Fertilizer Research 16: 195–206 (1988)

Response of rice cultivars to phosphorus supply on an oxisol[1]

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Accepted 15 April 1988

Key words: Genotypic differences, *Oryza sativa* L., oxisol, P-uptake efficiency, upland rice

Abstract. Genotypic differences in absorption or utilization of P might be exploited to improve efficiency of fertilizer use or to obtain higher productivity on P-deficient soils. The objective of this study was to evaluate responses by 75 genotypes of upland rice (*Oryza sativa* L.) to two soil P levels in two field experiments. In the first experiment, soil P levels (Mehlich 1) were $1.5\,\mathrm{mg\,kg^{-1}}$ and $5\,\mathrm{mg\,kg^{-1}}$, and in the second experiment, $3\,\mathrm{mg\,kg^{-1}}$ and $4.7\,\mathrm{mg\,kg^{-1}}$ of soil, respectively. Rice cultivars differed significantly in shoot dry matter production at flowering, grain yield, and plant P status. Based on a grain yield efficiency index, cultivars were classified as P-efficient or P-inefficient. Shoot dry matter was more sensitive to P-deficiency but was not related to grain yield. Phosphorus use efficiency was higher under the low P treatment. Phosphorus uptake was significantly correlated with dry matter, P concentration and P-efficiency ratio. Results of this study indicate that genetic differences in P-use efficiency exist among upland rice cultivars and may be exploited in breeding programs.

Introduction

Although phosphate is probably the most thoroughly studied plant nutrient in agriculture and countless phosphate trials have been carried out worldwide, much still remains to be learned about the practical aspects of the management of low-P acid soils and the mechanisms governing differential responses of crop plants to phosphate [12, 14].

At present, successful crop production on phosphate-deficient soils depends on the use of fertilizers to meet the needs of the crop. However, farmers are facing difficulties with increasing fertilizer costs, especially in developing countries. An integrated fertilizer-plant breeding approach seems likely to give more economically viable and practical results in the immediate future. In the long run, fertilizer P use will be necessary to replenish soil supplies.

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[1] Contribution from National Rice and Bean Research Center of EMBRAPA, Goiania, Goias, Brazil and Appalachian Soil and Water Conservation Research Laboratoy, Beckley, WV, USA.

Table 1. Lime and fertilizer application during 4 consecutive years in the 2 experiments.

Year	kg ha^{-1}					Lime t ha^{-1}
	N	Soil P levels		K	Micronutrients	
		Low	High			
1981/82	35	9	44	33	5 Zn	3
1982/83	50	44	176	50	5 Zn	3
1983/84	50	44	88	83	5 Zn + 40 FTE-BR-12	3
1984/85	50	—	44	83	40 FTE-BR-12	3

N was applied as $(NH_4)_2SO_4$, P as super triple phosphate, K as KCl, and micronutrients as $ZnSO_4$ and fritted glass material (FTE-BR-12).

The possibility of exploiting genotypic differences in absorption and utilization of P to improve efficiency of P fertilizer use has received considerable attention in recent years [2, 4, 9, 15].

Lack of a clear definition of nutrient use efficiency has led to variation in the classification of species or cultivars according to their production potential under low nutrient levels [3]. The phosphate use efficiency of plants can be defined in several ways: 1) plants that accumulate higher concentrations of P when grown at a given level of P are more efficient [5]; 2) production of a large quantity of harvestable dry matter per unit time and area when grown in a medium that has less than sufficient P available for maximum yield under the existing environmental conditions [11]; 3) maximum dry matter production per unit of P taken up [1]; 4) maximum dry matter production at a constant plant P content [3]; 5) root efficiency, which is an expression of P uptake on a unit dry weight of roots or root length and/or root surface area; 6) ability to produce maximum dry matter with a given amount of applied phosphate [3, 11].

Numerous methodological problems frequently make the proper explanation of results obtained in screening genotypes impossible. Therefore, for mineral stress studies some important considerations should be taken into account: 1) uniform growth medium (soil or solution culture); 2) uniform ecological conditions; 3) well-defined evaluation parameters (morphological, physiological or biochemical); 4) screening techniques must be simple and should permit evaluation of a large number of materials with reasonable precision; 5) selection of appropriate sites (i.e. soil should be deficient in determined nutrient, if the objective of the study is to determine tolerance to low level); 6) minimum and maximum nutrient levels should be known in advance; 7) if possible, at least 3 fertility levels should be considered, (i.e. low, medium, and high); 8) greenhouse results should be verified under field conditions and vice-versa; 9) in screening for a determined nutrient efficiency, other nutrients must be present in adequate amounts; 10) efficient and non-efficient cultivars should be included in the genotype screening; and 11) plant materials should be genetically uniform.

The objective of this study was to evaluate rice cultivars/lines for phosphorus use efficiency. Efficient genotypes can be used directly in advanced field trials at the regional or national level if they have other desirable characteristics. If not, they can be used in breeding programs.

Materials and methods

Two field experiments were conducted at the EMBRAPA-National Rice and Bean Research Center's Experimental Station Capivara, Goiania, Brazil during 1984–1985. In the first and second experiments respectively, 25 and 50 upland rice cultivars/lines were tested. Cultivars/lines used in the first experiment had been selected in a preliminary experiment the preceeding year. The cultivars/lines tested were considered to be the best materials in the breeding programs at the Rice and Bean Research Center. The 2 experiments were located in adjacent areas, and soil analyses of the two experimental sites was the same. The test soil was a Dark Red Latosol, having an initial pH of 5.1, extractable P-0.8, K-23, Ca-40, Mg-24, and Al-45 mg kg^{-1}.

Phosphorus and K were extracted by the Mehlich 1 extracting solution (0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4). Phosphorus was determined by colorimetry and K by flame photometry. Aluminum, Ca and Mg were extracted with 1 M KCl and determined by titration with EDTA and NaOH, respectively. The same experimental sites had been used for P screening trials over the previous 4 years. Quantities of fertilizer and lime applied in the 4 cropping seasons are presented in Table 1. In the first 3 years, all fertilizers were broadcast at the time of planting and incorporated with a rototiller. In the last year (1984/1985), all fertilizers were banded, except P, which was broadcast and incorporated at the time of sowing. Soil samples were taken from the 2 experimental sites after rice germination. In the first experiment soil analysis revealed 1.5 and 5 mg kg^{-1} of P at the low and high levels, whereas in the second experiment, low and high levels of P were 3 and 4.7 mg kg^{-1}, respectively. A P level of 5 mg kg^{-1} using Mehlich 1 extraction solution is considered optimum for upland rice in the Central region of Brazil [13].

The treatments consisted of a factorial arrangement of P levels and cultivars. A split-plot design was used with P levels as main plots and cultivars as subplots. In the first experiment, each cultivar was planted in 2 rows of 5 m each and treatments were replicated 3 times. In the second

Table 2. F-values for analysis of variance of dry matter, grain yield, and plant P status parameters

Source of variance	Dry matter	Grain yield	P-conc.	P-uptake	ER-P
Experiment 1					
Cultivar (CV)	189.15**	2.01*	1.07NS	21.39**	1.07NS
P	243.96**	4.09*	2.12NS	43.57**	1.59NS
CV × P	74.70**	0.89NS	0.54NS	9.25**	0.51NS
Experiment 2					
Cultivar (CV)	149.27**	109.85**	2.47**	12.94**	2.45**
P	3084.02**	151.28**	133.24**	696.76**	124.72**
CV × P	36.80**	4.71**	1.80**	3.87**	1.93**

*,** Significant at the 0.05 and 0.01 levels, respectively.

NS = Not significant.

P-conc. = P content per unit of dry matter, P-Uptake = P conc. × dry matter, and ER-P = kg dry matter/kg P absorbed.

Experiment 1 and 2 were conducted at the same time.

experiment, each cultivar was planted in 4 rows of 5 m each and replicated 2 times.

Above ground plant parts were sampled at flowering to determine dry matter and phosphorus content. Plant material was dried to constant weight and milled. Ground material was digested with a 2:1 mixture of nitric and perchloric acid and analyzed colorimetrically for P.

Statistical Analysis System (SAS) Programs were used for analysis of variance and to calculate corrrelation coefficients and regression equations relating growth and P-uptake parameters.

Results and discussion

Analyses of variance was used to examine the main effects of cultivars, P levels and interactions of CV × P. F-values for shoot dry matter, grain yield, P-concentrations in shoot, P-uptake by shoot (P-conc. × dry matter), and P-efficiency ratio (ER-P = dry matter produced per unit P absorbed) are presented in Table 2. In the first experiment, the main effects and their interactions were highly significant (P = 0.01) for dry matter, and P uptake. But for grain yield, significance was observed only at the 5% level and the CV × P interaction was nonsignificant. In this experiment, P-concentration and ER-P were not significantly affected by main treatments and their interactions. In the second experiment, dry matter, grain yield, and all three

Table 3. Dry matter (DM) at flowering and grain yield (GY) of 25 rice cultivars at low (1.5 mg kg^{-1}) and high (5 mg kg^{-1}) P levels (Experiment 1).

Cultivar/line	Days		Dry matter t ha^{-1}		Grain yield t ha^{-1}		DMEI	GYEI
	Flower.	Physiol. maturity	Low P	High P	Low P	High P		
CNA095-BM30-BM27P-9	85	108	1.74o	2.19i	0.98i-k	1.78b	0.17m	0.61c-f
CNA095-BM30-BM29P-2	85	108	2.59n	3.52h	1.73e	2.56b	0.39lm	1.55a-e
CNA511-16-B-5	85	108	2.48n	3.55h	1.99cd	1.98b	0.38lm	1.38a-f
CNA511-16-B-3	85	108	3.21m	3.60h	1.96d	2.13b	0.49kl	1.46a-f
CNA511-16-B-6	85	108	3.31lm	3.82gh	2.13bc	2.13b	0.55j-l	1.59a-d
CNA095-BM30-BM9-4	85	108	2.98m	3.33h	2.50ab	2.89ab	0.43kl	2.28a
CNA515-11-B-2	95	120	3.15m	4.69ef	1.38f	1.73b	0.64i-k	0.83b-f
CNA515-11-B-5	95	120	4.00ij	4.38fg	1.15gh	1.71b	0.76h-j	0.69b-f
IRAT144	95	120	2.58n	3.44h	2.35a	2.33b	0.39lm	1.92ab
CNA104-B-68-B-2	106	129	4.32hi	5.60cd	1.72e	1.86b	1.05fg	1.12a-f
CNA108-B-28-8-2B-2	106	129	4.04ij	5.18de	1.02h-j	1.30b	0.91gh	0.46d-f
CNA444-BM38-7-B-5	106	129	5.96d	5.53cd	0.87j-l	0.83b	1.43de	0.25f
CNA444-BM38-1-B-2	106	129	5.11g	6.83b	1.14gh	1.23b	1.51d	0.49d-f
CNA449-BM15-3-B-5	106	129	5.44fg	8.00a	2.18b	2.41b	1.88c	1.83a-c
CNA449-BM15-1-B-5	106	129	5.79de	8.38a	1.38f	1.45b	2.10b	0.70b-f
CNA449-BM-15-1-B-2	106	129	7.25b	8.16a	1.46f	1.66b	2.56a	0.85b-f
CNA449-BM15-1-B-4	106	129	4.37h	5.69cd	0.83kl	0.98b	1.07fg	0.29ef
CNA449-BM15-3-B-4	106	129	6.52c	8.33a	2.37a	2.33b	2.35a	1.93ab
CNA511-12-B-5	106	129	3.79jk	3.53h	1.22g	0.97a	0.58j-l	2.24a
CNA515-3-1	106	129	3.65k	5.42d	0.81l	0.89b	0.86g-i	0.25f
CNA104-B-18-P-1-L	106	129	3.63kl	6.17c	1.96d	2.07b	0.97gh	1.42a-f
IAC47	106	129	5.52ef	5.74cd	1.03hi	0.89b	1.37de	0.32d-f
IR3646-8-1-2	120	142	9.12a	1.11j	2.10b-d	2.02b	0.44kl	1.48a-f
IR5716-18-1	120	142	5.15g	5.46d	2.36a	2.73ab	1.22ef	2.25a
Salumpikit	120	142	6.48c	8.55a	1.75e	1.76b	2.41a	1.07a-f

Means in the same column followed by the same letter are not significantly different at P = 0.05 by Duncan's Multiple Range Test.

$$\begin{array}{c}\text{Dry matter or grain yield}\\ \text{efficiency index}\\ \text{(DMEI or GYEI)}\end{array} = \frac{\text{Yield at Low P level}}{\begin{array}{c}\text{Experimental Mean Yield}\\ \text{at Low P}\end{array}} \times \frac{\text{Yield at High P level}}{\begin{array}{c}\text{Experimental Mean Yield}\\ \text{at High P}\end{array}}$$

plant P status parameters were highly significant for cultivars, P-treatments and CV × P interactions.

Results related to dry matter, grain yield, dry matter efficiency index (DMEI) and grain yield efficiency index (GYEI) are presented in Tables 3 and 4. Rice cultivars responded to P fertilization, but the response varied with cultivar. Shoot dry matter and grain yield of 75 rice cultivars/lines were

Table 4. Dry matter (DM) at flowering and grain yield (GY) of 50 rice cultivars at low (3 mg kg^{-1}) and high (4.7 mg kg^{-1}) P levels (Experiment 2).

Cultivar/line	Days		Dry matter, t ha^{-1}		Grain yield, t ha^{-1}		DMEI	GYEI
	Flower.	Physiol. maturity	Low P	High P	Low P	High P		
CNA4125	87	110	3.35p-t	4.02pq	1.36h-j	1.53g-i	0.69q	1.23j
CNA4164	87	110	3.25q-u	5.04ij	1.99cd	2.36c	0.83n-p	2.72de
CNA4166	87	110	4.18h-k	6.09d	2.23b	2.56bc	1.30de	3.48b
CNA4180	87	110	3.43o-r	5.09hi	2.49a	2.72b	0.89mn	4.02a
CNA4209	87	110	2.82v	3.26s	1.19j-m	1.59gh	0.47s	1.12j-l
CNA4361	87	110	2.82v	3.41s	0.99l-o	1.37h-k	0.49s	0.80m-q
CNA4476	87	110	4.80ef	4.54l-o	1.95cd	2.74b	1.08h-j	3.16c
CNA4617	87	110	2.46w	3.84qr	1.57f-h	1.91ef	0.48s	1.77h
CNA4640	87	110	3.10r-v	4.14n-q	1.62fg	1.74fg	0.66qr	1.67h
CNA5164	87	110	3.76l-n	5.60e	1.99cd	2.51bc	1.07ij	2.97cd
CNA5165	87	110	4.39gh	5.02l-k	2.28b	3.06a	1.12g-i	4.13a
CNA5166	87	119	4.42gh	4.67kl	2.11bc	2.31cd	1.05i-k	2.89d
IREM238	87	110	3.43o-r	3.87qr	1.40h-j	1.83e-g	0.67q	1.52hi
IREM239	87	110	3.52t-v	4.54lm	1.08l-n	2.06de	0.69q	1.32ij
GA4135	87	110	3.52n-q	5.18gi	1.44g-i	1.94ef	0.93l-n	1.66h
L80-67	87	110	3.10s-v	3.57rs	1.61fg	2.45bc	0.56rs	2.34fg
CNA511-16-B-5	87	110	4.26hi	4.40l-o	1.85de	1.99ef	0.95k-m	2.18g
CNA4122-BM31-BM41-9	87	110	2.38w	4.09o-q	0.99l-o	1.16j-m	0.49s	0.36t-x
CNA3178	98	124	3.69m-o	6.03d	0.87o-r	0.92m-p	1.13g-i	0.46r-v
CNA4140	98	124	3.78lm	6.16d	1.67ef	1.60gh	1.18f-h	1.58hi
CNA4301	98	124	4.20h-k	4.70j-l	0.99l-o	1.09j-n	1.01j-l	0.65o-t
CNA4475	98	124	3.47n-q	5.25f-i	0.76qr	1.06k-n	0.93l-n	0.48r-u
CNA5172	98	124	4.25h-j	6.06d	1.38h-j	1.41h-j	1.31d	1.15jk
GA4206	98	124	5.07c-e	4.94i-k	1.32i-k	1.36h-l	1.27d-f	1.04j-m
Cuiabana	98	124	4.60fg	4.40l-o	1.06l-n	1.08k-n	1.03i-l	0.68n-s
CNA108-B-28-13-1	98	124	2.49w	4.05pq	1.21j-l	1.13j-m	0.51s	0.81m-p
CNA4181	101	124	3.96i-m	4.69kl	0.70rs	0.93m-p	0.94k-n	0.38s-w
CNA5169	101	124	5.66a	6.06d	1.29i-k	1.56gh	1.75c	1.20jk
CNA5170	101	124	5.68a	5.94d	0.97m-q	1.12j-m	1.72c	0.64n-t
CNA5171	101	124	5.43ab	6.83bc	0.91n-r	0.93m-p	1.81b	0.50q-u
CNA5174	101	124	4.97c-e	6.62c	1.00l-o	0.89m-q	1.67c	0.54p-u
CNA4141	105	130	2.91v	5.94d	0.77p-r	0.70o-s	0.88mn	0.32u-x
CNA4172	105	130	3.24q-u	5.13hi	0.98m-p	1.01l-o	0.85m-o	0.59o-u
CNA4178	105	130	4.85ef	5.54ef	0.53st	0.49r-t	1.37d	0.15wx
CNA4199	105	130	4.88cd	7.02b	1.19j-m	1.30h-l	1.75c	0.92k-n
CNA4210	105	130	4.03i-l	5.40e-h	0.97m-q	1.11j-m	1.11g-j	0.63n-t
CNA4216	105	130	5.22bc	7.09b	1.01l-o	1.12j-m	1.89b	0.67n-s
CNA4591	105	130	5.19b-d	8.60a	1.04l-o	1.21i-m	2.27a	0.75n-r
CNA4634	105	130	3.99k-m	3.48s	0.33t	0.44st	0.69q	0.08wx
CNA5163	105	130	3.37o-s	5.05ij	0.40t	0.49r-t	0.86mn	0.11wx
NA5167	105	130	3.76l-n	4.41l-o	1.86de	2.31cd	0.84m-o	2.53ef
CNA5175	105	130	5.26bc	4.50l-n	1.03l-o	1.14j-m	1.21e-g	0.69n-r
CA780284	105	130	2.38w	4.11o-q	0.38t	0.49rt	0.49s	0.11wx
CA820048	105	130	2.10uv	3.29s	0.36t	0.48rt	0.50s	0.11wx

higher at the high P level than at low P. On the average, shoot dry matter production increased about 22% from the low to the high P treatment. Similarly, grain yield also increased about 14% with the application of the high P level as compared with the low P level, across 75 cultivars. This indicates that shoot dry matter was more sensitive to P application than grain yield.

Table 5. P-concentration, P-uptake and P-use efficiency ratio (ER-P) of 25 rice cultivars (Experiment 1).

Cultivar/line	P-conc. g kg^{-1}		P-uptake kg ha^{-1}		ER-P kg DM/kg P absorbed	
	Low P	High P	Low P	High P	Low P	High P
CNA095-BM30-BM27P-9	1.4ab	1.3a	2.4m	3.1hi	718ab	729a
CNA095-BM30-BM29P-2	1.4ab	1.3a	3.6k-m	4.6gh	778ab	769a
CNA511-16-B-5	1.4ab	1.7a	4.2ml	6.0fg	714ab	590a
CNA511-16-B-3	1.5ab	1.5a	4.8i-l	5.4f-h	694ab	667a
CNA511-16-B-6	1.6ab	1.6a	5.3g-l	6.1fg	628ab	628a
CNA095-BM30-BM9-4	1.4ab	1.7a	4.2k-m	5.7fg	729ab	597a
CNA515-11-B-2	1.4ab	1.5a	4.4j-m	7.0e-g	714ab	667a
CNA515-11-B-5	1.7a	1.7a	6.8d-i	7.4d-f	590b	590a
IRAT144	1.5ab	1.7a	3.9k-m	5.9fg	670ab	588a
CNA104-B-68-B-2	1.3ab	1.3a	5.6f-k	7.3d-g	774ab	813a
CNA108-B-28-8-2B-2	1.4ab	1.4a	5.6e-k	7.3d-g	714ab	729a
CNA444-BM38-7-B-5	1.4ab	1.2a	8.3cd	6.6e-g	714ab	857a
CNA444-BM38-1-B-2	1.5ab	1.5a	7.7c-f	10.3a-c	670ab	670a
CNA449-BM15-3-B-5	1.3ab	1.4a	7.1d-h	11.2a-c	813ab	714a
CNA449-BM15-1-B-5	1.6ab	1.5a	9.2bc	12.6a	628b	667a
CNA449-BM15-1-B-2	1.5ab	1.5a	10.9b	12.2ab	677ab	670a
CNA449-BM15-1-B-4	1.5ab	1.6a	6.3d-j	9.1c-e	611ab	628a
CNA449-BM15-3-B-4	1.7a	1.5a	11.1ab	12.5a	590b	670a
CNA511-12-B-5	1.5ab	1.5a	5.7e-k	5.3f-h	667ab	667a
CNA515-3-1	1.3ab	1.4a	4.7i-l	7.6d-f	769ab	718a
CNA104-B-18-PY-1-L	1.4ab	1.6a	5.1h-l	9.9b-d	714ab	625a
IAC47	1.4ab	1.3a	7.2c-e	7.5d-f	729ab	813a
IR3646-8-1-2	1.4ab	1.5a	12.8a	1.7i	714ab	694a
IR5716-18-1	1.4ab	1.7a	7.2d-g	9.3c-e	718ab	588a
Salumpkit	1.1b	1.5a	7.1d-h	12.7a	917a	679a

Means in the same column followed by the same letter are not significantly different at $P = 0.05$ by Duncan's Multiple Range Test.

One interesting feature of this study is that dry matter increased with increasing length of the growth cycle of cultivars as expected, but the grain yield decreased. Cultivars/lines with growth cycles of 108–110 days (32% of the total cultivars) produced 3304 kg ha^{-1} dry matter at low P and 4182 kg ha^{-1} at the high P level. When the growth cycle was 120–124 days (21% of the total cultivars), dry matter yield was 4187 kg ha^{-1} at low P and 5264 kg ha^{-1} at high P. When the dry matter of cultivars having a growth cycle of 130 days (40% of the total cultivars) was computed, it was 4409 kg ha^{-1} at low P and 5665 kg ha^{-1} at high P level. Grain yields of the same groups of cultivars were 1679, 1087, and 833 kg ha^{-1} at low P level and 2101, 1160 and 944 kg ha^{-1} at the high P level, respectively.

Table 6. P-concentration, P-uptake and P-use efficiency ratio (ER-P) of 50 rice cultivars at low (3 mg kg^{-1}) and high (4.7 mg kg^{-1}) P levels (Experiment 2).

Cultivar/line	P-conc. g kg^{-1}		P-uptake kg ha^{-1}		ER-P kg DM/kg P absorbed	
	Low P	High P	Low P	High P	Low P	High P
CNA4125	1.5a-d	1.6c-e	5.0e-o	6.4p-s	679b-e	625a-d
CNA4164	1.4a-d	1.6c-e	4.6h-p	8.1f-r	718b-e	635a-d
CNA4166	1.3b-e	1.5de	5.4d-m	9.1c-l	813b-e	670a-c
CNA4180	1.4a-d	1.5de	4.8f-p	7.6g-r	714b-e	667a-c
CNA4209	1.5a-d	1.7b-e	4.2j-p	5.6s	677b-e	607a-e
CNA4361	1.8a	1.9a-d	5.1d-o	6.5o-s	563e	528c-e
CNA4476	1.1de	1.6c-e	5.3d-m	7.1j-s	917ab	607a-d
CNA4617	1.5a-d	1.8a-e	3.7m-p	6.9l-s	670b-e	556b-e
CNA4640	1.2c-e	1.8a-e	3.7m-p	7.4h-s	857bc	563b-e
CNA5164	1.5a-d	1.6c-d	5.6d-l	9.0c-m	670b-e	627a-d
CNA5165	1.4a-d	1.5de	6.2c-e	7.5g-s	718b-e	667a-c
CNA5166	1.1de	1.5de	4.9f-o	7.0k-s	909ab	670a-c
IREM238	1.4a-d	1.5de	4.8f-p	5.8rs	718b-e	670a-c
IREM239	1.3b-e	1.4e	3.9k-p	6.4q-s	774b-e	729a
GA4135	1.1de	1.9a-d	3.9l-p	9.8c-g	917ab	528c-e
L80-67	1.5a-d	1.7b-e	4.6g-p	6.1rs	670b-e	590a-e
CNA511-16-B-5	1.5a-c	2.0a-c	6.8b-d	8.8e-o	625c-e	505de
CNA4122-BM31-BM41-9	1.4a-d	1.9a-d	3.3op	7.8g-s	718b-e	528c-e
CNA3178	1.6a-c	1.6c-e	5.9c-i	9.6c-h	628c-e	625a-d
CNA4140	1.5a-d	1.6c-d	5.7d-k	9.8c-g	667b-e	625a-d
CNA4301	1.6a-c	1.8a-e	6.7b-e	8.4e-q	628c-e	557b-e
CNA4475	1.6a-c	1.6c-e	5.6d-l	8.4e-q	635c-e	627a-d
CNA5172	1.5a-d	1.5d-e	6.4b-g	9.1c-l	670b-e	667a-c
GA4206	1.8a	1.9a-d	9.1a	9.4c-j	563e	528c-e
Cuiabana	1.2c-e	1.8a-e	5.5d-l	7.9f-r	839b-d	557b-e
CNA108-B-28-13-1	1.6a-c	1.9a-d	4.0k-p	7.7g-s	625c-d	528c-e
CNA4181	1.4a-d	1.6c-e	5.6d-l	7.5h-s	714b-e	627a-d
CNA5169	1.4a-d	1.6c-e	7.9ab	9.7c-h	718b-e	625a-d
CNA5170	1.4a-d	1.6c-e	8.0ab	9.5c-h	718b-e	627a-d
CNA5171	1.4a-d	1.6c-d	7.6a-c	10.9c-d	729b-e	635a-d
CNA5174	1.1d-e	1.4e	5.4d-m	9.3c-k	917ab	714ab
CNA4141	1.5a-d	1.8a-e	4.4i-p	10.7b-d	679b-e	563b-e
CNA4172	1.3b-e	1.6b-e	4.2j-p	8.7d-p	769b-e	607a-e
CNA4178	1.4a-d	1.6c-e	6.8b-e	8.9c-m	729b-e	625a-d
CNA4199	1.4a-d	2.0a-c	6.8b-d	14.0a	718b-e	501de
CNA4210	0.8e	1.9a-d	3.6n-p	10.2b-f	1125a	528c-e
CNA4216	1.7ab	1.5de	8.9a	10.6b-e	590de	670a-c
CNA4591	1.7ab	1.8a-e	8.8a	15.36a	588de	563b-e
CNA4634	1.2c-e	1.8a-e	4.7g-p	6.3q-s	857bc	556b-e
CNA5163	1.3b-e	1.6c-e	4.4i-p	8.1f-r	774b-e	625a-d
CNA5167	1.4a-d	1.8a-e	5.3d-m	7.9f-r	718b-e	557b-e
CNA5175	1.1de	1.5de	5.8d-i	6.8n-s	917ab	667a-c
CA780284	1.3b-e	1.6c-e	3.1p	6.6n-s	813b-e	634a-d

Table 6. (continued).

Cultivar/line	P-conc. g kg^{-1}		P-uptake kg ha^{-1}		ER-P kg DM/kg P absorbed	
	Low P	High P	Low P	High P	Low P	High P
CA820048	1.2c-e	2.2a	3.6n-p	7.3i-s	833b-d	458e
GA4120	1.4a-d	1.9a-d	4.6g-p	8.5e-q	718b-e	528c-e
CNA444-BM38-2B-4	1.4a-d	2.0a-c	5.1d-o	11.1bc	718b-e	505de
CNA461-BM3-1-B-3	1.6a-c	2.2a	6.3b-h	12.1b	635c-e	555e
IAC47	1.5a-d	2.2a	6.1c-i	9.0c-m	670b-e	486de
CNA4411	1.5a-d	1.8a-e	4.6g-p	8.4e-q	867b-e	557b-e
CNA4453	1.5a-d	1.5de	6.5b-f	9.0c-m	679b-e	670a-c

Means in the same column followed by the same letter are not significantly different at P = 0.05 by Duncan's Multiple Range Test.

This means longer growth cycle cultivars of upland rice produce higher dry matter, but it does not necessary follow that these cultivars also produce higher grain yield. In principle, cultivars of longer growth duration have the capacity to produce higher grain yield because of a longer period of grain filling [16]. The most plausible reasons for the decrease in grain yield with the advancement of the growth cycle of the cultivars are moisture stress at critical times and panicle blast disease. These two factors frequently limit upland rice production in Brazil [8, 10]. This means that when a crop grows for a longer duration under unfavorable conditions, as is the case of upland rice in Brazil, it has more chances to suffer from these two growth limiting factors. In conclusion, the principle of longer growth duration of a cultivar leading to higher production is only applicable when all growth factors are at optimum levels. This principal is not often applicable for upland rice production in South America, Africa, and Asia [6]. This point should be given prime consideration in breeding cultivars of upland rice for these regions of the world.

Phosphorus efficiency index (EI) was calculated to classify cultivars/lines with high yield at both low and high P levels (Tables 3 and 4). This index is useful in separating high yielding, stable, P-efficient genotypes from low yielding, unstable and P-inefficient genotypes. Genotypes having EI higher than 1 are considered P-efficient, inefficient genotypes are in the range of 0–0.5 efficiency index, and genotypes in between these two limits are considered intermediate in P-use efficiency. These ratings, although selected arbitrarily, are supported when dry matter and grain yield means are compared by Duncan's Multiple Range Test.

The efficiency indexes were computed for dry matter and grain yield. Given that dry matter was not related to grain yield in this case and grain

Table 7. Coefficient of linear correlation between dry matter, grain yield, and P-uptake parameters in rice cultivars.

Variables	Dry matter	Grain yield	P-conc.	P-uptake	ER-P
Experiment 1					
Dry matter	1.00				
Grain yield	−0.08NS	1.00			
P-conc.	−0.04NS	0.13NS	1.0		
P-uptake	0.94**	−0.04NS	0.28**	1.00	
ER-P	0.02NS	−0.12NS	−0.98**	−0.30**	1.00
Experiment 2					
Dry matter	1.00				
Grain yield	0.08NS	1.00			
P-conc.	0.17*	−0.05NS	1.00		
P-uptake	0.85**	0.03NS	0.65**	1.00	
ER-P	−0.17*	0.02NS	−0.96**	−0.62**	1.00

*,**Significant at the 0.05 and 0.01 levels, respectively.
NS = Not significant.

yield is the ultimate goal for farmers, grain yield was used as the sole criterion for classifying P-efficient and inefficient cultivars. According to this criterion, the most P-efficient cultivars/lines were: CNA 5165, CNA 4180, CNA 4166, CNA 4476, CNA 5164, CNA 5166, CNA 4164, L80-67, CNA 511-16-B-5, CNA 095-BM30-BM9-4, IR 5716-18-1, CNA 511-12-B-5, CNA 4617, IRRAT 144, CNA 449-BM15-3-B-4, CNA 4640, GA 4135, CNA 449-BM15-3-B-5, CNA 4140, IREM 238, CNA 511-16-B-6, CNA 095-BM30-BM29P-2, IR 3646-8-1-2, CNA 511-16-B-3, CNA 104-B-18-PY-1-2, IREM 239, CNA 511-16-B-5, and CNA 4125. The most inefficient cultivars/lines were: CNA 4411, CNA 4634, CN 820048, CA 780284, CNA 5163, CNA 4178, GA 4120, CNA 444-BM38-70B-5, CNA 515-3-1, IAC 47, CNA 4141, CNA 449-BM15-1-B-4, CNA 4122-BN31-BM41-9, CNA 4181, CNA 108-B-28-8-2B-2, CNA 44-BM38-1-B-2, CNA 3178, CNA 4474, and CNA 5171.

Tissue phosphorus concentration, P-uptake and P-efficiency ratios are presented in Tables 5 and 6. There was not much difference in tissue P-concentrations in cultivars grown at the low and high P levels. The average P-concentration for 75 cultivars was 1.4 g kg^{-1} at the low P level and 1.6 g kg^{-1} at the high P level. This similarity was due to dilution effects. At the high P level, plant growth was increased, which brought the tissue P concentration at par with the low P level. Phosphorus uptake was higher at high P level as compared to the low P level, which is related to high dry matter production at the high P level. Across the 75 cultivars, the P uptake values were 5.95 and 8.18 kg P ha^{-1} at low and high P levels, respectively. Phosphorus efficiency ratio was higher at the low soil P level. Across the 75 rice cultivars, about 719 kg of shoot dry matter was produced by the time of flowering per kg of P absorbed at the low P level, while at the high P level shoot dry matter production was 639 kg per kg of P absorbed. The higher P efficiency at the low P level may be related to P uptake, which is higher at low P concentrations [7].

Coefficients for liner correlations between dry matter, grain yield, P concentration, P uptake and P-efficiency ratio are presented in Table 7. Grain yield and dry matter were not related to each other in either of the two experiments. P-uptake was highly correlated with dry matter production and tissue P-concentration in 75 rice cultivars. Plant P status parameters were not related to grain yield. Phosphorus efficiency ratio was negatively related to dry matter, P-concentration and P-uptake. This negative correlation may reflect the strong growth response of rice cultivars to P fertilization and, therefore, may represent a dilution effect due to increased growth.

A stepwise regression method was used to quantify the relation between dry matter as a dependent variable and tissue P-concentration, P-uptake and ER-P as independent variables. These three variables accounted for 98% of the variation ($R^2 = 0.98^{**}$) in shoot dry weight in the first experiment ($Y = 77.78 - 14912.76$ P-conc. $+ 677.50$ P-uptake $+ 3.08$ ER-P) and 97% ($R^2 = 0.97^{**}$) in the second experiment ($Y = 5611.08 - 3114.76$ P-conc. $+ 616.29$ P-uptake $- 0.93$ ER-P). Phosphorus concentration, P-uptake and P-use efficiency did not account for a significant portion of the variation in grain yield.

Acknowledgements

Financial support to the senior author was provided by the Brazilian Scientific and Technological Research Council (CNPq) during the course of preparation of this manuscript. The authors wish to thank Drs. W.R. Kussow, University of Wisconsin; G.E. Wilcox, Purdue University; U.R. Bishnoi, Alabama A & M University; and R. Singh, West Virginia University for their valuable suggestions and comments.

References

1. Asher CJ and Loneragan JF (1967) Response of plants to phosphate concentration in solution culture. I. Growth and phosphorus content. Soil Sci 103: 225–233
2. Baligar VC and Barber SA (1979) Genotypic differences of corn for ion uptake.Agron J 71: 870–883
3. Blair GJ and Cordero S (1978) The phosphorus efficiency of three annual legumes. Plant and Soil 50: 387–398

4. Caradus JR (1983) Genetic differences in phosphorus absorption among white clover populations. Plant and Soil 72: 379–383
5. Clark RB and Brown JC (1975) Corn lines differ in mineral efficiency. Ohio Rep 60: 83–86
6. De Datta SK (1975) Upland rice around the world. In: IRRI (ed.) Major research in upland rice, pp. 2–11. International Rice Research Institute, Los Banos, Philippines
7. Fageria NK (1976) Effect of P, Ca and Mg concentrations in solution culture on growth and uptake of these ions by rice. Agron J 68: 726–732
8. Fageria NK (1980) Rice in Cerrado soils with water deficiency and its response to phosphorus. Pesq agropec bras, Brasilia. 15: 259–265
9. Fageria NK and Barboso Filho MP (1982) Evaluation of rice cultivar for phosphorus absorption. Pesq agropec bras, Brasilia. 16: 777–782
10. Faria JA, Prabhu AS and Zimmermann FJP (1982) Effect of nitrogen fertilization and fungicide spray on blast and upland rice productivity. Pesq agropec bras, Brasilia. 17: 847–850
11. Fox RH (1978) Selection for phosphorus efficiency in corn. Commun Soil Sci Plant Anal 9: 13–37
12. Haynes RJ (1984) Lime and phosphate in the soil-plant system. Adv Agron 37: 249–315
13. Kussow WR, Corum KR and Dall'acqua FM (1976) Agro-economic interpretation of fertility experiments. EMBRAPA/CNPAf Techn Bull 4, 49 pp
14. Lal R (1986) Soil surface management in the tropics for intensive land use and high sustained production. Adv Soil Sci 5: 1–109
15. Nielson NE and Barber SA (1978) Differences among genotypes of corn in the kinetics of P uptake. Agron J 70: 695–698
16. Yoshida S (1972) Physiological aspects of grain yield. Ann Rev Plant Physiol 23: 437–464