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Long-Term Phosphorus Fertilizer Effects on Phosphorus Uptake, Efficiency, and Recovery by Upland Rice on an Ultisol

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ABSTRACT

Phosphorus (P) deficiency is a major constraint to upland rice production on highly weathered, low activity clay soils in the humid zone of West Africa. There is a paucity of information on the long-term fertilizer P effects on rice on these soils. A field experiment was conducted for six years (1993–1998) to determine the response of four upland rice cultivars to fertilizer P applied at 0, 45, 90, 135, and 180 kg P ha^{-1} only once in 1993, and to residual P in 1994, 1995, 1996, and 1998. The experimental site was located on an Ultisol, low in available P, in the humid forest zone of Côte d'Ivoire, West Africa. This paper discusses long-term P effects on P uptake and efficiency of upland rice cultivars. The cultivars evaluated differed in cumulative agronomic and physiological P efficiencies, and the efficiencies were higher at lower P rates for the P-efficient cultivars.

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The P uptake response and P harvest index were affected by P rate and its residual effect, which decreased with time after P was applied. The mean cumulative recovery of applied P in five crops of four rice cultivars varied from 5.5 to 9.4%. The results suggest that the variation in P efficiency of the cultivars is due to differences in the efficiency of utilization of P for grain production.

Key Words: Cumulative P response; Agronomic and physiological P efficiency; P utilization efficiency; P uptake and grain production; P harvest index.

INTRODUCTION

Phosphorus (P) deficiency has been identified as the major constraint to crop production on tropical, low-activity clay Ultisols and Oxisols.[1,2] In the humid zone of West Africa, not only are the soils low in P,[2,3] but the applied P is converted into insoluble forms by reactions with iron and aluminum oxides at the prevailing acid conditions.[3–5] There is a paucity of reports dealing with the long-term responses of rice to P fertilizers. Such information however can provide useful leads for developing P management strategies.[2]

Maintaining an adequate P concentration in the soil solution is necessary for improved crop production. Under these conditions, a combination of P-efficient genotypes and improved P management strategy is more practical for achieving sustainable crop production for crops such as upland rice.[6] With this objective, a field experiment was conducted for six years (1993–1998) to determine P response of four promising upland rice cultivars to fertilizer P and its residual value in an Ultisol. In a previous paper, we reported on the residual value of fertilizer P in terms of effects on grain yield, grain yield response and available P during the six years of study.[7] Results showed that there was a rapid loss of available P in the Ultisol[7] because of its fixation by sesqui-oxides.[5] This resulted in decreased yields and yield responses with time since P fertilizer was applied.[7] This paper considers the results of the long-term cumulative P fertilizer effects on P uptake, agronomic (kg grain kg^{-1} P applied) and physiological (kg grain kg^{-1} P uptake) efficiencies and recovery by upland rice cultivars. The results on P recovery by crops along with yield responses are useful in assessing the fertilizer P requirements of crops.[8,9]

MATERIALS AND METHODS

Experimental Site

A field experiment was conducted from 1993 to 1998 at the Centre National de Recherche Agricole (CNRA) station near Man (7.2° N, 7.4° W; 500 m altitude), Côte d'Ivoire (West Africa) to determine the fertilizer P response of four upland rice cultivars on an Ultisol in the humid forest zone. On average, the experimental site receives an annual rainfall of about 2000 mm in a mono-modal season. The rainfall received during the growing season (June to October) was highly variable during 1993–1998, from 684 to 1668 mm. The experimental site was under bush fallow for the last three years before initiation of the experiment and the fallow vegetation at the site was dominated by *Chromolaena odorata* (Compositae).

Soil

The soil at the experimental site is an Ultisol with acidic pH and low in available and total P. Soil samples were collected from surface (0–0.2 m) and sub-surface (0.2–0.4 m) layers before initiating the experiment. They were air-dried and ground to pass a 2-mm screen before analyses. For determining organic carbon (C), total nitrogen (N) and total P, the soil samples were ground to pass a 0.25-mm screen. For soil analyses (Table 1), pH was measured by a glass electrode using a soil to water or 1 *M* KCl ratio of 1:2.5. Organic C was determined using the Walkley–Black method[10] and total N as described by Bremner and Mulvaney.[11] Total P was determined by digesting the samples with perchloric acid, and available P was determined using Bray 1 extractant [12].

Field Experiment

The land at the experimental site was cleared by slashing the vegetation, which was removed from the plots. The land was disc plowed and harrowed in preparing the seedbed.

In 1993, five rates of fertilizer P (0, 45, 90, 135, and 180 kg P ha^{-1}) as triple super phosphate (TSP) were used to determine the response of four promising upland rice cultivars: WAB 56-125, WAB 56-104, WAB 56-50 (all three cultivars bred at WARDA) and IDSA 6 (local improved check). The three WAB cultivars have since been released to farmers for cultivation under

Table 1. Chemical characteristics of the Ultisol in 0–0.2 and 0.2–0.4 m depths at the experimental site at Man, Côte d'Ivoire at the initiation of the long-term experiment in 1993.

	Soil depth (m)	
Soil characteristic	0–0.2	0.2–0.4
pH (water)	4.9	4.8
pH (KCl)	4.0	4.0
Organic C ($g\,kg^{-1}$)	13.5	10.0
Total N ($mg\,kg^{-1}$)	950	780
Total P ($mg\,kg^{-1}$)	155	125
Bray 1 P ($mg\,kg^{-1}$)	2.7	1.8

upland conditions in Ivory Coast. Fertilizer was applied to individual plots by broadcasting and incorporating in the top 5–6 cm soil layer. Seeds were hand drilled 2–3 cm deep along the rows at a uniform depth and covered with soil. The four rice cultivars with five rates of P fertilizer were arranged in a randomized complete block design, with four replications. The cultivars were sown in rows at the spacing of 0.25 m. The plot size was 5 m × 3 m. All plots received N (as urea) at a rate of 100 kg $N\,ha^{-1}$, applied in three splits at sowing, tillering, and booting stages of the crop. A uniform, basal application to all plots of potassium (K) at a rate of 100 kg $K\,ha^{-1}$ as potassium chloride was made. The pre-emergence herbicide, Ronstar, was used to control weeds; in addition, plots were hand weeded at 4 and 6 weeks after emergence of the crop.

The experiment was repeated in 1994, 1995, 1996, and 1998 as the four rice cultivars were grown on the same plots without any new fertilizer P applications, to determine response to the residual P applied in 1993. All plots received an annual application of fertilizer N (as urea) at a rate of 100 kg $N\,ha^{-1}$, applied in three splits and K (as potassium chloride) at a rate of 100 kg $K\,ha^{-1}$. All other details of the experiment were the same as in 1993.

The crops were harvested at maturity, and grain and straw yields were recorded. Grain yield was recorded at 14% moisture content and the straw yield on a dry weight basis, by drying the samples at 60°C for 48 h. Grain and straw samples were analyzed for P by digesting the ground samples with a 2:1 mixture of nitric and perchloric acids. The P in the digests was analyzed following the vanadomolybdate yellow color method.[13] The results reported are the averages of four replicates and the P concentrations in plant tissue within replications did not differ significantly ($P = 0.05$).

The data were analyzed statistically using the analysis of variance procedure.

RESULTS AND DISCUSSION

Cumulative Direct and Residual Effects on Grain Yield and Phosphorus Uptake

Without application of fertilizer P, total grain yield and P content in the biomass of five crops of the four rice cultivars were similar (Table 2). With application of fertilizer P, there were significant differences among the cultivars and WAB 56-125 and WAB 56-50 gave significantly higher grain yields than the check IDSA 6. Phosphorus application significantly increased

Table 2. Total grain yield and P uptake in five successive crops of four upland rice cultivars in a long-term experiment (1993–1998) on an Ultisol. Fertilizer P was applied only once in 1993.

P rate (kg ha^{-1})	WAB 56-125	WAB 56-104	WAB 56-50	IDSA 6	Mean
Total grain yield (t ha^{-1}) of five crops grown in 1993, 1994, 1995, 1996 and 1998					
0	4.64	4.64	5.34	5.01	4.91
45	6.87	6.47	6.85	5.21	6.35
90	7.60	7.29	7.81	6.00	7.18
135	8.87	7.40	7.99	7.40	7.92
180	8.26	7.44	7.98	7.11	7.70
Mean	7.25	6.65	7.19	6.15	
LSD (0.05) for comparing cultivars = 0.686					
LSD (0.05) for comparing P rates = 0.613					
Total P uptake (kg ha^{-1}) of five crops					
0	9.1	8.1	9.6	10.2	9.3
45	13.5	13.0	12.6	13.6	13.2
90	16.8	14.5	15.6	15.3	15.6
135	19.5	16.6	17.5	20.2	18.5
180	19.5	18.0	18.3	20.8	19.2
Mean	15.7	14.0	14.7	16.0	
LSD (0.05) for comparing cultivars = 1.17					
LSD (0.05) for comparing P rates = 1.04					

grain yield and the highest mean grain yield was obtained at 135 kg P ha^{-1}, which did not differ from the yield at the highest P rate (180 kg P ha^{-1}).

Rice cultivars differed significantly in total P uptake in grain plus straw. Total P uptake in IDSA 6 was significantly higher than in WAB 56-104 and WAB 56-50, but was similar to the P uptake by WAB 56-125. Total P content in rice cultivars increased significantly with the rate of applied P up to 135 kg P ha^{-1} (Table 2).

In a previous report, it was shown that the residual effects of fertilizer P in the Ultisol, as judged by the grain yield and grain yield response of the upland rice cultivars, were small and they decreased rapidly with time after P was applied. A rapid loss of available P in the soil was also indicated by the values of P extracted by Bray 1.[7] The rapid loss of Bray 1 extractable P was likely caused by reversion of soluble P into insoluble forms by reactions with iron and aluminum oxides.[5]

Results on the changes during 1993–1998 in total P uptake effect (obtained by subtracting P uptake by plants grown in 0 P from that by plants grown in the plus P treatments) of the four rice cultivars showed that there was a rapid decrease in P content (Table 3). There were no clear differences in the four cultivars tested except that the WAB cultivars generally gave greater P uptake response, especially with direct P. The P uptake response was highest in 1993 for the four cultivars with fresh P and the response increased with P rate. The P uptake response decreased from values between 94 and 350% of the 0 P control treatment in 1993 to values between 38 and 141% of the control in 1995 and to values between 0 and 62% of the control in 1998 (Table 3). These changes in P uptake are similar to the changes in grain yield response reported earlier[7] and support the conclusion that the residual value of fertilizer P in tropical soils such as Ultisols and Oxisols is considerably lower[3,14] than those reported for calcareous soils such as Vertisols and some Alfisols.[15,16] Lime application could increase the effect of residual P by converting Fe–P and Al–P into Ca–P, but upland rice farmers in the region cannot afford. These findings have implications for developing a management strategy for crops such as upland rice.[2]

Cumulative Direct and Residual Phosphorus Effects on the Recovery of Applied Phosphorus

The data on P fertilizer recovery are the averages for the four rice cultivars because P recovery was similar for the cultivars tested. The apparent P recovery fraction (%) was maximal in 1993, the year in which the P fertilizer was applied. The % of P recovered by the crop decreased with the increase in P

Table 3. Total P uptake response of four upland rice cultivars to direct P in 1993 and to residual P in 1994, 1995, 1996, and 1998 on an Ultisol. Fertilizer P was applied only once in 1993.

P rate	P uptake ($kg\,ha^{-1}$)[a]					P uptake, % of control				
($kg\,ha^{-1}$)	45	90	135	180	Mean	45	90	135	180	Mean
WAB 56-125										
1993	2.5	4.0	4.1	4.9	3.9	182	286	293	350	278
1994	0.5	1.7	2.2	2.4	1.7	26	89	116	240	118
1995	0.6	0.7	1.1	1.1	0.9	38	44	69	69	55
1996	0.7	0.9	1.9	1.3	1.2	47	60	127	87	80
1998	0.1	0.4	1.1	0.7	0.6	4	15	41	26	22
WAB 56-104										
1993	2.5	3.0	3.1	3.9	3.1	192	231	238	300	240
1994	0.7	1.7	2.4	2.0	1.7	54	131	185	154	131
1995	0.7	0.7	1.1	1.0	0.9	54	54	85	77	68
1996	0.6	0.6	1.1	1.4	0.9	38	38	69	88	58
1998	0.4	0.4	0.8	1.6	0.8	15	15	31	62	31
WAB 56-50										
1993	1.7	3.3	3.5	4.5	3.3	94	183	194	250	180
1994	0.5	1.7	1.8	2.5	1.6	33	113	120	167	108
1995	0.6	0.8	1.2	0.8	0.9	43	57	86	57	61
1996	0.0	0.1	0.7	0.6	0.4	0	5	33	26	16
1998	0.2	0.1	0.7	0.3	0.3	37	4	25	11	12
IDSA 6										
1993	2.6	3.2	5.1	3.6	3.6	153	188	300	212	213
1994	1.0	1.1	2.4	3.2	1.9	59	65	141	188	113
1995	1.0	0.8	1.2	2.4	1.4	59	47	71	141	80
1996	0.0	0.5	1.0	1.1	0.4	0	25	50	55	33
1998	0.0	0.0	0.3	0.3	0.2	0	0	10	10	5

[a] Phosphorus uptake response obtained by subtracting P uptake by rice grown in respective 0 P from P uptake in the plus P treatments. Total P uptake in O P treatments by the four rice cultivars in 1993, 1994, 1995, 1996 and 1998 were, WAB 56-125: 1.4, 1.9, 1.6, 1.5 and 2.7; WAB 56-104: 1.3, 1.3, 1.3, 1.6 and 2.6; WAB 56-50: 1.8, 1.5, 1.4, 2.1 and 2.8; IDSA 6: 1.7, 1.7, 1.7, 2.0 and 3.1 $kg\,P\,ha^{-1}$, respectively.

rate from 45 to 180 $kg\,P\,ha^{-1}$ and with time after application of P (Table 4). Phosphorus fertilizer recovery in the rice crops grown in 1996 and 1998 was very low for WAB 56-125 and WAB 56-104 and the values were negligible in the case of IDSA 6 and WAB 56-50 (data not shown).

Table 4. Apparent P recovery fraction (%) of P fertilizer in five crops of rice (grain plus straw) grown on an Ultisol in 1993, 1994, 1995, 1996, and 1998. Fertilizer P was applied only once in 1993. The data presented are averages over the four upland rice cultivars.

P rate ($kg\ ha^{-1}$)	Apparent P recovery fraction (%)[a]			
	45	90	135	180
1993	5.2	3.8	2.9	2.4
1994	1.5	1.7	1.6	1.4
1995	1.6	0.9	0.9	0.7
1996	0.7	0.6	0.9	0.6
1998	0.4	0.2	0.5	0.4
Total (1993–1998)	9.4	7.2	6.8	5.5

[a] Phosphorus recovery fraction (%) = (P uptake in plus P − P uptake in 0 P)/(P applied) × 100.

The mean total P recovered in five crops of rice cultivars varied from 5.5 to 9.4% (Table 4) and some differences were observed among the cultivars evaluated. The P recovery fraction ranged from 4.8 to 6.7% for WAB 56-50, from 5.7 to 9.8% for WAB 56-125, from 5.9 to 10.2% for IDSA 6 and from 5.4 to 11.0% for WAB 56-104 (results not presented). The results demonstrate that apparent recovery of the P fertilizer in five crops of rice on the Ultisol was low and decreased rapidly with time after P application. This information can be used for developing P management strategies for crops such as upland rice that is commonly grown on Ultisols in the humid zone of West Africa.[6]

There is a paucity of reports on the recovery of fertilizer P, especially under long-term fertilizer P effects in tropical Africa,[3] but such information is needed for developing P uptake models for determining the fertilizer P requirements of crops.[8,9] From these results it would seem that annual application of P fertilizer at smaller rates should be a better option than application of larger rates once in two or three years. Also, economics involved in the use of fertilizer must be taken into consideration

Cumulative Agronomic and Physiological Phosphorus Efficiencies of the Cultivars

Agronomic P efficiency (AE-P) of the rice cultivars was calculated as the increase in grain yield by application of P and is expressed as kg grain kg^{-1} P applied. The physiological P efficiency (PE-P) of the cultivars was calculated from the P uptake data and is expressed as kg grain kg^{-1} P uptake in grain plus straw. The AE-P and PE-P are based on the cumulative P response obtained for five successive crops of rice.

The cumulative AE-P of the four cultivars varied from 4 to 50 kg grain kg^{-1} P applied and the efficiency decreased with increase in the rate of fertilizer P applied for the WAB cultivars (Table 5). However, in the case of IDSA 6, the AE-P increased with the rate of P applied up to 135 kg P ha^{-1}. Based on the mean values, averaged over four rates of P, AE-P was highest for WAB 56-125 (34 kg grain kg^{-1} P) followed by WAB 56-50 (27 kg grain kg^{-1} P), WAB 56-104 (24 kg grain kg^{-1} P) and IDSA 6 (11 kg grain kg^{-1} P) (Table 5). The cumulative AE-P for WAB 56-125 and WAB 56-104 was significantly higher than that of IDSA 6, but was similar to that of WAB 56-50. The cultivar IDSA 6 compared to WAB cultivars, allocated less P for grain production, although the total P uptake in grain plus straw were similar to those of WAB cultivars.[17]

Table 5. Cumulative agronomic P efficiency (AE-P) and physiological P efficiency (PE-P) of four upland rice cultivars determined in a long-term experiment (1993–1998) on an Ultisol. Fertilizer P was applied only once in 1993 and crops were grown in 1993, 1994, 1995, 1996, and 1998.

P rate (kg ha^{-1})	WAB 56-125	WAB 56-104	WAB 56-50	IDSA 6	Mean
Cumulative AE-P (kg grain kg^{-1} P applied)					
45	50	41	34	4	32
90	33	29	27	11	25
135	31	20	20	18	22
180	20	16	15	12	16
Mean	34	27	24	11	
LSD (0.05) for comparing cultivars = 12.8					
LSD (0.05) for comparing P rates = 12.8					
Cumulative PE-P (kg grain kg^{-1} P uptake)					
45	509	498	544	383	484
90	452	503	501	392	462
135	455	446	457	366	431
180	424	413	436	342	404
Mean	460	465	485	371	
LSD (0.05) for comparing cultivars = 29.6					
LSD (0.05) for comparing P rates = 29.6					

The cumulative PE-P of the four rice cultivars varied from 342 to 544 kg grain kg^{-1} P uptake in grain plus straw and generally decreased with increasing rate of P applied. The three WAB cultivars gave significantly higher cumulative PE-P than IDSA 6 (Table 5). The mean PE-P of the cultivars, averaged over four rates of fertilizer P, varied from 371 to 485 kg grain kg^{-1} P uptake and was highest for WAB 56-50, followed by WAB 56-104, WAB 56-125 and IDSA 6 (Table 5).

These results (Table 5) show that WAB cultivars are more P efficient than the check cultivar IDSA 6 and are in agreement with the results reported earlier for the direct response of P fertilizer.[17] The WAB cultivars compared to the local Check IDSA 6 maintained their higher AE-P and PE-P when cumulative P response was used as the criterion for computing the efficiencies.

Phosphorus Harvest Index and Phosphorus Efficiency

The relatively poor AE-P and PE-P of the check cultivar IDSA 6 when compared with the three WAB cultivars was due to its lower ability to accumulate absorbed P in the grain; this is exemplified by significantly lower P harvest index, defined as (P content in the grain)/(total P content in the grain plus straw) (Table 6). The WAB cultivars maintained higher harvest indices than IDSA 6 for direct and residual fertilizer P responses during 1993–1998. For example, the P harvest indices of the WAB cultivars, averaged over the four rates of fertilizer P, varied from 65 to 76%, while for IDSA 6, the P

Table 6. Changes in P harvest indices (%) of four upland rice cultivars in a long-term (1993–1998) experiment on an Ultisol. The data are averaged over five rates of fertilizer P (0, 45, 90, 135, and 180 kg P ha^{-1}) applied only once in 1993; crops were grown in 1993, 1994, 1995, 1996, and 1998.

	P harvest index (P uptake in grain)/(Total P uptake in grain plus straw)					
Cultivar	1993	1994	1995	1996	1998	Mean
WAB 56-125	72	76	72	66	67	71
WAB 56-104	76	76	69	66	70	71
WAB 56-50	71	73	69	65	69	69
IDSA 6	57	69	60	63	64	63
Mean	69	74	68	65	68	

LSD (0.05) for comparing cultivars = 4.6
LSD (0.05) for comparing years = 4.1

harvest index varied from 57 to 69%. Based on the overall mean values, the WAB cultivars had 6 to 8% higher P harvest indices (mean range 69 to 71%) than IDSA 6 (mean 63%).

It was reported that IDSA 6 had a lower harvest index than the three WAB cultivars and it was only slightly improved by P fertilization, which, however, caused further improvement in the harvest indices of the latter.[17]

The results showing the genetic variation in the internal P efficiency of the rice cultivars are in accord with those reported by Fageria et al.[18] who pointed out that differences in P use efficiency of the rice cultivars were due to difference in their ability to transport absorbed P to the grain.

CONCLUSIONS

Upland rice is a relatively P-efficient crop and the evaluation of P requirements of some promising upland rice cultivars showed that they require a total P uptake in grain plus straw of about 2 kg to produce one t grain yield.[9] The potential exists for selecting cultivars with a high efficiency in grain production. Selection of rice cultivars that acquire more P or that have better P efficiency is an important strategy for adaptation to harsh rained upland growing environments in the humid tropics where P deficiency is acute and constrains crop production.[6] The highly weathered Ultisols and Oxisols in the humid zone of West Africa are the obvious examples.

From the results presented, it can be concluded that the higher P efficiency observed in the case of improved WAB upland rice cultivars (WAB 56-125, WAB 56-104, and WAB 56-50) compared to IDSA 6 is due to higher efficiency of utilization of P for grain production.

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