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Direct and residual phosphorus effects on grain yield-phosphorus uptake relationships in upland rice on an ultisol in West Africa

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Abstract

Phosphorus (*P*) deficiency is a major constraint to crop production on highly weathered, low-activity clay soils in the humid zone of West Africa. Past research suggested a linear relationship between grain yield and P uptake over a range of fertilizer P applied to upland rice cultivars. However, there is lack of information on how these relationships are affected by the long-term fertilizer P effects, although such information is needed for developing P management strategies because phosphate fertilization effects last for several seasons. Results from a long-term field experiment (1993-1998) conducted to determine the response of four improved upland rice cultivars to fertilizer P (0, 45, 90, 135 and 180 kg P ha^{-1}) applied only once in 1993 and to its residues in 1994, 1995, 1996 and 1998, were used to determine grain yield and P uptake relationships. The soil at the experimental site, in the humid forest zone of Côte d'Ivoire (West Africa), was an Ultisol with acidic pH and low in available P. Significant linear relationships (R varying between 0.796 and 0.956) were observed between grain yield and total P uptake for each of the crops grown during 1993-1998. The results indicate that P uptake based models can be used to determine P requirements of rice cultivars under direct and residual P.

Keywords: Grain yield; Phosphorus uptake; Phosphorus requirement; Direct and residual phosphorus effects; Phosphorus management; Harvest index

Introduction

Apart from water shortages, soil infertility is the major constraint to crop production and productivity in most of the tropical regions of the world (Black 1993; Bationo et al. 2008). Phosphorus (P) deficiency is identified as a major constraint to crop production on acid tropical, low-activity clay Ultisols and Oxisols (Sanchez and Salinas, 1981; Von Uexkull and Mutert, 1995; Sahrawat et al. 2001a). The upland ecosystem in West Africa is very important to rice production (Enyi 1984; Sahrawat et al. 2001a). About 70% of the upland rice is grown in the humid zone of the sub-region on acid low-activity clay soils, mostly Ultisols and some Oxisols and Alfisols. Low concentration of soluble P on highly weathered Ultisols and Oxisols limits crop production and productivity. In the humid zone of West Africa, the soils are not only low in P but the applied soluble P is converted to insoluble forms by reactions with iron and aluminum oxides (Juo and Fox, 1977; Owusu-Bennoah et al., 1997; Sahrawat et al., 2001a; Abekoe and Sahrawat, 2001, 2003).

Upland rice is a robust crop and rice cultivars adapted to acid low P soil conditions perform well when fertilized with P (Sahrawat et al., 2000). Upland rice cultivars have relatively low P requirement (Sahrawat, 2000) and P-efficient cultivars may give better performance under both fresh and residual P. An approach that integrates the use of P efficient cultivars with P nutrition is needed for the sustainability of upland rice-based production systems. The availability at the West Africa Rice Development Association (WARDA) of improved and P-efficient upland rice cultivars, well adapted to acid soil conditions, stimulated crop and resource management research, especially P management for stabilizing and sustaining the productivity of upland rice-based systems (Sahrawat et al., 2000).

Optimal use of P (along with nitrogen and other limiting nutrients) is critical for increasing the productivity of acid upland soils in the humid regions of west and central Africa. Assessment of the nutrient sufficiency and requirements is an integral component of research on efficient and rational use of nutrient inputs from external sources in production systems (Sahrawat, 2006).

Soil and plant analyses are employed for determining the nutrient requirements of crops for a yield target. Our earlier studies showed that soil P test using Bray 1 reagent or P concentration in the tops of upland rice plants at the tillering growth stage can be used for predicting grain and biomass yields of rice grown on Ultisols and Alfisols (Sahrawat et al. 1997, 1998). The critical limit of Bray 1P in the soil at 90% relative rice grain yield varied from 12.5 to 15.0 mg kg^{-1} soil for the four rice cultivars (Sahrawat et al., 1997). Using plant tissue P concentration as the criterion, the critical concentration of P in the whole rice plant tops at the tillering growth stage at 90% relative grain yield was found to be 2 g P kg^{-1} for the four rice cultivars (Sahrawat et al., 1998). The results showed that upland rice cultivars differed in the external P requirement (P concentration in the growing medium), they did not differ in their internal P requirement (P concentration in the plant tissue) (Sahrawat et al. 1997, 1998; Sahrawat, 2006). Research also showed that yield- total P uptake relationships can be used for determining fertilizer P requirements of crops such as sorghum and upland rice grown on calcareous and acid upland soils (Sahrawat, 2000, 2006).

Despite a great deal of research on soil P, much remains unknown about the response of improved upland rice cultivars to residual P on soils such as Ultisols in the humid zone of West Africa. Also, there is a need to establish grain yield and P uptake relationships for direct and residual P for developing long-term P management strategies. With this objective the results from a long-term field experiment (1993-1998) conducted to determine the P response of four promising upland rice cultivars to direct and residual P on an Ultisol (Sahrawat et al., 2001b), were used to determine the grain yield-P uptake relationships.

Materials and methods

Experimental site

The site at which the long-term (1993-1998) P experiment was conducted is located in the humid forest zone at Centre National de Recherche Agricole (CNRA) station near Man (7.2°N, 7.4°W; 500 m altitude), Côte d'Ivoire, West Africa. The site receives an annual rainfall of about 2000 mm in a mono-modal rainy season. The rainfall received during the growing season, from June through October, was highly variable and varied from 684 to 1668 mm during the duration of the experiment (Table 1). The experimental site was under bush fallow for the last three years before initiation of the experiment and the fallow vegetation was dominated by *Chromolaena odorata* (Compositae).

Table 1. The rainfall received during the growing season (June through October) of rainfed upland rice crops in a field experiment conducted for six years (1993-1998) at the Man site in Côte d'Ivoire.

Growing season	Rainfall received (mm)
1993	953
1994	684
1995	1396
1996	1668
1997	970
1998	1454

Soil

The soil at the experimental site was an Ultisol with acidic pH and low in available P. Soil samples were collected from surface (0-0.2m) and sub-surface (0.2-0.4 m) layers before initiating the experiment. The samples were air-dried and ground to pass a 2-mm screen before analysis. For organic C, total N and total P analyses, the samples were ground to pass a 0.25-mm screen. For the soil analyses reported (Table 2), pH was measured by a glass electrode using a soil to water or 1 M KCl solution ratio of 1:2.5. Organic C was determined using the Walkley-Black method (Nelson and Sommers, 1982) and total N as described by Bremner and Mulvaney (1982). Total P was determined by digesting the samples with perchloric acid, and extractable P was determined using Bray 1 extractant (NH_4F-HCl solution) to extract P using a soil to extractant ratio of 1:7 (Olsen and Sommers, 1982).

Table 2. Chemical characteristics of the Ultisol at two depths at the experimental site at Man, Côte d'Ivoire at the initiation of the long-term experiment in 1993.

Characteristic	Soil depth (m)	
	0-0.2	0.2-0.4
pH (water)	4.9	4.8
pH (1 M 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

Field experiment

A field experiment was conducted for six years (1993-1998) to determine the response of four upland rice cultivars to direct and residual P (Sahrawat et al., 2001b). The land at the experimental site was cleared by slashing the vegetation. The slashed vegetation was removed from the plots. The land was disc plowed and harrowed for preparing 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 P response of four promising upland rice cultivars: WAB 56-125, WAB 56-104 and WAB 56-50 (all three cultivars bred at WARDA), and IDSA 6 (an improved local check cultivar). The three WAB cultivars have since been released to farmers for cultivation in upland ecology in Côte d'Ivoire. Fertilizer was applied to individual plots by broadcasting and incorporating in the top 5-6 cm soil layer. Seeds were hand drilled 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 factorial randomized complete block design, with four replications; and rice cultivars were main plots and P rates as the sub-plots. The cultivars were sown in rows at spacing of 0.25 m. The plot size was 5 x 3 m. All plots received N at a rate of 100 kg N ha^{-1}, applied in three splits at planting, tillering and booting stages of the crop. A uniform, basal application to all plots of K at a rate of 100 kg K ha^{-1} as potassium chloride was also made. Pre-emergence herbicide Ronstar was used for controlling weeds. In addition, plots were also 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 fresh fertilizer P applications to determine response to the residues of fertilizer 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 at planting, tillering and booting stages of the crop, and K 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 straw yield was recorded 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 samples with a 2:1 mixture of nitric and perchloric acids. The P in the digests was analyzed following the vanadomolybdate yellow color method. Phosphorus uptake was obtained by multiplying P concentration with the yield.

The data were subjected to regression analysis to determine the relationships between grain yield and total P uptake for each of the five rice crops.

Results and discussion

Based on the pooled data for the four rice cultivars at five rates of P fertilizer (0, 45, 90, 135 and 180 kg P ha^{-1} applied only once in 1993) (Table 3), significant linear relationships (R varying from 0.796 to 0.956) were observed between grain yield and total P uptake in grain plus straw for direct and residual P for each of the rice crops grown in 1993, 1994, 1995, 1996 and 1998.

The relationships between grain yield and total P uptake in the plant biomass were described by the following linear regression equations:

1993: Grain yield (t ha^{-1}) =0.637 + 0.253 P uptake (kg ha^{-1}); R = 0.809 (n = 20) (1)
1994: Grain yield = 0.647+0.230 P uptake; R = 0.796 (2)
1995: Grain yield = 0.461+0.267 P uptake; R = 0.800 (3)
1996: Grain yield = 0.206+0.452 P uptake; R = 0.956 (4)
1998: Grain yield = -0.118+0.453 P uptake; R = 0.818 (5)

From these regression equations (1-5), the amount of total P uptake in grain plus straw to produce 1 t rice grain yield varied from 2 to 2.5 kg P ha^{-1} for direct, first, second, third and fourth residual P effects.

These results indicate that P requirements of rice cultivars for a given target yield can be determined using models based on total P uptake at harvest. The results of the present study extend the applicability of linear relationships between grain yield and P uptake, observed for direct P response in upland rice and sorghum (Sahrawat 1999, 2000), to long-term P effects covering both direct and residual P.

It was also observed that the higher grain yield response of the WAB cultivars for direct and residual P is due to their higher P use efficiency. The WAB cultivars had higher P harvest index (P content in the grain/total P content in grain plus straw) than IDSA 6 for direct and residual P responses during 1993-1998 (Table 4). This resulted in higher grain yields in the WAB cultivars compared to IDSA 6 for similar amounts of total P uptake in the plant biomass (Table 3). These results further indicate that upland rice cultivars selected with higher harvest index are also likely to have greater P use efficiency; and harvest index can be a useful criterion for selecting P efficient upland rice cultivars for growing in the acid upland soils (Sahrawat et al. 2000).

The linear relationships between grain yield and total P uptake for upland rice cultivars seem more general because the relationships were observed for both direct and residual P response during 1993-1998. Significant linear relationships between grain yield and total P uptake were also earlier observed in field studies for sorghum grown on a Vertisol under semi-arid tropical conditions (Sahrawat 1999) and for upland rice on an Ultisol in the humid forest zone (Sahrawat 2000) for direct P response.

In conclusion, significant linear relationships between grain yield and total P uptake of the rice crops for direct and residual P demonstrate that simple models based on P uptake can be used for determining the P requirements of crops.

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Table 3. Grain yield and total P uptake in grain plus straw of four upland rice cultivars in response to fertilizer P and its residues in a long-term experiment (1993-1998) on an Ultisol. Fertilizer P was applied at five rates only once in 1993.

P rate	Grain yield (t ha^{-1}) and (P uptake, kg ha^{-1}) in 1993-1998				
(kg ha^{-1})	1993	1994	1995	1996	1998
-	WAB 56-125				
0	0.75(1.4)	1.14 (1.9)	0.91 (1.6)	0.81 (1.5)	1.03 (2.7)
45	2.05 (3.9)	1.31 (2.4)	1.15 (2.2)	1.19 (2.2)	1.17 (2.8)
90	2.35 (5.4)	1.70 (3.6)	1.26 (2.3)	1.18 (2.4)	1.11 (3.1)
135	2.22 (5.5)	1.78 (4.1)	1.37 (2.7)	1.84 (3.4)	1.66 (3.8)
180	2.46 (6.3)	1.70 (4.3)	1.25 (2.7)	1.49 (2.8)	1.36 (3.4)
LSD(0.05)	0.398	0.589	0.258	0.380	0.471
-	WAB 56-104				
0	1.04 (1.3)	0.89 (1.3)	0.81 (1.3)	1.00 (1.6)	0.90 (2.6)
45	1.94 (3.8)	1.17 (2.0)	1.04 (2.0)	1.28 (2.2)	1.04 (3.0)
90	2.29 (4.3)	1.61 (3.0)	1.04 (2.0)	1.33 (2.2)	1.02 (3.0)
135	1.84 (4.4)	1.60 (3.7)	1.11 (2.4)	1.44 (2.7)	1.41 (3.4)
180	1.97 (5.2)	1.23 (3.3)	1.05 (2.3)	1.60 (3.0)	1.59 (4.2)
LSD(0.05)	0.348	0.405	0.242	0.289	0.404
-	WAB 56-50				
0	1.09 (1.8)	0.84 (1.5)	0.83 (1.4)	1.15 (2.1)	1.43 (3.1)
45	1.97 (3.5)	1.12 (2.0)	1.09 (2.0)	1.20 (2.1)	1.47 (3.0)
90	2.36 (5.1)	1.68 (3.2)	1.16 (2.2)	1.28 (2.2)	1.33 (2.9)
135	2.19 (5.3)	1.52 (3.3)	1.29 (2.6)	1.46 (2.8)	1.53 (3.5)
180	2.42 (6.3)	1.54 (4.0)	1.13 (2.2)	1.44 (2.7)	1.45 (3.1)
LSD(0.05)	0.227	0.391	0.337	0.311	0.503
	IDSA 6				
0	1.07 (1.7)	0.90 (1.7)	0.75 (1.7)	1.09 (2.0)	1.20 (3.1)
45	1.69 (4.3)	1.04 (2.7)	0.84 (2.7)	0.94 (1.8)	0.70 (2.1)
90	1.61 (4.9)	1.13 (2.8)	1.00 (2.5)	1.27 (2.5)	0.99 (2.6)
135	1.97 (6.8)	1.43 (4.1)	1.22 (2.9)	1.44 (3.0)	1.34 (3.4)
180	1.36 (5.3)	1.39 (4.9)	1.57 (4.1)	1.54 (3.1)	1.35 (3.4)
LSD(0.05)	0.617	0.389	0.376	0.467	0.629

Table 4. The changes in 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.

year	Pharvest index (P uptake in grain/Total P uptake in grain plus straw) x 100				
	WAB 56-125	WAB 56-104	WAB 56-50	IDSA 6	LSD (0.05)
1993	72	76	71	57	
1994	76	76	73	69	
1995	72	69	69	60	
1996	66	66	65	63	
1998	67	70	69	64	
Mean	71	71	69	63	4.6

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