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Phosphorus mass balances for successive crops of fertilised rainfed rice on a sandy lowland soil

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Abstract

Raising and sustaining rice yields in the rainfed lowlands requires an understanding of nutrient inputs and outputs. On sandy lowland rice soils, managing phosphorus (P) supply is a key factor in achieving increased yields and sustainable production. Phosphorus inputs, rice yields, and crop P uptake were used to quantify P requirements of rice: together with results on soil P fractions, P balance sheets were constructed over five consecutive cropping seasons on a sandy Plinthustalf near Phnom Penh, Cambodia. Grain yields ranged from 665 to 1557 kg ha^{-1} with no added P. Average yields increased significantly with P fertiliser application over five consecutive crops by 117, 139 and 140% when the phosphate fertiliser was applied at 8.25, 16.5 and 33 kg P ha^{-1}, respectively. Without added P fertiliser, a net loss of 1.2 kg P ha^{-1} per crop was estimated with straw return and 2.0 kg P ha^{-1} per crop with straw removed from the field, whereas, with added P fertiliser, there was a net P gain in the soil of 5.6 or 9.5 kg ha^{-1} per crop when straw was removed and returned to the soil, respectively. After one crop, the addition of P fertiliser significantly ($P < 0.01$) increased recovery in all soil P fractions. Across five successive crops, repeated application of 16.5 and 33 kg P ha^{-1} rates resulted in progressive P accumulation in the soil, especially a labile NaOH–Po pool, but had no effect on yields and P uptake of rice. By contrast, 8.25 kg P ha^{-1} per rice crop was generally adequate for grain yields of 2.5–3.0 t ha^{-1} and to maintain soil P pools.

Abbreviations: ANOVA – analysis of variance; DAT – days after transplanting; LSD – least significant difference; PI – panicle initiation; Pi – inorganic phosphorus; Po – organic phosphorus; PR – phosphate rock; RCBD – randomised complete block design; SE – standard error

Introduction

In rainfed lowlands, depletion of nutrients from soil is common and will continue without changes in fertiliser additions (Sheldrick et al. 2002). If depletion continues, it will ultimately lead to soil degradation and a reduced capacity to increase crop production (Sheldrick et al. 2002). Nutrient balance based on appropriate fertiliser application rates and nutrient composition in relation to harvested yields is a critical factor in maximizing the grain yield of a single crop and for maintaining yield over successive crops (Dobermann et al. 1996; Nakamura and Matoh 1996).

Increasing concerns about the sustainability of fertility status of rainfed lowland rice soils has prompted a number of studies on nutrients budgets at national, regional and farm scales in South and Southeast Asia, and at a global scale (Nakamura and Matoh 1996; Lefroy and Konboon 1998; Dobermann and White 1999; Cho et al. 2000; Sheldrick et al. 2002). The calculation of nutrient budgets as a tool for managing nutrient supply for rainfed lowland rice has considerable promise because of its relative simplicity compared to alternative approaches such as soil and plant testing, and simulation modelling (Bell et al. 2001). However, Lefroy and Konboon (1998) pointed out that many of the assumptions underlying calculations of nutrient budgets need more rigorous support from field research.

In the past, a number of studies in the rainfed lowland rice areas have focused on short-term input–output measurements of rice crop responses to P fertiliser application (De Datta and Gomez 1982). However, there is inadequate understanding and data on longer-term P balance sheets for rainfed lowland rice ecosystems to compare with that assembled by Dobermann et al. (1996) and Greenland (1997) for the intensive, irrigated lowland rice ecosystems. Nutrient budgets are needed for P input–output dynamics for various target rice yield levels on different soil types in diverse agro-ecosystems, including rainfed lowland rice on highly weathered sandy soils.

Pheav et al. (2003) indicated that P removal with the harvest of rice crops does not exceed 50% of fertiliser P (16.5 kg ha^{-1}) added to that crop at transplanting. Similar findings were also reported elsewhere in Southeast Asia (Linquist et al. 1998; Dobermann and White 1999; Linquist et al. 2000): the unabsorbed P is retained in the soil and/or may be lost from the system. In order to achieve more efficient fertiliser use, it is necessary to explore the forms in which the remaining P is retained in the soil and its turnover process for subsequent crop uptake.

With repeated P fertiliser application, an accumulation of P in soils may also be expected, but the fate of this for subsequent crop growth is not fully understood. In addition, P inputs by rainfall, irrigation water, crop residues, animal manures, as well as release of P by weathering of soil materials could influence the soil productivity (Dobermann and White 1999; Bell et al. 2001).

Losses of P occur both in surface run-off and sub-surface through-flow and these losses increase with the use of P fertiliser under irrigated rice production (Cho et al. 2000). Other losses include removal of P in animal products and transfer of manure to non-productive sites as well as losses to erosion and leaching. While P transformations in soils from adsorption–desorption processes and mineralization–immobilization reactions are often studied, P fertiliser losses from soils by sub-surface through-flow or leaching are often not considered particularly in the rainfed lowland rice areas (Greenland 1997).

The main objective of this paper was to construct a mass balance of P fertiliser over five consecutive rice growing seasons in a double-crop-lowland rice ecosystem on a sandy soil of Cambodia, and to quantify the fate of fertiliser P including the soil P by sequentially extracting soil P fractions.

Materials and methods

Experimental design and field plot management

The mass balance P experiment was carried out over five consecutive cropping cycles spanning 3 wet and 2 dry seasons. The trial that commenced in the wet season 1997 and ended in the wet season 1999, was conducted at the Cambodian Agricultural Research and Development Institute (CARDI) on a Prateah Lang soil (White et al. 1997a, b) or Plinthustalf (Soil Survey Staff 1994). Its main soil properties were: pH (1:1 H_2O) 5.4; 132 g clay kg^{-1}; 4 g organic matter kg^{-1} (Oberthur et al. 2000; see also Pheav et al. 2003). The experimental site had nearby stored run-off water available for irrigation during the dry season experiment.

The experiment was arranged in a randomised complete block design (RCBD) with four replications, and four levels of P fertiliser (0, 8.25, 16.5 and 33 kg P ha^{-1}) applied as triple-superphosphate (TSP). A level field without a recent history of P fertiliser application was selected for the trial. The individual plot size was 10 m × 10 m (100 m^2). Plots were separated by permanent bunds 30 cm high and 50 cm wide. A large bund was built around the entire experiment to prevent water flow across the experimental site. The site was subjected to levelling, ploughing and harrowing to ensure uniformity in the field. The plots were ploughed for the wet season crop in the early rainy season after rains wet the soil. During the dry season, the first ploughing and harrowing occurred 2 weeks before transplanting. The second land preparation was carried out just before rice transplanting in both the wet and dry seasons. In all cases, land preparation was done by animal traction. Nitrogen (N) as urea, potassium (K) as muriate of potash (KCl) and sulphur (S) as gypsum ($CaSO_4 \cdot 2H_2O$) were applied to all plots at the rates of 90 kg N, 50 kg K and 15 kg S ha^{-1}, respectively, to ensure that these nutrients did not limit plant growth (Seng et al. 2001). Within all plots, basal fertilizers were spread uniformly and incorporated into the soil to 15–20 cm depth before rice transplanting. Urea was applied in two equal splits: 50% was basally incorporated, whilst the other 50% was broadcast at panicle initiation (PI).

Rice cv. IR66 was sown. It is suited for both rainfed and irrigated-dry season lowland rice production in Cambodia (CIAP 1994). The rice seeds were pre-germinated by soaking in a wet sack for 48 h prior to broadcasting in the nearby nursery at a rate of 100 kg ha^{-1}. To enhance the initial growth of seedlings, the seedbed was treated with cow manure, N, P and K fertilisers at the rates of 50, 1, 0.5 and 0.5 kg per 100 m^2, respectively (Seng et al. 2001). The seedlings were transplanted when they were 25 days old. Three seedling samples (i.e. one sample covered an area of 400 cm^2) were randomly selected in the seedbed to determine the seedling weight and nutrient contents at transplanting. From each sample, a sub-sample of about 10 g was taken for nutrient analysis. Healthy seedlings with similar physical appearance were selected for transplanting with 2–3 plants per hill at a spacing between hills of 20 cm × 20 cm. Missing hills were replaced at 5–7 days after transplanting (DAT) to ensure uniform plant density in plots. Weeds were pulled by hand at 4 weeks after transplanting, and the second time at 50% rice flowering. Fresh weed biomass was recorded at each sampling time, and 100 g fresh weight was sub-sampled, oven-dried at 70 °C for 48 h, weighed for dry biomass, and subsequently analysed for P content. In this experiment, the effects of insect pests and diseases during both the wet and dry seasons were below the economic impact threshold hence no pesticides were applied.

Plant sampling and yield measurements

At maturity, rice was harvested in the central 7 m × 7 m (49 m^2) portion of each plot by cutting stems at ground level to measure total grain and straw fresh weights. Samples were randomly taken from the harvested materials, and then oven-dried at 70 °C for 48 h to determine the dry weight. The dry sub-samples of both grain and straw were milled by an electrical grinder, and then two 10 g sub-samples were packed in a plastic bag and stored in a cool room at 4 °C prior to utilisation. Phosphorus concentrations in plant materials were determined, using inductively coupled plasma atomic emission spectrometry (ICP-AES) after digesting the samples with concentrated HNO_3 at 140 °C (Zarcinas et al. 1987). Root biomass was taken, based on three random samples in every plot after harvesting. Each sample comprised about 400 cm^2 (soil from between plants and on each side of rice plants were taken and mixed), taken by spade to a depth of 20 cm in the harvested area. After sampling, all root samples were mixed together before washing to remove the soil, and then double-rinsed with DI water. The fresh weight of each sample was recorded before oven-drying at 70 °C for 48 h to determine the dry weight. Phosphorus concentrations in roots were also determined with ICP-AES followed the procedures described above.

Soil and water sampling and their analyses

Initial soil samples were taken before fertiliser application to the first crop. Three randomly placed cores per plot were taken to 20 cm depth, and mixed to form a composite sample. A sub-sample of 100 g was taken, air-dried and coarse organic debris removed. The soil was then crushed and sieved through a 2-mm screen, and packed (20 g per sample) for nutrient analyses at Murdoch University in Perth, Western Australia. After each cropping season, soils were again sampled in the same manner as detailed above. Each location of soil sampling was clearly identified, so further sampling from the same location was avoided. A sequential soil P fractionation analysis based on Hedley et al. (1994) was used, including modifications to the method as described in Pheav et al. (2003).

Measurements of rainfall were continuously taken with a rain gauge within the experimental period in both the wet and dry seasons. Rice grown during the wet season, July–November relied entirely on rainfall. The rainfall over the three consecutive years within the wet season rice growing period was 884, 892 and 863 mm, which deposited 0.40, 0.40 and 0.39 kg P/ha in 1997, 1998 and 1999, respectively (data not shown). During the dry season: January–April, the input of water by rainfall was extremely low (data not shown) and the initial soil–water content low, so that the experimental plots were fully irrigated. The volume of water at each irrigation was measured by a flow-meter, and water samples were taken at three times (start, middle, and just before stopping the irrigation). The average amount of water supplied for each dry season crop was 3328 m^3 ha^{-1} (equivalent to about 333 mm of rainfall), which supplied 0.55 kg P ha^{-1} per crop (data not shown).

Shallow and deeper piezometers were randomly located over the experimental area as a pair into the soil at 20 and 60 cm depths, respectively. The deeper piezometers were installed approximately 40 cm below the plough-pan. The paired piezometers were placed in all plots which received 33 or 0 kg P ha^{-1} in order to monitor water levels perched above the plough-pan, which may influence P accumulation and leaching processes. Plastic pipes (PVC) of 5-cm diameter, and either 60 or 100 cm long were used. The tubes were open-ended and perforated around the base, the tops protruded at least 40 cm above the surface, and were capped with polyethylene covers. Solution samples were withdrawn with a syringe from the piezometers, except if the water level was close to the base of the tubes when an air pump was used to recover the solution via a micro polyethylene tube. To prevent the mixing of water in the piezometer with standing water in the field, a cement collar was placed around each tube at the interface of each soil layer. The water depth in each piezometer was measured every 3 days, and the leachate P solution was sampled weekly commencing immediately after rice transplanting. Collected samples of rain, irrigation, and leachate solutions were frozen at −18 °C prior to analysis. Phosphorus concentrations in all samples were analysed using the ammonium molybdate–antimony potassium tartrate–ascorbic acid method of Lachat Instruments (1996).

Statistical analysis

For each cropping cycle, a one-way analysis of variance for each of the growth and soil parameters measured was carried out to determine treatment effects using IRRISTAT software packages, version 4.03 (IRRI 1997). Where the treatment effects were significant, means were compared using the least significant differences (LSD) and the standard errors (SE) were also used to examine the data.

Results

Dry matter and yield responses to P application

Straw and grain yields responded positively ($P < 0.01$) to P fertiliser applied to all cropping seasons (Table 1). Except for crops 4 and 5, 8.25 kg P ha^{-1} was sufficient for maximum yields of grain. In crops 2–5, 16.5 kg P ha^{-1} was required for maximum straw yield, and in crops 4 and 5 for maximum grain yield 16.5 kg P ha^{-1} was also needed (data not shown). Apart from the higher grain yield of 3485 kg ha^{-1} in crop 5, the maximum grain yields across all crops were relatively similar, ranging from 2483 to 2831 kg ha^{-1}. Straw biomass was substantial higher in the dry season crops relative to the wet season crops. However, higher root dry weights were obtained in the three wet season crops (Table 1). Hence straw–root ratio was substantially higher in the dry season crops (Table 1), with the exception of crop 5 (data not shown). By contrast, harvest index (HI) was generally lower in the dry season crops, especially at the higher P rates (Table 1). Harvest index averaged 0.3 without added P and 0.5 with applied P.

Across all treatments and cropping seasons, the grain yields of rice ranged from 665 to 1557 kg ha^{-1} without added P, and from 2305 to 3435 kg ha^{-1} in the highest P treatment (data

Table 1. Yields, straw to root ratio, harvest index and internal P use efficiency of rice at harvest in response to different levels of applied P fertilizer on a sandy lowland soil over five consecutive cropping (3 wet and 2 dry) seasons, 1997–1999. The values are averages of three and two cropping cycles for the wet and dry seasons, respectively.

P applied rate (kg P ha^{-1})	Grain dwt. (kg ha^{-1})	Straw dwt. (kg ha^{-1})	Root dwt. (kg ha^{-1})	Straw/root ratio	[a]Harvest index	[b]P use efficiency (kg grain kg^{-1} P)
Average for the wet season						
0	1207	1672	1681	0.97	0.37	1099
8.25	2580	3192	1965	1.67	0.5	756
16.5	2832	3500	2094	1.77	0.5	528
33	2813	3674	2297	1.3	0.5	399
LSD (0.05)	339.3**	556.0**	350.7*	–	–	–
Average for the dry season						
0	800	1235	1590	0.7	0.45	1192
8.25	2195	3810	1740	2.2	0.45	694
16.5	2412	4176	1837	2.3	0.4	644
33	2484	4715	1885	2.55	0.4	477
LSD (0.05)	348.5**	803.0**	ns	–	–	–

[a]Calculated from the grain yield divided by the total plant weight (grain + straw + root).
[b]Calculated from the grain yield divided by the rate of applied P treatments (Tables 2 and 3).
–: Data was not statistically analysed.
Statistical significance of the treatments: ns: not significant, *$P \leq 0.05$, **$P < 0.01$.

not shown). Phosphorus fertilizer application increased the average grain yields significantly ($P < 0.01$) from that without P added over five consecutive crops by 117, 139 and 140% with P fertiliser applied at rates of 8.25, 16.5 and 33 kg P ha^{-1}, respectively (Table 1). The biomass of roots was 17, 36 and 38% higher in the plots with P applied at 8.25, 16.5 and 33 kg ha^{-1}, respectively, compared to the plot with no P added but differences were not significant for the two dry season crops (Table 1).

Internal P use efficiency ranged from 399 to 1192 kg grain kg^{-1} P (Table 1). Phosphorus absorbed was converted most efficiently into grain where no fertiliser P was applied and approximately halved in the P fertilizer treated plots (Table 1). Total P uptake in above-ground biomass ranged from 12.0 kg P ha^{-1} in the wet season (Table 2) to 14.4 kg P ha^{-1} in the dry season (Table 3) at the average grain yield of 2680 kg ha^{-1} (Table 1) in the 33.0 kg P ha^{-1} plot. On average, 42% of the total P taken up by the plant was contained in the rice grain (Tables 2 and 3).

Mass balances of P fertiliser

The mass balance of P was calculated as the difference between the total P uptake by the plant, and the input of P supplied from different sources and from recycled plant residues such as rice straw and roots. When rice straw was removed from the plot, the net P removal by rice plants from the first crop was 51, 39 and 29% of the P fertilizer at 8.25, 16.5 and 33.0 kg P ha^{-1}, respectively (Figure 1a). The net P removal was greater for dry than wet season crops, and generally increased with successive crops for each season (Figure 1a, c, e vs. b, d). The average removal by rice per crop including straw was 74, 57 and 41% of the added P fertiliser inputs at 8.25, 16.5 and 33.0 kg ha^{-1}, respectively (Figure 1a–e).

In the first crop, net P loss from the soil was 1.26 kg P ha^{-1} in the nil-P plot when straw was removed (Figure 1a), and this removal declined to 0.48 kg P ha^{-1} if straw was returned. By comparison, across all cropping seasons P losses from the system were calculated at 1.95 and 1.17 kg ha^{-1} per crop for the nil-P plot with straw removed or straw returned to soils, respectively (Tables 2 and 3; Figure 1). With the application rate of 33.0 kg P ha^{-1}, 62% of applied P fertiliser was retained in the extractable P fractions with straw removed, or 78% with straw returned to soils (Tables 2 and 3; Figure 1). With repeat applications of 33.0 kg P ha^{-1} per crop, the net-P gain after five consecutive crops was 103 kg P ha^{-1} when straw was removed (Table 4),

Table 2. Wet season phosphorus mass balances for rice with different P fertiliser inputs in a field experiment, grown on a lowland sandy soil during the 3 years, 1997–1999. The values are averages of wet season crops in three cropping cycles. Mass balance calculated for two scenarios, with removal of straw (the actual practice), or by assuming that straw was returned.

Input/output	Treatment (kg P ha^{-1})				[a]Statistical significance	[b]LSD (0.05)
	0	8.25	16.5	33		
Total P input (kg ha^{-1}) (*A*)	0.62	8.87	17.12	33.62	–	–
Plant uptake (kg ha^{-1})						
Rice grain (*B*)	1.14	3.48	5.43	6.83	**	1.46
Rice straw (*C*)	0.8	2.07	3.04	4.73	**	0.67
Weed biomass (*D*)	0.1	0.11	0.23	0.46	ns	–
Mass balance (kg ha^{-1})						
Straw removed from soil						
P removed ($B + C + D$)	2.03	5.66	8.7	12.03	**	1.88
P retained [$A - (B + C + D)$]	−1.41	3.21	8.42	21.6	**	1.89
Straw returned to soil						
P removed ($B + D$)	1.24	3.6	5.66	7.29	**	1.46
P retained [$A - (B + D)$]	−0.62	5.28	11.46	26.33	**	1.46

[a]Statistical significance of the treatments: ns: not significant, $**P < 0.01$.
[b]The least significant difference at $P \leq 0.05$.
–: Data of P input was not statistically analysed.
Total P input = fertilizer P + seedling P + rainwater P; seedling P = 0.23 kg ha^{-1}, and rainwater P = 0.4 kg ha^{-1}.
Phosphorus mass balance calculation in each crop does not consider an input from previous crop/crops.

Table 3. Dry season phosphorus mass balances for rice with different P fertiliser inputs in a field experiment, grown on a lowland sandy soil during the two years, 1997–1998. The values are averages of dry season crops in two cropping cycles. Mass balance calculated for two scenarios, with removal of straw (the actual practice), or by assuming that straw was returned.

Input/output	Treatment (kg P ha^{-1})				[a]Statistical significance	[b]LSD (0.05)
	0	8.25	16.5	33		
Total P input (kg ha^{-1}) (*A*)	0.80	9.05	17.30	33.80	–	–
Plant uptake (kg ha^{-1})						
Rice grain (*B*)	0.73	3.31	3.77	5.28	**	0.93
Rice straw (*C*)	0.77	3.24	4.65	6.84	**	1.35
Weed biomass (*D*)	0.34	1.04	1.44	2.29	*	0.80
Mass balance (kg ha^{-1})						
Straw removed from soil						
P removed ($B + C + D$)	1.84	7.60	9.86	14.40	**	1.78
P retained [$A - (B + C + D)$]	−1.04	1.46	7.44	19.40	**	1.78
Straw returned to soil						
P removed ($B + D$)	1.06	4.36	5.21	7.57	**	1.23
P retained [$A - (B + D)$]	−0.27	4.69	12.09	26.23	**	1.23

[a]Statistical significance of the treatments: $*P < 0.05$, $**P < 0.01$.
[b]The least significant difference at $P \leq 0.05$.
–: Data of P input was not statistically analysed.
Total P input = fertilizer P + seedling P + rainwater P + irrigated water P; seedling P = 0.23 kg ha^{-1}, irrigated water P = 0.55 kg ha^{-1}, and rainwater P = 0.2 kg ha^{-1}.
Phosphorus mass balance calculation in each crop does not consider an input from previous crop/crops.

or 131 kg P ha^{-1} when the straw was returned to soils (Tables 2–4), equivalent to 62 and 81% of the added fertiliser P, respectively.

Whilst the flux of water through the soil profile was not determined, P concentration in the leachate solution collected from piezometers was

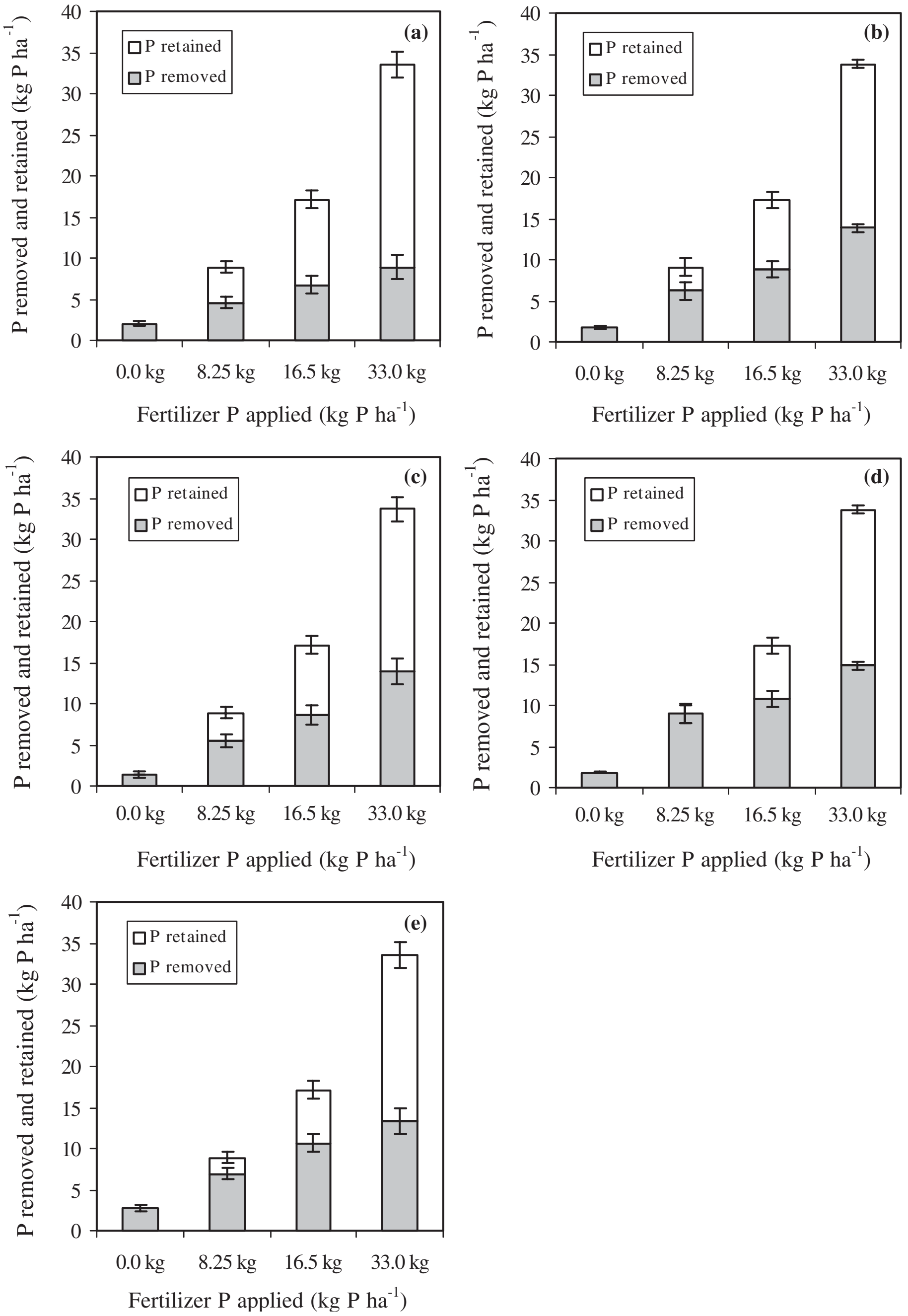

Figure 1. Phosphorus removal by rice crops and P retained in soil after each crop, grown on a lowland sandy soil of Cambodia over five consecutive cropping (3 wet: a, c, e; and 2 dry: b, d) seasons, 1997–1999. The values are means of four replicates. Phosphorus removed and retained was calculated with the removal of straw (actual practices). Phosphorus retained in the soil of each crop did not consider residual inputs from previous crop/crops.

measured in the present study. Phosphorus concentrations averaged 0.05–0.153 mg P l^{-1} in the deep (60 cm depth) and shallow (20 cm depth) bore holes, respectively, within the highest applied P plot (33.0 kg P ha^{-1}) during the dry season 1998, whereas, concentrations ranged from 0.005

Table 4. Predicted cumulative P supply, P recovery and the percent P inputs unaccounted for in soils at each harvest from different applied P fertiliser on a lowland sandy soil of Cambodia over five consecutive cropping (3 wet and 2 dry) seasons, 1997–1999. The values are means of four replicates.

P inputs (kg P ha^{-1})		[a]Cumulative soil-P (kg P ha^{-1})	[b]Soil-P recovery (kg P ha^{-1})	[c]Unaccounted for P inputs (kg P ha^{-1})	(%)
P fertilizer	[d]P addition				
Crop 1, wet season 1997					
8.25	0.62	4.32	3.01	1.32	30
16.50	0.62	10.36	7.97	2.39	23
33.00	0.62	24.70	16.67	8.03	33
Crop 2, dry season 1997					
8.25	0.80	7.15	4.49	2.66	37
16.50	0.80	18.77	13.09	5.68	30
33.00	0.80	44.59	28.90	15.69	35
Crop 3, wet season 1998					
8.25	0.63	10.54	7.30	3.24	31
16.50	0.63	27.24	20.91	6.33	23
33.00	0.63	64.30	40.60	23.70	37
Crop 4, dry season 1998					
8.25	0.79	10.61	7.15	3.45	33
16.50	0.79	33.71	23.08	10.63	32
33.00	0.79	83.19	56.25	26.95	32
Crop 5, wet season 1999					
8.25	0.62	12.53	8.09	4.44	35
16.50	0.62	40.16	29.37	10.79	27
33.00	0.62	103.58	80.18	23.40	23

[a]Phosphorus accumulated in soil after each crop, calculated by summing up the P retained in soil for the current crop and the P retained in soil from the previous crop, assuming P removals only in grain, straw and weed. Derived from Tables 2 and 3 and/or Figure 1.
[b]Calculated by subtracting the values for P fractions in the nil-P plot from each the remaining treatment values. Three analysed P fractions (Resin-P, NaOH–Pi and NaOH–Po) were summed to compute above values.
[c]Calculated by subtracting the P recovery in soil ([b]) from the predicted cumulative P supply in soil ([a]).
[d]P additional inputs = seedling P + rainwater P + irrigated water P (for dry season only).

to 0.135 mg P l^{-1} during the wet season 1999 (Table 5).

Soil P fractions

In the first crop, the addition of P fertiliser significantly increased ($P < 0.01$) all soil P fractions. Organic P (NaOH–Po) was the major soil P pool from which a maximum of 8.07 mg kg^{-1} (equivalent to about 20 kg P ha^{-1}) was extracted after 33.0 kg P ha^{-1} had been applied to one cropping cycle (Figure 2).

Across five consecutive crops, the extractable resin-P pool significantly ($P < 0.05$) increased for each of the added P levels. Largest increases ($P < 0.01$) were obtained for the NaOH–Pi and NaOH–Po extractable pools with repeated fertiliser applications (Figure 2). The values increased from 2.6 to 10.9 mg kg^{-1} for the NaOH–Pi pool, and from 8.1 to 29.6 mg kg^{-1} for the NaOH–Po pool extracted after the first crop and fifth crop, respectively, from the soil treated with 33.0 kg P ha^{-1} per crop (Figure 2).

When data was fitted with the Mitscherlich model, the resin P pool and total plant P uptake were significantly ($r^2 = 0.80$) correlated (Figure 3). The NaOH–Pi and NaOH–Po fractions, particularly the NaOH–Pi pool, were slightly better correlated ($r^2 = 0.82$) with total plant P uptake (Figure 3).

Discussion

Rice yield responses to P fertiliser application

Phosphate fertiliser applied to one crop can often meet the requirements of the subsequent crop or crops in a cropping sequence (Pheav et al. 2003). Applying P fertiliser at rates higher than 8.25 kg ha^{-1} did not increase the grain yield

Table 5. Phosphorus concentrations in soil solution in the high-P plots in the 20-cm and 60-cm depth piezometers, after fertiliser P (33.0 kg ha^{-1}) was applied to transplanted rice on a lowland sandy soil of Cambodia during the dry season 1998 and in the wet season 1999. Values are the means of four replicates with standard errors (SE).

Period after transplanting (week)	Shallow borehole (20-cm depth)			Deep borehole (60-cm depth)		
	Perched water level (mm)[a]	P conc. in soil (mg l^{-1})	SE	Perched water level (mm)[a]	P conc. in soil (mg l^{-1})	SE
Crop 4, dry season 1998						
Week 2	80	0.334	0.124	−50	0.067	0.005
Week 4	80	0.190	0.025	−20	0.061	0.005
Week 6	110	0.142	0.036	−10	0.055	0.005
Week 8	100	0.058	0.048	10	0.050	0.002
Week 10	80	0.042	0.021	−10	0.018	0.004
Average	–	0.153	–	–	0.050	–
Crop 5, wet season 1999						
Week 1	90	0.290	0.020	70	0.012	0.001
Week 3	150	0.121	0.050	110	0.009	0.000
Week 5	170	0.112	0.073	120	0.003	0.000
Week 7	140	0.092	0.050	60	0.001	0.000
Week 9	120	0.062	0.015	120	0.001	0.000
Average	–	0.135	–	–	0.005	–

[a]Note that positive and negative values of the height of perched water represent ground water levels above the soil surface and at below the surface.

except in crops 4 and 5 (Table 1). Moreover, repeated applications of P at 8.25 kg ha^{-1} or higher had no effect on yields above that obtained with a single application. These results suggest an optimal P fertiliser rate comparable to the recommendation for sandy Prateah Lang soils of Cambodia, which is for 10 kg P ha^{-1} (Seng et al. 2001). However, the recommended rates for Cambodian soils have not considered the question of residual value of P fertiliser nor the long term P rates required to maintain soil P at levels which result in optimal yields. Linquist et al. (2000) suggested that supplying P fertiliser at rates higher than the plant requirements could significantly increase P loss to the system through leaching from sandy soils with high water percolation and low P sorption capacity. Hence if P leaching or other P losses were significant, there would be little advantage in applying more than the recommended minimum rate to achieve maximum yields. However, as the present study showed, in two seasons out of five, a higher rate of P would be beneficial for increasing grain yields. On the other hand, all cropping cycles in our experiments were well watered, but in most years rice crops under rainfed conditions may suffer loss of soil–water saturation during establishment or during flowering (Fukai 2001) which may decrease P uptake (Seng et al. 1999; Huenin-Elie et al. 2003). In this case, there could be a benefit to having higher available P reserves in the soil, accumulated from greater than the apparent optimum P application rates.

In our previous study also on the Prateah Lang soil (Pheav et al. 2003), an initial application of about 17 kg P ha^{-1} was sufficient to maintain yields at about 3.0 t ha^{-1} for two successive crops, but yields declined in the third crop and in the fourth crop returned to the same levels as in crops that received no P fertilizer. The P fertiliser rate of 8.25 kg P ha^{-1} per crop was also enough to produce an average grain yield of 2400 kg ha^{-1}, and maintain a positive P balance after all five cropping seasons (Tables 2 and 3; Figure 1). Yield potentials on the Prateah Lang soil under rainfed conditions are presently in the range of 2.5–3.0 t ha^{-1}, suggesting that 8–10 kg P ha^{-1} is a sound recommendation for annual P fertiliser additions with rainfed lowland rice crops (Seng et al. 2001), although twice that rate applied every 2 years would be equally effective. In a recent survey of 100 farmers in the Takeo province in southeast Cambodia, where the Prateah Lang soil was prevalent, average P fertilizer additions by farmers were 6–9 kg P ha^{-1} (Ieng et al. 2002). Hence, the average rates applied by farmers in Takeo province were generally too low to maintain

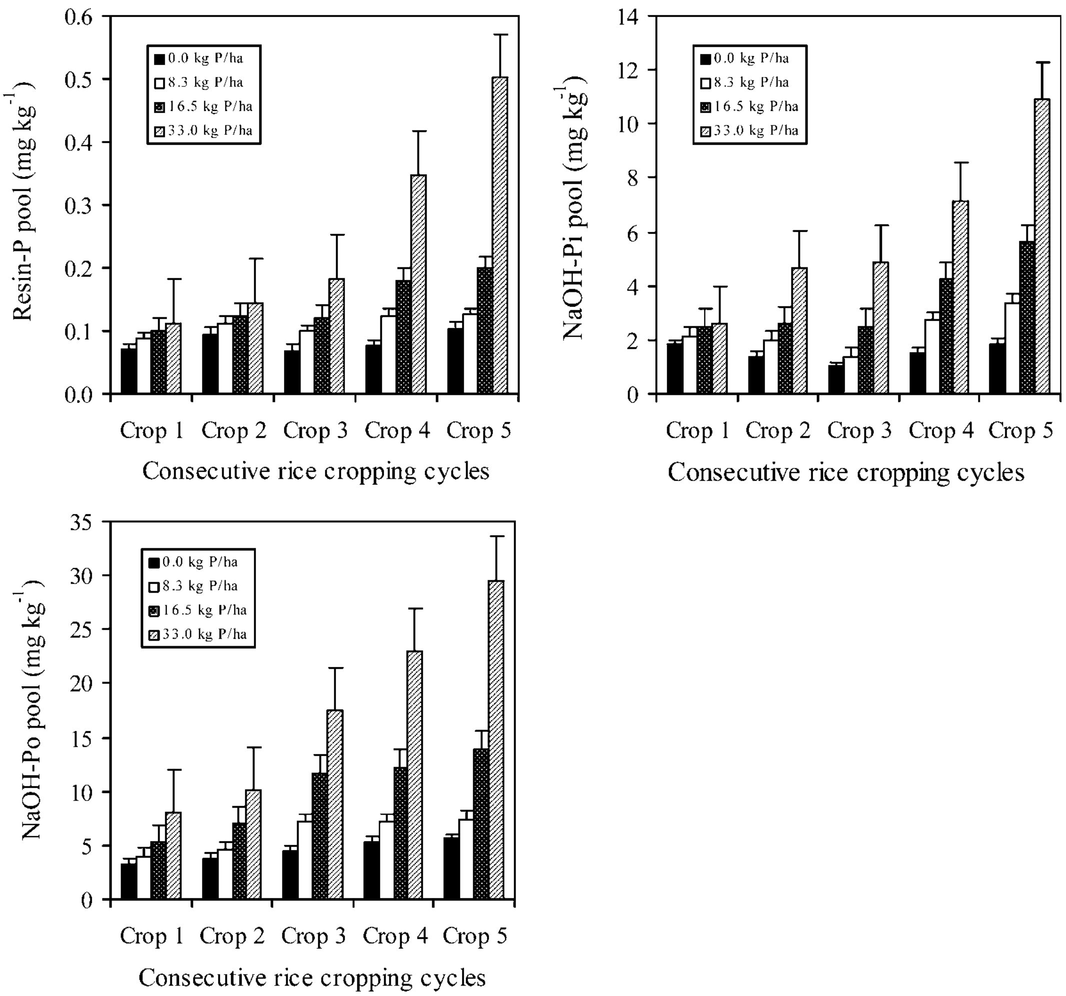

Figure 2. Soil P fractions in response to different levels of P inputs on a lowland sandy soil in Cambodia over five consecutive cropping (3 wet and 2 dry) seasons, 1997–1999. Values are means of four replicates. Vertical bars represent standard errors of four replicates. Note the change in scale of *Y*-axes.

a positive soil P balance, but only marginally so. In other provinces of Cambodia where adoption of fertilizer has been slower, the deficit of P is probably greater. On the other hand, if farmers' average yield is less than 2.0 t ha^{-1} as is generally the case at present (Ieng et al. 2002), then their rate of P addition may maintain positive P balance. Considering all these factors, the present recommendation for Prateah Lang soil is probably a reasonable trade-off between the economics of not achieving higher yield in the two seasons out of five when higher P is needed for maximum yield, and applying extra P needlessly in the remaining years.

Resin-P, and NaOH–Pi and NaOH–Po extractable pools did not increase much with the repeated application of 8.25 kg P ha^{-1}, because plants took up 84% of applied P fertiliser and only 16% remained in the soil after each crop (Figure 1). This suggests that P deficiency would re-occur without repeated annual P fertiliser applications of 8–10 kg P ha^{-1} to rice crops. Adding 16.5 kg P ha^{-1} initially and then topping-up P fertiliser with annual addition of 8–10 kg P ha^{-1} would be a lower risk strategy for maintaining labile P pools, and achieving optimal yields of following crops, but requires a higher initial investment in fertiliser.

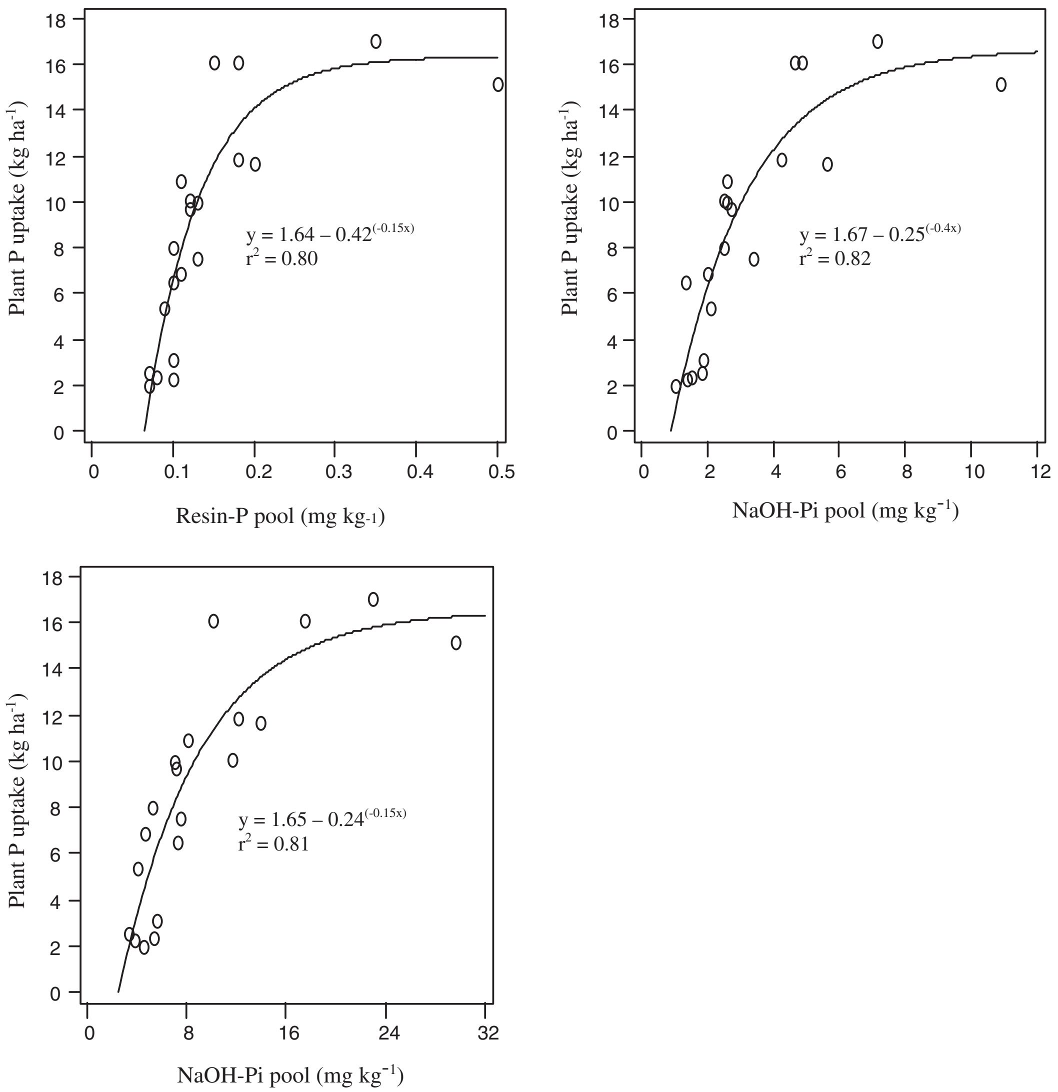

Figure 3. The relationship between the total P uptake of rice and soil P extractable pools, grown on a lowland sandy soil of Cambodia over five consecutive rice cropping (3 wet and 2 dry) seasons 1997–1999. The values plotted are the means from one to five cropping cycles.

Straw and root dry matter appear to increase in most crops with higher P rates, unlike grain yield. Straw–root ratio was high for the dry season crops, by contrast with harvest index (Table 1). Total P uptake of rice varied considerably from crop to crop depending mostly on straw dry matter as straw-P uptake accounted for at least 50–55% of the total plant P uptake (Tables 2 and 3). Potential grain yield in the dry season was apparently limited to a greater extent than dry straw. Indeed, all of the crops in this experiment produced relatively low yields considering the inputs and management. Pheav et al. (2003) suggested that maximum lowland rainfed rice yields in Cambodia were limited by the climatic yield potential rather than nutrition, pests and diseases, or water management. Alleviation of these constraints by agronomic means or plant breeding may be possible, but realisation of the increased yield potential might then require a re-formulation of fertiliser recommendations, including those for P, N, K and S. For example, crop 4 in the dry season removed in rice grain all of the P added at 8.25 kg ha^{-1} unlike any of the other crops where at least a modest surplus of P was carried forward for the next crop.

Mass balances of P fertilized rice growth

The P available for rice uptake comes from the fertilisers applied, soil P pools, seedling P, rainfall and irrigation water. The supply of P in rainfall and irrigation averaged 0.4 and 0.55 kg ha^{-1} per crop, respectively (Tables 2 and 3). Hence, as reported by Aberdin Mian et al. (1991) for Bangladesh, the annual inputs of most nutrients by irrigation water, particularly P were higher than by rainfall. However, over most of the rainfed lowlands which occur in South and Southeast Asia, no irrigation is applied in the wet season (Wade et al. 1999), and hence, only the rainfall inputs are of direct relevance to the P mass balance of these rainfed environments.

Nutrient content in rainfall is known to vary with season and with proximity to natural and anthropogenic sources (Lefroy and Konboon 1998). The burning of organic matter, whether occurring naturally or anthropogenically is another source of nutrients in rain. Lefroy et al. (1988) reported that at Ubon Ratchatani, Northeast Thailand, where burning of rice straw is common at least 2.2 kg P ha^{-1} per wet season was supplied through rainfall. Despite the low P concentration in rainfall combined with the difficulty for accurately estimating its P content (Lefroy and Konboon 1998), the contribution of P from the rainfall was an important P input in unfertilised soils and hence would be significant for resource-poor rainfed lowland rice farmers using little or no P fertiliser.

Across all cropping cycles, crop yields were similar in both the 8.25 and 16.5 kg P ha^{-1} treatments (Table 1; Figure 1). After application of 8.25 kg P ha^{-1}, the total P uptake for each crop averaged 80% (data not shown) of P fertiliser applied, and about 20% of P fertiliser that was applied, was retained in soil as the residual P for following crops. By contrast, at higher levels (16.5–33.0 kg P ha^{-1}) of P fertiliser application, P accumulated progressively in the soil over consecutive rice crops, but had no further effect on yields and P uptake as shown by a poor correlation ($r^2 = 0.22$) between the grain yield and cumulative P in the soil (data not shown).

Phosphorus retention and recycling can be significantly improved by the return of rice straw that contained an average of 2.5 kg P ha^{-1} (Tables 2 and 3). Although the P concentration in rice straw was generally low compared to other plant materials, such as grain and/or young shoots, straw incorporation can significantly affect the P mass balance and should be considered in long-term P management strategies especially when P fertiliser rates only aim to maintain soil P levels.

As the major inputs of organic matter to the soil (De Datta 1989; Alberto et al. 1996), straw and roots are a primary source of organic P that could be significant in the P mass balance, especially in the plots that did not receive P fertiliser. Understanding the dynamics of turnover time and the factors affecting release of organic P into the plant available pool is particularly important in the context of the highly weathered sandy Prateah Lang soil of Cambodia. Moreover, Seng et al. (1999) indicated that the decrease in P availability under intermittent loss of soil water saturation was minimized when the soil was treated with rice straw. Addition of straw maintained a lower redox potential during the period of loss of soil–water saturation and this decreased the extent of oxidation of Fe^{2+} and hence minimised decreases in P availability due to reactions with Fe oxides (Seng et al. 1999, 2004). Thus, straw and roots of rice incorporated in the soil may have significant indirect effects on P supply to subsequent rice crops in addition to direct supply of P in organic forms.

On average, 25–30% of P fertiliser were apparently not accounted for in the soil analysis (Table 4). Three possible explanations seem to account for the apparent loss of P. Firstly, only three P fractions (Resin-P, NaOH–Pi and NaOH–Po) were extracted through the sequential P fractionation scheme. It is likely that the unaccounted for P was incorporated in microbial biomass or in more recalcitrant P fractions, which were not extracted by Resin, or NaOH. Indeed, results of Pheav et al. (2003) showed that other soil P pools such those extracted by H_2SO_4–P and occluded P (Residual-P) do respond to P fertiliser applications and would need to be quantified to fully account for the fate of added P fertiliser. Pheav (2002) also showed that the microbial biomass P was a significant pool in the same soil in a pot study. Secondly, there may be some losses of P in rice grain, straw and stubble that falls to the ground but this is not considered to be a significant quantity. Thirdly, losses of P through leaching are possible (Lefroy and Konboon 1998; Linquist et al. 2000), but rarely quantified in lowland rice fields.

In the P fertilised plots, higher P concentrations were found in the shallow (20-cm depth) rather than in the deep (60-cm depth) boreholes, suggesting that the plough pan that usually occurs at 15–20 cm depth in the sandy Prateah Lang soil, was a major barrier to P downwards movement. Below 20-cm depth, P concentrations in boreholes were generally unaffected by P fertiliser application. Therefore, below 20-cm depth the low P concentrations (0.01–0.07 mg P l^{-1}: Table 5) reflect limited P leaching. Low Resin-P values even with repeated P fertilizer application further suggests soil solution P was not high enough for significant leaching. At present, there may be excess P sorption capacity in the plough-pan layer to prevent P leaching. Phosphorus concentrations in both the 20-cm depth and 60-cm depth piezometers varied with time of sampling (Table 5). The leaching process may vary with levels of perched water and the ground water table. When the ground water level drops, the down-flow of standing water from perched surface through the soil profile permits leaching (downwards). However, when the ground water is above the base of the plough pan and especially above the soil surface, high upward pressure of the water table prevents water infiltration and P leaching.

In our present study, the estimate of average P leached was about 0.1 kg ha^{-1} per crop from application of 33.0 kg P ha^{-1} to the sandy Prateah Lang soil (see Pheav 2002 for detailed calculations). An upper estimate of the leaching loss based on the measured maximum P concentration in the soil solution within the rooting zone (i.e. 0.14 mg P l^{-1}: Table 5) and an estimate of the percolation rate based on rainfall less evapotranspiration in the wet season (e.g. 637 mm), gave a maximum leaching loss of 0.9 kg P ha^{-1}. The small P concentration in soil solution at 60-cm depth is however good evidence that the leaching had a negligible effect on the P balance. The small amount of leachate P recovery could be attributed to the fact that P loss was quantified only during the rice growing-period (from transplanting to harvesting), and therefore may have missed some periods of P leaching; and to a higher P sorption capacity of the high clay content of the subsoil layer in the Prateah Lang soil (Pheav et al. 2002). Even though no surface run-off occurred in this experiment, in many rainfed lowland systems substantial losses may be expected from P removal in sediment-laden run-off (Cho et al. 2000). In cracking clay soils, which occupy a significant portion of the rainfed lowlands in northwest Cambodia (White et al. 1997a, b), bypass flow of particulate and dissolved P may occur during early wet season rain after the dry season. Cho et al. (2000) estimated that about 0.2 kg P ha^{-1} per rice cropping season was leached from irrigated paddy loamy clay soils of central Korea. Hence, the possibility of significant P leaching remains an unresolved issue for P nutrient management in lowland rice cropping systems. Phosphorus leaching needs to be more thoroughly studied, especially on deep sandy rainfed lowland rice soils. In addition, before reaching a final conclusion about leaching, P fluxes and losses through both vertical and lateral flow paths need to be examined.

Dobermann et al. (1996) assembled data sets from 11 experimental sites in intensive, irrigated rice ecosystems of the tropics covering a wide range of soils with different P supplying capacity. In plots where no P fertiliser was added, the average net loss per crop of 7–8 kg P ha^{-1} was 6–7 times higher than that of the sandy Prateah Lang soil of Cambodia (1.0–1.2 kg P ha^{-1}). With added P fertiliser, there was a net gain of 4.0–5.0 kg P ha^{-1} per crop for irrigated rice ecosystems compared with 5.0–7.0 kg P ha^{-1} per crop on the Prateah Lang soil (Tables 2 and 3). The lower net P loss and the higher net P gain for sandy Prateah Lang soil, by contrast with irrigated rice soils of Dobermann et al. (1996), and Dobermann et al. (1998) suggest that nutrient deficiencies, particularly for P are much less common with irrigated lowland rice soils but also can be attributed to the higher yields attained.

Phosphorus fractionation of a sandy rice soil

Low P recovery from the resin-extractable P pool (0.26 kg ha^{-1}) on the sandy Prateah Lang soil of Cambodia after harvest of rice was also reported in Pheav et al. (2003), suggesting that plants take up P from this fraction, and deplete it more rapidly than other major pools. On the highly-weathered sandy lowland rice soils, Pheav et al. (2003) suggested that the resin-extractable P fraction was not a sufficiently large soil P pool to supply plant P requirements without continuous replenishment from the other soil P pools of which NaOH–Pi, NaOH–Po and Residual-P were the most substantial responsive soil P pools measured. Plant P uptake was well correlated with NaOH–Pi and NaOH–Po extractable fractions as it was with the Resin-P (Figure 3) suggesting that under flooded conditions P associated with all these extracted fractions was plant available. The P fractionation scheme used in the present study did not include microbial biomass P (Hedley et al. 1994), and this too may be a significant pool of plant available P. Soil microorganisms are important in the transformation of labile organic and inorganic forms of P in soils. In spite of very low levels of microbial biomass in soils (2–3% of total P), it is generally able to absorb inorganic P when supplied with easily available P forms, and later release this P through mineralisation (Smith 1987)

With repeated P fertiliser applications, Resin-P, NaOH–Pi, and NaOH–Po extractable fractions were increased, but the NaOH–Po fraction increased most (Figure 2). Read et al. (1977) found that P fertilizer added repeatedly or in excess, either as a single addition or annually for many seasons to prairie soils resulted in accumulation of the NaOH–Po and Residual-P fractions. Since the Residual-P pool contains both organic and inorganic P fractions, the build-up of the Residual-P fraction partially comes from reactions of added inorganic P fertiliser, and partly from the converted plant residues (Zhang and MacKenzie 1997). The amount and form of plant materials such as straw and roots returned to the soil may have a significant bearing on the magnitude of the soil organic P pool in both NaOH-extractable and Residual fractions.

In the nil-P soils, levels of P in each of the fractions remained essentially unchanged over the five consecutive rice crops, including NaOH–Pi, NaOH–Po and Residual-P fractions (Figure 2). As discussed earlier, P is recycled from straw and roots of rice plants to the soil. The Prateah Lang soil is above the flood level of the Mekong river and hence weatherable minerals are not available from alluvial deposition, so the size of this pool is probably small since the parent material is Pleistocene age and ferrolysis appears to be an active weathering process in the soil (White et al. 1997a, b). Without adding P fertiliser, plants can maintain low yields, suggesting that in this case microbial activity could play a role in turnover of P by mineralising the organic NaOH–Po fraction to maintain the plant available pool. Tiessen et al. (1983) demonstrated that NaOH–Po associated with soil organic matter linked to the coarse silt and fine clay mineral fractions was quite labile and may undergo significant changes during crop growing seasons. Microorganisms can use most of the NaOH–Po fraction in highly weathered soils with low labile Pi content (Chauhan et al. 1981) and at least release a fraction of it for incorporation into more labile organic P and inorganic P pools.

Unlike the present experiment which grew dry season rice with irrigation, in rainfed lowlands straw and roots are usually left in the field either as standing residue or incorporated into the soil after the wet season harvest. This combined with the residual fertiliser P from the previous crop would affect biomass of volunteer pastures that grow in the dry season and early wet season in rainfed lowland ecosystems (Pheav et al. 2005). The fate of residual fertilizer P and its availability to the following crop has been examined by Pheav et al. (2003). However, a better understanding of P turnover between harvest in the early dry season and planting at the start of the following main wet season is needed to incorporate into a model of P cycling in the rainfed lowland rice ecosystems of Cambodia.

Conclusions

Taken together, the present results and those in Pheav et al. (2003) suggest P fertiliser supply initially at about 17.0 kg P ha^{-1}, and then subsequently at 8–10 kg P ha^{-1} per crop is adequate to maintain grain yields of 2.5–3.0 t ha^{-1}, a positive P balance in the soil, and an adequate available soil P level for crop requirements in sandy rainfed lowland rice soils. Sustaining greater yields will require higher P input.

Application rates of P fertiliser higher than that recommended, resulted in lower percentage P recoveries in plant intake; increased residual P associated with organic P and/or occluded P; and P losses from the top-soil are more likely to occur when the ground water table drops below the soil surface, and when strong lateral water flow occurs.

The gaps identified from the present study on P cycling in sandy soils of rainfed lowlands relate to: P losses through leaching or run-off; on-going reactions of residual P fertiliser; effects of rice straw on biomass production and P uptake of the early wet season volunteer pastures and/or pre-rice field crops; the fate of P recycled from either rice straw or other crop residues returned to the soil during land preparation for the main wet season rice crop, and; the cycling of P though microbial biomass.

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