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ចំលើយតបនៃដំណាំស្រូវចំការ ទៅនឹងការដាក់ជីផូស្វ័រនៅលើដី ដែលបានបញ្ចេញទឹក ក្រោយពេលពន្លិចទឹក ក្នុងរយៈពេលផ្សេងៗគ្នា

RESPONSE OF UPLAND RICE TO PHOSPHORUS ON DRAINED SOILS SUBJECTED TO DIFFERENT PERIODS OF PRIOR FLOODING

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សង្ខេបអត្ថបទ

ការបាត់បង់ភាពឆ្អែតទឹកនៃដីម្តងម្កាល ត្រូវបានគេជឿថា ធ្វើឱ្យទិន្នផលស្រូវធ្លាក់ចុះជារឿយៗ ដោយវាកង្កឱ្យមានកង្វះជីជាតិផូស្វ័រ ប៉ុន្តែយន្តការនេះ មិនទាន់ត្រូវបានសិក្សាឱ្យពិស្តានៅឡើយទេ។ ការពិសោធន៍ក្នុងផ្ទះកញ្ចក់ត្រូវបានធ្វើលើដីអាស៊ីតនៃតំបន់ទំនាបប្រទេសកម្ពុជាចំនួន ២ ប្រភេទ (ក្រុមដីគោកត្រប់-ដីឥដ្ឋខ្មៅ និង ក្រុមដីប្រទះឡាង-ដី ខ្សាច់) ដោយបានដាក់បន្ថែមជីផូស្វាត (P) មុន ឬក្រោយពន្លិចទឹក ដើម្បីតាមដានពីឥទ្ធិពល នៃពេលវេលាដាក់ជី P ទៅលើការលូតលាស់នៃដំណាំស្រូវចំការ។ ដីទាំងពីរប្រភេទត្រូវបានដាក់ជីផូស្វាតក្នុងកំរិត ៤៥ mg P/kg ដី រួចទើបពន្លិចទឹកអស់រយៈពេល ០ ១ ២ និង ៤ សប្តាហ៍ ឬត្រូវបានដាក់បន្ទាប់ពីការពន្លិចទឹករួចរាល់ហើយ។ ក្រោយពីធ្វើការសំងួត និងបុកដីរួច ដីទាំងនោះត្រូវបានផ្សើមដោយទឹកក្នុងកំរិតសំណើមដីស្រែ រួចហើយធ្វើការដាំដុះស្រូវចំការ អស់រយៈពេល ៦ សប្តាហ៍។

ការដាក់ជី P ទៅលើដីខ្សាច់ រួចពន្លិចទឹកអស់រយៈពេល ៤ សប្តាហ៍ បានធ្វើអោយម៉ាស់ស្ងួតនៃដើមស្រូវធ្លាក់ចុះ ចំណែកនៅលើដីឥដ្ឋ ប្រើរយៈពេលតែមួយសប្តាហ៍ប៉ុណ្ណោះ។ ក៏ប៉ុន្តែនៅពេលដែលជី P ត្រូវបានដាក់ក្រោយពេលពន្លិចទឹក នោះម៉ាស់ស្ងួតនៃដើមស្រូវមិនធ្លាក់ចុះទេ ដោយមិនគិតពីរយៈពេលនៃការពន្លិចទឹកជាមុន។ ប៉ូតង់ស្យែលរេដុកម្ម និងតំលៃ pH ដី មានការធ្លាក់ចុះក្នុងពេលពន្លិចទឹក ដែលជាហេតុនាំអោយមានការកើនឡើង នូវតំលៃនីស្សារណកម្ម Fe^{2+} និងសមត្ថភាពស្រូបយក P របស់ដី។ បរិមាណនៃនីស្សារណកម្ម Fe^{2+} អាសេតាត មានទំនាក់ទំនងយ៉ាងជិតស្និទ្ធនឹងបរិមាណ P ដែលដីស្រូបយក (r^2 =0.96-0.98)។ នីស្សារណកម្មនៃ Olsen និង Bray-1 P មានទំនាក់ទំនងយ៉ាងខ្លាំងទៅនឹង ម៉ាស់ដើមស្ងួត និងកំហាប់ P នៅក្នុងដើម ដែលបញ្ជាក់ថាជីជាតិ P ដែលភាពសេរីរបស់វាត្រូវបានកំណត់ដោយរយៈពេលនៃការពន្លិចទឹកជាមុន គឺជាកត្តាដែលកំរិតនូវការលូតលាស់របស់ដំណាំស្រូវ។

រួមសេចក្តីមកការដាក់ជីផូស្វាត មុនពេលពន្លិចទឹក ពុំមានប្រសិទ្ធិភាពល្អ ក្នុងការបង្កើនការលូតលាស់បេស់ដំណាំ ស្រូវចំការឡើយ។ ការនេះបណ្តាលមកពី កំនើននៃការបង្ខាំធាតុ P ជាមួយដែកអុកស៊ី-អ៊ីដ្រុកស៊ីត ដែលកើតមានក្នុងកំឡុងពេល ដែលដីធ្វើអុកស៊ីតកម្មនៅពេលវាស្ងួត។ ការធ្លាក់ចុះភាពសេរីរបស់ P ក៏អាចទាក់ទងទៅនឹងកំនើន នៃសមត្ថភាពចាប់យកធាតុ P នៃដីក្នុងពេលពន្លិចទឹក និងបញ្ចេញទឹកផងដែរ។

ពាក្យគន្លឹះ: ដីអាស៊ីត, ដីពន្លិច-បញ្ចេញទឹក, pH ដី, ប៉ូតង់ស្យែលរេដុកម្ម, នីស្សារណកម្មដែក និង ផូស្វ័រ, ការចាប់ធាតុផូស្វ័រ, ការស្រូបធាតុផូស្វ័រ, ដីស្រែទំនាប

ABSTRACT

Low rice yields following intermittent loss of soil-water saturation are believed to involve, on occasions, P deficiency but the possible mechanisms have not been studied in detail. In the present pot experiments, two acid lowland soils from Cambodia (Koktrap -black clay soil and Prateah Lang- sandy soil) were treated with P either before or after flooding to investigate the effect of the timing of P application on its effectiveness for upland rice growth. Phosphate fertiliser (45 mg P/kg soil) was added to both soils before flooding for periods of 0, 1, 2 and 4 weeks, or after drying the flooded soils. After air-drying and crushing, the soils were wet to

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field capacity and the upland rice grown in them for six weeks.

The addition of P 4 weeks before flooding decreased shoot dry matter in the sandy soil and in the black clay soil after only 1 week of flooding. But when P was added after drying the soils, shoot dry matter was not decreased regardless of the period of prior soil flooding. Soil pH increased and redox potential (Eh) decreased during flooding, resulting in an increase in acetate extractable Fe and the phosphate sorption capacity of soils. There was a close relationship between P sorbed and acetate extractable Fe (r^2=0.96–0.98). Olsen and Bray-1 extractable P strongly correlated with shoot dry matter and shoot P concentrations indicating that P, the availability of which was controlled by the period of prior flooding, limited the growth of upland rice.

It was concluded that phosphate fertiliser added before flooding was relatively ineffective in increasing growth in the upland rice. This was attributed to the increase in occlusion of P within ferric oxyhydroxides formed during subsequent oxidation of the soils. Decrease P availability may also have been associated with a greater phosphate sorption capacity of the soils during flooding and drying of soils. The implications of this for P supply to rice in intermittently flooded lowlands, and for P fertilizer requirements of pre- and post-rice upland crops are discussed.

Key words: Acid soils, flooded-drained soils, soil pH, redox potential, extractable P and Fe, P sorption, P uptake, lowland rice soils.

INTRODUCTION

The decrease of growth and grain yield of rainfed rice on the lowlands in southeast Cambodia has been reported to result from a temporary loss of soil-water saturation by apparently inducing phosphorus (P) deficiency in rice (Seng *et al*., 1999). The reason behind the decreased P uptake by rice plants following loss of soil-water saturation was believed to be associated with increased P sorption capacity in the dry soils. While the exact mechanisms involved are not yet fully understood, it was postulated to have been caused by the reactions of phosphate with amorphous iron oxides formed during flooding (Seng *et al*., 1999).

Willett and Higgins (1978) showed that oxidation or drying of previously flooded soils decreased the level of oxalate extractable Fe and phosphate sorption capacity of some Australian soils. Phosphorus added after drying of recently flooded soils was more available to upland crops than if it was added before flooding. But this was dependent on clay content, the level of organic matter, and the level of reducible Fe in the soils. Willett (1982) found that P added after drying the soils was not immobilised if soils were low in reducible Fe and organic matter.

Since the forms and availability of Fe vary between soil types and with the duration of flooding (Ponnamperuma, 1976), the capacity of soils to sorb added P fertiliser following increased duration of flooding may also vary. It was hypothesised that when soils were flooded for lowland rice, then dried to upland conditions this would restrict the availability to upland crops of P added before flooding; and that the availability of P for a subsequent upland crop depends on duration of prior flooding. The objective of this study was to investigate the effect that different periods of flooding had on the effectiveness of applied phosphate fertiliser before flooding relative to P applied after flooding using upland rice growing in two Cambodian lowland rice soils.

MATERIALS AND METHODS

Soils

A Koktrap (black clay soil or Kandic Plinthaquult) and a Prateah Lang (sandy soil or Plinthustalf) (White *et al*., 1997) were sampled to a depth of 0–10 cm from several locations in one field located in Toul Koktrap Rice Research station, southeast Cambodia. The soils had been continuously cultivated once per year during the rainy season for a very long period of time. These soils are known to be infertile, and respond strongly to P fertiliser application (Seng *et al*., 1999). Despite the low P status and the repeated use of the soils for rice cultivation, rice grown on these two soils is generally fertilised with relatively small amounts of P fertiliser (Dubus and Richard, 1997). Samples of each soil were collected during the dry season, bulked, and allowed to air-dry for 72 hours. Crop residues were removed by hand and the samples crushed to pass through a 2 mm sieve. Detailed chemical properties of the soils were reported in Seng *et al*. (2001).

Experimental procedure

Replicate 5 kg portions of soil (air-dried basis) were weighed and placed into plastic pots. There were 4 flooding periods (0, 1, 2, and 4 weeks). Each flooding treatment received either P applied before flooding or P applied after drying of the flooded soils. All potted soils received a complete set of basal nutrients (mg element/kg of soil) after air-drying: N=25 (urea), Ca=20.4 ($CaCl_2.2H_2O$), K=87.3 (K_2SO_4), Mg=21.1 ($MgSO_4.7H_2O$), B=0.1 (H_3BO_3), Zn=0.9 ($ZnSO_4.7H_2O$), Cu=0.3 ($CuSO_4.5H_2O$), Mn=1.4 ($MnSO_4.H_2O$), and Mo=0.1 ($Na_2MoO_4.2H_2O$). Phosphate fertiliser (45 mg P/kg, as KH_2PO_4) was added to half the pots before flooding. The remaining pots received this level of P after drying of the flooded soils. After the addition of nutrients, the soils were thoroughly mixed by shaking end-over-end.

Designated potted soils were flooded and incubated under glasshouse conditions at temperatures ranging from 25–40°C for 0, 1, 2, and 4 weeks by adding sufficient de-ionised water to flood soils to a depth of 2–3 cm. Flooding times were arranged so that all treatments could be dried at the same time. At the end of flooding, soils were air-dried for 48 hours under glasshouse conditions by spreading them thinly on a clean plastic sheet. After air-drying, soils of each pot were crushed and then re-potted. Phosphate fertiliser was applied to those treatments which did not receive P fertiliser before flooding. After P and basal fertiliser addition, the soils were thoroughly mixed by hand. All re-potted soils were then incubated with de-ionised water at field capacity.

Upland rice cultivation

Upland rice was grown as a test crop because of its tolerance to Mn toxicity, and responsiveness to P. Twelve seeds of P-responsive upland rice, *cv.* Sita were sown in each pot to a depth of 2–3 cm. The soils were maintained at field capacity throughout the six-week growing period. After the seedlings were well established (about 9 days after sowing), they were thinned to 8 plants per pot. No additional N was added to the soils after the basal application, and no N deficiency symptoms were evident prior to harvesting at six weeks. Shoot dry matter yields were determined and sub-samples were collected for P concentration analysis.

Soil and plant analyses

Soil pH and redox potentials (Eh) were measured at the end of each flooding and drying period with a portable pH-Eh meter possessing a glass calomel electrode for pH and a platinum electrode for Eh. For dry samples, the pH and Eh values were measured with a 1:5, soil to water ratio with the same meter (Rayment and Higginson, 1992).

Acetate extractable Fe and P were determined by shaking 2 g of wet soil with 50 ml of 1 *M* sodium acetate buffer (pH 3.0) for 5 minutes (TARC, 1973). The concentrations of Fe and P were measured at 490 and 580 nm, respectively, using a Jeneway 6051 colorimeter.

Soil samples of all treatments were taken before planting and at harvest of upland rice for Olsen and Bray-1 extractable P analysis. Bray-1 extractable P was analysed by hand-shaking 2 g of soil with 20 ml of 0.03 *M* NH_4F + 0.025 *M* HCl solution for 1 minute (Kalra and Maynard, 1994). The extracts were filtered immediately through a Whatman 42 filter paper. Olsen extractable P was obtained by shaking 2 g of soil with 40 ml of 0.5 *M* $NaHCO_3$ solution (pH=8.5) for 30 minutes (Rayment and Higginson, 1992; Kalra and Maynard, 1994). After shaking, the extracts were filtered through Whatman 42 filter paper. The concentration of P in the filtrates from each method was determined by the colorimetric procedures described by Kalra and Maynard (1994).

Samples of the soils that had been incubated flooded or dry for 0–4 weeks were air-dried for 48 hours and their P sorption curves determined by the method of Ozanne and Shaw (1967). Two-gram samples were shaken in 40 ml of solutions containing the following P concentrations (mg/l): 0, 10, 15, 20, and 30 for the black clay soil, and 0, 3, 5, and 10 for the sandy soil. The concentrations of P remaining in solution after 17 hours were determined by the colorimetric procedure of Anderson and Ingram (1993).

Shoots samples were milled, and P concentrations determined in concentrated HNO_3 digests (Zarcinas *et al.*, 1987) using an inductively coupled plasma atomic emission spectrometry.

Statistical analysis

For each soil type, analysis of variance was carried out to determine the treatment effects using IRRISTAT 4.0 software (IRRI, 1997).

RESULTS

Response of soil chemical properties

Both soils were strongly acidic when dry, with pH values of about 4.4. Flooding for 4 weeks increased these values to about 5.5 and 6.2 in the black clay and sandy soils, respectively (Fig. 1). At the same time, redox potential (Eh) decreased from about 600 mV to about 300 mV in the black clay, and 100 mV in the sandy soils. Soil reduction was faster in the sandy soil than in the black clay soil, reflecting a poor buffering capacity of the former soil. Soil pH and Eh returned to their pre-flooded values after drying.

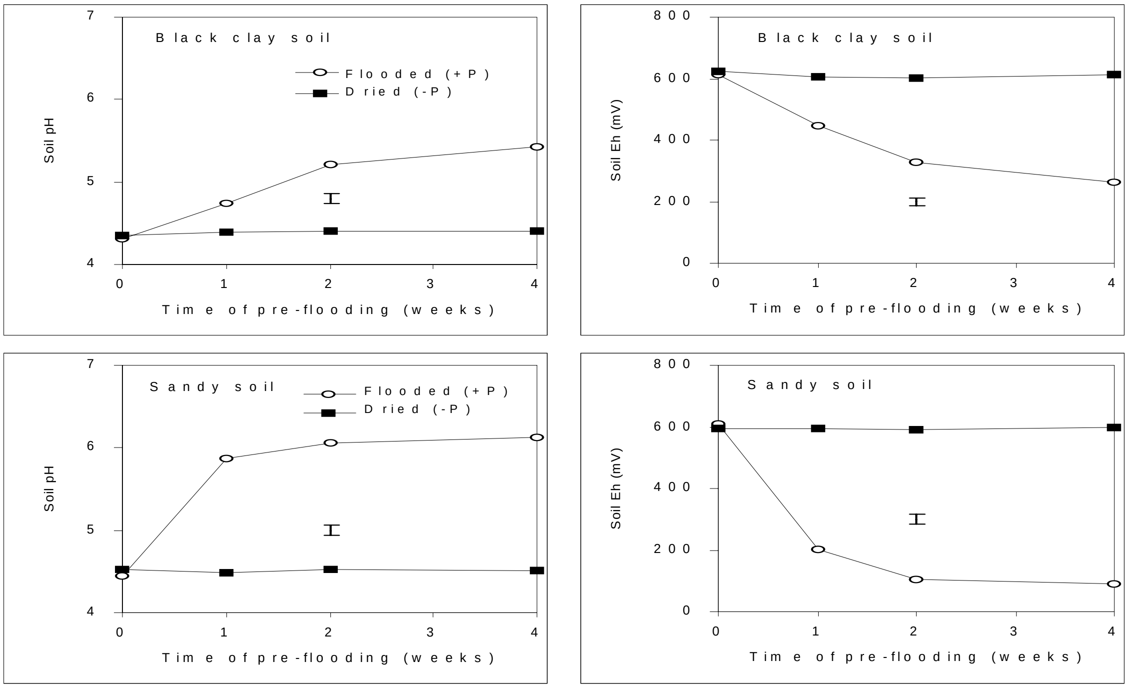

Figure 1. Changes in pH and Eh during flooding. Plotted values are means of 3 replicates. Bars indicate LSD values at *p*<0.05.

Flooding for 4 weeks increased values of acetate extractable Fe from about 30 mg/kg to 300 and 450 mg/kg in the black clay and sandy soils, respectively (Fig. 2). Flooding also increased acetate extractable P from about 1.3 to 5 mg/kg in the black clay soil, and from about 1.5 to 4 mg/kg in the sandy soil. The maximum value of acetate extractable P in the sandy soil was reached after 2 weeks of flooding, but in the black clay soil acetate extractable P values continued to increase until 4 weeks of flooding (Fig. 2). After the soils had dried out, the levels of acetate extractable Fe and P returned to their pre-flooded values.The sorption of P by soils varied markedly with both the period of flooding and soil type. Flooding for 4 weeks increased the P sorption capacity of both soils substantially, but the sandy soil sorbed much less P than the clay soil (Fig. 3). Based on P sorbed at 0.2 mg P/l in the equilibrium solution, the sandy soil under oxidised conditions (0 wk) sorbed about 15 mg P/kg, one-fifth that of the clay soil. There were positive relationships between P sorbed and acetate extractable Fe in both soils suggesting that the forms of Fe associated with increases in acetate extractable Fe during flooding were responsible for or strongly correlated with those causing the increased P sorption capacity of flooded soils (Fig. 4).

Olsen or Bray-1 extractable P values were higher in the sandy soil than in the black clay soil. The Olsen or Bray-1 extractable P values measured on dry soils without P were not significantly different between periods of soil flooding (Table 1). This suggests that duration of flooding did not affect the forms of native soil P measured in the dry soils using the Olsen and Bray-1 extractants. By contrast, flooding for 2 weeks or more significantly (*p*<0.05) depressed the extractability of P fertiliser added before flooding by decreasing levels of Olsen and Bray-1 extractable P in both soils without rice (Table 1) Subsequently, the levels of Olsen or Bray-1 extractable P in both soils decreased significantly with periods of flooding after growing upland rice on these treatments. In addition, the extractability of P fertiliser added after drying of flooded black clay and sandy soils were not diminished by periods of pre-flooding (Table 1). This

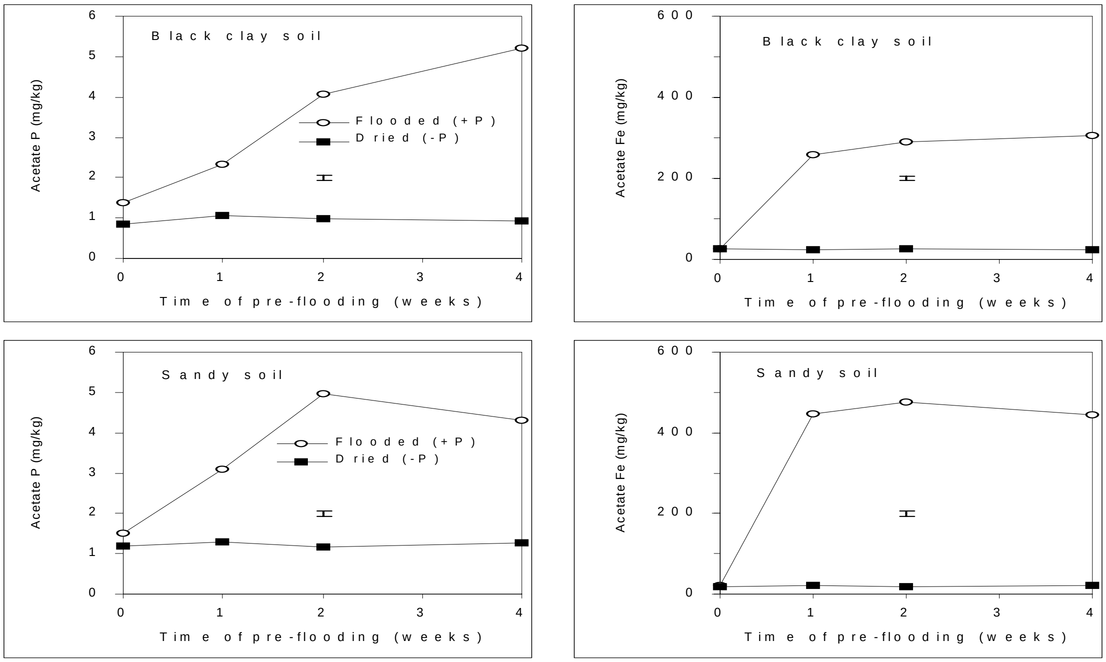

Figure 2. Changes in acetate extractable Fe and P during flooding and after drying of the black clay or sandy soil subjected to 0-4 weeks flooding. Flooded soils received P fertiliser before flooding, whereas dried soils did not receive any P fertiliser at time of measuring. Plotted values are means of 3 replicates. Bars indicate LSD values at *p*<0.05.

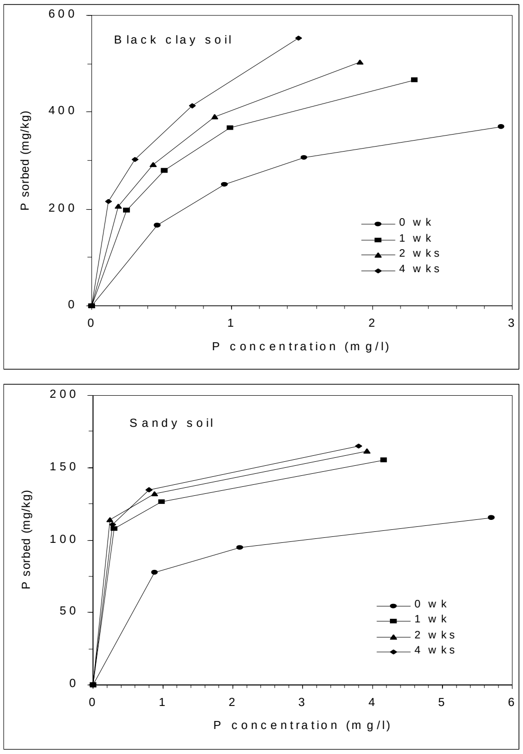

Figure 3. Phosphate adsorption curves of air-dried soils following incubation flooded or dry for the indicated periods.

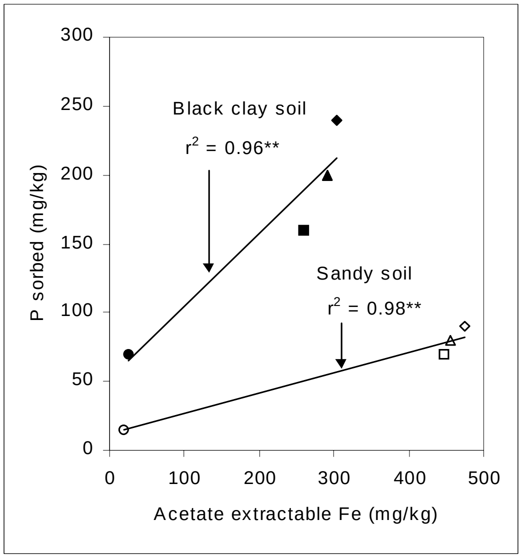

Figure 4. Relationships between P sorbed and acetate extractable Fe in the black clay and sandy soils. Plotted data are means of 3 replicates on each flooded treatment receiving P before flooding at 0 (circles), 1 (squares), 2 (triangles), and 4 (diamonds) weeks. Values of P sorbed were predicted from Figure 6-3, based on P sorbed at 0.2 mg/l in solution.

Table 1. Response of extractable P values in the black clay and sandy soils to flooding and different times of phosphate (P) fertilisation for growing upland rice. Measurements done on oxic soil samples. Presented values are means of 3 replicates.

Addition of P#	Time of flooding (weeks)	Extractable P (mg/kg)			
		Black clay soil		Sandy soil	
		Olsen	Bray-1	Olsen	Bray-1
Without P (-Rice)					
	0	1.12	0.70	2.32	1.17
	1	1.11	0.68	2.32	1.13
	2	1.10	0.68	2.31	1.15
	4	1.10	0.69	2.30	1.15
P added before flooding (-Rice)					
	0	1.64	1.18	2.83	1.72
	1	1.59	1.14	2.78	1.68
	2	1.48	1.01	2.69	1.60
	4	1.45	0.96	2.66	1.58
P added before flooding (+Rice)##					
	0	1.46	1.10	2.73	1.64
	1	1.42	1.05	2.69	1.61
	2	1.31	0.92	2.59	1.53
	4	1.30	0.85	2.57	1.50
P added after drying (+Rice)##					
	0	1.53	1.15	2.75	1.71
	1	1.51	1.14	2.74	1.70
	2	1.50	1.13	2.73	1.68
	4	1.49	1.13	2.72	1.69
LSD (P added x Time of flooding)		*0.08*	*0.08*	*0.12*	*0.08*

suggests that the availability of P to upland rice from added P fertiliser was greater when P was added after drying of flooded soils than when P was added before flooding.

Response of shoot dry matter yields and P uptake

Addition of P fertiliser before flooding depressed the growth of the subsequently planted upland rice provided the period of flooding was ≥1 week on the black clay soil and ≥4weeks on the sandy soil. The reduction in growth of upland rice was greater in the black clay soil than in the sandy soil (Fig. 5). When P fertiliser was applied, after drying of flooded soils, plant growth was similar irrespective of pre-flooding periods.

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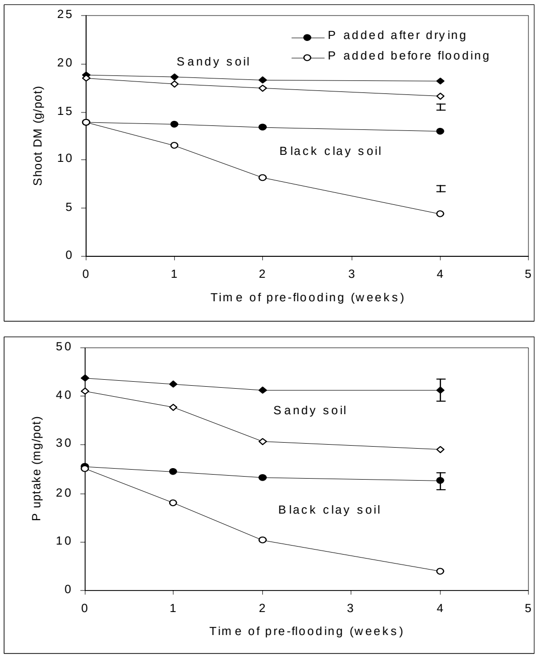

Figure 5. Response of shoot dry matter (DM) and P uptake of upland rice to the addition of P. Plotted values are means of 3 replicates. For each soil type, bars indicate LSD (P added x Time) values at *p*<0.05.

Relationships between shoot dry matter yields and Olsen or Bray-1 extractable P values

In black clay soil both shoot dry matter yield (r^2=0.90–0.92) and shoot P (r^2=0.92–0.96) were positively correlated with soil P concentrations extracted by Olsen or Bray-1 reagents (Fig. 6). In the sandy soil, the relationships were even closer (r^2=0.92–0.99) than for the black clay soil (Fig. 6). The positive relationships suggest that the P extractable by Olsen or Bray-1 reagents was available for the growth of upland rice.

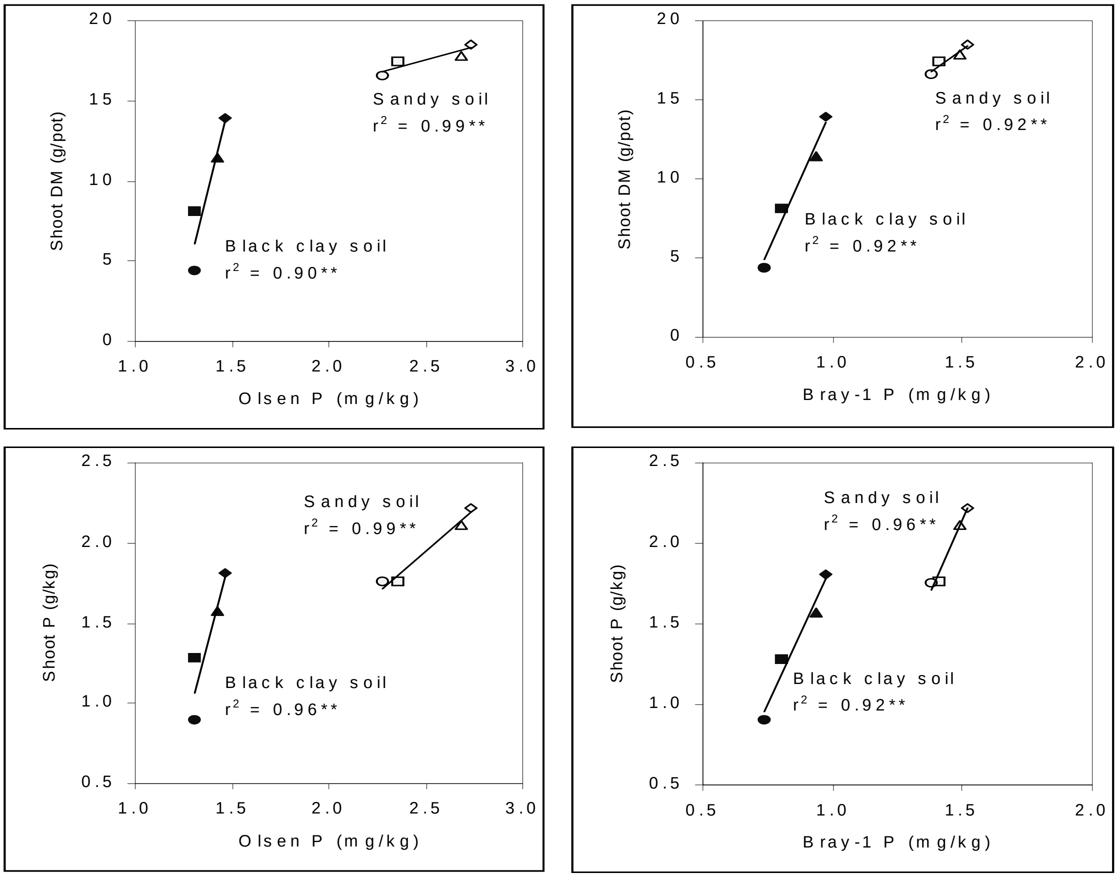

Figure 6. Relationship between shoot dry matter (DM) of upland rice or shoot P concentrations with Olsen and Bray-1 extractable P measured after rice harvested on the black clay and sandy soils subjected to 0 (diamond), 1 (triangle), 2 (square), and 4 (circle) weeks of prior flooding. Plotted values are means of 3 replicates for treatments receiving P fertiliser before flooding.

DISCUSSION

The changes in soil pH, Eh, and acetate extractable Fe and P during flooding were consistent with previous studies on the black clay soil and sandy soils (Seng *et al*., 1996, 2001). The purpose of the present discussion is to explore the mechanism by which temporary loss of soil water saturation in lowland rainfed rice soils may induce P deficiency, as reported by Seng *et al*. (1999).

Effect of flooding periods on the availability to upland rice of P added before flooding

The most significant effect of soil flooding and flooding duration was a decrease in the effectiveness of applied P fertiliser as reflected in decreased rice dry matter. The decrease in effectiveness of applied P was correlated with a marked increase in acetate extractable Fe and in P sorption capacity of the soils albeit after re-drying for analysis. Correspondingly, there was a close relationship between acetate extractable Fe and P sorbed. The greater P sorption of reduced soils has previously been associated with a transformation of less reactive ferric oxyhydroxides to more reactive ferrous compounds in soils with value of oxalate extractable Fe greater than 1 g/kg, pH 4.4–6.4, and organic carbon 5.6–41 g/kg (Khalid *et al.*, 1977). Indeed, since P fertiliser was added before flooding, there was the opportunity for P sorption on reactive ferrous compounds formed during flooding, and acetate extractable Fe appears to correlate closely with the sorption of P on such Fe compounds. On oxidation or drying of the soils, any labile P or P present in the soil solution during flooding had the possibility of co-precipitation with ferrihydrite formed during oxidation as indicated by a significant decline in acetate extractable Fe and P, and this process would markedly restrict the availability of P for the growth of a subsequent upland rice crop (Willett, 1982, Willett, 1991). Further evidence was a marked decline in Olsen or Bray-1 extractable P values measured on each of the oxic treatments of the recently flooded soils where P fertiliser was added before flooding prior to planting rice. This decline may be expected because the occluded P or Fe^{3+} phosphate compound is less readily extractable than the surface-bound P (Willett, 1982). The decreased extractability of added P in these low-P soils with time of flooding could have been associated with increased levels of acetate extractable Fe during flooding, indicating that the greater the amount of Fe reduced during flooding, the greater the amount of P occluded on re-oxidation. Patrick *et al.* (1974) found that in most of the soils of Louisiana USA they tested, a greater proportion of added P was adsorbed in soil that was alternately flooded and dried to field capacity than in soil that was continuously flooded.

The reduction of upland rice growth on the sandy soil was not as marked as that on the black clay soil despite large increases in acetate extractable Fe in the sandy soil. This could be due to the low P sorption capacity in the sandy soil which could have been associated with the effects of its low level of clay, and low organic matter, in addition to levels of oxalate extractable Fe (Seng *et al*., 2001).

Effect of pre-flooding periods on the availability of P added after drying to upland rice

It was found that, after drying, soil pH, Eh, and acetate extractable Fe values of the soils returned to their pre-flooding values regardless of flooding duration. There was a corresponding decrease in P sorption capacity of the dried soils. This indicates that following drying there was a change in soil properties which influence P sorption, and hence P fertiliser added to the dried soils was more effective than if added before flooding. If applied after drying, the Fe^{2+} had presumably already oxidised to ferric oxyhydroxides, and the soils would be less reactive with P. Any decline in the availability of added P in this environment may be attributed to a surface-sorbed P on ferric oxyhydroxides rather than through occlusion. Evidence to support this were the values of Olsen or Bray-1 extractable P measured after growing rice on soils receiving P fertiliser added after drying, which showed no significant difference in values for the respective extractants between prior flooding periods.

Willett (1982) found that P added 16 days after drainage of some flooded alluvial soils rich in reducible Fe (32–62 g/kg) and organic carbon (60–66 g/kg) was strongly immobilised, and subsequently ineffective for increasing wheat growth. In other soils which were low in reducible Fe and organic matter (soil 3, 4, and 5), he found that P added after drying was not immobilised. His latter results (for soil 3, 4, and 5) are consistent with those of this study. The soils used in the present experiment had levels of citrate-dithionite-bicarbonate extractable Fe (cdb-Fe: 1.5–3.3 g/kg) and organic carbon (5–15 g/kg) (Seng *et al*., 2001) lower than those in soil 3, 4, and 5 of the above study (cdb-Fe: 4.5–8.0 g/kg, organic carbon: 10–48.5 g/kg). This clearly shows that on the major rice soils of southeast Cambodia, with low levels of reducible Fe and organic matter, the availability to upland crops, including rice, of P fertiliser added after drying of the flooded soils was not restricted by periods of prior flooding, and hence shoot dry matter weights of rice were not decreased by duration of pre-flooding. This considerably simplifies the P fertilizer strategy for upland crops grown immediately after rice in double cropping patterns. However, the present results also suggest that upland crops grown after rice will obtain only limited benefit from P applied previously to the rice. Further research would be needed to determine whether in double cropping, it was preferable to add most of the P to the upland crop or to the rice in order to optimise P uptake by both.

Conclusion

The availability to upland rice of P fertiliser added before flooding was substantially limited by the duration of flooding as indicated by a substantial decline in extractability of P added before flooding both prior to and after planting rice. This was associated with increases in acetate extractable Fe during flooding, and attributed to sorption of P or/and occlusion of P within ferric oxyhydroxides formed during subsequent oxidation of the soils. As a result, there were substantial decreases in P uptake and shoot dry matter of upland rice growing in these soils. By contrast, P fertiliser added after drying of flooded soils remained highly available to upland rice regardless of the periods of pre-flooding. This was attributed to the fact that phosphate was added after the formation of ferric oxyhydroxides, the form of Fe less reactive with phosphate.

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