Phosphorus loss potential and phosphatase activities in paddy soils

S. Wang[1], X. Liang[2], G. Liu[1], H. Li[3], X. Liu[1], F. Fan, W. Xia[1], P. Wang[1], Y. Ye[2], L. Li[2], Z. Liu[1], J. Zhu[4]

[1]*Institute of Soil and Fertilizer and Resources and Environment, Jiangxi Academy of Agricultural Sciences/Key Laboratory of Plant Nutrition and Fertilizer, Ministry of Agriculture, P.R. China/Key Laboratory of Crop Ecophysiology and Farming System for the Middle and Lower Reaches of the Yangtze River, Ministry of Agriculture, P.R. China/National Engineering and Technology Research Center for Red Soil Improvement, Nanchang, P.R. China*
[2]*Institute of Environmental Science and Technology, College of Environmental and Resources Sciences, Zhejiang University, Hangzhou, P.R. China*
[3]*Zhejiang Academy of Agricultural Sciences, Hangzhou, P.R. China*
[4]*Renewable Energy and Environmental Engineering, Department of Bioproducts and Biosystems Engineering, Southern Research and Outreach Center, University of Minnesota, Waseca, USA*

ABSTRACT

The effects of phosphorus (P) fertilizer on P loss potential, soil Olsen-P and neutral phosphatase activities in paddy soils fertilized with superphosphate or pig manure (PM) were evaluated in this paper. Data were collected from a field experiment in the Tai Lake Basin, China. Superphosphate rates were 0, 17.5, 26.7, and 35.0 kg P/ha, and PM rates were 0, 1.4, 2.1, and 2.8 t/ha for each crop, respectively. Soil Olsen-P in the plow layer increased to a greater extent with PM than with superphosphate. Pig manure increased neutral phosphatase activities in the plow layer compared with PM-free treatment. In contrast, superphosphate inhibited neutral phosphatase activities compared with superphosphate-free treatment. Spring application of P fertilizer markedly increased the total P of surface water in November (< 0.01 vs. 0.10 mg/L) compared with P-free treatment. The total P of shallow groundwater at a 75 cm depth was ~0.01 mg/L. Phosphorus fertilizer did not influence Olsen-P or neutral phosphatase activities under the plow layer. Downward movement of P did not occur. Appropriate rate of P application of 26.2 kg P/ha for each crop in this soil reduced the risk of P loss in the paddy wetland ecosystem.

Keywords: soil Olsen-P; neutral phosphatase activity; water total phosphorus; loss potential; paddy wetland ecosystem

Phosphorus (P) fertilizers are widely applied to the paddy wetland ecosystems in subtropical China (Ma et al. 2011) to promote high crop yields. However, P fertilizer use efficiency levels

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are quite low (10–20%; Shen et al. 2004), indicating that much of the applied P may remain in the soil or may be transported to the surrounding water. Environmental concerns about the concomitant risk of P runoff and leaching are increasing (Kronvang et al. 2009).

Excessive use of P fertilizers was found to increase the risk of P runoff and leaching (Sharpley et al. 2009). Heckrath et al. (1995) reported high concentrations of total P in drainage water from plots with soil Olsen-P content greater than 60 mg/kg for silt loam and silt clay loam soil types. The condition of sandy textured soil is a factor that can favor the scenario of downward movement of P (Máthé-Gáspár and Fodor 2012).

If organic P fertilizers such as pig manure (PM) are applied according to crop nitrogen (N) requirements (Miller et al. 2011) in the Tai Lake Basin region, China, the P application is excessive. Much of the P applied is fixed by soil. While application of PM may lead to P loss risk due to the increasing Olsen-P, PM allows recycling of manure nutrients if properly managed such as reduced-drainage or zero-drainage (Li et al. 2009) in paddy wetland ecosystems using dikes, plow pans, and plants (Wang et al. 2012a).

Soil phosphatases, including neutral phosphatase, can dephosphorize organic P and thus improve soil Olsen-P (Saha et al. 2008), which may contribute to the P loss potential. Fertilizer exerts an influence on soil phosphatase activities (Albrecht et al. 2010). Subsequently, the elevated Olsen-P may suppress phosphatase activities (Kiss et al. 1975). Phosphatase activities are not a straight forward measurement of P status (Wang et al. 2011).

The aim of our study was to investigate the effects of P fertilizer on P loss potential, and to suggest an optimum P fertilizer rate to minimize P loss potential from a paddy field experiment in Tai Lake Basin region, China.

MATERIAL AND METHODS

Site description. The site was located in the Tai Lake Basin, Jiaxing research station (120°40'E, 30°50'N), Zhejiang, China. The climate is subtropical with annual mean rainfall 1200 mm and mean temperature 15.7°C.

The experiment was established in 2005 and has been continuing since then. Rice (*Oryza sativa* L.) was transplanted in June and harvested in November. Rape (*Brassica napus* L.) was transplanted in November and harvested in May of the following year. The soil was classified as Stagnic Anthrosol. The saturated hydraulic conductivity was 0.087 cm/day. The water table fluctuates from 60 cm (from March to October) to 75 cm (from November to next February) in the field. The initial soil properties of the plow layer (0–15 cm) showed the following: pH_{H_2O}, 6.8; organic C, 20.3 g/kg; total P, 1.53 g/kg; CEC, 8.10 $cmol_+$/kg; and bulk density, 1.04 g/cm^3.

Fertilizer treatments and management. The experiment included two groups of tests for superphosphate and PM for four different rates for each crop season. The N and K rates for all the treatments were complemented to 180 kg N/ha as urea and 125 kg K/ha as potassium chloride, respectively. For superphosphate, the treatments (kg P/ha) were (1) P0 – 0; (2) P1 – 17.5; (3) P2 – 26.2; and (4) P3 – 35.0. For PM on dry weight basis, the treatments (t/ha) were (1) PM0 – 0; (2) PM1 – 1.4; (3) PM2 – 2.1; and (4) PM3 – 2.8. The PM contained 12.5 g P/kg, 37.3 g N/kg, and 35.0 g K/kg. Therefore, it supplied 17.5, 26.2, and 35.0 kg P/ha in PM1, PM2, and PM3, respectively. Pig manure became thoroughly decomposed before application. Phosphorus fertilizers were applied as basal fertilizers.

Dikes and plastic sheeting were used to hydrologically isolate the plots (4 m × 5 m) to 30 cm depth. The experiment was arranged in a randomized complete block design with three replications. Non-experimental border plots surrounded the rows. Field practices, such as tillage, irrigation, and weed control, were carried out according to the local farming practices.

Sampling and analysis. Five soil samples per plot were collected from random locations for the plow layer in May 2008, 2009, and 2010, and in November 2008 and 2009 using a soil probe of 3-cm diameter. Five locations were selected randomly for soil profile sampling in November 2010. The samples from each plot were mixed to prepare a composite sample. As P transformation and runoff are related to the sampling depth, the plow layer was divided into a 0–5 cm layer for the top surface layer and a 5–15 cm layer for the subsurface layer. The soil samples were collected from the 0–5 and 5–15 cm layers in May and November 2008 and 2009, and in May 2010, and from the 0–5, 5–15, 15–30, 30–45, 45–60, and 60–75 cm layers in November 2010. Olsen-P was determined for all the soil samples by extracting samples with a 0.5 mol/L $NaHCO_3$ solution (pH = 8.5) using 1:20 soil to solution ratio. Neutral phosphatase activities were determined for samples in November 2010 using nitrophenyl phosphate disodium as the substrate. The soil samples were incubated in a citric-phosphate buffer solution (pH = 7.0) at 37°C for 3 h. The nitrophenyl phosphate was extracted by transferring the soil with the aid of 1 mL of 0.5 mol/L $CaCl_2$ and 4 mL of 0.5 mol/L NaOH. The color intensity was measured in a spectrophotometer at 578 nm (Alef and Nannipieri 1995). In this article, 'phosphatase' refers to neutral phosphomonoesterase, except where noted.

Samples of paddy surface water and groundwater in November 2010 were collected and analyzed for total P. To reduce pH to 2, 0.25 mL of 4.0 mol/L HCl was first injected into each flask. Before drainage in November 2010, the samples for each plot were individually taken with six to eight random extractions from the paddy surface water using a syringe, and then integrated to form a composite plot sample. Two to three hours after soil profile sampling in November 2010, the paddy groundwater permeated at a 75 cm depth was sampled at each profile core hole using a 75 cm long plastic pipe. The unfiltered water samples were then frozen (–6°C). Prior to analysis, the samples were thawed and digested by $K_2S_2O_8$ at 120°C for 30 min. The total P was determined with a continuous-flow automated analyzer at 700 nm (APHA 1995).

Plant samples, which were divided into grain and straw, were collected after the crop harvest. The plant samples were digested in concentrated H_2SO_4 and H_2O_2, and the P concentration in the digestion was determined using the molybdate-blue method.

Data analysis. Analysis of variance (ANOVA) was performed to analyze the difference between treatment means. Statistical differences among treatment means were determined using the Duncan's least significant difference (*LSD*) test at the 0.05 probability level.

Table 1. Soil Olsen-P (mg/kg) in 2008, 2009, and 2010

Time	Depth (cm)	P0	P1	P2	P3	PM0	PM1	PM2	PM3
May 2008	0–5	16.3^{a}	19.8^{b}	22.2^{c}	24.5^{d}	16.2^{a}	23.5^{b}	29.8^{c}	37.7^{d}
	5–15	15.4^{a}	18.7^{b}	21.6^{c}	23.4^{d}	15.3^{a}	22.9^{b}	28.7^{c}	37.0^{d}
November 2008	0–5	16.0^{a}	20.0^{b}	22.9^{c}	25.7^{d}	15.9^{a}	24.0^{b}	31.6^{c}	41.5^{d}
	5–15	15.3^{a}	18.9^{b}	21.7^{c}	24.5^{d}	15.1^{a}	23.3^{b}	29.4^{c}	37.8^{d}
May 2009	0–5	15.5^{a}	19.7^{b}	23.2^{c}	26.3^{d}	15.4^{a}	24.3^{b}	33.5^{c}	44.7^{d}
	5–15	15.1^{a}	18.6^{b}	21.9^{c}	25.2^{d}	15.0^{a}	23.5^{b}	30.7^{c}	38.6^{d}
November 2009	0–5	15.2^{a}	19.9^{b}	24.1^{c}	27.2^{d}	15.1^{a}	24.8^{b}	35.9^{c}	48.6^{d}
	5–15	15.0^{a}	18.8^{b}	22.5^{c}	26.1^{d}	14.8^{a}	24.1^{b}	31.6^{c}	39.5^{d}
May 2010	0–5	14.7^{a}	19.6^{b}	24.4^{c}	27.7^{d}	14.6^{a}	25.1^{b}	38.0^{c}	51.5^{d}
	5–15	14.5^{a}	18.5^{b}	23.0^{c}	26.6^{d}	14.5^{a}	24.4^{b}	32.5^{c}	40.6^{d}
November 2010	0–5	14.4^{a}	19.8^{b}	25.1^{c}	28.8^{d}	14.3^{a}	25.6^{b}	40.2^{c}	55.4^{d}
	5–15	14.2^{a}	18.8^{b}	23.6^{c}	27.5^{d}	14.2^{a}	24.9^{b}	33.4^{c}	41.7^{d}
	15–30	16.2^{a}	16.0^{a}	16.3^{a}	16.8^{a}	16.2^{a}	16.0^{a}	16.6^{a}	16.2^{a}
	30–45	12.2^{a}	12.3^{a}	12.6^{a}	12.7^{a}	12.6^{a}	12.3^{a}	12.4^{a}	12.3^{a}
	45–60	8.7^{a}	8.7^{a}	8.5^{a}	8.7^{a}	8.9^{a}	8.7^{a}	8.7^{a}	8.9^{a}
	60–75	5.4^{a}	5.5^{a}	5.4^{a}	5.4^{a}	5.4^{a}	5.4^{a}	5.4^{a}	5.5^{a}

Values with the same letter do not differ ($P > 0.05$, Duncan's *LSD* test) among the same superphosphate or pig manure (PM) treatments. For superphosphate, the treatments (kg P/ha) were (1) P0 – 0; (2) P1 – 17.5; (3) P2 – 26.2; and (4) P3 – 35.0. For pig manure, the treatments (t/ha) were (1) PM0 – 0; (2) PM1 – 1.4; (3) PM2 – 2.1; and (4) PM3 – 2.8. The same as fellow

Table 2. Average annual crop yields and P uptake under different P fertilizers rates

Treatment	P0	P1	P2	P3	PM0	PM1	PM2	PM3
Rice grain yield (kg/ha)	7417^{a}	7533^{a}	7617^{a}	7620^{a}	7411^{a}	8417^{b}	8917^{c}	8922^{c}
Rice grain P content (g/kg)	2.74^{a}	2.86^{a}	2.89^{a}	2.93^{a}	2.74^{a}	2.78^{a}	2.80^{a}	2.81^{a}
Rice straw yield (kg/ha)	3845^{a}	4851^{a}	5148^{a}	5769^{a}	3840^{a}	5976^{b}	6331^{b}	6337^{b}
Rice straw P content (g/kg)	0.96^{a}	0.98^{a}	1.00^{a}	1.00^{a}	0.95^{a}	1.12^{b}	1.24^{c}	1.25^{c}
Rice uptake (kg P/ha)	24.0^{a}	26.3^{a}	27.1^{a}	28.1^{a}	23.9^{a}	30.1^{b}	32.9^{c}	33.1^{c}
Rape yield (kg/ha)	913^{a}	1048^{b}	1120^{c}	1170^{c}	911^{a}	937^{a}	1405^{b}	1478^{b}
Rape grain P content (g/kg)	3.04^{a}	3.28^{b}	3.33^{b}	3.38^{b}	3.04^{a}	3.53^{b}	3.96^{c}	3.96^{c}
Rape straw yield (kg/ha)	5462^{a}	6269^{b}	6698^{c}	6997^{c}	5459^{a}	5601^{a}	8401^{a}	8462^{a}
Rape straw P content (g/kg)	0.86^{a}	0.96^{b}	0.96^{b}	0.97^{b}	0.85^{a}	0.97^{b}	1.07^{c}	1.07^{c}
Rape uptake (kg P/ha)	7.5^{a}	9.4^{b}	10.1^{b}	10.8^{b}	7.4^{a}	8.7^{b}	14.6^{c}	15.0^{c}

For superphosphate, the treatments (kg P/ha) were (1) P0 – 0; (2) P1 – 17.5; (3) P2 – 26.2; and (4) P3 – 35.0. For pig manure, the treatments (t/ha) were (1) PM0 – 0; (2) PM1 – 1.4; (3) PM2 – 2.1; and (4) PM3 – 2.8

RESULTS AND DISCUSSION

Soil Olsen-P. The P fertilizers increased paddy soil Olsen-P in the plow layer (0–15 cm) compared with P-free treatment (Table 1). There was a significant difference in Olsen-P at the same layer between treatments.

The soil P balance was different in different treatments. The soil P was exhausted in the treatments without P fertilizer (Table 2). The soil P balance was slightly negative in the treatments P1 and PM1. The amount of P applied in the treatments P2, P3, PM2, and PM3 was more than P uptake by crops. The P application rate of 26.2 kg P/ha for each crop was optimum for soil P balance and crop uptake. There was a significant difference in Olsen-P between treatments. Much of the P applied to paddy wetland ecosystems remains in the soil, except for 10–20% assimilated by crop (Shen et al. 2004). Part of the residual soil total P contributed to Olsen-P.

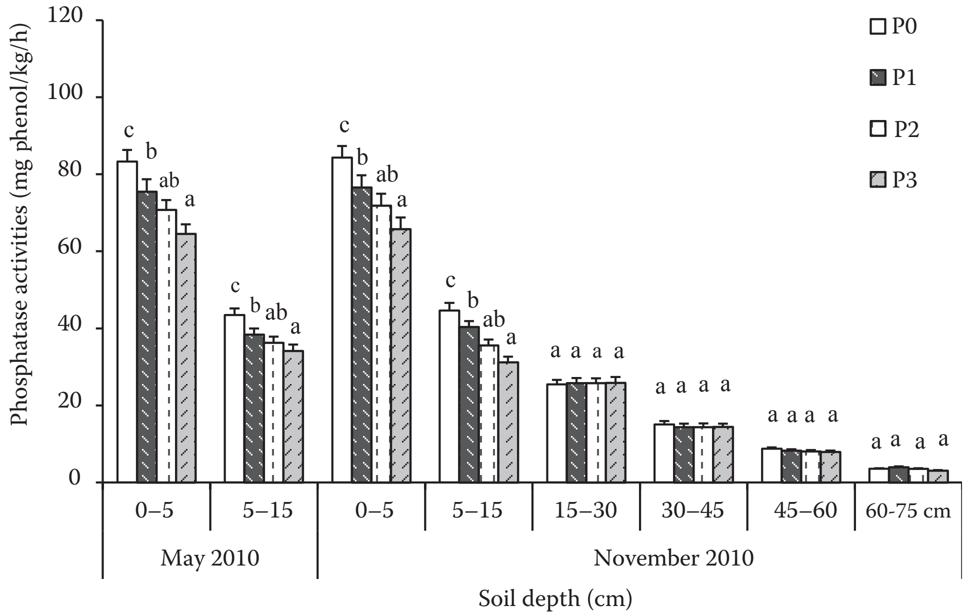

Figure 1. Phosphatase activities in the soil profile (0–75 cm) under superphosphate treatment. The treatments (kg P/ha) were (1) P0 – 0; (2) P1 – 17.5; (3) P2 – 26.2; and (4) P3 – 35.0

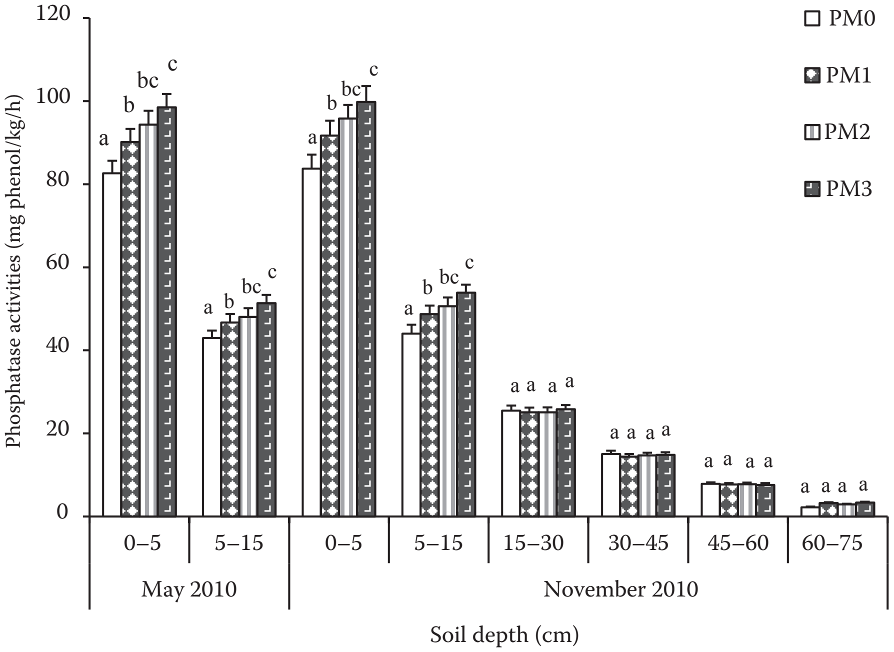

Figure 2. Phosphatase activities in the soil profile (0–75 cm) under pig manure (PM) treatment. For pig manure, the treatments (t/ha) were (1) PM0 – 0; (2) PM1 – 1.4; (3) PM2 – 2.1; and (4) PM3 – 2.8

The Olsen-P increased to a greater extent with PM than with superphosphate, because of the positive effect of PM on Olsen-P. Organic manure application reduced the ability of the soil to fix P (Guo and Wang 2013). Pig manure applied to soil can increase the turnover of P through the stimulation of microbial biomass. Pig manure also contains high-molecular-weight compounds such as humic and fulvic acids that inhibit P sorption (Xavier et al. 2009).

The Olsen-P under the plow layer was not influenced by P fertilizers. Phosphorus is effectively retained in the plow layer by sorption. In November 2010, the Olsen-P under the plow layer was low and changed gently, which was inconsistent with the changes in the Olsen-P in the plow layer and the P fertilizer rates (Table 1). Olsen-P was less than 10 mg/kg in the > 30 cm layers. Olsen-P did not move down. This was also probably because of the plow pans developed.

Soil phosphatase activities. Phosphorus fertilizer affected soil phosphatase activities in the plow layer. In May and November 2010, superphosphate significantly decreased soil phosphatase activities in the plow layer compared with P0 (Figure 1).

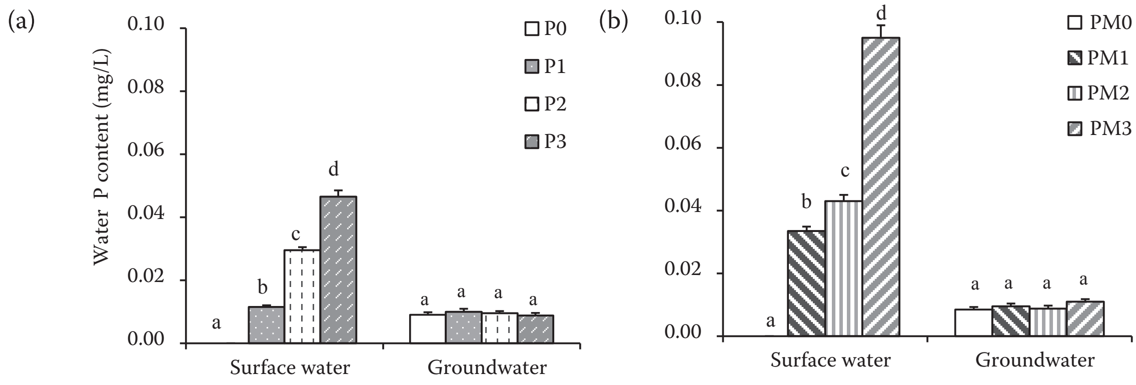

Figure 3. Total P of paddy surface water and groundwater after rice (in November) under superphosphate treatment (a) or pig manure (PM) treatment (b) For superphosphate, the treatments (kg P/ha) were (1) P0 – 0; (2) P1 – 17.5; (3) P2 – 26.2; and (4) P3 – 35.0. For PM, the treatments (t/ha) were (1) PM0 – 0; (2) PM1 – 1.4; (3) PM2 – 2.1; and (4) PM3 – 2.8

Phosphatase activities may be suppressed by PO_4^{3-}. Where available P is low, the microbial biomass is an active producer of the phosphatase enzymes. Soil phosphatase activities were higher in the 0–5 cm layer than in the 5–15 cm layer, being similar to the trend of results in constructed wetlands reported by Kong et al. (2009).

In the plow layer, PM significantly increased phosphatase activities compared with PM0 (Figure 2). Soil phosphatase activities in the plow layer decreased in the following order: PM treatment > superphosphate treatment (Figures 1, 2). The organic fertilizer stimulated microorganism activities (Nayak et al. 2007) and increased the capacity to protect and maintain soil enzymes (Saha et al. 2008). The effects of PM stimulation may be larger than that of Olsen-P inhibition on soil phosphatase activities.

The rate and source of P fertilizer did not affect phosphatase activities under the plow layer, implying that the phosphatase enzyme did not move downward. Phosphatase activities decreased with increasing soil depth (Figures 1, 2), dramatically in the plow layer and then gently under the plow layer due to the decreasing soil organic matter (Wang et al. 2012b) and oxygen with depth.

Water total P. Phosphorus fertilizer increased the total P of paddy surface water, which may increase the loss risk of P runoff. Before the drainage in November 2010, the total P of paddy surface water in the superphosphate treatments varied from < 0.01 to 0.05 mg P/L (Figure 3a). In the PM treatments, the total P of surface water varied from < 0.01 to 0.10 mg/L (Figure 3b). The P fertilizer significantly increased the total P of paddy surface water, and no P was found in paddy surface water when no P fertilizer was applied. The total P of paddy surface water increased more with PM than with superphosphate. This was consistent with the results of Olsen-P in the plow layer. At the P application rate of 26.2 kg P/ha, the total P of paddy surface water was low.

The P fertilizer did not increase the total P of paddy groundwater at a 75 cm depth, implying that there was no P leaching, being consistent with the soil Olsen-P results. In November 2010, the total P of paddy groundwater at a 75 cm depth was about 0.01 mg/L (Figure 3). There were no significant differences in the total P of paddy groundwater among treatments, confirming no P downward movement also due to the plow pans.

Be concerning of soil Olsen-P, phosphatase activities, the total P of paddy surface water, and crop grain yield, the P application of 26.2 kg P/ha is suggested for each crop for the rice-rape rotation in this soil. Rice paddies exhibit P sink properties especially for PM because of the soil, plants and microorganisms as well as the dikes and mature plow pans.

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Corresponding author:
Associate prof. Xin-Qiang Liang, Ph.D., Institute of Environmental Science and Technology,
College of Environmental and Resources Sciences, Zhejiang University, Yuhangtang Road 866#,
310 058 Hangzhou, P.R. China
e-mail:liang410@zju.edu.cn