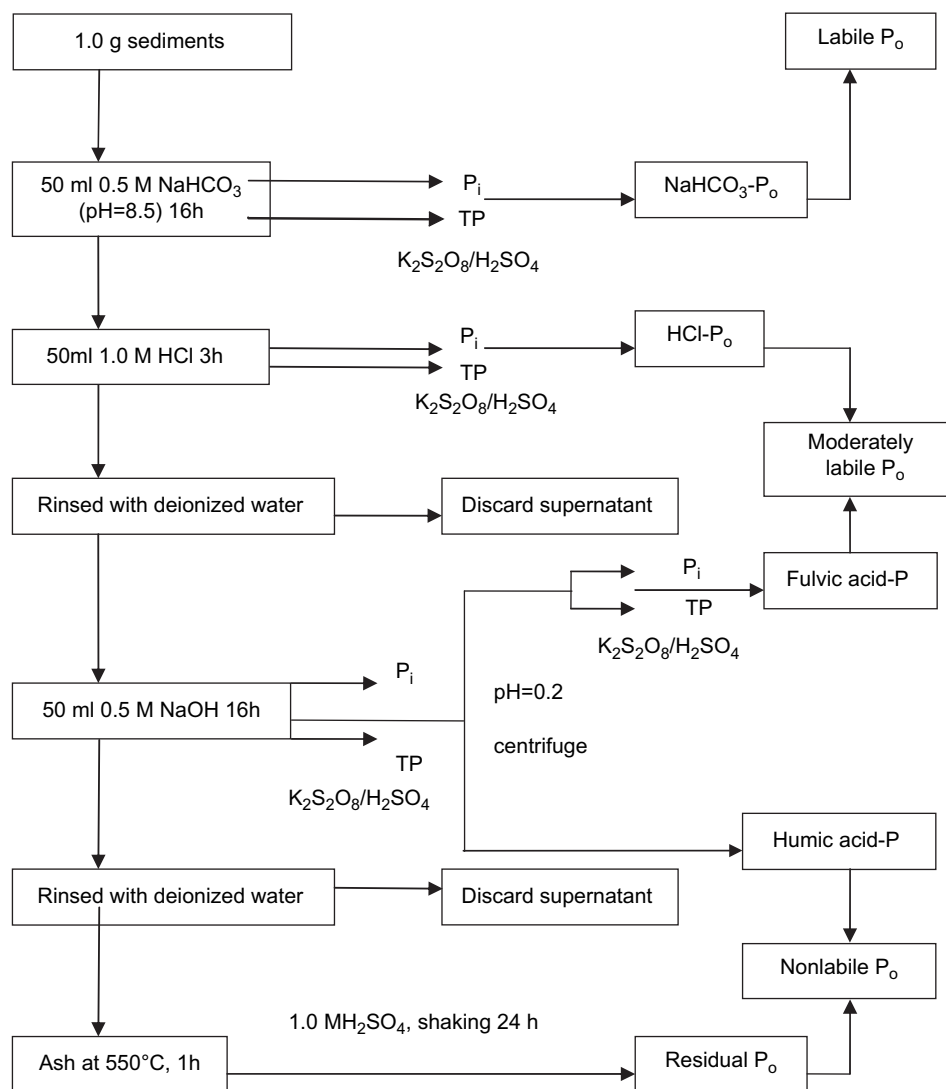


Fig. 1. The fractionation procedure of organic phosphorus (P_o) fractions in the sediments.

prior to P analysis. P_o in the sample solutions was calculated by subtracting P_i from TP. TP in all extracts was measured after an aliquot was digested with $K_2S_2O_8 + H_2SO_4$ (Rowland and Haygarth, 1997). For all samples, triplicates were analyzed and the results were expressed as their average. Experimental data were subjected to standard analysis of variance technique appropriate to a factorial randomized block design. Wherever appropriate, the treatment means were compared at 5% level of significance using least significant difference. The recovery (%) of P_o was measured as the ratio of the P_o concentration determined by extraction to that determined by ignition.

Compared to Bowman and Cole (1978), the used procedure was modified in the following four aspects: (1) horizontal shaking time was extended in order to reach high extraction efficiency. This procedure involved sequential extraction of sediments with 0.5 M $NaHCO_3$ (16 h), 1.0 M HCl (3 h) and 0.5 M NaOH (16 h). (2) P_i extracted in NaOH was treated as the individual P_i fraction, because the main alkali-labile P_o compounds were phosphate diesters, which degraded to phosphate monoesters rather than free phosphate in those schemes (Turner et al., 2003). (3) The precipitation of humic acid fraction was achieved at a lower pH (pH 0.2) than that in Bowman and Cole's method (pH 1.0–1.8). Within the scope of pH 1.0–1.8, a portion of highly resistant P_o compounds, such as inositol pentaphosphate (IPP, IP_5) and hexaphosphate (HHP, IP_6) remained in solution, being regarded as the moderately resistant fraction in error (Hong and Yamane, 1980). Further, this pH shift cannot affect P_o recovery for lake sediments (Bedrock et al., 1995). (4) The

residual P_o fraction after the extractions was analyzed in this study using the ignition method. Therefore, this procedure was feasible to fractionate P_o in sediments, due to the longer shaking time for labile P_o and P_o associated with humic substances and an additional step for residual P_o determination; thus the results were relatively accurate for P_o concentrations in lake sediments.

3. Results and discussion

3.1. Sediment characteristics

The chemical component concentrations in lake sediments are shown in Table 2. For six sediments, TP varied greatly, ranging from 440.3 to 1691.2 $mg\ kg^{-1}$ and P_i was the main P fraction. On the whole, the rank order of TP in sediments was consistent with the trophic status of those studied lakes. P_i ranged from 295.6 to 1496.3 $mg\ kg^{-1}$, accounting for 56.4–88.5% of TP. P_o ranged from 144.7 to 423.4 $mg\ kg^{-1}$. Relative contribution of P_o was 11.5%, 19.7% and 32.9% in Lake Meiliang, Lake Yuantouzhu and Lake Gonghu,

Table 2
General chemical characteristics of the studied sediments^a

Parameters	Yangtze River region			Southwestern China Plateau		
	Lake Meiliang	Lake Yuantouzhu	Lake Gonghu	Lake Hongfeng	Lake Baihua	Lake Erhai
TP (mg kg ⁻¹)	1691.2	830.0	440.3	697.4	1383.3	873.8
P _i (mg kg ⁻¹)	1496.3 (88.5)	666.1 (80.3)	295.6 (67.1)	393.5 (56.4)	959.9 (69.4)	640.0 (73.2)
P _o (mg kg ⁻¹)	194.9 (11.5)	163.9 (19.7)	144.7 (32.9)	303.9 (43.6)	423.4 (30.6)	233.8 (26.8)
OM (%)	7.62	7.17	5.29	15.25	16.86	10.03

^a Values in parentheses were the percentage to TP in sediments.

respectively. However, they were lower than those from Southwestern China Plateau, namely Lake Hongfeng (43.6%), Lake Baihua (30.6%) and Lake Erhai (26.8%). This suggests that different sediments had different concentrations and distributions of P_o fractions due to their different drainage basin and pollution sources. Industrial and domestic wastewater was the major pollution source with its contribution of more than 70% of total P input in Lake Taihu, while the relative contribution of agricultural non-point source pollution was approximately 15% (Qin et al., 2002). However, most lakes in Southwestern China Plateau were far away from local cities, where weathering and erosion were the main processes in the carbonate watershed (Wu et al., 1997).

Except for Lake Meiliang and Hongfeng, OM varied with TP in other sediments. OM in Lakes Erhai, Hongfeng and Baihua ranged from 10.03% to 16.86%. For the sediments from Lakes Meiliang, Yuantouzhu and Gonghu, OM ranged from 5.29% to 7.62%. OM was significantly correlated with P_o ($R = 0.963$, $p < 0.01$). P compounds were important component of OM in sediments. P_o was mineralized and subjected to microorganism reaction, accompanied by OM degradation during the early diagenesis. The decomposition of P_o fraction was also vital for the P alteration in lake sediments. As a result, OM and P biogeochemical cycles (especially for P_o) were closely associated in sediments (Ingall and Van Cappellen, 1990; Ruiz-Fernández et al., 2002).

3.2. P_o fractionation in sediments

Concentrations, relative distributions and the recovery of different P_o fractions are presented in Table 3. The recovery of P_o ranged from 94.3% to 101.1%, with an average of $98.5 \pm 2.2\%$. This suggests that total P_o in sediments was satisfactorily extracted with this procedure. P_o was mainly

composed of moderately labile and nonlabile P_o, ranging from 68.1 to 170.7 mg kg⁻¹ and 67.3 to 221.2 mg kg⁻¹ with the relative contribution of 31.3–47.8% and 46.5–64.9% to total P_o, respectively. Labile P_o ranged from 8.6 to 18.3 mg kg⁻¹ with a relative contribution of 3.8–6.0%. HCl-P_o fraction was predominant in the moderately labile P_o, accounting for 6.6–32.7% of total P_o. Fulvic acid-P accounted for 11.5–24.7% of total P_o. Nonlabile P_o consisted of humic acid-P and residual P_o with relative contributions of 7.7–16.8% and 29.9–57.2% to total P_o. Therefore, different P_o fractions ranged greatly in different sediments. However, the rank order is the same: residual P_o > HCl-P_o > fulvic acid-P > humic acid-P > NaHCO₃-P_o, with their average relative proportion 8.7:4.6:3.2:2.1:1.0. In summary, labile and moderately labile P_o contributed to 37.3–53.5% relative to total P_o. Approximately 50% of total P_o can be degraded for phytoplankton uptake. Similar results were also reported in Lake Erken (Rydin, 2000). The labile P_o was less than 6% in the sediments, close to 7% in soils (Bowman and Cole, 1978). For the sediments, the low labile P_o may be attributed to the relatively high solubility in aqueous environments and its strong interaction at the sediment–water interface (Oluyedun et al., 1991).

The moderately labile P_o was the main fraction in Lakes Meiliang, Yuantouzhu and Gonghu, ranging from 68.1 to 93.5 mg kg⁻¹ with a relative contribution of 47.3–47.8%; while nonlabile and labile P_o were the minor fractions, ranging from 67.3 to 91.0 mg kg⁻¹ and 8.6 to 11.0 mg kg⁻¹, accounting for 46.5–46.7% and 5.6–6.0%. However, nonlabile P_o was dominant in the sediments from Lakes Erhai, Hongfeng and Baihua, ranging from 150.1 to 221.2 mg kg⁻¹, with a relative contribution of 54.0–64.9%. Moderately labile and labile P_o were the minor fractions, ranging from 72.5 to 170.7 mg kg⁻¹ and 8.7 to 18.3 mg kg⁻¹. The P_o fractions

Table 3
Concentrations, relative distributions and the recovery of different P_o fractions in the sediments

Sediments	Labile P _o		Moderately labile P _o				Nonlabile P _o				Total extracted P _o mg kg ⁻¹	Total P _o mg kg ⁻¹	Recovery %
	NaHCO ₃ -P _o		HCl-P _o		Fulvic acid-P		Humic acid-P		Residual P _o				
	mg kg ⁻¹	%	mg kg ⁻¹	%	mg kg ⁻¹	%	mg kg ⁻¹	%	mg kg ⁻¹	%			
Lake Meiliang	11.0	5.6	63.9	32.7	29.6	15.1	21.3	10.9	69.7	35.7	195.5	194.9	100.3
Lake Yuantouzhu	9.3	6.0	42.6	27.6	30.5	19.7	26	16.8	46.2	29.9	154.6	163.9	94.3
Lake Gonghu	8.6	6.0	41.1	28.5	27	18.8	23.9	16.6	43.4	30.1	144.0	144.7	99.5
Lake Hongfeng	18.3	6.0	52.3	17.0	44	14.3	28.5	9.3	164.2	53.4	307.3	303.9	101.1
Lake Baihua	17.5	4.3	123.4	30.1	47.3	11.5	35.5	8.7	185.7	45.4	409.4	423.4	96.7
Lake Erhai	8.7	3.8	15.3	6.6	57.2	24.7	17.8	7.7	132.3	57.2	231.3	233.8	98.9
Mean	12.2	5.1	56.4	23.5	39.3	16.3	25.5	10.6	106.9	44.5	240.4	244.1	98.5±2.2

and factors affecting their accumulation and release primarily depended on OM composition (Oluyedun et al., 1991). Many lakes in Yangtze River region are shallow, in contrast to deep lakes from Southwestern China Plateau. In sea and deep lakes, autochthonous and/or allochthonous particulate OM underwent intensive degradation and was recycled into aquatic ecosystems, only a small recalcitrant fraction (including relatively resistant P_o) ultimately reaching the surface sediments (Wakeham and Lee, 1993; Ergin et al., 1996). The downward flux of suspended substances and OM in shallow lakes were higher than those in deep lakes although OM was quickly decomposed due to intensive hydrodynamic condition and complex microorganism activities at the sediment–water interface (Hu and Pu, 2000; Wang, 2001). This is consistent with the significant correlation between OM and P_o , as mentioned in earlier paragraphs.

Residual P_o ranged from 43.4 to 69.7 mg kg⁻¹ and 132.3 to 185.7 mg kg⁻¹, with relative contributions of 29.9–35.7% and 45.4–57.2% in the sediments from Yangtze River region and Southwestern China Plateau. This is similar to previous results in Lake Ontario (51%) (Oluyedun et al., 1991). The maximum contribution of residual P_o to total P_o reached 57.2% in this study. Actually, residual P_o was also an essential nutrient component in aquatic ecosystems. For example, phytate (IP₆) in the residual P_o fraction was ubiquitous in lake sediments, as a member of inositol phosphates congeners (Golterman et al., 1998). Previous studies also demonstrated that phytate deposited in coastal marine sediments can be hydrolyzed to lower inositol phosphates and free phosphate (Suzamura and Kamatani, 1995). It was worth mentioning that phytate was identified in both NaOH fractions in sediments (Golterman et al., 1998) and 1.0 M HCl fractions in soils and animal manure by enzymatic hydrolysis (He et al., 2006a,b). Therefore, it is crucial to clarify the concentration and composition of residual P_o fraction, which can provide valuable information to better understand the geochemical processes of P and lake eutrophication.

3.3. Relationships between P_o fractions and other factors

The concentrations and relative distributions of P_i fractions extracted simultaneously with P_o fractionation are shown in Table 4. HCl- P_i was the dominant fraction in the sediments from Lakes Meiliang, Yuantouzhu, Gonghu and Erhai, ranging from 175.8 to 909.5 mg kg⁻¹, with the relative contribution of

Table 4
Concentrations and relative distributions of P_i fractions in the lake sediments

Sediments	NaHCO ₃ - P_i		HCl- P_i		NaOH- P_i		P_i mg kg ⁻¹
	mg kg ⁻¹	%	mg kg ⁻¹	%	mg kg ⁻¹	%	
Lake Meiliang	474.2	31.7	909.5	60.8	112.6	7.5	1496.3
Lake Yuantouzhu	228.4	34.3	357.9	53.7	79.8	12.0	666.1
Lake Gonghu	52.3	17.7	175.8	59.5	67.5	22.8	295.6
Lake Hongfeng	72.5	18.4	33.7	8.6	287.3	73.0	393.5
Lake Baihua	174.7	18.2	374.6	39.0	410.6	42.8	959.9
Lake Erhai	115.0	18.0	375.6	58.7	149.4	23.3	640.0

53.7–60.8% of total P_i ; NaHCO₃- P_i and NaOH- P_i were the minor fractions, ranging from 52.3 to 474.2 mg kg⁻¹ and 67.5 to 149.4 mg kg⁻¹, and contributed 17.7–34.3%, 7.5–23.3% of total P_i , respectively. In Lakes Hongfeng and Baihua, NaOH- P_i was predominant, ranging from 287.3 to 410.6 mg kg⁻¹, accounting for 42.8–73.0% of total P_i .

Ivanoff et al. (1998) divided P_i into labile fraction (NaHCO₃- P_i) and nonlabile fraction (HCl- P_i and NaOH- P_i) according to their relative solubility. Obviously, the relative distribution of NaHCO₃- P_i is in agreement with the trophic conditions of the lakes studied, except for Lake Hongfeng. Moreover, high labile P (NaHCO₃- P_i , labile and moderately labile P_o) concentrations were observed in sediments from Yangtze River region, in contrast to those from Southwestern China Plateau. This difference may be related to the transformation between P_i and P_o fractions in different lacustrine environments. In fact, P fractions in surface sediments were in a dynamic equilibrium with the overlying water (Penn et al., 1995), which can transform each other under certain environmental conditions (Istvánovics, 1993; Rydin, 2000; Jin et al., 2006). Sediment bacterium were able to take up excessive P and form intracellular polyphosphate during aerobic conditions, while these P_o compounds were rapidly mineralized to P_i during anaerobic conditions, resulting in subsequent release from the sediments (Khoshmanesh et al., 2002). It was reported that microbe activities prevailed in the surface sediments from Yangtze River region (Wang et al., 2006).

The relationships between P_o fractions and other factors are shown in Table 5. There was a significant and positive correlation between nonlabile P_o and OM ($R = 0.981$, $p < 0.01$), P_o ($R = 0.956$, $p < 0.01$) and NaOH- P_i ($R = 0.954$, $p < 0.01$). Labile and moderately labile P_o were also significantly correlated with OM, P_o and NaOH- P_i , but they were not significantly correlated with TP, P_i , NaHCO₃- P_i and HCl- P_i . Similar results were also reported in paddy soils where there was a strongly positive correlation between P_o fractions (except for highly resistant P_o) and soil OM, P_o and bioavailable P (Feng et al., 2001). This study indicates that the nonlabile P_o may become a potential source of available P for aquatic phytoplankton and bacteria, although it was considered as the highly resistant fraction.

3.4. Relationship between P_o fractions and pollution status of the sediments

The six sediment samples can be divided into three categories based on TP concentrations: heavy pollution (TP > 1300 mg kg⁻¹),

Table 5
Correlation coefficients between P_o fractions and other geochemical parameters

	OM	TP	P_i	P_o	NaHCO ₃ - P_i	HCl- P_i	NaOH- P_i
Labile P_o	0.917**	0.222	0.032	0.855*	0.141	0.294	0.904*
Moderately labile P_o	0.797	0.558	0.373	0.915*	0.101	0.082	0.899*
Nonlabile P_o	0.981**	0.216	0.001	0.956**	0.284	0.288	0.954**

* $p < 0.05$, ** $p < 0.01$.

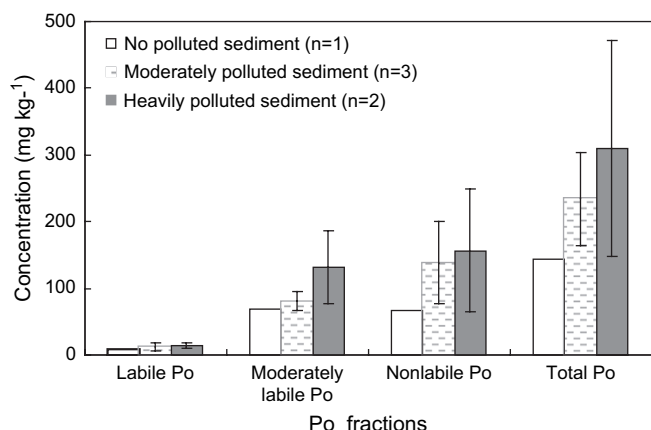


Fig. 2. Concentrations of P_o fractions in different polluted sediments. The pollution status of the sediments was based on TP concentrations: heavily pollution with TP > 1300 mg kg⁻¹, moderately pollution with 500 mg kg⁻¹ < TP < 1300 mg kg⁻¹ and no pollution with TP < 500 mg kg⁻¹.

moderate pollution (500 mg kg⁻¹ < TP < 1300 mg kg⁻¹) and no pollution (TP < 500 mg kg⁻¹). According to Chinese environmental dredging common standards, when TP > 500 mg kg⁻¹, the lake sediment is considered to be polluted, and should be dredged (Liu et al., 1999).

The rank order of total P_o and P_o fractions in those sediments was: heavily polluted sediments > moderately polluted sediments > non-polluted sediments (Fig. 2). In terms of P_o, the heavily polluted sediments were more hazardous for lake eutrophication than moderately and non-polluted ones. This suggests that the role of P_o for lake eutrophication should be paid more attention, in particular for the heavily polluted sediments. It is interesting to note that the relative distribution of labile and moderately labile P_o fractions for no polluted sediments was 3.6–11.4% higher than that of polluted sediments (Table 3), indicating that various P_o fractions can be transformed in different polluted sediments.

4. Conclusions

Based on a soil P_o fractionation scheme, residual P_o fraction analyses in sediments were emphasized, and high P_o recovery was obtained. The fractions and concentrations of P_o in the surface lake sediments from the middle and lower reaches of Yangtze River region and Southwestern China Plateau were studied. The results show that the rank order of different P_o fractions was: residual P_o > HCl-P_o > fulvic acid-P > humic acid-P > NaHCO₃-P_o, with their average relative proportion 8.7:4.6:3.2:2.1:1.0. Among them, residual P_o accounted for 29.9–57.2% of total P_o. All P_o fractions, especially nonlabile P_o, were significantly and positively related to organic matter, P_o and NaOH-P_o, and were not significantly correlated with total P, P_i, NaHCO₃-P_i and HCl-P_i. High concentrations of labile P (NaHCO₃-P_i, labile and moderately labile P_o) were observed in sediments from Yangtze River region, possibly suggesting that the transformation between P_i and P_o occurred in different lake environments. P_o fractions in the heavily polluted

sediments were higher than those in moderately and non-polluted sediments.

However, the lability and bioavailability of various P_o fractions based on chemical solubility by conventional fractionation schemes should be interpreted with caution, because there was no direct evidence to confirm this (Turner et al., 2005). With the importance of P_o in the environment being recognized, further investigation is badly needed in order to understand the nature and dynamics of P_o. Recently, enzymatic hydrolysis or solution ³¹P NMR spectroscopy coupled with sequential fractionation has been shown to be effective for characterizing P_o in soils, animal manure and lake sediments (He et al., 2006a,b; Ahlgren et al., 2005).

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