លក្ខណៈសំរូបកម្មនិងការផ្លាច់ចេញ និង ចលនការរំដោះចេញនៃសារធាតុផូស្វ័រ នៅលើ ដីស្រូវស្រែទំនាបបីប្រភេទផ្សេងគ្នា នៅក្នុងប្រទេសកម្ពុជា

PHOSPHATE SORPTION-DESORPTION BEHAVIOUR, AND PHOSPHORUS RELEASE CHARACTERISTICS OF THREE CONTRASTING LOWLAND RICE SOILS OF CAMBODIA

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អត្ថបទសង្ខេប

ការយល់ដឹងនូវលក្ខណៈសំរូបកម្ម (sorption) និងការរំដោះចេញ (release) នៃសារធាតុផូស្វ័រ (P) នៃប្រភេទដីផ្សេង១ ពិតជា អាចជួយសំរួលបានដល់ការកំណត់នូវវត្តិវការសារធាតុផូស្វ័រសំរាប់ការលូត លាស់របស់ដំណាំស្រូវ ។ ទាំងពិសោធន៍នៅក្នុងលស្នុកក្នុងឆ្នាំងកញ្ចក់ និង នៅក្នុងមន្ទីរពិសោធន៍

ត្រូវបានធ្វើឡើងដើម្បីពិនិត្យមើលនូវឥន្ទនការឆ្លុះអង្វែងនៃការរំដោះចេញរ ុនសារធាតុផូស្វ័រពីដី តាមរយៈការប្រើប្រាស់ ជី ទៅលើរបៀលតាស់ដំុងរបស់ដំណាំស្រូវ និងធ្វើការកំណត់ផងដែល នូវលក្ខណៈសំរូបកម្ម និង ការផ្លាច់ចេញ (desorption) នៃសារធាតុ ផូស្វ័រនៅលើដីផ្សេងគ្នាបីប្រភេទនៃប្រទេសកម្ពុជា ជាអាទ៍រួមមានៈ ក្រុមដីប្រទេស្ឡាង គោកត្រប់ និង ក្រុមដីទូលសំរោង ។ ចំពោះពិសោធន៍ នៅក្នុងឆ្នាំងកញ្ចក់ គឺដំណាំស្រូវត្រូវបានដាំដុះ ចំនួន ៥ វដ្តជីវិតជាបន្តបន្ទាប់ ដោយក្នុង១វដ្តជីវិតមានរយៈពេលពី ៦ ទៅ ៨ សប្តាហ៍ ដោយប្រើ ជីផូស្វ័រចំនួន ៤ កំរិត ០, ៥, ១០, និង ២០ មក្រ/តក្រជី ។ ចលនការសំរូបកម្ម និង ការផ្លាច់ចេញ (sorption-desorption isotherms) នៃសារធាតុផូស្វ័រ ត្រូវបានប្រព្រឹត្តទៅដោយដំបូងឡើយធ្វើអោយដីមានតុល្យភាព (equilibrate) ជាមួយកំរិតផូស្វ័រផ្សេង១ ដូចជា ០, ១០, ២០, និង ៤០មក្រ/តក្រជី ក្នុងសូលុយស្យុងកាល់ស្យុមក្លួ (CaCl₂) ដែលមានកំហាប់ ០.០១ ម៉ូល នៅសីតុណ្ហភាព ២៥ អង្សារសេ ។

នៅលើប្រភេទដីខ្សាច់ប្រទេស្ឡាង និង ដីឥដ្ឋទូលសំរោង ការដាក់ជីផូស្វ័រក្នុងបរិមាណ ១០មក្រ/តក្រជី មានលក្ខណៈគ្រប់គ្រាន់សំរាប់ អោយដំណាំស្រូវបង្កើតបាននូវបរិមាណអតិបរិមានៃ ចំនួនដើមបែក កំពស់ដើម ទំងន់សារធាតុស្ងួត កំហាប់សារធាតុផូស្វ័រ និង បរិមាណ សំរូបផូស្វ័រសរុប (total P uptake) ដោយរុក្ខជាតិ ។

ផ្ទុយទៅវិញនៅលើក្រុមដីឥដ្ឋអាស៊ីតគោកត្រប់ ដំណាំស្រូវត្រូវការសារធាតុផូស្វ័ររហូត ដល់បរិមាណ ២០មក្រ/តក្រជី ដើម្បីអោយការលូតលាស់ និងបរិមាណសំរូបផូស្វ័រសរុបរបស់វាមានលក្ខណៈ អតិបរិមា ។ ជារួមយើងសង្កេត ឃើញថានៅលើគ្រប់ប្រភេទដី បន្ទាប់ពីពីរវដ្តដាំដុះរួចមក ការលូតលាស់របស់ដំណាំស្រូវត្រូវថយចុះយ៉ាងខ្លាំងនៅគ្រប់កំរិតដី ដែលបាន ប្រើប្រាស់នៅក្នុងវដ្តដាំដុះទី១ ក៏ប៉ុន្តែការថយចុះខាងផ្នែកទិន្នផល និង បរិមាណសំរូបផូស្វ័រសរុបរបស់ដំណាំស្រូវ ដែលដាំដុះនៅលើប្រភេទដីឥដ្ឋ ទូលសំរោង និង គោកត្រប់ មានលក្ខណៈតិចតួចជាងដំណាំស្រូវ ដែលដាំដុះនៅលើដីខ្សាច់ប្រទេស្ឡាង ។

ទំរង់ផូស្វ័រអាចស្រូបបានដោយរុក្ខជាតិ (Resin-P) គឺជាទំរង់ (fraction) មួយដែលមានបរិមាណតិចជាងគេបំផុត បើប្រៀបធៀប ទៅនឹងទំរង់ផូស្វ័រចំបង១នៅក្នុងដីដូចជា NaOH-Pi, NaOH-Po និង Residual-P នៅលើគ្រប់ប្រភេទដី ។ ក៏ប៉ុន្តែទំរង់ផូស្វ័រ Resin-P នេះត្រូវបានគេពិនិត្យឃើញនៅលើដីខ្សាច់ប្រទេស្ឡាង មានបរិមាណច្រើនជាង នៅក្នុងដីឥដ្ឋទូលសំរោង និង គោកត្រប់ ។ គេតកត់សំគាល់ឃើញ ទៀតថា មានការថយចុះខាងបរិមាណនៃគ្រប់ទំរង់ផូស្វ័រ ជាពិសេស ទំរង់ផូស្វ័រចំបង១ (NaOH-Pi, NaOH-Po និង Residual-P) នៅគ្រប់វដ្តដាំដុះដំណាំស្រូវ ។ បញ្ហានេះអាចបណ្តាលមកពីប្រតិកម្មជាបន្តបន្ទាប់នៃជីផូស្វ័រវិលលបានប្រើជ ាមួយជី បន្ថែមទៅលើបរិមាណផូស្វ័រ សរុប ដែលដំណាំស្រូវស្រូបយកក្នុងវដ្តដាំដុះនីមួយ១ ។

នៅក្នុងលស្នុកក្នុងឌីស្តូត (oxidized condition) ប្រភេទដីឥដ្ឋគោកត្រប់ និង ទូលសំរោង ស្រូបសារធាតុផូស្វ័រ ៥ ដង ច្រើនជាង ប្រភេទដីខ្សាច់ប្រទេស្ឡាង នៅពេលកំរិតផូស្វ័ររូបមាណជា

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២០មក្រ/តក្រដី ត្រូវបានប្រើប្រាស់ ។ ការផ្ដាច់ចេញនូវសារធាតុផូស្វ័រពីដី ត្រូវបាន សង្កេតឃើញដំបូងឡើយមានបរិមាណច្រើននៅលើដីខ្សាច់ប្រទេសឡាង ប៉ុន្តែវាក៏បានថយចុះមកវិញឆាប់រហ័សជាងដីខ្ពង់ ទួលសំរោង និង គោកត្រប់ នៅពេលគេបង្កើនចំនួននិស្សារណកម្ម (extraction) នៃដី ។ ហើយគេពិនិត្យឃើញទៀតថា បរិមាណសរុបនៃផូស្វ័រដែលផ្ដាច់ ចេញពីដីខ្ពង់គោកត្រប់ និង ទួលសំរោង ច្រើនជាងដីខ្សាច់ប្រទេសឡាង ។ ការស្រូបសារធាតុផូស្វ័រដ៏ច្រើនលើសលប់របស់ដីប្រភេទឥដ្ឋ ក៏បាននាំឱ្យសំណល់នៃសារធាតុផូស្វ័រ មានប្រសិទ្ធភាពយូរអង្វែងងងដែរ ទៅលើការដាំដុះដំណាំស្រូវ ។

ពាក្យគន្លឹះ៖ ដីស្រូវស្រែទំនាប សារធាតុផូស្វ័រ លក្ខណៈនៃការរំដោះចេញ ប្រសិទ្ធភាពកាកសំណល់ ទំរង់ផូស្វ័រនៃដី សំរុបកម្ម និងការផ្ដាច់ចេញ

ABSTRACT

Understanding the P sorption and release characteristics of different soils can help in determining fertiliser P requirements for the growth of rice (*Oryza sativa* L.). Glasshouse and laboratory experiments were undertaken to observe the long-term release characteristics of P from added fertiliser for the early growth of rice, and also to determine P sorption-desorption behaviour of three contrasting lowland soils from Cambodia: Prateah Lang (Plinthustalf), Koktrap (Plinthaquult) and Toul Samroung (Endoaqualf). In the pot experiment, rice was treated with four P rates (0, 5, 10 and 20 mg/kg soil) and grown over five successive cropping cycles, each of six to eight weeks. Phosphorus sorption-desorption isotherms were constructed by equilibrating with 0, 10, 20 and 40 mg P/l in 0.01 M CaCl$_2$ solution at 25 ^{o}C.

On the sandy Prateah Lang (PL) and clayey Toul Samroung (TS) soils, addition of 10 mg P/kg soil was adequate in the first crop for maximum tiller number, plant height, total dry matter, P concentration, and total P uptake. By contrast, about 20 mg P/kg was needed for the maximum growth and total P uptake on the clayey acid Koktrap (KT) soil. After two crops, plant growth progressively declined at all P levels, but the decrease in yields and total P uptake on the clayey TS and KT soils was slower than for plants grown on the sandy PL soil.

Resin-P extractable was the smallest P fraction compared to other major soil-P (NaOH-Pi, NaOH-Po and Residual-P) pools in all soil groups, but recovery from the Resin-P pool was higher in the sandy PL soil than in the clayey TS and KT soils. The declining amounts recovered from all the extractable soil P fractions, especially major soil P (NaOH-Pi and Po and Residual-P) pools with succeeding rice crops grown on all the soils could be attributed to continued reactions of the added P fertiliser by soils in addition to plant P uptake during each plant-growing cycle.

The clayey KT and TS soils sorbed five-fold more P than the sandy PL soil in oxidized conditions. Phosphorus desorption was initially greatest from the sandy PL soil: but with increasing numbers of soil extractions, the release of sorbed P declined faster than in the clayey KT and TS soils. The cumulative desorbed P was greater from the clayey KT and TS soil than from the sandy PL soil. The greater P sorbed by the clayey soils should ensure a longer duration of the residual P effect.

INTRODUCTION

The cause of limiting phosphorus (P) supply for rice crops may be low total P contents and/or a high P sorption capacity of the soil. In Cambodia, the extent to which soil groups identified by White *et al*. (1997a,b) for rice agronomic management differ in their P sorption-desorption behaviour and P release characteristics has yet to be tested. Some studies have been conducted on the short-term crop responses to P fertiliser application (CIAP, 1995, 1996; White and Seng, 1997), and a recent study examined residual value of applied P fertiliser over 5 successive rice crops on the Prateah Lang soil (Pheav *et al*., 2003). Other studies have also examined the dynamics of P availability under alternating reduced and oxidized conditions (Seng *et al*., 1999). It is crucial to determine the long-term P supplying characteristics of a range of important rainfed lowland rice soils in Cambodia.

Understanding of the P sorption-desorption processes of different soils can help in determining comparative P requirements for plants (Kuo *et al*., 1988). The agronomic efficiency of P fertiliser is strongly dependent on the P sorption-desorption capacity of the soils (Singh and Gilkes, 1991). Hence, data on soil chemical properties, including P sorption-desorption reactions in different soils is critical for managing P fertiliser supply and recommendations. Indeed, for further developing soil P management strategies and recommendations, soils may be grouped together on the basis of their ability to release and retain P from fertiliser added, as well as native soil P.

Phosphate sorption characteristics of the soil are important properties in determining fertiliser requirements of crop growth, because adsorbed P

equilibrates with P in the soil solution and this P is, in turn, the immediate source of P for plant uptake (Fox and Searle, 1980). Soil properties and environmental conditions affect the P adsorption capacity (Syers *et al*., 1971; Goldberg and Glaubig, 1988; Cristensen, 1989; Sposito, 1989; Zachara *et al*. 1989; Schuster, 1991; Lee *et al*. 1996).

Adsorption capacities typically vary amongst soil types. Some soils have low sorption capacities and hence hold small reserves of P within the soil. The P sorption of soils developed on materials high in quartz was moderate to low, and these soils have modest fertiliser requirements (Mokwunye, 1977). However, other soils have high sorption capacities, and probably, a high capacity to retain P within the soil for an extended period. Fox and Searle (1980) reported that all soils, in which 2:1 and 1:1 type clays predominate, as a general rule, absorb large amounts of P. Sandy soils may have less sorption per unit soil weight, whereas, soils rich in clay minerals and sesquioxides have the greater sorption (Sanyal *et al*., 1993). In a study of P sorption of two soils of southeast Cambodia, Seng (2000) found that a black clayey acidic soil (Koktrap: White *et al*., 1997a, b) sorbed about five-fold greater P concentration than a sandy acid soil (Prateah Lang: White *et al*., 1997a,b) under oxidised conditions.

In summary, with various soil types in different environments, P sorption-desorption processes have been found to vary with forms of Fe and Al, soil pH, organic carbon, clay and carbonate contents and other soil properties (Saunders, 1965; Hinga, 1973; Ballard and Fiskell, 1974; Holford and Patrick, 1979; Ping and Michaelson, 1986). More details of relevant soil properties and soil-water regimes influencing the P sorption-desorption mechanisms in lowland and upland soils were reviewed by Pheav (2002).

However, the factors associated with P sorption-desorption processes in major Cambodian rice soils have not been fully identified. This research was conducted to determine the long-term P release characteristics, and availability of P from fertiliser added to the flooded soils planted to rice over five successive cropping cycles each separated by a 2-week oxidised fallow period. The P sorption-desorption behaviour in three contrasting lowland rainfed rice-growing soils of Cambodia was also examined under the aerobic conditions.

MATERIALS AND METHODS

Soil sampling

Three contrasting soil types were selected for both the pot and P sorption-desorption experiments: Prateah Lang (PL), Koktrap (KT) and Toul Samroung (TS) (White *et al*., 1997a,b); Plinthustalf, Plinthaquult and Endoaqualf (Soil Survey Staff, 1994). Prateah Lang and Koktrap soils both varied from moderately to strongly acidic, whereas, the Toul Samroung soil was closer to neutral. Their main properties are presented in Table 1.

The soils used in both the glasshouse and laboratory experiments originated from farmers' rice paddy fields in Cambodia. Usually, these soils were cultivated with rice during the wet season each year. The top 20-cm layer was collected during the dry season when soil was in fallow. Care was taken to ensure soil samples were collected from fields with no recent history of inorganic P fertiliser application. Soils were sun-dried and crushed, all stones and coarse organic debris removed, and then the soils were sieved to pass through a 2-mm screen.

Table 1. Selected properties of the three major rainfed lowland rice-growing soils of Cambodia used for both pot and laboratory experiments (0-20 cm depth, sieved to < 2.0 mm). Values are means of 249 samples.

Major properties	Prateah Lang soil	Toul Samroung soil	Koktrap soil
pH (1:1 H_2O)	5.4	5.6	5.1
Organic C (g/kg)	4.0	9.0	13.0
Sand (g/kg)	498	355	279
Silt (g/kg)	370	410	293
Clay (g/kg)	132	229	416
CEC [$cmol_c$ (+)/kg]	3.7	15.9	8.1
Exch. Ca [$cmol_c$ (+)/kg]	1.2	7.1	1.1
Exch. Mg [$cmol_c$ (+)/kg]	0.5	3.3	0.6
Exch. K [$cmol_c$ (+)/kg]	0.1	0.2	0.1
Exch. Na [$cmol_c$ (+)/kg]	0.4	0.3	0.3

Data source: Oberthur et al. (2000)

Pot experiment

The P exhaustion pot experiment was conducted in the glasshouse within the compound of the Ministry of Agriculture, Forestry and Fisheries, Phnom Penh, Cambodia. This pot trial was commenced in July 1998 (wet season), and ended in May 1999 (dry season). Five consecutive cropping cycles of rice were examined. Rice plants were grown for six weeks prior to harvest in the first cycle and for eight weeks during the second to fifth cycles. The experiment was arranged as a randomized complete block (RCB) design with factorial combinations of three soil types (PL, KT and TS) and four levels of P fertiliser (0, 5, 10 and 20 mg P/kg soil) with four replicates, giving a total of 48 pots.

Phosphate fertiliser was supplied as potassium dihydrogen orthophosphate (KH_2PO_4). In addition to P fertiliser, other nutrients in solution were applied basally to the soil during the first cycle at the following rates (mg/kg soil): NH_4NO_3: 200; K_2SO_4: 142; $CaCl_2.2H_2O$: 71; $MgSO_4.7H_2O$: 21; $MnSO_4.H_2O$: 15; $ZnSO_4.7H_2O$: 10; $CuSO_4.5H_2O$: 5; H_3BO_3: 0.71 and Na_2MoO_4: 0.6. From one week after planting, 4 ml of NH_4NO_3 solution (28 mg N/kg soil) was also top-dressed weekly to ensure that plants did not experience N deficiency at any stage. Phosphorus fertiliser was only added at the beginning of the first cycle, whereas N, K, S and Mg fertilisers were applied in every cropping cycle. Based on symptoms of N, K, S and Mg deficiencies that appeared in plants in the first cropping cycle, these fertilisers were increased in subsequent cycles to equal rates (mg/kg) used by Lor *et al*. (1996): NH_4NO_3: 479; KNO_3: 230; Na_2SO_4: 110; and $MgCl_2.2H_2O$: 137. The application of complete micronutrients (as shown above) was repeated at the beginning of the fifth cropping cycle.

The soil was mixed thoroughly before 10-kg portions were placed in double plastic lined bags into undrained PVC pots. All nutrients were firstly applied to the soil surface, allowed to sun dry and then mixed by shaking to distribute the nutrients evenly throughout the soil. The soil was then wetted with deionised water (DI) to field capacity one week before germinated rice seeds were planted. Thereafter, all pots were flooded to a depth of 4-5 cm and maintained at this level throughout the rice-growth cycle by daily watering. Between cycles dry soils for two weeks.

Rice (*Oryza sativa* L.), cv. IR64 seeds were germinated for 48 to 72 h in Petri-dishes on a filter paper moistened with a combination of 1.0 mM $CaSO_4$ and 10 μM H_3BO_3 solution at room temperature (modified from De Datta, 1981). Ten germinated rice seeds per pot were sown at 0.5 to 1.0

cm depth. One week after emergence, healthy plants with similar physical appearance were selected and thinned to five plants per pot. All pots were re-positioned every three days to avoid positional effects on plant growth.

Six to eight weeks after sowing, when rice was at the maximum tillering stage, shoot and roots were harvested to determine dry matter (DM) and the P content of plants. Shoots were cut at ground level, and roots gently pulled up by hand and recovered after careful washing with DI water to remove soil. Both shoot and roots were oven-dried at 75 °C for 48 h until reaching constant weight. Fresh and dry weights of plant samples were recorded. Plant height and tiller number per pot were also measured. After oven drying, plant materials were chopped and finely milled by an electrical grinder, then a sub-sample of about 10 g/sample was packed in a sealed plastic bag and stored at 4 °C prior to utilisation. Phosphorus concentrations were determined with inductively coupled plasma atomic emission spectrometry (ICP-AES) after samples were digested with concentrated nitric acid (HNO_3) at 140 °C (Zarcinas *et al*., 1987).

In each cropping cycle, soils were sampled at harvest from those pots that received nil-P and the highest P (20 mg/kg soil) levels. The flooded soil was stirred thoroughly and 50 g/pot removed from 0-10 cm depth. The soil samples were oven-dried at 50 °C, and then crushed, their coarse organic debris was removed and samples were packed (20 g/sample) for subsequent nutrient analyses. A sequential soil P fractionation method was used, involving modifications to the procedure of Hedley *et al*. (1994) to make it suitable for highly weathered sandy soils of Cambodia as described in Pheav *et al*. (2003).

Phosphorus sorption-desorption experiment

All soil samples were incubated in aerobic conditions at constant temperature of 25 °C for 2 weeks prior to the soil P sorption-desorption analyses. Phosphorus sorption-desorption experiments used the procedures of Ozanne and Shaw (1967).

For P sorption: triplicate 1.0 g samples of the air-dry soil were placed in 50-ml centrifuge tubes and suspended in 20 ml of 0.01 M $CaCl_2$ solution containing 0, 10, 20 and 40 mg P/l as KH_2PO_4. In each tube, two drops of ethanol-free chloroform were added to minimize microbial activity. Equilibration was carried out in an end-over-end shaker for 17 h with temperature at 21-25 °C. The samples were then centrifuged for 10 minutes at 2000 rpm, and filtered through Whatman # 42 filter paper. Phosphorus in the solution was determined by the method of Murphy and Riley (1962). The amount of P sorbed was

calculated from the difference between initial and final P concentrations.

Phosphorus desorption was quantified by initially equilibrating air-dried soil samples, that were pre-treated with the same P levels as above, with 20 ml of 0.01 M $CaCl_2$. The amount of P sorbed by the soil after a 17-h equilibration represented the starting value for absorbed P. The soils were subjected to sequential desorption with 20 ml of 0.01 M $CaCl_2$ (P-free), re-equilibrated in the end-over-end shaker for 17 h at 21-25 ^oC. Phosphorus in the extracts after centrifugation and filtration was analysed as described above. This cycle was repeated until P recovery in the extracts approached zero (below detection) or a constant value. Normally, a total of 8 to 18 extractable steps are required, depending on soil types and P concentrations added (Rhue *et al*., 1994; Harris *et al*., 1996; Villapando and Graetz, 2001). Desorbable P was determined by summing the total P desorbed after successive extractions.

Statistical analysis

For every cropping cycle of the pot experiment, an analysis of variance (Two-way ANOVA) for each of the growth parameters was undertaken to determine treatment effects using the IRRISTAT software package for Windows, version 4.03 (IRRI, 1997). When the treatment effects were significant, the least significant difference (LSD) was used for mean comparisons.

RESULTS

Growth and P uptake response to phosphorus fertiliser

Plants grown on all the soils responded strongly to the application of P fertiliser for all the characters measured. With 10 mg P/kg added to soils, plant height, tiller number (Table 2), shoot and root dry matter (DM) (Figure 1), and total plant P uptake (data not shown) significantly ($p<0.01$) increased. About 10 mg P/kg applied to Prateah Lang (PL) and Toul Samroung (TS) soils was required for maximum shoot DM of rice in crop one, and 20 mg P/kg soil was required for the maximum shoot DM on Koktrap (KT) soil.

Table 2. Response of maximum tiller number and plant height of rice to single application of P fertilisers 6 to 8 weeks after sowing on three contrasting lowland rice soils of Cambodia over five successive cropping cycles. The values are means of four replicates. Data of the nil-P treatment is not presented here because of other basal nutrients than P were applied different levels from the P treated plots, and varied from one crop to another.

Treatment		Crop 1		Crop 2		Crop 3		Crop 4		Crop 5	
Soil	P level	Tiller	Height	Tiller	Height	Tiller	Height	Tiller	Height	Tiller	Height
	(mg/kg)	(no/pot)	(cm)	(no/pot)	(cm)	(no/poi)	(cm)	(no/pot)	(cm)	(no/pot)	(cm)
PL	5	65	73	17	49	17	40	11	43	10	32
	10	76	64	24	54	37	47	19	48	10	31
	20	86	74	60	66	42	50	21	53	10	33
KT	5	35	62	14	48	11	43	10	38	13	38
	10	40	67	13	47	22	47	14	44	18	40
	20	53	68	53	67	59	57	43	66	28	48
TS	5	32	67	31	61	10	44	10	35	10	32
	10	53	72	33	59	16	45	12	31	10	28
	20	54	78	46	65	42	58	17	53	21	41
F (PL)		**	*	**	**	**	ns	**	ns	ns	ns
F (KT)		**	**	**	**	**	**	**	**	**	**
F (TS)		**	**	**	*	**	*	**	**	**	**
F (S x P)		**	**	**	**	**	*	**	**	**	**

* Indicates statistical significance amongst P treatments: ns: not significant,* $p\leq0.05$, **$p<0.01$.

A four-fold increase in shoot DM was recorded with the application of P at 20 mg/kg on the PL soil, more than six-fold on the KT soil, and up to eight-fold on the TS soil, compared to pots receiving no P fertiliser (Figure 1). Root dry weights showed similar responses to those of the shoot DM in the first crop. The greatest increase in the root growth was obtained for the plants growing on the PL soil with 10-20 mg P/kg soil treatment (Figure1).

Phosphorus concentrations in shoots increased sharply ($p<0.01$) with P fertiliser application. The P concentrations of the shoots were 2.6, 2.0 and 1.8 g P/kg for the PL, TS and KT soils, respectively, at 20 mg P/kg treatment (data not shown) in the first crop in each treatment (data not shown). By contrast, from the second crop, P concentrations in the shoots of the plants grown on the TS and KT soils were greater than in those plants grown on the PL soil (data not shown).

The shoot dry weight was positively correlated with P concentrations in plants grown on all the soil groups over five successive rice crops (Figure 2). Indeed, total P uptake increased with P fertiliser application on all the soils. The highest P uptake by rice grown on the PL soil was about two-fold greater than for the plants grown on both the KT and TS soils at the 20 mg P/kg soil (Figure 2). The reduction of total P uptake over successive cropping cycles was closely related with decreasing shoot DM, especially with lower P supply (Figures 1, 2). The decline in rice growth was greater for plants growing on the PL soil than for those plants growing on the KT and TS soils (Figure 1).

Soil P fractions

Resin-extractable P was the smallest (< 0.2 mg P/kg) amongst all P fractions of all soil types (Figure 3). The Resin-P extractable fraction, however, was higher in the sandy PL soil than in the clayey KT and TS soils. After one crop, both labile P (NaOH-Pi and NaOH-Po) and occluded P (Residual-P) fractions were the largest pools of extracted P from all the soils (Figure 3). The size of extractable P pools decreased on all the soils in succeeding cropping cycles. The decline in labile NaOH-P pools was greater in the clayey KT and TS soils than in the sandy PL soil (Figure 3).

The total P uptake of rice was almost equally well correlated with the soil P levels in each of the fractions for all three soil groups (Figure 4). Plant P uptake was much more responsive in the PL soil to increases in each of the P fractions than in other soils.

Phosphorus sorption-desorption levels

The sandy PL soil adsorbed about one-fifth of the P adsorbed by clayey KT and TS soils when P in the initial solution was 20 mg P/l (Figure 5). Amongst the three soil groups, KT adsorbed almost 100 % of P applied even when the addition of P was up to 40 mg P/l, whereas, only about 75 % and 26 % of the added P fertiliser in solution were sorbed by the clayey TS and PL soils, respectively (data not shown).

The desorption of P was much greater in the sandy PL soil than the clayey TS and KT soils after the first soil extraction with all added P levels (Figure 6)
. Phosphorus released from the PL soil after one desorption cycle was about two-fold and six-fold higher than the clayey TS and KT soils, respectively. However, after two extractions the desorbed P from the TS and KT soils decreased only slightly or remained constant at about 5 and 3 mg P/kg for more than eight soil extractions, unlike the sandy PL soil, on which the desorbed P level dropped quickly and levelled off at close to zero at the fifth soil extraction (Figure 6).

There was a negative relationship between P sorption and total P uptake of rice grown on different soil types (data not shown). For example, with P added at 20 mg/l, the soils sorbed about 81, 384 and 395 mg P/kg, corresponding with the total uptake of 127, 64 and 57 mg P/pot by rice plants growing on the PL, TS and KT soils, respectively (Figure 4). This suggested that the more P that was sorbed by the soil, the less available the P was for plant uptake.
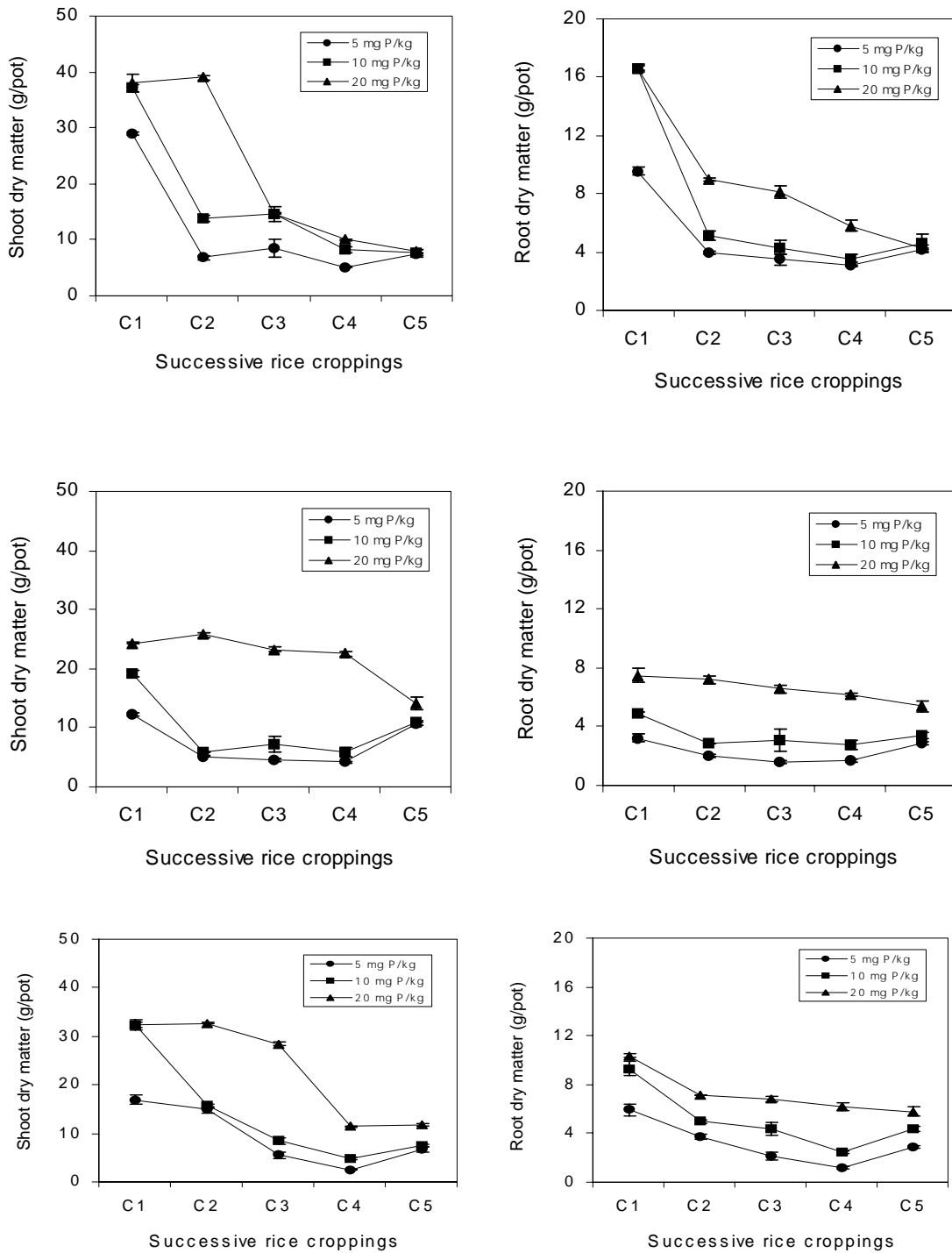
Figure 1. Shoot and root dry matter of rice in response to single applications of different P levels on the three contrasting lowland rice soils of Cambodia over five successive cropping cycles. Plotted values are means of four replicates. Vertical bars represent standard errors of four replicates. Data of the nil-P treatment is not presented here because of other basal nutrients than P were applied different levels from the P treated plots, and varied from one crop to another.
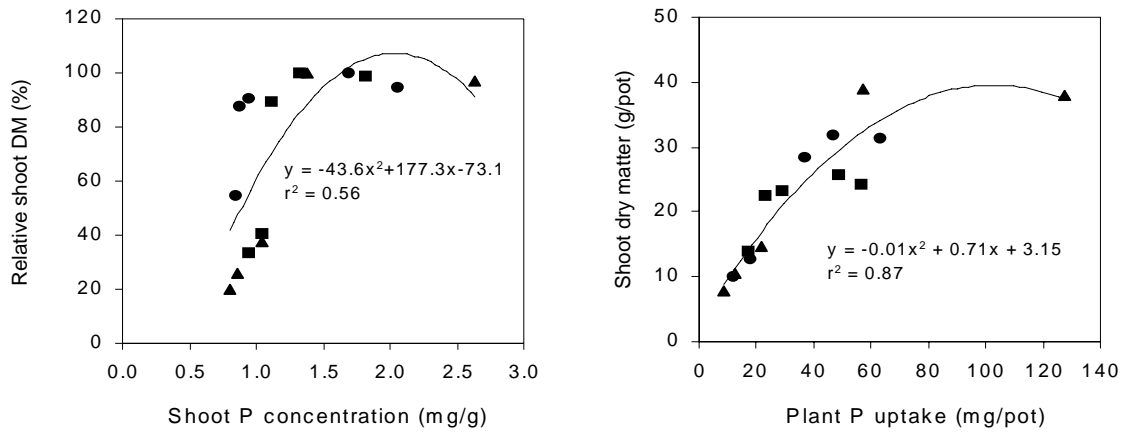
Figure 2. The relationship between the relative shoot DM and shoot-P concentration, and total plant P uptake (shoot and root) of rice grown with the high-P (20 mg P/kg) on the three contrasting lowland rice soils of Cambodia (¡¶: Prateah Lang; ¡´: Koktrap; ¡½: Toul Samroung) over five successive cropping cycles. Plotted values are means of four replicates.
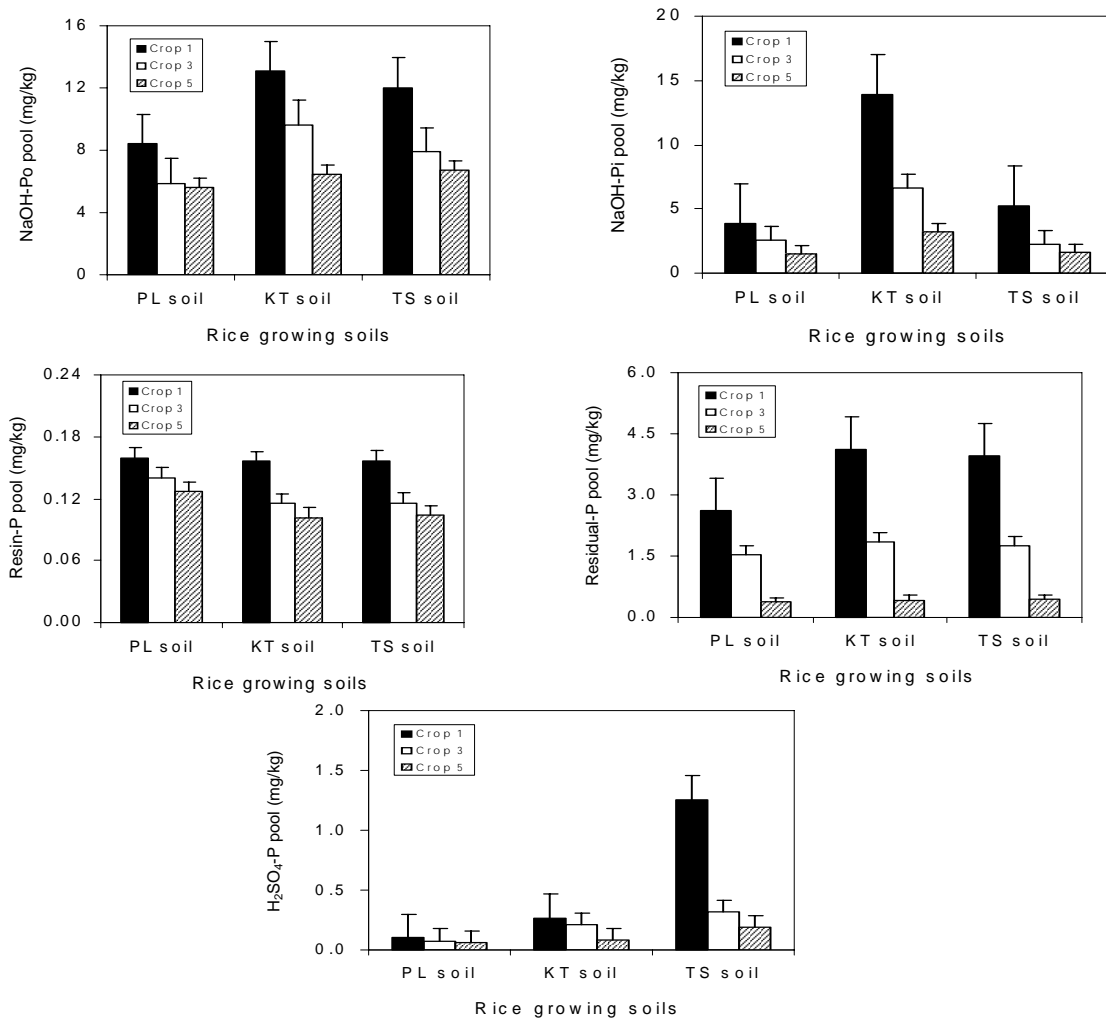

Figure.3 Extractable P fractions of the Pateah Lang (PL), Koktrap (KT), and Toul Samroung (TS) soils with the high-P (20 mg/kg) treated soil over five successive cropping cycles. Plotted values are means in the first, third and fifth crops. Vertical bars denote standard errors of four replicates.
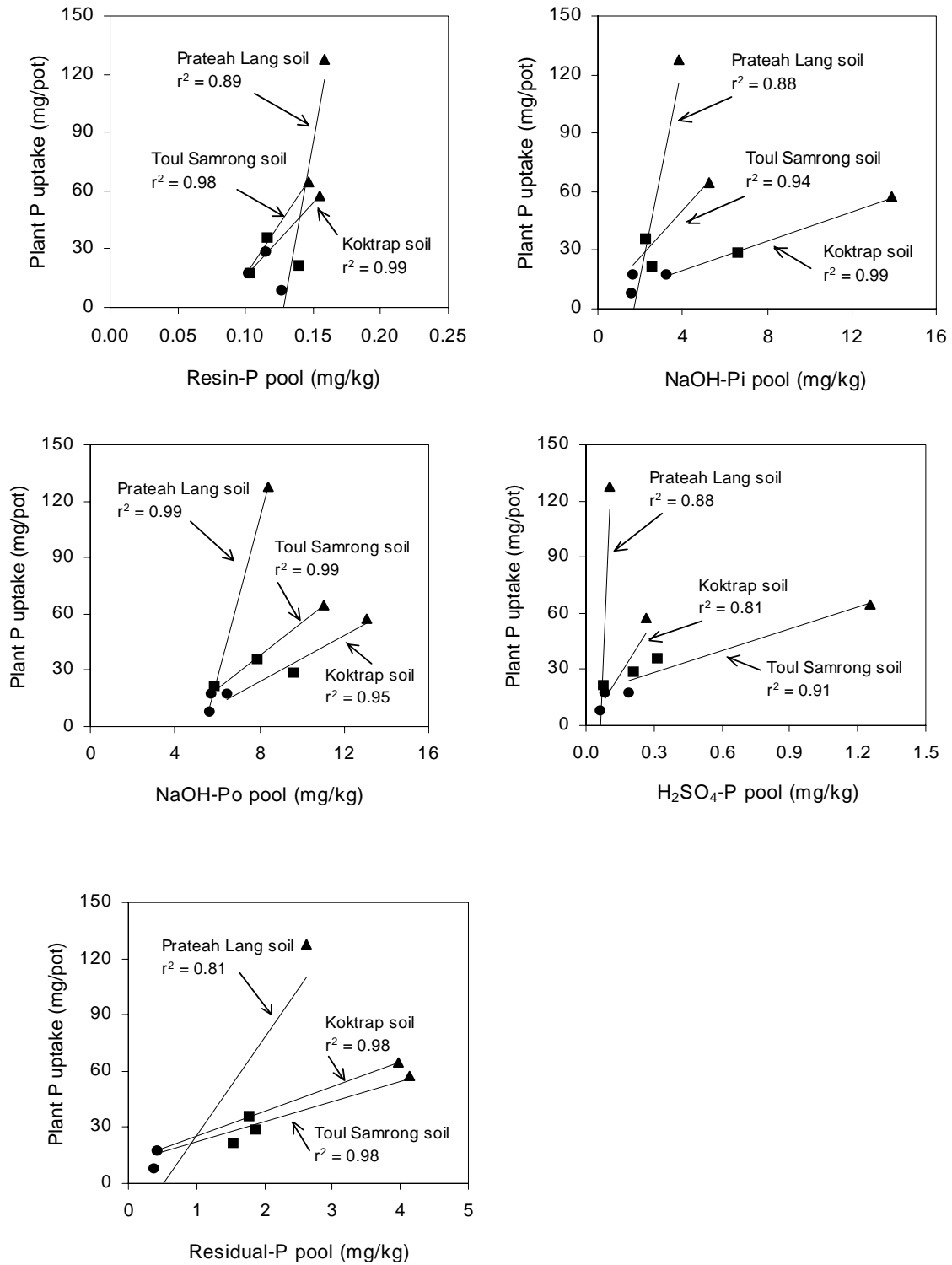
Figure 4. The relationship between soil-P fractions and total P uptake of rice grown with the high-P (20 mg/kg) treatment on the three contrasting lowland soils over five successive rice cycles. Values are the means of P fertiliser treatments in the first (¡¶), third (¡´), and fifth (¡½) crops. Note the change in scales of X-axis.
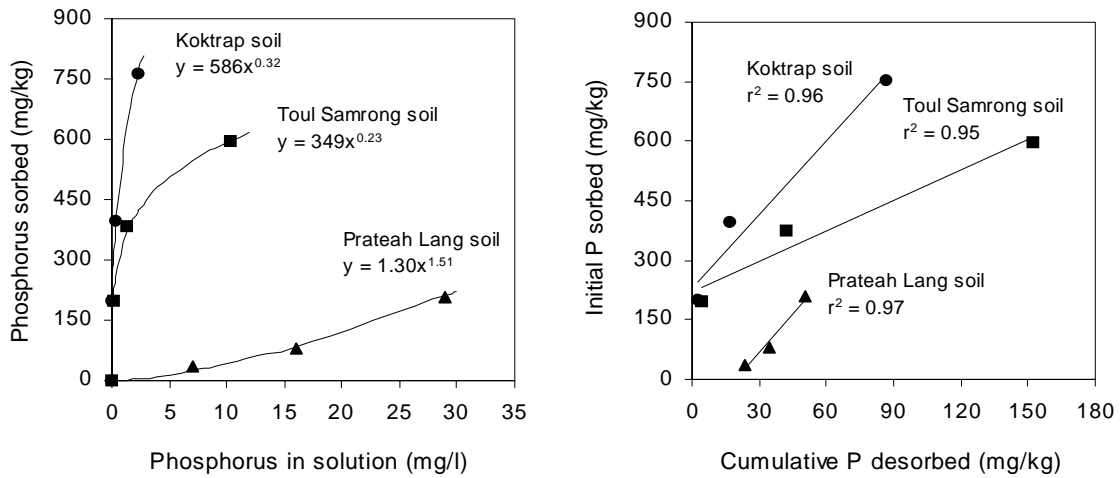
Figure 5. Phosphate sorption isotherms fitted by the Freundlich model, and the relationship between the initial P sorbed, and cumulative P-desorbed after eight successive soil extractions of the three contrasting rainfed lowland rice-growing soils of Cambodia. Plotted values are means of three replicates.
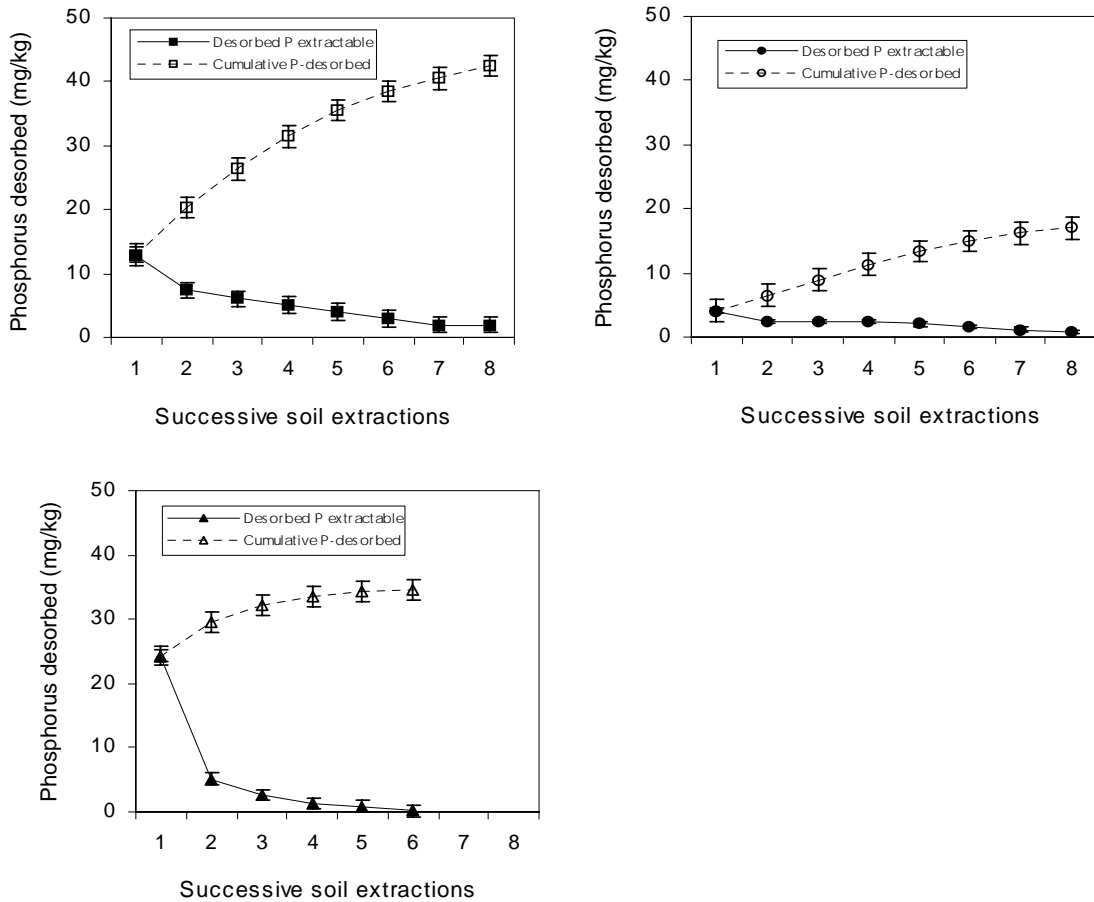

Figure 6. Sequential P desorption and cumulative P desorption of three rainfed lowland rice soils of Cambodia equilibrated over six to eight successive soil extractions after initial loading with 20 mg P/l added in solution. Plotted values are means of three replicates. Vertical bars represent standard errors of three replicates.

Table 3. Phosphorus uptake and efficiency of phosphorus recovery of rice plants from single applications of P fertiliser on three contrasting lowland rice soils of Cambodia over five successive cropping cycles. The values are means of four replicates.

Soil type	Rice cropping cycle	Plant P uptake (mg/pot)			[†]Recovery of P fertiliser (%)
		Shoot	Root	Total plant	
Prateah Lang	Crop 1	96.6	29.4	126.1	56
	Crop 2	49.6	5.6	55.2	20
	Crop 3	17.6	3.8	21.4	4
	Crop 4	9.6	2.5	12.1	-1
	Crop 5	7.1	1.4	8.4	-2
	[‡]Cumulative P	180.5	42.6	223.1	77
Koktrap	Crop 1	49.5	7.7	57.2	20
	Crop 2	45.2	4.7	49.9	16
	Crop 3	25.8	2.7	28.5	6
	Crop 4	20.2	3.1	23.3	2
	Crop 5	15.1	2.5	17.6	1
	[‡]Cumulative P	155.8	20.7	176.4	45
Toul Samroung	Crop 1	56.1	7.3	63.3	25
	Crop 2	42.6	3.9	46.5	17
	Crop 3	33.2	2.9	36.7	12
	Crop 4	11.5	1.7	13.2	1
	Crop 5	12.9	3.6	16.4	2
	[‡]Cumulative P	156.2	19.4	175.6	57

[†] Recovery of P fertilizer for each crop was calculated by subtracting values of the nil-P treatment.
[‡] Cumulative P uptake of plants from fertilizer: values are the sum from crop 1 to crop 5.
Crop 1: means that rice plants received 20 mg P/kg soil in that crop; Crop 2: indicates the second crop after P applied, i.e. the first crop using residual P, and so on for Crop 3, Crop 4 and Crop 5.

Discussion

Growth and P uptake in response to P supply, and its relationship to P sorption-desorption processes

The maximum vegetative growth of rice was obtained for up to two successive crops with the high-P (20 mg/kg) treated soils. However, from the second cropping cycle onwards all other aspects of growth and P uptake declined progressively at all added-P levels (Table 2; Figure 1). This decrease could be attributed largely to the removal by the plants of the most readily available P from fertiliser P application in the previous cropping cycle. Other factors involved in the decline in growth of rice are discussed in following sections.

The shoot and root dry matter of rice growing in the sandy PL soil was greater than that for plants grown on the clayey TS and KT soils with all levels of applied P fertiliser in the first crop (Figure 1). This result is consistent with the findings of Seng *et al.* (1999) that rice dry matter in the KT soil, were less than those of plants grown in the sandy PL soil. The greater shoot growth of plants in the PL soil for a given P addition may be attributed to the low P sorption capacity of this sandy soil. Available P as reflected in Resin-P level in the sandy PL soil was greater than in the clayey TS and KT soils (Figure 5), suggesting that the greater P availability in the PL soil increased shoot and root dry matter. This hypothesis was further supported by the shoot/root

ratios, which decreased more strongly in the clay TS and KT soils compared to the sandy PL soil (data not shown) as is typical of P limitations (Asher and Loneragan, 1967).

In the first crop, maximum shoot DM was received with the application of 10 mg P/kg soil on the sandy PL soil, whilst rice shoot dry weight responded up to the highest P (20 mg/kg) fertiliser application on the clayey TS and KT soils (Figure1). This result clearly indicates that rice crops respond differently to P fertiliser application on the three soils types due to their various P sorption capacities, suggesting different levels of P fertiliser should be applied on each of the soils in order to achieve a target rice yield. The following are recommended P fertiliser rates (kg P/ha) for rice production: for PL soil (10-23); TS soil (15-40); and for KT soil (15-46) (White *et al*., 1997b; Dobermann and White, 1998; Seng *et al*., 2001). The high rate is generally recommended for modern-high-yielding rice varieties grown with favourable conditions (e.g. good crop management and rainfall or supplementary irrigation), whereas, the low rate is suggested for traditional rice varieties grown with less favourable growing conditions.

There are various kinds of P fertilizers commonly used in lowland rice production (Sanyal and De Datta, 1991). Apart from phosphate rock (PR), they supply similar available P to rice in most lowland soils, except on very strongly acid or alkaline soils in which sorption or precipitation processes of P are the major concern (De Datta, 1981). The results from previous studies of Pheav (2002) demonstrated that application of either TSP or KH_2PO_4 increased yield and P uptake of rice on the sandy PL soil. Based on more rapid dissolution of PR in low pH soil (Hammond *et al*., 1986), and the high P sorption capacity of the KT soil as discussed below, it is suggested that PR would be an effective P fertilizer source for the clayey acidic KT soil. This is supported by the results of a glasshouse experiment by White *et al*. (1999), who reported that P from TSP was more available to plants than P from other sources on the coarse-textured Prey Khmer and Prateah Lang soils, whereas, P from PR was more available than TSP on the clayey KT and TS soils. There remains a need for both short- and long-term research under field conditions on lowland rice soils to determine the effectiveness of different P fertilizers including PR, particularly, when loss of soil-water saturation occurs.

The greater total P content in rice plants grown on the PL soil after one crop corresponded with a greater initial rate of P released from the soil after the first extraction of the P desorption experiment (Figures 2, 6). However, a greater decline in P desorption was observed from the sandy PL soil than from the clayey TS and KT soils after one soil extraction. The cumulative P released from the clayey TS soil was greater than from the sandy PL soil after five successive extractions (Figure 6). Even after eight successive extractions, total desorbed P on KT soil was only 50 % of that on PL soil. This suggests that total P uptake would be reduced when rice plants were grown on the sandy PL soil, after most of easily desorbable P was removed in the first and second crops. These results are similar to those in a field experiment on the same soil type reported in Pheav *et al*. (2003).

The P sorption of the soil may be a good predictor of residual effects of P fertiliser on different soils. Sanchez (1980) reported that the duration of residual effects of different rates of applied P fertiliser varied considerably with soil properties. For example, with P fertiliser application at 20 mg P/kg, the maximum shoot DM was maintained for two crops on the PL soil, a result that is consistent with the findings in the field experiment on the same soil type (Pheav *et al*., 2003). On the sandy PL soil after crop 2, the shoot DM declined sharply. This contrasts with the plants grown with residual P fertiliser on the clayey TS and KT soils. The shoot dry weight of these plants decreased steadily with each cropping cycle, but the values after crop 2 exceeded those of the plants growing on the sandy PL soil (Figure 1). This suggests that a higher residual P value can be obtained on the clayey KT and TS soils than the sandy PL soil. This was also supported by the P desorption experiment (Figure 6). Soils that have high P sorption rates may release P into soil solution spread over a longer period of time.

The amount of P recovered in succeeding rice cropping cycles was less than the total amount of fertiliser P applied. Approximately, 25, 45 and 55 % (Table 3) of the P applied at 20 mg/kg were retained in the sandy PL, clayey TS and KT soils, respectively, as residual P after five successive rice cropping cycles. The amount of P (75 %) removed from the sandy PL soil in this pot experiment was greater than that removed by rice plants (55 %) on the same soil in the field experiment of Pheav *et al*. (2003). This could be due to removal of both roots and shoots from the pot experiment in each cropping cycle, whereas, some P in the form of rice stubble and roots was potentially available for return to the soil in the field condition. The greater amount of P retained in the clayey KT and TS soils than that in the sandy PL soil could be the result of high P sorption capacity of these clayey soils, and to reactions of added P with mineral fractions in the soil that remove a significant portion of P from plant available pools. The greater aggregation of the clayey soils may also contribute to increased P sorption (see below).

Phosphorus fractionation in relation to crop growth

That resin extracted the least amongst all soil P pools, is consistent with the findings reported on the sandy PL soil for field conditions (Pheav, 2002; Pheav *et al.*, 2003). However, the level of the Resin-P pool was greater in the sandy PL soil than in the clayey TS and KT soils (Figure 3). The sandy PL soil had the lowest P sorption capacity, and consequently, more of the added P remained free in the soil solution. However, after three consecutive crops, resin-extractable P had declined in all soil types, and this was reflected in decreased plant growth.

The amounts recovered from all the soil P pools, especially from major fractions (NaOH-Pi, NaOH-Po and Residual-P) declined with succeeding rice crops grown on all the soils, but the decline in these labile NaOH-extractable pools was greatest in the clayey KT and TS soils. This decrease can be explained by the occurrence of continuous sorption of the added P fertiliser by soils during each the plant-growing periods in addition to plant uptake. Indeed, NaOH-Pi was the fraction that declined most rapidly amongst the major soil P pools over five successive rice-cropping cycles (Figure 3). This is consistent with the results of the field experiment reported in Pheav (2002); and Pheav *et al.* (2003), and the significance was also discussed in those publications. The reason for the decline in labile inorganic NaOH-Pi pool could be the biological immobilization of the soil inorganic P fraction (Zhang and MacKenzie, 1997), as well as depletion due to plant uptake in every crop. In addition to plant uptake, McLauglin *et al.* (1988) demonstrated that some of the inorganic P pool was taken up by microorganisms, which eventually was incorporated into the organic P pool as microbial detritus.

Phosphorus sorption-desorption processes of lowland rice soils

Phosphorus sorption-desorption processes vary with soil types and soil-water conditions (oxidation and reduction). Each of the soils differed significantly in physico-chemical characteristics, including clay content, pH, organic matter, hydrous oxides of Fe and Al (Oberthur *et al.*, 2000; Seng, 2000). The lower P sorption capacity of the sandy PL soil could be due to a low level of clay, organic matter, and oxalate extractable Fe contents of the soil (Pheav *et al.*, 1996; Oberthur *et al.*, 2000; Seng, 2000). In other oxidised rice soils, the P sorptivity generally correlated well with the clay content and oxalate extractable Fe (Fox and Kamprath, 1970; Willett and Higgins, 1978; Loganathan *et al.*, 1987; Willett and Cunningham, 1983; Bennoah and Acquaye, 1989; Seng, 2000). The low oxalate extractability of Fe in the sandy PL soil indicates that ferric hydrous oxides present were generally well crystallised (McKeague and Day, 1966; Willett and Cunningham, 1983). Crystalline Fe oxides are relatively inactive in P sorption under the aerobic soil conditions (Henry, 1961; Willett and Higgins, 1978).

Variable charge clays, especially Fe and Al hydrous oxides contribute significantly to P sorption capacities in tropical acidic rice soils, particularly at low pH when surface positive charge is increased (Fox and Searle, 1980). Amongst the two clayey acidic soils reported in this study, P sorption appeared to be greater in the KT soil with lower pH and a higher organic matter content than the clayey TS soil (Pheav *et al.*, 1996; Oberthur *et al.*, 2000). Sorption of freshly added P by highly weathered soils was shown by Hartikainen (1983) and Barrow (1984) to increase as soil pH level decreased. However, a decrease in pH may also favour desorption of P already in the soil (Kirk *et al.*, 1990). In the variable-charge soils, this may be because the increase in surface positive charge as the pH decreases favours diffusion of P out of the soil particles along the electro-chemical gradient (Barrow, 1984). A positive correlation between the soil organic matter and P sorption of the soil has been found by several workers (Kanabo *et al.*, 1978; Mizota *et al.*, 1982; Bennoah and Acquaye, 1989; Niskanen, 1990). The role of organic matter in P sorption in acid soils has often been attributed to the association of the soil organic matter with hydrous sesquioxides forming Fe and Al chelates, which provide more active surfaces for P sorption (Saunders, 1965; Fox and Searle, 1980; Sanyal *et al.*, 1993).

The decrease in P desorption with successive extractions was observed to be greater from the sandy PL soil than from the clayey TS and KT soils (Figure 6). The greater value of initial P desorption was possibly influenced by the pH of the soil: increasing the pH positively affected the desorption rate (De Smet *et al.*, 1998). When the soil was equilibrated with 20 mg P/l, the sandy PL soil adsorbed 87 mg P/kg, and subsequent cumulative desorbable-P over six repeated soil extractions was about one-third of the initial amount of sorbed P. This is consistent with the results of vander Zee and van Riemsdijk (1991); and De Smet *et al.* (1998), who estimated that, in acidic sandy loam or loamy sand soils, the amount of reversibly adsorbed P to be one-third of the total sorbed P. The same authors found further that the total amount of the reversibly adsorbed-P was highly correlated to the oxalate extractable P and Fe of the soil.

Although our study did not measure soil-aggregation, other researchers demonstrated that soil aggregates, particularly in clay soils, had a strong influence on P sorption-desorption processes. Cornforth (1968); Nye and Stauton (1994); and Linquist *et al.* (1997) suggested further that diffusion

of P into the interior of soil aggregates may be the cause of the declining plant P availability with time on well structured soil. With depletion of P around the soil aggregates, P diffusion from the inside of aggregates to the outside, and the accessibility of rice roots to this P within the soil aggregates, could become important influences on residual P supplying capacity of the soil (Wang *et al.*, 2001). Soil descriptions of White *et al.* (1997a, b) indicated that TS and KT soil had more aggregate development than the sandy PL soil, but longer residual effect of P fertiliser application.

CONCLUSIONS

Availability of P fertiliser to plants depends, to a large degree, on the sorption and subsequent release of P from the soil surfaces. The vegetative growth of rice on the sandy PL soil was much greater than on the clayey TS and KT soils after equal amounts of P fertiliser were added. The increase in P concentration and total P uptake of rice plants growing on the PL soil was attributed to increased available P in the Resin-P extractable fraction because of the lower P sorption capacity of this sandy soil. However, sandy PL soil had less residual P than the clayey KT and TS soils due to its lower P sorption capacity. This may imply the need for more intense management of P supplied to the sandy PL soil to ensure adequate residual P value, and for maintaining the maximum growth of rice plants on this soil. By contrast the present results predict a longer residual value for P in the KT and KS soils.

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