



Downward movement of phosphorus in paddy soil installed in large-scale monolith lysimeters

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Abstract

Soils around Taihu Lake area, located in Yangtze River Delta (Jiangsu Province, China), have been continuously applied with phosphorus (P) fertilizer for at least 40 years and growing rice (*Oryza sativa* L.) under water submergence in summer, in rotation with wheat (*Triticum aestivum* L.) in winter. Because of the accelerated eutrophication of Taihu Lake, there is great concern as to whether P from rice cropping systems is one of the non-point pollutants responsible for the eutrophication. The experiment was carried out with five treatments and four random arranged replications under rice and wheat rotation on Gleyi-stagnic Anthrosols installed in large-scale monolith lysimeter from 2002 to 2003, and soil water penetration rate was adjusted to 3–5 mm d⁻¹, a typical rate in corresponding field soil. The leachate samples were collected at certain intervals for analysis of dissolved P. Soil samples were collected for P fractionation after rice was harvested in 2003. Data indicated that there was no correlation between concentration of dissolved P in leachates (at the 70 cm depth) and the P fertilization rates under present experiment condition, suggesting that the soil still had strong affinity to P despite long history of continuous P fertilization. However, considerable number of leachate samples, collected particularly in early submergence, contained P at concentrations that could cause eutrophication. Calculated leaching losses of P were 0.11 and 0.071 kg P ha⁻¹ in 2002 and 2003, respectively. More P fertilizer application resulted in more accumulation at top soil layer and deeper downward P movement in soil profile. Downward movement of Olsen-P, Al-P, and Ca₂-P was observed in deeper soil layers than that of Fe-P and Ca₈-P, and accumulation of Fe-P and Al-P were quantitatively more significantly than Ca₂-P and Ca₈-P.

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1. Introduction

Movement of phosphorus (P) through soil into groundwater has generally been considered to be insignificant because P is fixed firmly by soil colloids or organic matter. However, some experiments on

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upland soils showed that small but significant quantities of P can move through soil, entering groundwater which eventually emerges as surface water, and contributing to eutrophication. P leaching losses occur especially in those areas where soil P concentrations are already very high, soil P sorption capacities are low (sandy soils and high organic matter soils), and subsurface transport is enhanced by artificial drainage systems resulted in extensive preferential flow occurs through soil crack and biopores (Sharpley and Withers, 1994; Sims et al., 1998; Eghball et al., 1996; Elrashidi et al., 2001). Enriched P content and good drainage of soils can facilitate P losses by leaching. Conditions favoring downward movement of P are likely met in the submerged paddy soils around Taihu Lake, China. However, literature available on downward movement of P in soil profiles has been focused on upland or freely draining soils (Schwab and Kulyingyong, 1989; Heckrath et al., 1995; Turner and Haygarth, 2001) and relatively little is known about submerged paddy soils.

Cropping system in this area is typically rice (*Oryza sativa* L.) and winter wheat (*Triticum aestivum* L.) in rotations. Phosphorus (P) fertilizer (together with nitrogen fertilizer) has been continuously applied for at least four decades at the rate about $60 \text{ kg P ha}^{-1} \text{ yr}^{-1}$, most of which are applied in wheat season. Soils are typically water-submerged during most of rice growing season (from early June to early October), with 2–3 periods of alternative wetting and drying, each period lasting for 3–5 days. This practice generally provides reduced conditions that favor the release of P from particles and oxides. Typical Eh of field soils during rice season ranges from -100 to $+250$ mv depending on soils and soil depth. Water submergence also favors downward movement of leaching solution, which may contain dissolved P (DP). Leaching rate of field soils in the area is $3\text{--}5 \text{ mm d}^{-1}$, which is considered as optimal rate for better rice growth (Xu et al., 1998). Soils with leaching rate higher than this are considered water-wasting soils and lower than this often create Eh too low for rice growth. Lateral leaching is insignificant as Taihu area is topographically a basin plain. Because of above-mentioned agronomic and edaphic background, there is great concern as to whether P from rice cropping systems is one of the non-point pollutants responsible for the accelerated eutrophication of the

lake. Previous research stressed the P losses through surface runoff (Boo, 1994; Zhang et al., 2003a,b) and relatively less is known about P losses through leaching. Information on P losses from paddy soils is important not only for Taihu Lake area but also for the other rice growing areas.

Enriched soil P from fertilizers is subjected to fractionation into different P pools, which can be characterized according to their extractability by different chemical reagents (Pardo et al., 2004; Tiyapongattana et al., 2004). Chemical extractability of different P fractions is often related to their mobility and availability. Villapando and Graetz (2001), for example, demonstrated that the labile P pool (NH_4Cl -extractable) was the main source of P that moved into the Bh horizon from the overlying A and E horizons, indicating the likelihood of P being transported to nearby ditches by drainage water. Newman and Pietro (2001) also reported that P fluxes from the soil to the overlying water are a function of the mobility of different P fractions. Fractionation of soil P can therefore provide useful information for assessing the risk of soil P as the potential sources of eutrophication in aquatic systems. Unfortunately, literatures so far provide little information on P fractionation in the soils of the region. This information is particularly needed for the soils with long history of continued P fertilization.

Object of present work was to examine downward movement of soil P under different fertilization rates.

2. Materials and methods

2.1. Study site and the soil

The experiments were carried out at Changshu Agroecological Experiment Station affiliated to Institute of Soil Science, Chinese Academy of Sciences, Changshu, Jiangsu Province ($31^{\circ}32'45''\text{N}$ and $120^{\circ}41'57''\text{E}$). It is located in Taihu region and belongs to northern subtropical humid climatic zone, with mean annual temperature, 15.5°C ; sunshine, 2202.9 h ; annual solar radiation, 118 kcal/cm^2 ; annual rainfall, 1038.4 mm (60–70% of which occurs from June to October); annual non-frost period, 224 days. The experimental soil developed from lacustrine deposit is Gleyi-stagnic Anthrosols according to

Table 1
Selected properties of the soil used

Soil depth (cm)	Texture (American system)	pH	Organic matter (g kg ⁻¹)	Total N (g N kg ⁻¹)	Total P (g P kg ⁻¹)	Total K (g K kg ⁻¹)	Olsen-P (mg P kg ⁻¹)	Exchangeable K (mg K kg ⁻¹)
0–16	Silty sandy clay loam	7.18	37.9	2.02	0.71	17.33	6.7	103
16–23		7.78	32.71	1.74	0.68	17.71	3.98	97
23–41		7.73	18.52	0.38	0.56	18.07	2.79	119
41–70	Silty sandy loam	7.44	4.14	0.42	0.60	21.05	2.96	92
70–100		7.63	19.73	0.91	0.36	23.77	2.69	170

FAO soil taxonomy system. Rice and winter wheat rotation is typically practiced. Soil water table is around 70 cm in wheat season (from October to early June) and 45 cm in rice season. After wheat harvest, soil columns were prepared for monolith lysimeter studies. Selected properties of the soil are listed in Table 1.

2.2. Experimental design

Monolith lysimeters were taken from the site representative of typical agronomical practices of the region, such as fertilizer species and application rates. All monolith lysimeters were taken from one site so as to minimize the heterogeneity of the lysimeters. Fig. 1 showed the design of the lysimeters. Each lysimeter was made of PVC tube with 80 cm height, 7 mm thickness, and 40 cm outer diameter. Soil column was obtained by removing the surrounding soil by careful digging and leaving a cylindrical intact column

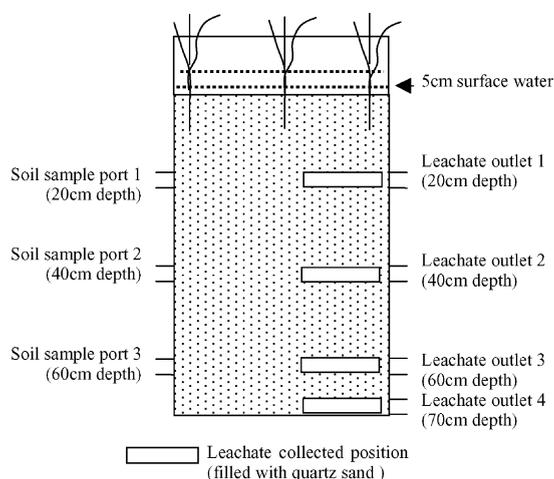


Fig. 1. Design of the lysimeters.

standing. The standing column was carefully chiseled to 70 cm in height and 38.6 cm in diameter. Inner surface of PVC tube was coated with paraffin and the soil column was inserted into the tube. The bottom was then sealed with a PVC plate. Additional paraffin was added along the soil–tube interface so as to prevent preferential leaching. There were several leachate outlets and soil sampling ports at certain height, which facilitated water and soil sampling. Small PVC tubes with an open strip facing up were filled with quartz sand and inserted into the column to collect leachate. Each monolithic soil contained 1170 cm² effective planting area.

The soil lysimeters were placed on a shelf, for convenience of collecting leachates, in a shelter that allowed rains and light to be managed. The soil columns were then water-submerged for 2 days and rice genotypes of Suxianggeng and Wuyugeng were respectively transplanted in 2002 and 2003, and wheat genotype Yangmai-10 was planted after rice harvest. Wheat seeds were seeded onto surface soil by hand, with small amount of soil to cover the seeds, but without mixing the top soil layer. Rice seedlings were transplanted after the soil was submerged, without mixing the top soil either. The experiment included five treatments under rice–wheat rotation system with four randomly arranged replicates (Table 2). Urea (N content 46.2%) was in basal and split application at two season, superphosphate (P content 6.1%) was applied basally at rice season, and potassium chloride (K content 49.8%) were applied basally at two season.

Rice was irrigated with tap water containing no detectable P. Five centimeter of overlying water layer was maintained except a few days of alternative drying and rewetting at the end of tillering stage (required practice for better growth). Overall vertical leaching rate (side leaching outlets were blocked) was controlled at 3–5 mm d⁻¹, a typical leaching rate of

Table 2
Fertilizer rates of experiment

Treatments	Rice			Wheat		
	N (kg N ha ⁻¹)	P (kg P ha ⁻¹)	K (kg K ha ⁻¹)	N (kg N ha ⁻¹)	P (kg P ha ⁻¹)	K (kg K ha ⁻¹)
CK	0	0	0	0	0	0
N ₁ P ₁ K	180 (270) ^a	60	120	225	0	90
N ₂ P ₁ K	315	60	120	270	0	90
N ₂ P ₂ K	315	180	120	270	0	90
N ₂ P ₃ K	315	300	120	270	0	90

^a 180 and 270 kg N ha⁻¹ was N fertilizer rates, respectively, in 2002 and 2003.

the soils in field in this region (Xu et al., 1998), equivalent to 350–580 mL column⁻¹. The experiments were continued for 2 years (2002 and 2003).

2.3. Analytical methods

Leachates collected at certain intervals after P fertilizer application were filtrated (to separate particulate P), digested with potassium peroxy-sulphate and determined colorimetrically by ascorbic acid method described by Kuo (1996).

After three crops (rice–wheat–rice), the column soils were sampled in 2003 (one sample in every 2 cm from 0 to 10 cm, and one sample from each of 10–15, 15–20, 20, 40, and 60 cm layers) with steel cylinder of 15 mm outer diameter, air-dried and sieved to pass 2 mm sieve for determination of Olsen-P, or to pass 0.149 mm sieve for determination of total P (TP), organic P (O-P),

inorganic P (I-P), and sequential I-P extraction. TP, I-P, O-P were extracted with H₂SO₄–NaOH method (Bowman, 1989). Olsen-P was extracted with sodium bicarbonate (Olsen et al., 1954). I-P fractions were determined using the sequential I-P extraction procedure adapted to neutral or calcareous soils (Gu and Jiang, 1990). Ca₂-P was extracted with 0.25 mol L⁻¹ NaHCO₃ (pH 7.5), Ca₈-P extracted with 1 mol L⁻¹ NH₄Ac (pH 4.2), Al-P extracted with 0.5 mol L⁻¹ NH₄F (pH 8.2), Fe-P extracted with 0.1 mol L⁻¹ NaOH–0.1 mol L⁻¹ Na₂CO₃, Occluded P (Oc-P) extracted with 0.3 mol L⁻¹ sodium citrate + 1 g Na₂S₂O₄ + 0.5 mol L⁻¹ NaOH, and phosphorite or Ca₁₀-P extracted with 0.5 mol L⁻¹ H₂SO₄.

Biomass of rice and wheat plants harvested at mature stage was dried at 80 °C and digested with concentrated H₂SO₄–H₂O₂ for colorimetric measurement of P contents.

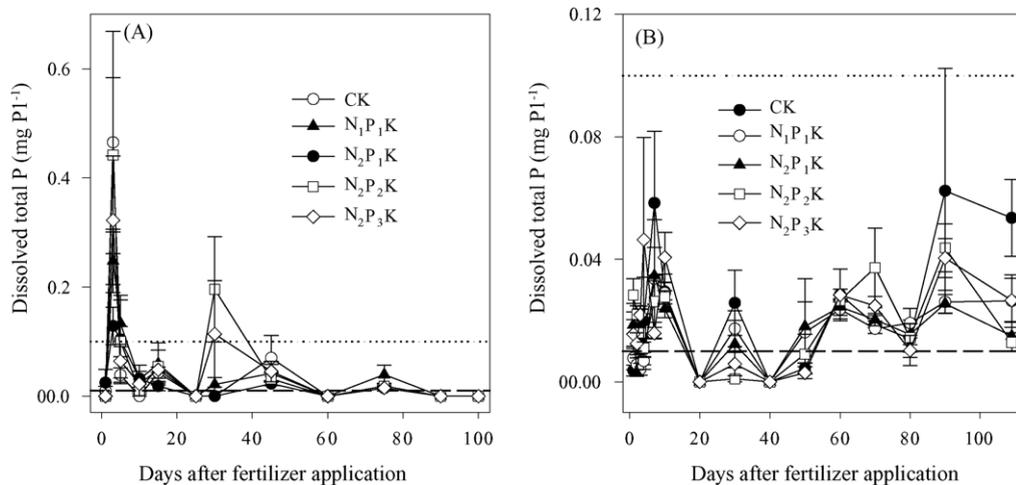


Fig. 2. Concentration of dissolved P in leaching water collected at 70 cm soil depth in 2002 (A) and 2003 (B). Dot line and dash line indicates concentration of 0.1 and 0.01 mg P L⁻¹, respectively. Vertical bars stand for standard errors over four separate samples.

Table 3
Percentage of drainage samples that exceeded different limits of P concentration in waters

Year of sampling	Days after fertilization	$\geq 0.02^a$ (mg P L ⁻¹ , %)	$\geq 0.05^b$ (mg P L ⁻¹ , %)	$\geq 0.10^c$ (mg P L ⁻¹ , %)	$\geq 0.20^d$ (mg P L ⁻¹ , %)
2002	0–10	53.7	45.0	35.0	17.5
	11–45	61.6	23.3	11.6	6.7
	46–100	8.8	1.2	0	0
2003	0–10	40.8	5.8	3.3	0.3
	11–50	11.2	2.5	0	0
	51–109	60.0	5.8	2.5	2.5

^a 0.02 mg P L⁻¹ is the limit of TP in stream water of Grade 1 according to Environmental Quality Standard for Surface Water, China (GB3838-2002) and also considered to be the level of surface water above which it may accelerate the eutrophication of surface water (OECD, 1982; Heckrath et al., 1995; Correll, 1998).

^b 0.05 mg P L⁻¹ is the limit of TP of Grade 3 of lakes/reservoirs according to GB3838-2002.

^c 0.10 mg P L⁻¹ is the limit of TP of Grade 2 according to GB3838-2002 and also the maximum concentration of dissolved P tolerated in ground water at mean highest water level set by Dutch regulators (Daniel et al., 1998).

^d 0.20 mg P L⁻¹ is the limit of TP of Grade 3 of streams according to GB3838-2002.

Data were presented as the mean of measurements on four separate samples and statistical analysis was performed with SPSS software package.

3. Results and discussion

3.1. Dissolved P in leachate

DP concentrations in leachates collected at 70 cm depth varied with sampling time (Fig. 2). There was no correlation between P fertilizer rates and P concentration in leachates, although very high rates of P fertilizer treatments were included. This implied that the soil still had strong affinity to P despite long history of continuous P fertilization. Nevertheless many leachate samples contained DP in concentration higher than 0.02 mg P L⁻¹, a value generally con-

sidered to be the level of surface water above which it may accelerate the eutrophication of surface water (OECD, 1982; Heckrath et al., 1995; Correll, 1998). Percentage of leachate samples that exceeded different limits of P concentration in waters out of total samples was summarized in Table 3. Higher percent of drainage water samples collected in 1–10 days after fertilization contained DP in excess to different standards than that of samples collected in the later

Table 4
Total leaching losses of P as measured in 2002–2003 during rice growth seasons

Treatments	2002		2003	
	mg P column ⁻¹	kg P ha ⁻¹	mg P column ⁻¹	kg P ha ⁻¹
CK	1.16	0.10	0.83	0.071
N ₁ P ₁ K	1.18	0.10	0.88	0.075
N ₂ P ₁ K	1.28	0.11	0.79	0.068
N ₂ P ₂ K	1.31	0.11	0.84	0.072
N ₂ P ₂ K	1.21	0.10	0.81	0.069
Average	1.23	0.11	0.83	0.071

Table 5
Effect of fertilizer rates on TP, I-P and O-P distribution with depth

Treatments	0–2 cm	2–4 cm	4–6 cm	6–8 cm
TP (mg P kg ⁻¹)				
N ₂ P ₃ K	1726 a	1195 a	1032 a	850 a
N ₂ P ₂ K	1477 b	800 b	729 b	748 ab
N ₂ P ₁ K	789 c	747 b	689 b	702 ab
N ₁ P ₁ K	866 c	738 b	702 b	676 ab
CK	664 d	667 b	670 b	652 b
I-P (mg P kg ⁻¹)				
N ₂ P ₃ K	1204 a	866 a	757 a	693 a
N ₂ P ₂ K	967 b	664 b	591 b	569 b
N ₂ P ₁ K	636 c	611 b	560 b	542 bc
N ₁ P ₁ K	699 c	605 b	557 b	539 bc
CK	521 c	578 b	505 b	505 c
O-P (mg P kg ⁻¹)				
N ₂ P ₃ K	522 a	329 a	195 a	
N ₂ P ₂ K	510 a	136 b	138 a	
N ₂ P ₁ K	152 b	136 b	129 a	
N ₁ P ₁ K	168 b	132 b	145 a	
CK	143 b	89 b	165 a	

Means followed by the same letter are not significantly different at $p < 0.05$.

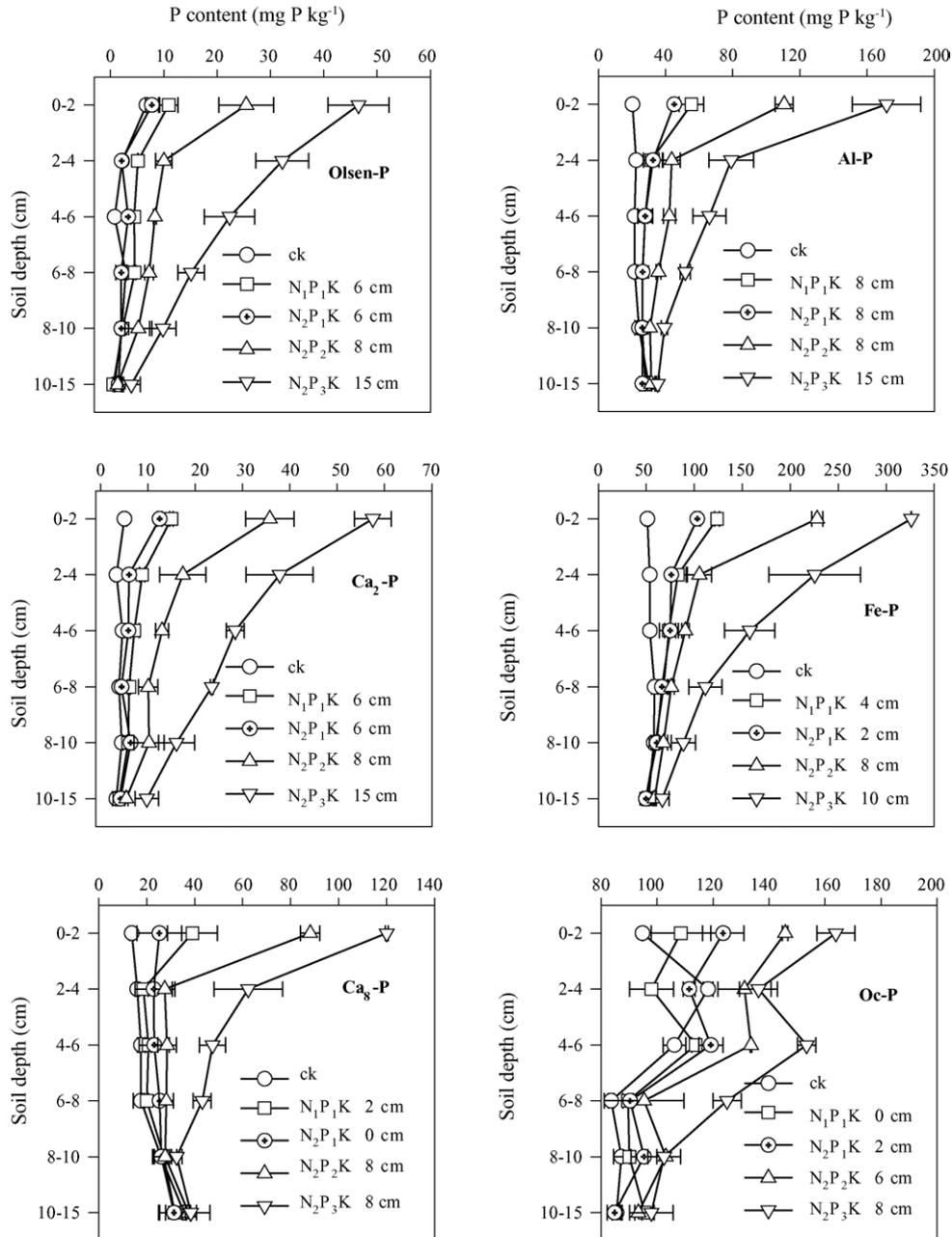


Fig. 3. Vertical profile soil P in different fractions under different fertilization rates. Horizontal bars stand for standard errors. Centimeters followed after figure legends represent the lowest soil depth at which the amount of the particular fraction of P was significantly different to that of check treatment.

stages. Data obtained in 2002, for example, showed that 53.7% of samples collected in the first 10 days contained DP higher than 0.02 mg P L⁻¹. However, the figure was only 8.8% when the leaching water

samples were collected in the period of 46–100 days after fertilization. Data obtained in 2003 showed similar trend. These data indicated that P leaching can occur, particularly in early period of submergence, at

Table 6

Net increase of I-P fractions contents at top 2 cm soil and the P movement depths at the end of 2003 rice growth

	Ca ₂ -P		Ca ₈ -P		Al-P		Fe-P		Oc-P	
	mg P kg ⁻¹	cm								
N ₂ P ₃ K	52.6	15	106.2	8	151.3	15	274.9	10	69.1	8
N ₂ P ₂ K	30.8	8	74.3	8	90.4	8	176.9	8	51.0	6
N ₂ P ₁ K	7.5	4	11.5	0	24.9	8	52.0	2	28.8	2
N ₁ P ₁ K	10.0	4	25.3	2	35.1	8	72.5	4	13.7	0

concentrations that could cause eutrophication, even for the soil with heavier texture.

During rice growth, measured seepage varied from 387 to 511 mL d⁻¹ column⁻¹, the mean seepage over all columns was 464 mL d⁻¹. The corresponding P leached per column varied from 1.16 to 1.31 mg P, and from 0.81 to 0.88 mg P, respectively, in 2002 and 2003. The mean leached P were 1.23 and 0.83 mg P column⁻¹, equivalent to 0.11 and 0.071 kg P ha⁻¹ (Table 4). These values of total P losses were less than 0.44 kg P ha⁻¹, the environmentally acceptable P losses (Van der Molen et al., 1998; Del Campillo et al., 1999), and far less than 0.965 kg P ha⁻¹, a leaching value reported on the basis of rice field investigation in Shanghai suburbs (Zhang et al., 1997).

3.2. Soil phosphorus

Compared with check (CK), all P application rate treatments resulted in significant increase of all P fractions in 0–2 cm top soils. Treatments of N₁P₁K, N₂P₁K, and N₂P₂K significantly increased TP in 0–4 cm layer while N₂P₃K significantly increased TP in 0–8 cm layer (Table 5).

Total I-P contents of N₁P₁K and N₂P₁K increased significantly in 0–2 cm top soil compared with CK, While I-P contents of N₂P₃K increased significantly to a depth of 8 cm, which was the most significant increase among all treatments. The difference of I-P

contents was significant between N₂P₂K and CK at the depth of 6–8 cm, no significant difference was found between N₁P₁K and N₂P₁K in this depth (Table 5).

Because no manure but superphosphate were applied only, O-P contents changed less than I-P. O-P contents increased significantly at the depth of 0–4 and 0–2 cm for N₂P₃K and N₂P₂K, respectively (Table 5). No significant changes for N₁P₁K and N₂P₁K were found, for the P₁ rates, 60 kg P ha⁻¹ yr⁻¹ just met crop uptake and no residual I-P transforming to O-P, or the transformation were too little to be detected.

Data of I-P fractions variations were shown in Fig. 3 and Table 6. Fe-P, Al-P, Ca₂-P, Ca₈-P and Olsen-P showed similar patterns of accumulation in top soils and of downward movement. All of these P fractions at top soils increased as the increase of P fertilization rates and downward movement of all of P fractions were more marked in the treatments with higher fertilization rates than in those with lower P rates. Significant increase of Al-P and Ca₂-P was observed in deeper soil layers than that of Fe-P and Ca₈-P, implying that the former two fractions of P were more mobile in the soil column than the later two. Accumulation of Fe-P and Al-P were quantitatively more significant than Ca₂-P and Ca₈-P, imply that part of fertilizer P was subject to fraction into Fe-P and Al-P in the soil. Occluded-P (Oc-P) contents of N₂P₂K and N₂P₃K increased significantly to the depth of 6 and 8 cm, respectively, as compared with the check.

Table 7

Apparent use efficiencies of P fertilizer in different treatments

	CK	N ₁ P ₁ K	N ₂ P ₁ K	N ₂ P ₂ K	N ₂ P ₃ K
P input in 2002 (g column ⁻¹)	0	0.70	0.70	2.10	3.51
P uptake by rice (g column ⁻¹)	0.22	0.76	0.93	0.99	1.06
Apparent use efficiency by rice (%)		77	100	36	24
P uptake by next crop wheat (g column ⁻¹)	0.13	0.31	0.30	0.42	0.54
Apparent use efficiency by rice plus wheat (%)		102	125	50	36

Excessive P application resulted in more P occluded (Table 6) by colloid film of ferric oxide. $\text{Ca}_{10}\text{-P}$ contents did not change significantly at any depth in all treatments under the experiment condition (data not shown), suggesting that $\text{Ca}_{10}\text{-P}$ be the most stable fraction of I-P.

3.3. Crop uptake of phosphorus and apparent efficiencies

Table 7 showed the crop uptake of P calculated based on concentration and biomass (root, seed and straw) of crops. Apparent use efficiency of P fertilizer in treatment of $\text{N}_2\text{P}_1\text{K}$ was highest, but it was not recommendable because it required higher level of N application than the normal rate treatment $\text{N}_1\text{P}_1\text{K}$. Apparent use efficiency in $\text{N}_1\text{P}_1\text{K}$ treatment was around 100%, implying that 60 kg P ha^{-1} was the best rate both agronomically and economically. P application rate higher than 60 kg P ha^{-1} might also increased the risk of soil P loss because of accumulation of P in excess of crop uses.

4. Conclusions

Soil P leaching occurred, particularly at early period of submergence, at the concentrations that could cause eutrophication of water. However, there was no correlation between concentration of dissolved P in leachates (at the 70 cm depth) and the P fertilization rates under present experiment condition, suggesting that the soil P contents had not arrived at “threshold”, above which P leaching is accelerated. Calculated leaching losses of P were 0.11 and $0.071 \text{ kg P ha}^{-1}$ in 2002 and 2003, respectively. Higher P fertilization rates resulted in more accumulation at top soil layer and deeper downward P movement in soil profile. Downward movement of Al-P and $\text{Ca}_2\text{-P}$ was observed in deeper soil layers than that of Fe-P and $\text{Ca}_8\text{-P}$, and accumulation of Fe-P and Al-P were quantitatively more significantly than $\text{Ca}_2\text{-P}$ and $\text{Ca}_8\text{-P}$.

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