*Nutrient Cycling in Agroecosystems* **48:** 209–215, 1997.
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# Direct and residual fertilizer phosphorus effects on yield and phosphorus efficiency of upland rice in an Ultisol

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Received 20 November 1996; accepted in revised form 13 March 1997

*Key words:* cummulative agronomic and physiological P efficiencies, grain yield, *Oryza sativa*, P harvest index, P recovery fraction, P residues

## Abstract

Phosphorus (P) deficiency is one of the major limiting factors for crop production in highly weathered soils in the humid zone of West Africa. Very few studies have evaluated the residual value of fertilizer P to rice in these soils. Field experiments were conducted for three years (1993–1995) to determine the response of four upland rice cultivars to fertilizer P applied at 0, 45, 90, 145 and 180 kg P ha$^{-1}$ only once in 1993, and to fertilizer P residues in 1994 and 1995. The soil at the experimental site, in the humid forest zone of Ivory Coast (West Africa), was an Ultisol, low in available P.

Grain yields of the rice cultivars were significantly increased by fertilizer P in 1993, and by the fertilizer P residues in 1994 and 1995 although the magnitude of response decreased with time since the fertilizer was applied. The cultivars differed in cumulative agronomic and physiological efficiencies, and the efficiencies were higher at the lower rates of P. The amounts of total P removed in three successive crops were similar for all the four rice cultivars although P harvest index was 10–12% higher in the P efficient than inefficient cultivars. The results suggest that the differences observed in the P efficiency of rice cultivars are due to differences in the internal efficiency of P.

## Introduction

Phosphorus deficiency is one of the most important nutrient disorders in highly weathered upland soils of West Africa's humid forest zone. Availability of P in those soils is reduced by the reaction of soluble P with iron and aluminum oxides (Juo & Fox, 1977; Mokwunye et al., 1986). Upland rice is a robust crop and rice cultivars that possess tolerance to soil acidity perform well in the acid uplands when fertilized with P (Sahrawat et al., 1995a). An effective and economically efficient P management strategy for upland rice grown on the acid uplands, requires accounting for the residual value of P fertilizer (Warren, 1992).

Despite a great deal of research on soil P much remains unknown about the residual value of fertilizer P to upland rice in the humid tropics of West Africa. The aim of this study, therefore, was to determine the response of upland rice cultivars to fertilizer P and to its residues in an Ultisol low in extractable P under rainfed cropping.

## Materials and methods

### *Experimental site*

Field experiments were conducted for three years (1993–1995) at the Institut des savanes (IDESSA) station near Man (7.2° N, 7.4° W; 500 m altitude) to measure fertilizer P response of four upland rice cultivars in an Ultisol in the humid forest zone of Ivory Coast. The site receives an annual rainfall of about 1700 mm. The rainfall received during the growing season (June–October) was highly variable: it was 953 mm in 1993, 684 mm in 1994 and 1396 mm in 1995. The experimental site was under a bush-fallow for the last three years before initiation of the experiment. The

*Table 1*. Some characteristics of the soil (0–20 cm and 20–40 cm depths) at the experimental site near Man, Ivory Coast at the initiation of the experiment in 1993

| Soil characteristic | Soil depth (cm) | |
|---|---|---|
| | 0–20 | 20–40 |
| pH (water) | 4.9 | 4.8 |
| pH (KCl) | 4.0 | 4.0 |
| Organic C (g $kg^{-1}$) | 0.135 | 0.100 |
| Total N (mg $kg^{-1}$) | 950 | 780 |
| Total P (mg $kg^{-1}$) | 155 | 125 |
| Bray 1 P (mg $kg^{-1}$) | 2.7 | 1.8 |

secondary vegetation was dominated by *Chromolaena odorata* (Sahrawat et al., 1995a).

*Soil*

The soil at the experimental site is an Ultisol low in extractable P. Some important characteristics of the soil are given in Table 1. The soil samples were collected from two soil depths (0–20 and 20–40 cm) before initiating the experiment, airdried and ground to pass a 2-mm screen before analysis. For organic C, total N and total P analysis the samples were ground to pass a 0.25-mm screen. For the analyses reported in Table 1, 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 & Sommers, 1982). Total N was determined as described by Bremner & Mulvaney (1982). Total P content in the soil was determined by digestion with perchloric acid and the exractable P was determined using Bray 1 extractant ($NH_4$ F-HCl solution) to extract P using a soil to extractant ratio of 1:7 (Olsen & Sommers, 1982).

*Field experiments*

The experimental land was cleared by slashing the vegetation, and slashed vegetation was removed from the plots. The land was prepared by disc plowing and harrowing the plots to obtain a good seed bed.

In 1993, five rates of P (0, 45, 90, 135 and 180 kg P/ha as triple superphosphate) were used to test the P response of four promising upland rice cultivars, consisting of three upland rices bred at WARDA (WAB 56-125, WAB 56-104 and WAB 56-50) and the local improved check IDSA 6. Fertilizer was applied plotwise 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. A randomized complete block design was used, with four replications. The cultivars were sown in rows at spacing of 25 cm. Each plot (5 × 3 m) received N (total 100 kg N $ha^{-1}$) in three splits at planting, tillering and flowering. A uniform, basal application of K (as muriate of potash) to all plots was also made to supply 100 kg K $ha^{-1}$. Plots were hand weeded at 4 and 6 weeks after seeding.

The experiment was repeated in 1994 and 1995 as the four rice cultivars were grown on the same plots without any fresh fertilizer P applications to measure response to the residues of fertilizer P applied in 1993. All plots received an annual application of fertilizer N at a rate of 100 kg N $ha^{-1}$, applied in three splits. Potassium was also applied at a rate of 100 kg K $ha^{-1}$ in the 1994 season. All other details of the experiment were same as in 1993.

The crops were harvested at maturity and grain and straw weights were recorded at 14% moisture. Grain and straw samples were analysed for P by digesting the samples with a 2:1 mixture of nitric and perchloric acids. The P in the digests was analysed following the vanadomolybdate yellow colour method.

The data were analysed statistically using analysis of variance.

## Results and discussion

*Grain yield response to fertilizer P and its residues*

In 1993, during the first year of the experiment, without applied P, the cultivar WAB 56-50 gave the highest grain yield, followed by IDSA 6, WAB 56-104 and WAB 56-125. All the four test cultivars showed a significant response of grain yield to P application with WAB 56-125 responding most and IDSA 6 least (Table 2). In 1993, with fresh P application, the maximum response of the cultivars varied and it was obtained at 87 kg for WAB 56-125, at 75 kg for WAB 56-104, at 139 kg for WAB 56-50 and at 103 kg $ha^{-1}$ for IDSA 6.

For each cultivar, P response model was fitted to the three years data using the trends obtained in the individual year analyses and using the dummy variables defined as:

($z_1$, $z_2$) = (0, 0) in 1993, (1, 0) in 1994 and (0,1) in 1995.

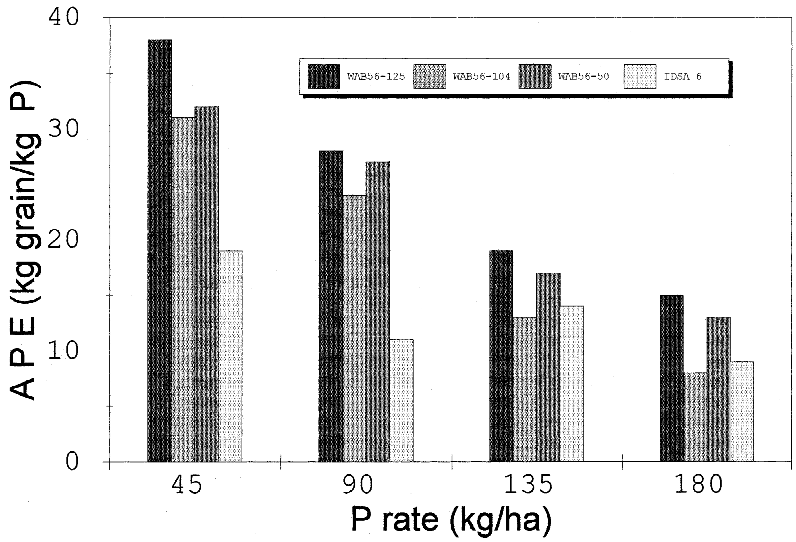


*Figure 1.* Agronomic P efficiency (APE) of four upland rice cultivars based on cummulative P response in three consecutive years (1993–95). Fertilizer P was applied only once in 1993.

*Table 2.* Grain yield (t $ha^{-1}$) of four upland rice cultivars in response to fertilizer P or its residues on an Ultisol in the humid forest zone of West Africa. Fertilizer P was applied only once in 1993

| | P (kg $ha^{-1}$) applied in 1993 | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 45 | 90 | 135 | 180 | LSD (0.05) |
| *WAB 56-125* | | | | | | |
| 1993 | 0.75 | 2.05 | 2.35 | 2.22 | 2.46 | 0.398 |
| 1994 | 1.14 | 1.31 | 1.70 | 1.78 | 1.70 | 0.589 |
| 1995 | 0.91 | 1.15 | 1.26 | 1.37 | 1.25 | 0.258 |
| *WAB 56-104* | | | | | | |
| 1993 | 1.04 | 1.94 | 2.29 | 1.84 | 1.97 | 0.348 |
| 1994 | 0.89 | 1.17 | 1.61 | 1.60 | 1.23 | 0.405 |
| 1995 | 0.81 | 1.04 | 1.04 | 1.11 | 1.05 | 0.242 |
| *WAB 56-50* | | | | | | |
| 1993 | 1.09 | 1.97 | 2.36 | 2.19 | 2.42 | 0.227 |
| 1994 | 0.84 | 1.12 | 1.68 | 1.52 | 1.54 | 0.391 |
| 1995 | 0.83 | 1.09 | 1.16 | 1.29 | 1.13 | 0.337 |
| *IDSA 6* | | | | | | |
| 1993 | 1.07 | 1.69 | 1.61 | 1.97 | 1.36 | 0.617 |
| 1994 | 0.90 | 1.04 | 1.13 | 1.43 | 1.39 | 0.389 |
| 1995 | 0.75 | 0.84 | 1.00 | 1.22 | 1.57 | 0.376 |

The P response equations for the four cultivars to fresh P in 1993 and to residual P in 1994 and 1995 were as follows:

WAB 56–125:

$$\text{Yield} = (0.746 + 0.3835z_1 + 0.1684z_2) \\ +(0.0459 - 0.04336z_1 - 0410z_2)X$$

$$(-0.00043 + 0.00049z_1 - 0.00043z_2)X^2$$
$$(+0.00000125 - 0.0000016z_1 - 0.0000013z_2)X^3$$
$$X^3, r^2 = 0.989 \quad (1)$$

where, X is the level of P applied only in 1993, and $z_1$ and $z_2$ are the dummy variable as defined above. The response of WAB 56-125 to P was cubic in 1993 and linear in 1994 and 1995.

WAB 56-104:

$$\text{Yield} = (1.0167 - 0.1364z_1 - 0.1995z_2)$$
$$+(0.03676 - 0.03162z_1 - 0.03071z_2)X$$
$$(-0.00036 + 0.00043z_1 + 0.00032z_2)X^2$$
$$+(0.00000103 - 0.0000015z_1 - 0.0000009z_2)$$
$$X^3, r^2 = 0.924 \quad (2)$$

The P response of the cultivar was cubic in 1993, quadratic in 1994 and there was no response in 1995.

WAB 56-50:

$$\text{Yield.} = (1.1643 - 0.3614z_1 - 0.3357z_2)$$
$$+(0.01821 - 0.00633z_1 - 0.01148z_2)X$$
$$(-0.0000656 + 0.0000218z_1 + 0.0000381z_2)$$
$$X^2, r^2 = 0.910 \quad (3)$$

The P response of the cultivar was quadratic in 1993 and 1994 and linear in 1995.

IDSA 6:

$$\text{Yield} = (1.07943 - 0.19685z_1 - 0.32457z_2)$$
$$+(0.014737 - 0.01074z_1 - 0.01393z_2)X$$
$$(-0.00007125 - 0.0000659z_1 + 0.0000917z_2)$$
$$X^2, r = 0.837 \quad (4)$$

The P response of IDSA 6 was quadratic in 1993 and linear in 1994 and 1995.

The response to residual P, one year after the application of P (first residual P) during the second year of the experiment in 1994, was much weaker but was significant for all four cultivars. The maximum responses to first residual P were obtained at the same P rates as in 1993 with fresh P application (Table 2).

The grain yield response to residual P, two years after the application of fertilizer P (second residual P) during the third year of the experiment in 1995, was weaker than that obtained in 1994 and was generally significant from P applied at 135 and 180 kg P/ha. The cultivar IDSA 6 gave the highest grain yield in response to second residual P resulting from the 180 kg P/ha rate, followed by WAB 56-125, WAB 56-50 and WAB 56-104. The cultivar WAB 56-104 did not give a significant response to second residual in the third year (Table 2).

These results are significant in that they show that fertilizer P applied in excess of the crop requirement (> 45 kg P $ha^{-1}$) resulted in significant residual P effects, in terms of grain yields, up to two years after application of P. The P residual effects, however, are weaker compared to those reported on Vertisols and Alfisols for crops other than rice (e.g. see, Sahrawat et al., 1995b; Warren, 1992). This is due to the reactions of soluble P with Al and Fe oxides that rendered the applied P less available to the rice crop (WARDA, 1990).

### *Cummulative agronomic P efficiency of the cultivars*

Agronomic P efficiency (APE) of the cultivars was calculated as the increase in grain yield by application of P and is expressed as kg grain kg $P^{-1}$ applied. The agronomic P efficiencies of the cultivars are based on the cummulative P response obtained for three years. The agronomic P efficiency of the four cultivars, averaged over four rates of P, and based on the cummulative P response during the three years, was highest for WAB 56-125 (25 kg grain $kg^{-1}$ P), followed by WAB 56-50 (22 kg grain $kg^{-1}$ P), WAB 56-104 (19 kg grain $kg^{-1}$ P) and IDSA 6 (13 kg grain $kg^{-1}$ P) (Figure 1). The cummulative agronomic P efficiency of the cultivars decreased with the increase in the level of P applied and it was highest at 45 kg P $ha^{-1}$ rate (Figure 1).

These results are in agreement with those reported by Sahrawat et al. (1995a). Based on response of the upland rice cultivars to fresh P, they reported that the WAB cultivars were more P efficient than IDSA 6. Our results showed that the cultivars maintained their P efficiency when cummulative P response of the cultivars was used as the criterion for P efficiency.

### *Cummulative physiological efficiency of the cultivars*

Physiological P efficiency (PPE) of the four cultivars, based on cummulative P response for three years, was calculated from the P uptake data and is presented as kg grain/kg P uptake (Figure 2). The average physiological P efficiency of the four cultivar varied from 381 to 518 kg grain/kg P uptake, and was highest for WAB 56-104, followed by WAB 56-50, WAB 56-125 and IDSA 6 in the descending order (Figure 2). These results are

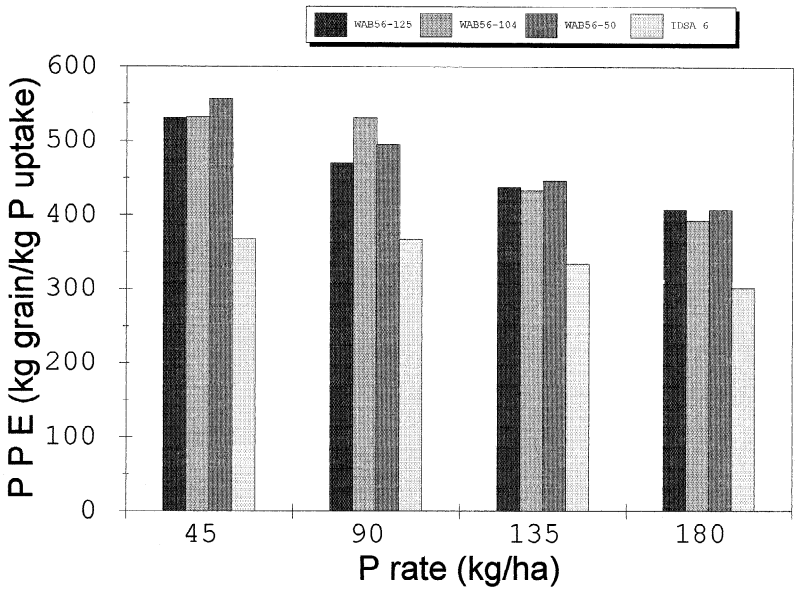


*Figure 2.* Physiological P efficiency (PPE) of four upland rice cultivars based on cummulative P response in three consecutive years (1993–95). Fertilizer P was applied only once in 1993.

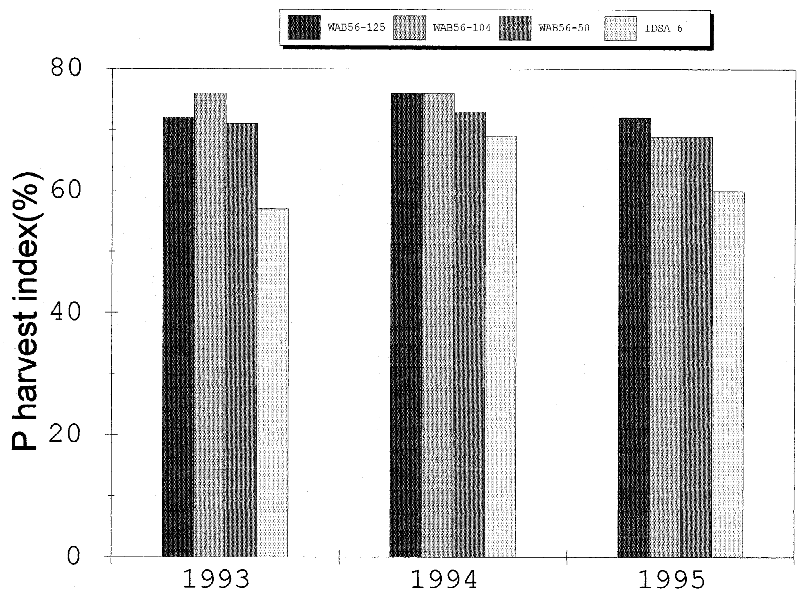


*Figure 3.* Phosphorus harvest index (%) of four upland rice cultivars grown consecutively for three years (1993–95). The data are averaged over five rates of fertilizer P applied only once in 1993.

in accord with those based on fresh P response reported by Sahrawat et al. (1995a)

*Internal efficiency of P: the mechanism of varietal differences in P efficiency*

The poor P efficiency of IDSA 6 compared to those of WAB cultivars was due to its lower P harvest index (P uptake in grain/total P uptake) (Figure 3). The higher

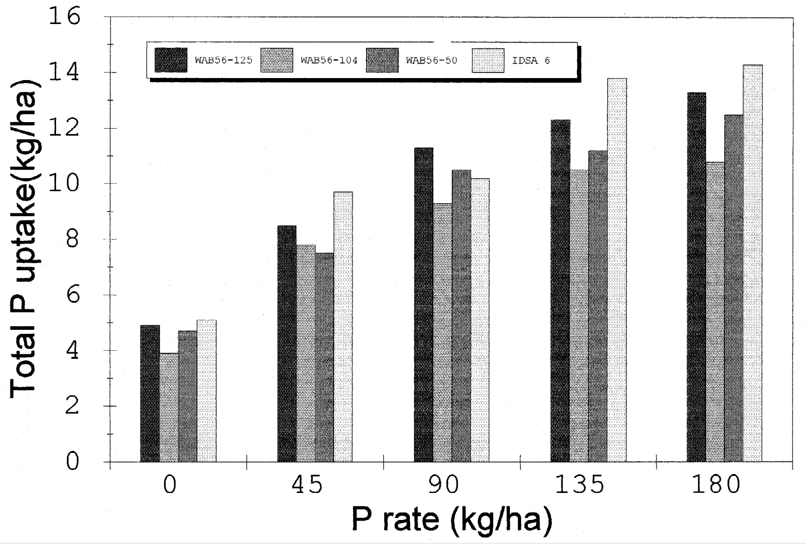


*Figure 4.* Total P uptake in three consecutive crops of four upland rice cultivars grown in 1993, 1994 and 1995. Fertilizer P was applied only once in 1993.

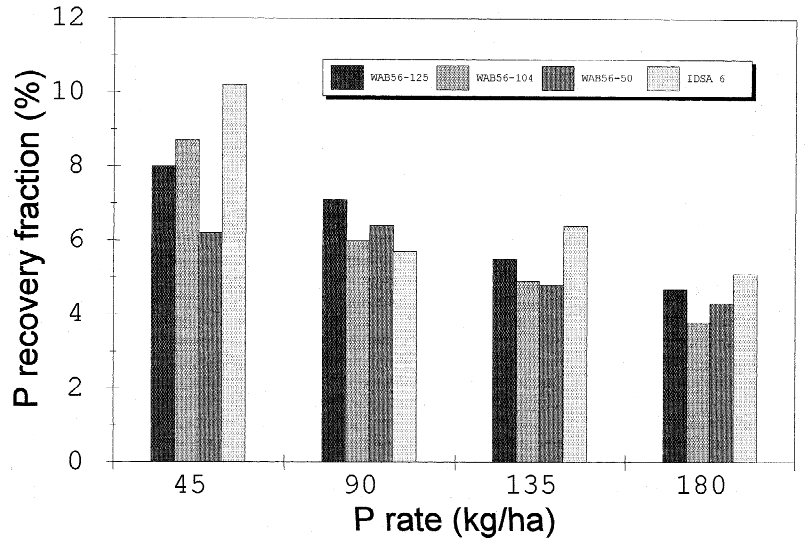


*Figure 5.* Apparent P recovery fraction (%) of fertilizer P by three crops of four upland rice cultivars grown in 1993, 1994 and 1995. Fertilizer P was applied only once in 1993.

P harvest index in the case of WAB cultivars resulted in higher internal efficiency of P than IDSA 6. The results showed that the mean P harvest indices of the three WAB cultivars, averaged over rates of fertilizer P, varied from 71 to 74% and that of IDSA 6 was 62%. The results further indicated that on average the WAB cultivars translocated about 10% more P into grain production than IDSA 6. The amounts of total P, averaged over five rates of fertilizer P, taken up in three crops of rice by the four cultivars were similar (Figure 4). Also the mean apparent recovery fraction of fertilizer P, averaged over five rates of P, in three crops of rice were similar for the four cultivars and varied from 5.4 to 6.9%. IDSA 6 gave the highest apparent P recovery, followed by WAB 56-125, WAB 56-104 and WAB 56-50 in the descending order (Figure 5).

The results suggest that the varietal differences observed in the improved WARDA bred rices (WAB

56-125, WAB 56-104 and WAB 56-50) and the improved traditional cultivar (IDSA 6) are due to differences in P harvest indices of the cultivars. The WAB cultivars had higher P harvest indices than IDSA 6 and they also showed higher P efficiency in grain production. These results showing genetic variation in the internal P efficiency of the rice cultivars are in accord with those reported by Fageria et al. (1988).

Our earlier results with these upland rice cultivars showed that IDSA 6 had the lowest harvest index than the three WAB cultivars and it was only slightly improved by P fertilization. On the other hand the three WAB cultivars had higher harvest indices and P application caused further better improvement (Sahrawat et al., 1995a).

Selection of upland rice cultivars that acquire more P or that have better P efficiency is an important strategy for adaptation in harsh rainfed growing environments where P deficiency is acute. Obvious examples are the highly weathered soils in the humid zone of West Africa.

In summary, our results suggest that higher P efficiency in the case of improved WAB cultivars compared to IDSA 6 is due to higher internal efficiency of P.

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