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# Phosphorus cycling in rainfed lowland rice ecosystems on sandy soils

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**Abstract**

Phosphorus cycling in rainfed lowland rice ecosystems is poorly understood. Soil drying and grazing of rice straw during the long dry season, the growth of volunteer pastures during the early wet season, and intermittent loss of soil-water saturation while the rice crop is growing are important distinguishing characteristics of the rainfed lowlands in relation to P cycling. We studied P cycling in an acid sandy rainfed lowland soil that covers about 30% of the rice growing area of Cambodia. Soils with similar properties in comparable rainfed sub- ecosystems occur in Laos and northeast Thailand. We developed a general schema of P pools and fluxes in the crop and soil for rice-based cropping systems in the rainfed lowlands of Cambodia. The schema was derived from a number of field experiments carried out over five consecutive cropping seasons to quantify the residual value of P fertiliser, P mass balances, soil P fractions, the effect on subsequent rice crops of crop residues and volunteer pastures incorporated into the soils, and the dynamics of P turnover in the soil. With a single rice crop yielding 2.5–3 t ha$^{-1}$, application of 8–10 kg P ha$^{-1}$ maintained yields and a small positive P balance in the soil. However, the soil P balance was sensitive to the proportion of rice straw returned to the soil. Volunteer pastures growing during the early wet season accumulated significant amounts of P, and increased their P uptake when soils were previously fertilised with P. These pastures recycled 3–10 kg P ha$^{-1}$ for the succeeding rice crops. While inorganic soil P pools extractable with ion exchange resins and 0.1 M NaOH appeared to be the main source of P absorbed by rice, microbial and organically-bound P pools responded dynamically to variation in soil water regimes of the main wet, dry and early wet seasons. The schema needs to be developed further to incorporate site-specific conditions and management factors that directly or indirectly affect P cycling, especially loss of soil-water saturation during the rice cropping cycle. The paper discusses the application of results for acid sandy soils to other significant rice soils in the rainfed lowlands of southeast Asia.

## Introduction

Rainfed lowland rice is generally grown in fields bunded to retain surface water, but the depth and duration of flooding of the soil varies greatly from year-to-year within a growing season, and spatially over relatively short distances within a field (Zeigler and Puckridge, 1995). Soils in the rainfed lowlands of southeast Asia generally have low levels of nutrients, especially N and P, and to a lesser extent K and S (Kawaguchi and Kyuma, 1968; Ragland and Boonpuckdee, 1987; Pheav et al., 1996; White and Seng, 1997; Linquist et al., 1998). Rice yields are typically half those in irrigated ecosystems (Wade et al., 1999). The amount and timing of rainfall is considered the main constraint to rice productivity, followed by low soil fertility. Small nutrient reserves in soils are exac-

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erbated by the effects of a changing water regime on nutrient forms and their availability in the soil (Bell et al., 2001).

The extremely variable soil-water regimes during the rice growing period have important implications for P cycling in rainfed lowland ecosystems. Availability of P is strongly influenced by water regime (Bell et al., 2001). Interactions between soil-water and nutrients can occur even without water stress *per se* (Seng et al., 1999; Seng et al., 2004). Indeed, Fukai et al. (1995) concluded from crop modelling that most of the effect of variable soil-water on rice yields in Northeast Thailand could be attributed not to drought *per se* but rather to the effects of low soil-water on nutrient availability.

Increased fertiliser use has played a leading role in increasing rice production under irrigated lowland conditions (De Datta and Gomez, 1982; Nakamura and Matoh, 1996). Dobermann and White (1999), and Dobermann and Fairhurst (2000) proposed a model of how management of P and other nutrients can be tailored to site-specific conditions in irrigated rice systems based on mass balances and measurements of nutrient availability in the soil and predicted plant uptake or demand. The model caters for relatively stable water and nutrient conditions in irrigated systems. It does not account for the more complicated dynamics of water-nutrient interactions in the rainfed lowlands.

For rainfed lowlands, a nutrient cycling model needs to account for fluctuations in nutrient availability and unpredictable water regimes (Bell et al., 2001; Fukai, 2001). Drying and oxidation of the soil during the dry season alters the availabilities of N and P in the soil as they do for irrigated rice when the soils are dried between crops. In parts of Southeast Asia, early wet season rainfall produces a period when soils are intermittently wet before the main wet season, and volunteer pasture growth occurs. The implications of growth and nutrient turnover during this season as well as from the grazing of rice straw during the dry season need to be considered in a P cycling model for rainfed lowlands. The aim of this paper is to synthesise results on the nature of P cycling in rainfed lowland cropping systems, particularly as it relates to rice production. We developed a general schema of P pools and fluxes in the crop and soil for rice-based cropping systems on sandy soils in the rainfed lowlands of Cambodia. The schema is derived primarily from two field experiments carried out over five consecutive cropping seasons to quantify the residual value of P fertiliser, P mass balances, soil P fractions, the effect of crop residues and volunteer pastures incorporated into soils on subsequent rice crops, and the dynamics of P turnover in the soil.

## A general schema of P cycling for rainfed lowland rice ecosystems

Figure 1 gives a general schema for P cycling in rice-based cropping systems in rainfed lowland ecosystems. Details of the studies that form the basis of the schema are reported in Pheav et al. (2003) and Pheav et al. (2004). In brief, two field experiments examined the residual value of P fertiliser, and P mass balances over five consecutive cropping seasons (3 wet and 2 irrigated dry) from 1997 to 1999. Phosphorus inputs (transplanted seedlings, fallow residues, rainfall, fertiliser) and outputs (grain, straw, leaching) and significant P pools (roots, soil P fractions in the 0–20 cm soil layer) were quantified. The experiments were located at the Cambodia Agricultural Research and Development Institute, Prateah Lang District, Cambodia, on an acid sandy lowland soil (Plinthustalf: Soil Survey Staff, 1994) typical of about 30% of the rice growing area in Cambodia (White et al., 1997a, b). These soils are generally deficient in P for rice production (White and Seng, 1997; Pheav et al., 2003). Soils with similar properties, in comparable rainfed sub-ecosystems can be found in Laos and northeast Thailand (Ragland and Boonpuckdee, 1988; Willett and Intrawech, 1988; Linquist et al., 1998; Bell and Seng, 2004). An improved, photoperiod non-sensitive cultivar, cv. IR66, was transplanted in both the main wet (July–November) and dry seasons (January–April) after a 25-day period of growth in the fertilised nursery (White et al., 1997b). Apart from P fertiliser treatments, each crop received nutrients (45 kg N, 30 kg K and 15 kg S $ha^{-1}$) plus additional N fertiliser (45 kg N $ha^{-1}$) at panicle initiation. Wet season crops received 860–890 mm rainfall, while dry season crops were fully irrigated. During crop growth, rainfall or irrigation maintained continuous standing water in the fields but soils dried after the main wet season rice crop and after the dry season crop. The field experiments were supplemented by a pot experiment that examined P sorption and desorption, and the effect of growing successive rice crops in three contrasting lowland rice soils of Cambodia (Pheav et al., 2002).

Prior to the fifth crop in the P mass balance experiment (Pheav et al., 2004), the effect of incorporating rice straw on rice growth and P uptake was examined

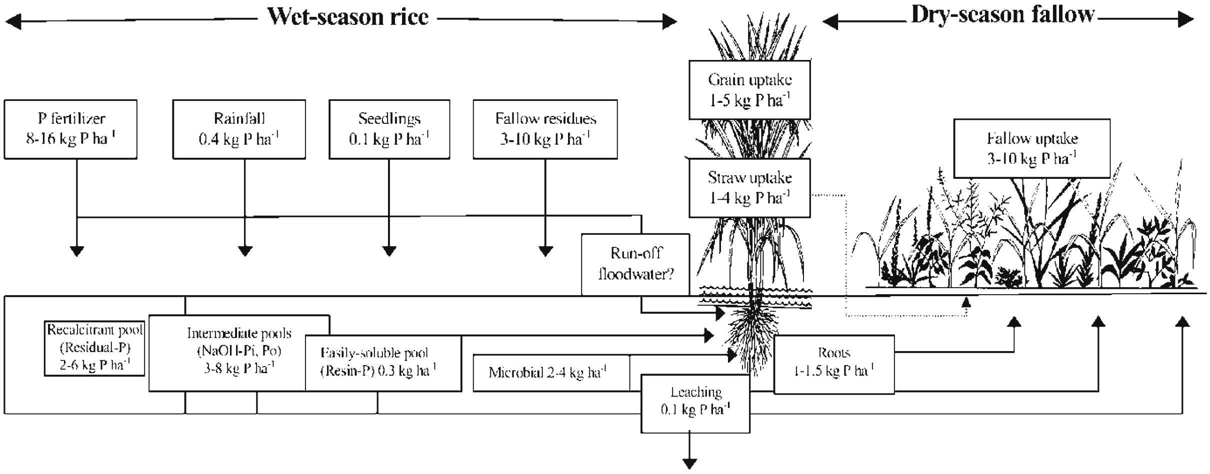


*Figure 1.* A general schema of phosphorus cycling in rainfed lowland rice ecosystems on sandy soils. The data are estimated ranges based on data of Pheav (2002) for Cambodia with rice grain yields of 1–4 t ha$^{-1}$.

in P treated plots. This study continued through to the beginning of the next main wet season rice crop to examine turnover of the straw and the effect of volunteer pasture incorporation into soils on P supply for subsequent rice crops. This study examined the dynamics of P in soil P fractions and in microbial biomass in the sandy rice soil subject to intermittent loss of soil water saturation. Soil P fractions were extracted using a modified Hedley procedure (Pheav et al., 2003). This study was supplemented by a pot experiment that examined the effect of different types of organic matter input on soil P fractions and rice P uptake (Pheav, 2002).

*Inputs of P*

The primary P inputs to the soil during the wet season crop are from fertiliser, rainfall, rice seedlings, irrigation water, and volunteer pastures that grow from the late dry season to the early wet season (Figure 1). Phosphorus in rainfall in southeast Cambodia was estimated to be 0.4 kg P ha$^{-1}$ year$^{-1}$, double the amounts estimated to be added through rainfall to rainfed sites elsewhere but comparable to amounts commonly supplied in irrigation water (Greenland, 1997). However, in our studies, only P accretion from the main wet season rainfall was quantified whereas that in dry deposition during the dry season and in early wet season rainfall was not. In northeast Thailand, Lefroy et al. (1988) estimated much larger P inputs from rainfall of 2.2 kg P ha$^{-1}$ year$^{-1}$, some of which was attributed to dry deposition following widespread burning of rice straw. Clearly the P input from rainfall may vary spatially in the rainfed lowlands. However, presumably dry deposition of P from ash generated from burning rice straw mostly recycles P within the same area, with no net gain of P over time. Indeed it is possible that winds may remove P from an area, so that this form of suspended particulate P may represent a loss to the ecosystem. The efficiency of recycling P through dry deposition of ash rather than re-incorporation of residues has not been investigated, but the dynamics of P availability from these sources over the cropping cycle may differ. Furthermore since the content of P in straw from unfertilised crops is low, amounts recycled through dry deposition of burnt rice straw are only likely to be substantial where residues from large well-fertilized rice crops are being burnt (Table 1).

Rainfed lowlands generally rely on rainfall and short distance run-off to flood the fields. Inputs from river floodwaters only occur in a minority of rainfed lowland areas. Uehara et al. (1974, cited by Greenland, 1997) measured average depositions with floodwater sediment of 4 kg P ha$^{-1}$ at three sites in the Mekong delta, and Greenland (1997) estimated that P additions in sediment range from 0.4 to 7 kg ha$^{-1}$ across all ricelands. Where the land is annually flooded by river water, P additions in sediment are sufficient to maintain rice yields of about 2 t ha$^{-1}$ without P fertiliser (Greenland, 1997), and, in agreement with this, rainfed rice soils of southeast Cambodia that are annually flooded rarely respond to P fertiliser (Seng et al., 2001).

*Table 1.* Phosphorus in rice straw and in fallow crops (legume and non-legume, roots and shoots) with P fertilizer application and with its residual effect in the field. Data are means from five rice cropping cycles and one fallow crop (Pheav, 2002; Pheav et al., 2003, 2004)

| P applied rates (kg P ha$^{-1}$) | Plant P content (kg P ha$^{-1}$) | | |
|---|---|---|---|
| | Rice straw | Legume | Non-legume |
| 0.00 | 0.81 | 0.21 | 3.43 |
| 8.25 | 2.66 | 1.44 | 6.64 |
| 16.5 | 3.37 | 1.92 | 10.51 |
| Significance[a] | ** | ** | ** |
| LSD (5%)[b] | 1.01 | 0.3 | 0.9 |

[a]Indicates statistical significance among treatments: $^{**}P < 0.01$.
[b]Indicates the least significant difference at $P = 0.05$.

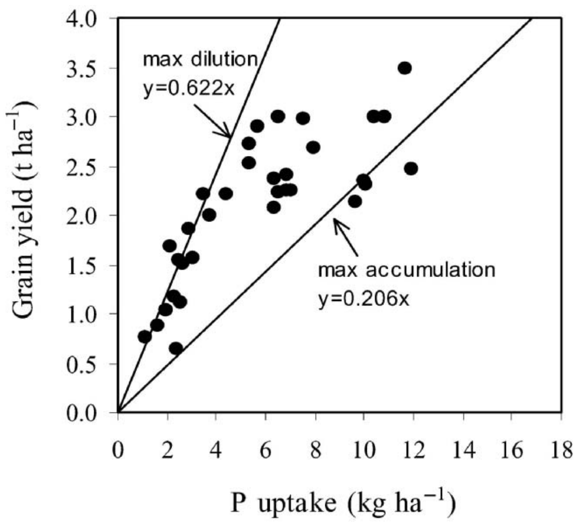


*Figure 2.* Relationship between grain yield and total P uptake at maturity for rice grown on an acid sandy lowland soil. Values plotted are means for plots with nil, fresh and residual fertiliser P. The lines from Witt et al. (1999) were derived from 2500 data sets from experiments with irrigated rice throughout S. and SE. Asia. The line of maximum accumulation indicates the minimum plant internal P efficiency observed in the data set; the line of maximum dilution indicates the maximum internal P efficiency. Points close to or below the line of maximum accumulation indicate that factors other than the availability of nutrients are limiting yield potential. (Pheav et al., 2003, 2004).

Seedlings are commonly grown in the same nursery field each year in the rainfed lowlands of Cambodia, so the transfer of P in transplanted seedlings may be considered an input to the main field. The amounts of P added in transplanted seedlings are likely to be relatively small in the overall P cycle. However, seedlings with more P at transplanting may exhibit increased vigour after transplanting leading to increased grain yield at maturity (Ros et al., 1997a, b). Hence, whilst small compared with total P inputs, seedling P may have a disproportionately large effect on yield and therefore on P outputs in grain as well as P retained in straw.

The increase in rice yield with return of the straw of a previous unfertilized crop is marginal (Ponnamperuma, 1984; Alberto et al., 1996; Pheav, 2002). In general, the biomass and P content of unfertilized crops are too small for their straw P content to have appreciable effects on the yield of a subsequent crop. In the unfertilized sandy lowland soil of Cambodia, mean P content in straw was 0.8 kg P ha$^{-1}$ (Table 1). Such P contents were associated with rice grain yield increases of 0.5 t ha$^{-1}$ in Laos (Linquist and Sengxua, 2001). However, greater yield increases would be expected with incorporation of rice straw from P fertilised crops which contained 2.7 kg P ha$^{-1}$ (Figure 2). In irrigated lowlands where 5 to 9 t of straw ha$^{-1}$ per cropping season (Oh, 1984) is incorporated alone or with inorganic fertilisers into the soils, significant yield increases have been reported. Such rates of straw addition are common in irrigated rice ecosystems (Greenland, 1997), but less so in rainfed lowlands because of lower yields (Dobermann and White, 1999).

During the dry season in rainfed lowlands with a tropical savannah climate (e.g. Cambodia, northeast Thailand, Laos), fields are usually left fallow. Early wet season rains trigger growth of volunteer pastures that can access residual P left over from the previous wet-season rice production. Volunteer pastures are likely to contain 3 to 10 kg P ha$^{-1}$ (Table 1), return of which to the soil will significantly benefit a following wet-season rice crop. Volunteer pastures are not usually a component of the P cycle in irrigated rice ecosystems (Greenland, 1997; Dobermann and White, 1999). Pheav (2002) suggests that incorporation of crop residues either as rice straw or weedy-volunteer pastures increases yields and P uptake of following rice, and also increases organic P pools, including microbial P, that are a source of P for the succeeding rice.

Pheav (2002) found that residual P from high fertiliser additions (16.5–33.0 kg P ha$^{-1}$) significantly increased biomass of volunteer pastures during the early wet season. The total biomass production and P uptake were significantly greater in non-legume compared with legume species at all levels of residual P (Table 1). This suggests that non-legume plants contribute much more to P turnover. However, increased legume biomass in the fallow system could be beneficial for nutrient cycling, especially for N because of symbiotic $N_2$ fixation and for P because of its large concentration in legume shoots and roots relative to non-legumes. In addition, the small C:N ratio of the legume crop residues would accelerate P release by decomposition (Tang et al., 1997, 1999). However, it is also possible that extra N added by symbiotic $N_2$ fixation will be lost during the early wet season by leaching and denitrification when soils are flooded prior to transplanting rice, so that net increase in N supply may be small.

In P-fertilised soils the amounts of P in microbial biomass also increased when crop residues were returned (Pheav, 2002). In low fertility soils the decomposition of organic residues can be accelerated in the presence of inorganic fertilisers, particularly N and P, if these elements are limiting to the activity of microbes (Sahrawat, 1979; Konboon et al., 1998). Nutrients immobilised in the microbial biomass are released subsequently but the timing of their release has a significant bearing on crop nutrient uptake. In the case of leguminous residues incorporated into the soil before transplanting rice, the release of most nutrients is rapid due to active biological processes in the low C:P ratio materials (Tang et al., 1997, 1999), making this component of the volunteer pasture more significant for P supply for the main wet season rice crop than its biomass suggests.

A further aspect is how conditions in the soil during the fallow affect P chemistry following flooding. Bücher (2001) measured changes in P fractions over three years of double irrigated-rice cropping in a perennially wet soil, as affected by crop residue management during the fallow seasons. She found that the labile P declined even in plots that received sufficient P fertilizer to more than off-set crop removals. During the fallow periods periodic drying of the soil tended to increase labile P in the soil, whereas maintaining the soil in an anaerobic condition during the fallow did not. The decline in labile P was greatest when tillage was delayed until the end of the fallow, resulting in more-reducing conditions in the soil, and it carried through to the succeeding rice crop. Supporting laboratory and greenhouse studies showed that changes in soil Fe with reduction and oxidation were responsible for the changes in P.

*Removals and losses of P*

Phosphorus fertiliser application doubled yields of the rice crop to which it was applied (Pheav et al., 2003, 2004). Phosphorus responses of this magnitude are to be expected over large parts of the rainfed lowlands though yield potentials and therefore total P demands are smaller than for irrigated rice (Dobermann et al., 1996; Greenland, 1997). Whereas in irrigated rice fields, Dobermann et al. (1996) reported a net loss of 7–8 kg P $ha^{-1}$ per rice crop without added P fertiliser, in the sandy rainfed lowlands of Cambodia, yield is strongly P-limited and P removal was about 2 kg P $ha^{-1}$ with straw removal or 1 kg P $ha^{-1}$ with straw returned (Figure 3a, b). The low removal of P in grain is a reflection of the crops being near the line of maximum dilution shown in Figure 2 (Pheav et al., 2003).

An initial application of 16.5 kg P $ha^{-1}$ was sufficient to maintain yields at about 2.5 to 3.0 t $ha^{-1}$ for two successive crops, but was only partially effective in the third crop and not at all in the fourth crop (Pheav et al., 2003). The P fertiliser rate of 8.25 kg P $ha^{-1}$ per crop was enough to produce a grain yield of at least 2.5 t $ha^{-1}$, and maintain a positive P balance in the soil after each of five successive cropping seasons (Figures 3, 4). This P rate also maintained adequate P levels in extractable P fractions. Applying P fertiliser at rates greater than 8.25 kg $ha^{-1}$ generally did not increase the grain yield (Pheav et al., 2004), but resulted in progressive P accumulation in the soil over consecutive rice crops (Figures 3, 4). Since maximum rice yields on the Prateah Lang soil under rainfed conditions are in the range 2.5 to 3.0 t $ha^{-1}$, the current recommendation of 8 to 10 kg P $ha^{-1}$ annually for rice crops (Seng et al., 2001) maintains a safe margin between P demand by the crop and P supply from the soil. By contrast, the P fertiliser rate in a single irrigated rice crop is often double this, and in double- or triple-cropped irrigated rice may be 40 kg P $ha^{-1}$ (Dobermann et al., 1996; Greenland, 1997). However, in the latter systems, net annual P gains of 4–5 kg P $ha^{-1}$ are reported (Dobermann et al., 1996).

Little information is available on P leaching losses or losses in run-off water in lowland rice paddies. Losses through leaching are thought to occur in sandy lowland rice soils with high water percolation and low P sorption capacity (Lefroy and Konboon, 1998; Linquist et al., 2000). Based on the measured maximum P concentration in the soil solution within the rooting zone (approx. 0.1 mg P $l^{-1}$: Pheav, 2002) and an

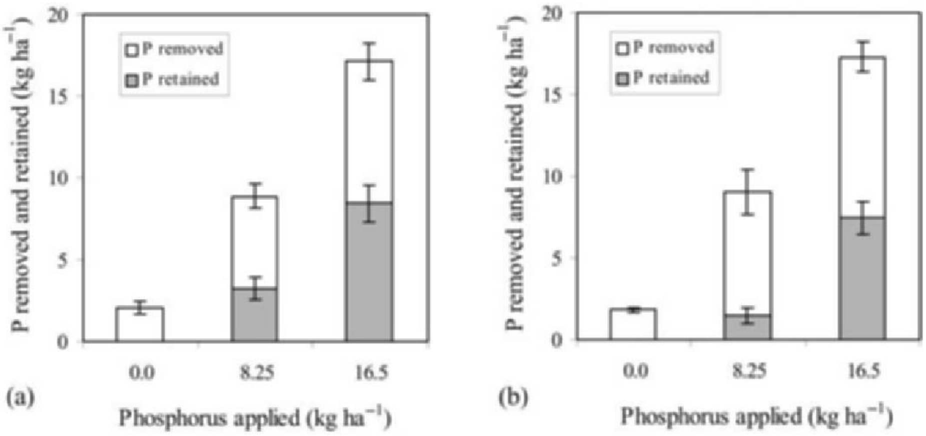


*Figure 3.* Mass balances of P in rainfed lowland rice on a sandy soil over five consecutive rice cropping seasons (Figure 3a means from three wet seasons and Figure 3b means of two irrigated dry season crops) with different P applications per crop. Values are means of four replicates (Pheav et al., 2004).

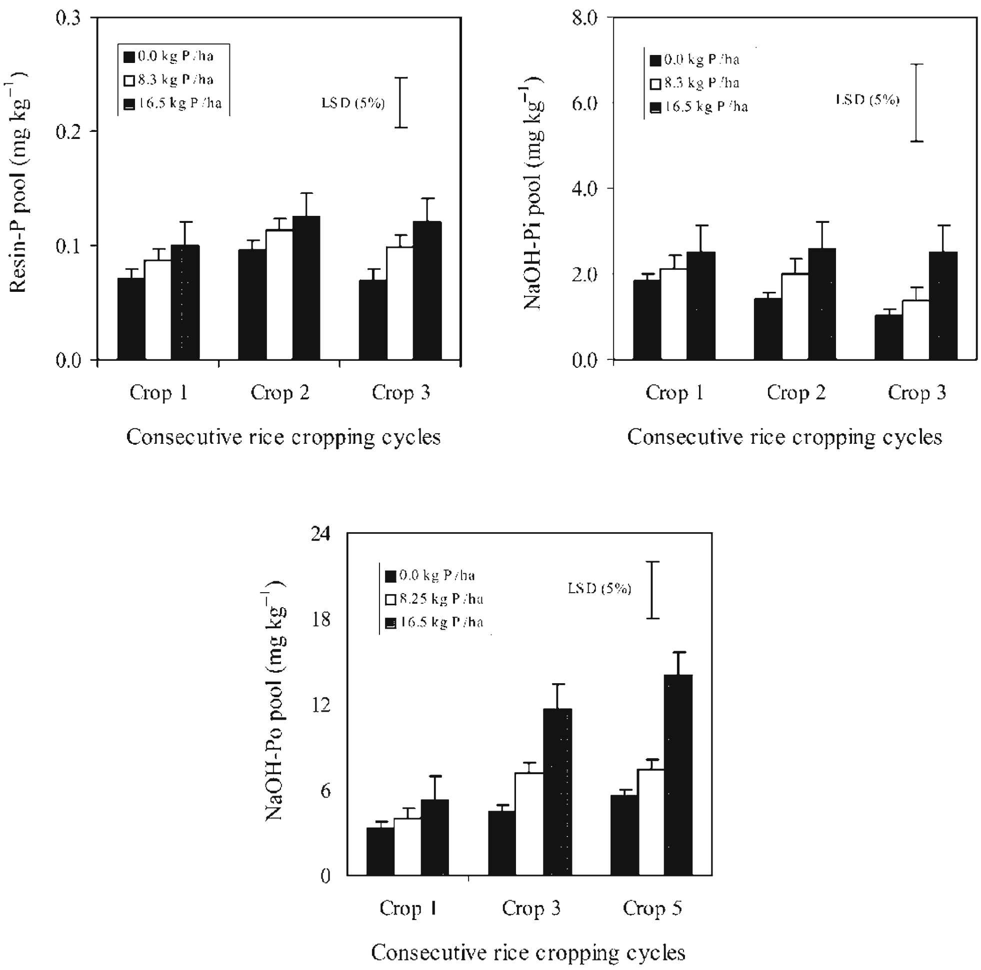


*Figure 4.* Changes in P fractions in a sandy soil over five consecutive rainfed lowland rice crops (3 wet seasons and 2 irrigated dry seasons) with different P applications per crop. Values are means of four replicates. Note the change in scale of Y-axes (Pheav et al., 2004).

estimate of the average percolation rate over the rice growing season based on rainfall less evapotranspiration (4–5 mm $day^{-1}$), Pheav et al. (2004) estimated a maximum leaching loss of about 0.89 kg P $ha^{-1}$ for rainfed lowland rice on the sandy Prateah Lang soil. By comparison, Cho et al. (2000) estimated that at least 0.2 kg P $ha^{-1}$ was leached from irrigated paddy loamy clay soils of central Korea, a similar level to that estimated for irrigated rice by Greenland (1997). Dobermann and White (1999) estimated that 1–2 kg P $ha^{-1}$ is leached from irrigated rice fields when annual P additions are 10–25 kg P $ha^{-1}$ and yield levels are 4–6 t $ha^{-1}$. Maximum rates of P leaching would only be possible when the groundwater drops below the root zone: conditions that do not suit high productivity of lowland rainfed rice (Fukai et al., 1995). If the groundwater is at or above the ploughpan, little P leaching is expected. In our study, after taking into account the fact that the water table was above the plough pan for significant periods during the growing season, the quantitative estimate of average P leached was only 10% of the maximum estimated (0.1 kg P $ha^{-1}$ per growing period) for the sandy Prateah Lang soil (Figure 1; for detailed calculations see Pheav, 2002).

Another possible loss of P is by removal in sediment-laden run-off. However, in general this form of P loss is prevented in experiments by bunds to contain water and P within plots (e.g. Pheav et al., 2003, 2004). On cracking clay soils such as those used to grow rainfed lowland rice in north west Cambodia (White et al., 1997a, b), bypass flow of particulate and dissolved P may redistribute P from the plough layer to below the root zone during the early wet season.

The decline in residual value of P fertiliser with successive crops was reflected in decreasing amounts recovered from all the soil P pools (Resin-P, NaOH-Pi, NaOH-Po, $H_2SO_4$-P, Residual-P) on three contrasting lowland rice soils of Cambodia (Pheav et al., 2002, 2003), suggesting that under flooded conditions all pools were supplying P directly and/or indirectly into the plant available pools. Comparison of the P pools in reduced and oxidised soil (data not shown) indicated that soil reduction mobilised P from all the pools including the Residual-P (Pheav, 2002). The decrease in extractable P is attributed, in part, to immobilisation during soil drying between crops in addition to depletion by plant uptake. It appears that P released by flooding or supplied by fertiliser or microbial mineralisation reacted readily and was incorporated into either labile organic P in the soil, or alternatively, was re-adsorbed or precipitated. The relative importance of soil P pools differed when analysed directly after sampling in a reduced condition compared to the soils that were air-dried before analysis. In the reduced soil, Resin-P and NaOH-Pi appeared to most significant pools for plant and microbial uptake. Most soil P fractions responded dynamically over time to changes in soil water regimes, particularly the Resin-P and NaOH-Pi fractions in the dry and early wet seasons (Figure 5): these changes were linked apparently to intermittent dry and wet cycles in the field during the fallow period. The smallest value of Resin-P and NaOH-Pi fractions were found in the early dry season (Figure 5). Both these inorganic P fractions again increased significantly at the late dry season and then fell slightly at the early wet season. By contrast, the labile organic P (NaOH-Po) fraction steadily increased till the early wet season (Pheav, 2002). It is suggested that soil drying during the dry season causes decreased mineralisation of organic P; it also leads to increased immobilisation of P in the soil organic matter (Sah and Mikkelsen, 1989a, b, c; Willett, 1991; Huguenin-Elie et al., 2003). The increase in inorganic P (Resin-P and NaOH-Pi) fractions at the early wet season can be attributed to the resumption of rainfall, which may accelerate mineralisation of organically-bound P in moist soil conditions or alternatively increase the solubility of Fe-P and Al-P minerals as anaerobic conditions develop. The subsequent decrease in inorganic P fractions at the early wet season could be due to depletion by the P uptake by volunteer pastures, which increased four-fold in biomass between the end of late dry season and early wet season (Pheav, 2002). These results suggest that in the rainfed lowlands with their variable soil water regimes during the dry, early wet and main wet seasons, the soil P pools are very dynamic in both aerobic and anaerobic conditions.

## Conclusions

The P cycling schema developed for sandy rainfed lowland soils has revealed several significant differences compared to those developed for irrigated rice by Greenland (1997) and Dobermann and White (1999). Differences relate largely to the smaller yield and hence smaller P removal by rice in the rainfed lowlands, but also to the P cycled through the volunteer pasture phase in the early wet season, and to the more dynamic soil water regimes that affect soil P pools. There remain gaps in the present P cycling schema

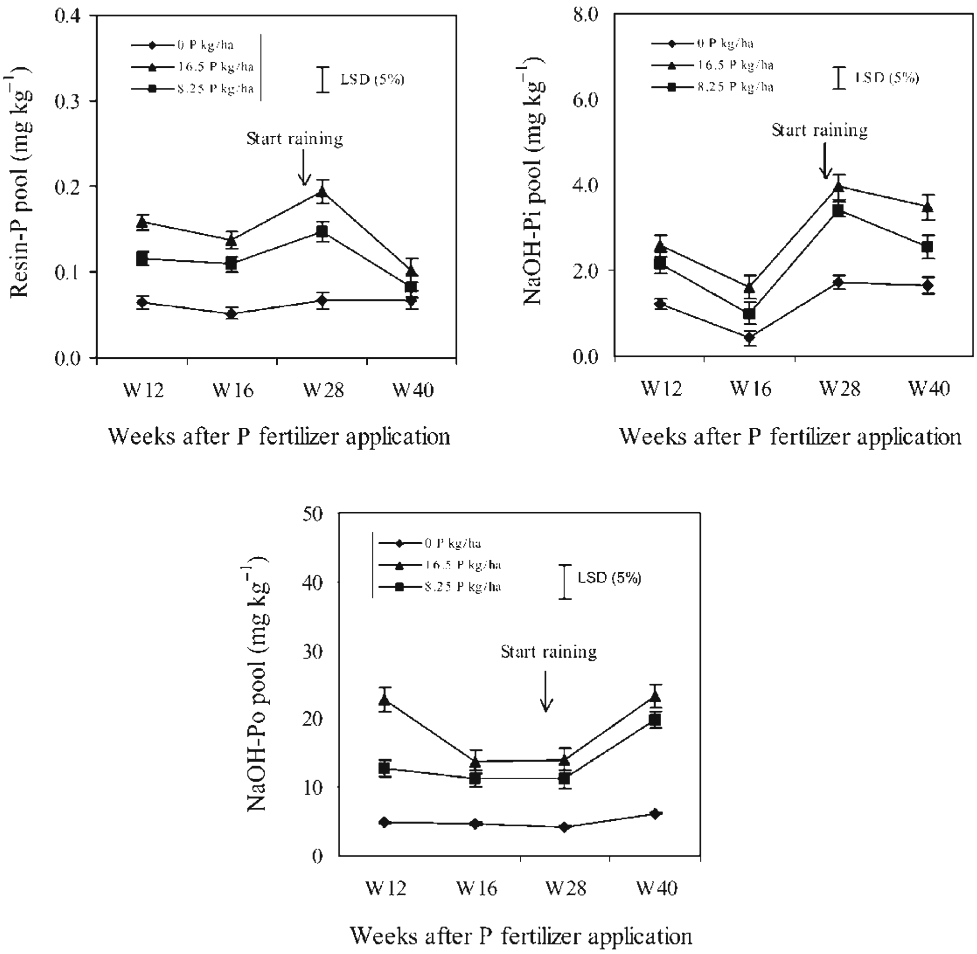


*Figure 5.* Changes in different soil-P fractions in the fallow period: dry season (W12 to W34), and early wet season (W34 to W40) on the plots that received different levels of residual P fertilizer plus straw incorporation in the field condition on a sandy soil. Plotted values are means of four replicates. Note the change in scale of Y-axes (Pheav, 2002). W1 corresponds with transplanting of the preceding main wet season rice crop.

for rainfed lowlands, suggesting further studies are needed on: (1) weeds which may be more prevalent in farmers' fields than experimental fields, affecting P removal in grain, and the amounts of P returned as residue to the soil; (2) pre-rice field crops, direct-seeded rice or double-cropped rice, each of which may change the P forms and availability for the main wet season rice crop; (3) long-term changes in soil properties, especially soil P pools under continuous rice cropping with P fertiliser use; (4) crop P response and mass balances in other major soil types of the rainfed lowlands; and (5) consequences of variable soil water regimes in the main wet season for soluble soil Al levels, P forms and the availability of fertiliser P and residual P and; (6) the effect of grazing animals during the dry season and early wet season on P recycling from the straw and volunteer pastures to the soil.

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