# THE ROLE OF TOLERANT GENOTYPES AND PLANT NUTRIENTS IN THE MANAGEMENT OF ACID SOIL INFERTILITY IN UPLAND RICE

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**Abstract**

As in other parts of the humid tropics, acid-related problems are the major constraint to crop production on low-activity clay soils in the humid and sub-humid zones of West Africa. The upland ecosystem of West Africa is very important to rice production. About 70% of upland rice is grown in the humid zone of the sub-region. To increase and stabilize rice productivity of the acid uplands at reasonable levels, a strategy is needed that integrates the use of tolerant cultivars with soil and plant-nutrient management. Research conducted on Alfisols and Ultisols of the humid-forest and savannah zones in West Africa showed that upland rice is a robust crop, possessing a wide range of tolerance to acid-soil conditions. Recent research at WARDA showed also that acid-soil tolerance can be enhanced through interspecific *Oryza sativa* × *O. glaberrima* progenies, which not only possess increased tolerance of acid-soil conditions, but also have superior overall adaptability to diverse upland environments in the sub-region. Our research on the diagnosis of acid-soil infertility problems on the Ultisols and Alfisols of the humid savannah and forest zones indicates that P deficiency is the most important nutrient disorder for upland rice. In the forest zone, response to N depended on the application of P. In the savannah and forest-savannah transition zones, N deficiency was more important than P deficiency. Among other plant nutrients, the application of Ca and Mg (as plant nutrients) did not appear initially to improve the performance of acid-tolerant upland rice cultivars. The results from a long-term study on an Ultisol with four acid-tolerant rice cultivars, revealed that they differed in agronomic and physiological P efficiencies, and the efficiencies were higher at lower rates of P. The amounts of total P removed in three successive crops were similar for all four cultivars although P-harvest index was 10 to 12% higher in the P-efficient than the inefficient cultivars. The differences observed in the P efficiency of the cultivars may be due to variability in internal efficiency of utilization of P. Overall, our research showed that rice productivity on the acid uplands can be improved by exploiting synergy between genetic tolerance and new P-management practices.

## 1. INTRODUCTION

Upland rice is the staple food of a hundred million people including some of the poorest in the world [1]. The upland ecosystem in West Africa is very important to rice production [2]. It is estimated that 70% of that upland rice is produced in the humid zone of the sub-region, primarily on Alfisols and Ultisols. While Alfisols dominate the savannah, transition (between forest and savannah) and dry forest zones, Ultisols and some Oxisols dominate the humid zones. In the high-rainfall Ultisol areas excessive weathering, leaching of bases and acidification make low fertility the major constraint to crop growth [3].

World wide, acid-related soil infertility is the major constraint to crop production on low-activity clay soils in the humid and sub-humid tropics. The nutrient-element problems commonly encountered are Al and Mn toxicity, and P, K, Ca and Mg deficiency, and toxicity × deficiency interactions [4, 5].

In the context of West African agriculture, we do not visualize farmers using amendments to ameliorate soil constraints – they face such difficulties in obtaining fertilisers to meet the nutritional needs of their crops. Under prevailing conditions, the most appropriate strategy is to develop cultivars of rice that are adapted to harsh rain-fed environments where soil acidity and P deficiency are the major factors limiting yields.

Interest in selecting and breeding of cultivars for adaptation to specific conditions was re-kindled by recent success at the West Africa Rice Development Association (WARDA) in producing fertile progenies between *Oryza sativa* and *O. glaberrima*. These possess desirable traits of both species, e.g. the superior yield and responsiveness to inputs, such as nutrients, of *O. sativa*, and the general hardiness, drought and acid-soil tolerance, and competitiveness against weeds, of *O. glaberrima* [6, 7]. In the long term, however, an integrated approach, in which genetic tolerance and plant-nutrient management are integrated, seems likely to be more practical and sustainable.

This paper reviews recent research that relates to acid soils and P-deficiency tolerance of upland-rice cultivars, including interspecific *O. sativa* x *O. glaberrima* progenies recently developed at WARDA. Results of research to clarify the role of plant nutrients, such as P, Ca and Mg, in reducing acid-soil infertility and genotypic differences in P-responsiveness and P-efficiency, are discussed. It is concluded that management of P nutrition of plant types that are adapted to acid-soil environments will make major contributions towards increasing yields and yield stability of upland rice.

## 2. CHARACTERISTICS OF WEST AFRICAN SOILS

### 2.1. Genesis, distribution and inherent chemical fertility of soils

The inherent fertility of soils in West Africa is closely related to the bedrock material from which they are derived. Because parent materials are not uniformly distributed and the climatic conditions under which weathering takes place are diverse, inherent fertility varies considerably [8–11]. And, as a result of intense leaching and weathering, many of the soils in the humid zone of West Africa have an acidic reaction and low inherent fertility with regard to major nutrients, especially N and P, and to micro-nutrient elements. Also, because of intense weathering, the clay mineralogy is dominated by kaolinite, and varying amounts of Fe and Al oxides. The soils are of low and variable cation exchange capacity (CEC) and accumulated organic matter is the main source of CEC and nutrients, especially N [8, 12, 13].

TABLE I. PHYSICAL AND CHEMICAL CHARACTERISTICS IN THE SURFACE (0–20 cm) SAMPLES OF ULTISOLS AT THE MAN SITE IN CÔTE D'IVOIRE USED FOR EVALUATING UPLAND RICE CULTIVARS FOR TOLERANCE OF ACID-SOIL CONDITIONS AND P DEFICIENCY, AND PLANT-NUTRIENT STUDIES, 1992–98

| Soil characteristic | Range |
|---|---|
| Clay (g $kg^{-1}$) | 220–250 |
| Sand (g $kg^{-1}$) | 450–490 |
| Silt (g $kg^{-1}$) | 290–300 |
| pH ($H_2O$) | 4.6–5.0 |
| pH (KCl) | 3.9–4.3 |
| Organic C (g $kg^{-1}$) | 13.0–15.0 |
| Total N (mg $kg^{-1}$) | 850–950 |
| CEC (cmol $kg^{-1}$) | 4.5–5.9 |
| Total P (mg $kg^{-1}$) | 145–165 |
| BRAY 1 P (mg $kg^{-1}$) | 3–6 |
| KCl extr. Al (cmol $kg^{-1}$) | 0.65–1.15 |
| DTPA extr. Zn (mg $kg^{-1}$) | 0.4–1.5 |
| Exchangeable cations (cmol $kg^{-1}$): | |
| K | 0.15–0.24 |
| Ca | 0.50–1.12 |
| Mg | 0.26–0.58 |

TABLE II. PERFORMANCE OF TWENTY-FOUR UPLAND-RICE CULTIVARS, BY GRAIN YIELD, GRAIN-YIELD EFFICIENCY INDEX (GYEI) AND RELATIVE YIELD (RY), ON AN ULTISOL AT MAN, CÔTE D'IVOIRE, 1993

| Cultivar | Yield ($t\ ha^{-1}$) | GYEI[a] | RY[b] |
|---|---|---|---|
| WAB 32-133 | 1.46 | 0.91 | 0.71 |
| CNA 4136 | 1.48 | 0.92 | 0.72 |
| WABC 165 (check) | 2.05 | 1.27 | 1.00 |
| WAB 33-25 | 1.55 | 0.96 | 0.76 |
| WAB 33-17 | 1.19 | 0.74 | 0.58 |
| WAB 56-39 | 1.73 | 1.07 | 0.84 |
| WAB 96-13-1 | 0.32 | 0.20 | 0.16 |
| IDSA 46 | 1.66 | 1.03 | 0.81 |
| TOX 1011-4-A2 | 1.20 | 0.75 | 0.58 |
| WAB 56-50 | 2.57 | 1.60 | 1.25 |
| IRAT 144 | 2.68 | 1.66 | 1.31 |
| WAB 32-46 | 1.09 | 0.68 | 0.53 |
| WAB 99-1-1 | 1.18 | 0.73 | 0.58 |
| WAB 32-55 | 2.02 | 1.84 | 0.99 |
| WAB 181-18 | 1.85 | 1.15 | 0.90 |
| IRAT 112 | 1.19 | 0.74 | 0.58 |
| IDSA 10 | 2.04 | 1.27 | 1.00 |
| IDSA 27 | 1.53 | 0.95 | 0.75 |
| WAB 56-125 | 2.09 | 1.30 | 1.02 |
| WAB 56-104 | 2.66 | 1.65 | 1.30 |
| ITA 257 | 1.36 | 0.84 | 0.66 |
| WAB 99-14 | 0.86 | 0.53 | 0.42 |
| IAC 164 | 1.87 | 1.16 | 0.91 |
| WAB 32-80 | 1.10 | 0.68 | 0.54 |

[a]Grain yield of the cultivar/mean yield of cultivars.
[b]Grain yield of the cultivar/yield of the check cultivar.

The soils in West Africa, particularly those south of 12°N are derived mostly from basement-complex rocks and the rest of the soils in the sub-region are from a range of sedimentary rocks. The basement complex is a varied formation of metamorphic and igneous rocks, consisting of schists, phyllites, granites, gneisses and occasional intrusions of more basic rocks. Generally, these produce soils of inherent fertility that is relatively higher than those generated from the sedimentary rocks. Both granite and schists weather to produce soils that are moderately fertile, except when they are developed under high rainfall, i.e. conditions that prevail in the humid and sub-humid zones [10, 14]. However, the most fertile soils of the basement complex are those developed over the more basic rocks such as hornblende, schist and gneiss, and the basic igneous intrusions. On the other hand, soils developed over shale, sandstone and mudstone are sandy in surface texture, and generally low in nutrient reserves [8, 10].

Among the various soil types, Alfisols predominate in the West Africa savannah, a region with annual rainfall of 800 to 1,500 mm in one (mono-modal) or two (bimodal) distinct seasons. They have a coarse-textured surface horizon, are low in silt, have low CEC and a relatively high base saturation compared to other soil orders of the sub-region [15]. Ultisols are also found extensively in the high rainfall regions of West Africa, e.g. in the coastal areas of Cameroon, Nigeria, Liberia, Côte d'Ivoire and Sierra Leone [16, 17]. According to Lal [15], Oxisols are predominant in the equatorial zone where rainfall is high. They have low CEC, have less than 40% base saturation, and are relatively infertile. Vertisols are widespread in semi-arid tropical Africa; in West Africa they are found mainly in the Accra plains of Ghana. Inceptisols and Entisols are perhaps the most fertile groups in tropical Africa; located along the flood plains of major rivers and valley bottoms, they are utilised for rice production because of the favourable moisture regime in the wet season [15].

The chemical environments in upland or aerobic soils are distinctly different from those of submerged soils, and several chemical constraints, especially those related to soil reaction and plant-nutrient availability, are more severe in the upland systems of humid West Africa [18].

The pH values of the soils used for upland-rice cultivation under rainfed conditions in the West African sub-region are generally in the acidic range, as a result of high rainfall and resultant leaching of bases from the profile. The soils of the wet forest zone, where annual precipitation is more than 1,750 mm – along the coastal regions in Guinea, Sierra Leone, South and West Côte d'Ivoire, south-west Ghana, south and east Nigeria – are thoroughly leached, very acidic with pH values from 4.0 to 5.0 and very low base saturation. In the semi-deciduous forest zone, where annual rainfall is between 1,150 and 1,750 mm, the soils are less leached and only slightly acid in reaction (pH 5.5 to 6.0) with moderate base saturation. In the savannah region, where the annual rainfall is less than 1,200 mm, leaching is less and the soils have pHs from near neutral to slightly alkaline [19]. Soil reaction affects nutrient availability and their balance in roots and shoots [20]. Strong acidity and low effective CEC restrict higher productivity of low activity clay soils [17, 21, 22]. Recent research has also indicated the importance of silicon (Si) deficiency for upland rice grown on highly weathered Ultisols and Oxisols in West Africa and South America [23, 24].

## 3. TOLERANCE OF ACID UPLAND SOILS

Since 1992, a large number of upland rice cultivars, including interspecific progenies, have been evaluated for tolerance to acid-soil conditions at "hot spot" sites in the field. Important physical and chemical characteristics of the soils (Ultisols or Ferric Acrisols) at the experimental site at Man in the humid forest zone of Côte d'Ivoire are summarized in Table I. The soil analyses were done as described by Sahrawat et al. [25]. On average, the site receives about 1,700 mm of rainfall annually.

In all experiments, the cultivars under evaluation received uniform application of 60 kg N, 36 kg P and 36 kg K $ha^{-1}$. The experiments were conducted in the wet season (June to October). Results from an evaluation of twenty-four cultivars in 1993 showed a wide range in grain yields, from 0.32 to 2.68 t $ha^{-1}$. Grain yield efficiency index (GYEI = grain yield of the cultivar/mean grain yield of the cultivars) and relative yield (RY = grain yield of the cultivar/grain yield of the check cultivar) values varied from 0.20 to 1.66, and from 0.16 to 1.31, respectively (Table II).

TABLE III. FREQUENCY DISTRIBUTION IN THE GRAIN YIELDS OF ONE HUNDRED AND TWENTY UPLAND-RICE CULTIVARS ON AN ULTISOL AT MAN, CÔTE D'IVOIRE, 1994

| Grain yield (t $ha^{-1}$) | Number of cultivars |
|---|---|
| 0.00 | 10 |
| 0.36–0.99 | 30 |
| 1.00–1.50 | 40 |
| 1.51–2.00 | 21 |
| 2.10–2.50 | 12 |
| 2.51–3.00 | 7 |

TABLE IV. SOIL FERTILITY-RELATED CONSTRAINTS, AND CULTIVAR REQUIREMENTS, FOR UPLAND RICE IN THE HUMID ZONE OF WEST AFRICA

| Constraints | Humid forest | Forest/savannah transition |
|---|---|---|
| Soil acidity | +++[a] | +[b]/++[c] |
| P deficiency | +++ | +, depends on N supply |
| N deficiency | depends on P supply | +++ |
| Shortened fallow | acidity, P deficiency | severe N deficiency |
| Plant type | acidity tolerant, P-efficient, weed-competitive | mild acidity tolerance, N-efficient, weed-competitive |

[a]Of major importance. [b]Important. [c]Locally important.

TABLE V. EFFECTS OF Si AND Mg ON THE PERFORMANCE OF UPLAND RICE ON AN ULTISOL AT ONNE, NIGERIA, 1986 WET SEASON [27]

| Treatment | Grain yield ($g\ m^{-2}$) | Discolouration index |
|---|---|---|
| None[a] | 234[b] | 66 |
| Mg[c] | 204 | 66 |
| Si[d] | 248 | 43 |
| Mg + Si | 314 | 42 |
| $LSD_{0.05}$ | 44 | 7 |

[a]All plants received uniform applications of N, P and K.
[b]Means for cvv. ITA 212, OS 6, FARO 27.
[c]At 22.5 kg $ha^{-1}$ as magnesium sulphate applied in two splits, 21 and 69 days after sowing.
[d]At 188 kg $ha^{-1}$as sodium silicate.

In 1994, one hundred and twenty upland-rice cultivars were evaluated on an Ultisol at the Man site. Grain yields varied from 0 to 3.0 t $ha^{-1}$. Ten cultivars failed to yield, whereas nineteen produced between 2.1 and 3.0 t $ha^{-1}$ of grain. Frequency distribution in grain yield is shown in Table III.

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A large number of *O. sativa* x *O. glaberrima* were evaluated for their performance at Man in 1996 and 1998. Some showed promise in that they out-yielded not only the *O. glaberrima* check cv. CG 14, but also the *O. sativa* check cv. WAB 56-104 (Figs. 1 and 2). In the 1996 season, grain yields of the interspecific lines varied between 0.68 and 2.47 t $ha^{-1}$. In 1998, another set of interspecific progenies produced grain yields varying from 0.50 to 3.50 t $ha^{-1}$. These results clearly indicate that the development of interspecific progenies has enhanced the rice plant's adaptability to typical upland, acid-soil conditions (low in bases and P supply), in this case in a humid-forest Ultisol.

In the 1997 and 1998 wet seasons, eleven promising interspecific cultivars were tested in Guinea, which has the largest area of upland rice in West Africa, in a farmer-participatory varietal selection project on farmers' fields [26]. Of these, WAB 450-I-B-P-38-HB and WAB 450-I-B-P-160-HB have been proposed by the national programme for release to farmers. Thus, the new plant type, adapted to the acid uplands, along with proper crop and nutrient management, may provide the basis for a sustainable rice-production system.

## 4. ROLE OF PLANT NUTRIENTS IN REDUCING ACID-SOIL INFERTILITY

In upland Ultisols and Oxisols in the tropics rice faces a complex of nutrient disorders caused by acid-soil conditions and low fertility. Apart from direct nutritional effects, acidity and low soil fertility also influence growth and yield through the incidence of diseases, such as grain discolouration characterized by brown or black spots on the husk [27]. At times, it is difficult to separate nutritional and pathological effects.

In West Africa, a number of fertility diagnostic studies in the field involving nutrient-omission experiments have clearly demonstrated that:

- Nitrogen and P deficiencies are the major factors affecting upland rice,
- More importantly, P deficiency is more important than N deficiency in the humid forest zone, whereas the reverse is true in the savannah and forest-savannah transition zones; because of intense leaching in the humid forest zones, the soils are acutely deficient in P, and N response of crops such as upland rice depends on the application of P [19],
- As a general rule, P deficiency becomes increasingly important from north to south in West Africa.

A generalized conceptual analysis of plant-nutrient problems in upland acid soils by agroecological zone, and the associated requirement for an upland rice plant type, is summarized in Table IV.

Yamauchi and Winslow [27] studied the effects of nutrient supplies on the performance of upland rice on Ultisols in Nigeria's humid zones. Applications of N, P, K, Mg and Si were necessary to produce high dry matter. Magnesium and Si were involved in protection against grain-discolouration disease and their application increased the grain yields of three varieties by an average of 34% (Table V).

Sahrawat et al. [28] studied the role of P, Ca and Mg in ameliorating acid-soil-related fertility problems in upland rice (cv. WAB 56-50) on an Ultisol in the humid forest zone of Côte d'Ivoire. Application of P alone [50 kg P $ha^{-1}$ as triple superphosphate (TSP)] or in combination with Ca (50 kg $ha^{-1}$) and Mg (50 kg $ha^{-1}$) significantly increased yields and agronomic and physiological P efficiencies, and improved the harvest index of the crop (Tables VI and VII). Application of Ca or Mg alone, or together, had no significant effects on yield, elemental composition of plant tops at tillering (Table VIII), or the uptake of macro- and micro-nutrients at harvest (Table IX). It was concluded that P deficiency was the most important nutrient disorder in the Ultisol studied, and that applications of Ca and Mg were initially less important to growth, yield, and plant-nutrient status of this acid-tolerant variety.

We have observed that upland rice is a robust crop, genetic tolerance of which can be utilized to select cultivars that can grow normally on acid upland Ultisols and Alfisols. Applications of P and N to such cultivars can contribute to increased yields and to yield stability of cropping systems as a whole. The use of suitable legume fallows can be utilized to improve the N economy of the intensified upland rice-based systems of West Africa [29].

TABLE VI. EFFECTS OF P, Ca AND Mg ON YIELD AND HARVEST INDEX OF RICE CULTIVAR WAB 56-50 ON AN ULTISOL AT MAN, CÔTE D'IVOIRE, 1994 [28]

| Treatment[a] | Grain yield (t ha$^{-1}$) | Straw yield (t ha$^{-1}$) | Harvest index (%) |
|---|---|---|---|
| Control[b] | 2.02 | 2.14 | 48 |
| P | 3.14 | 2.99 | 51 |
| Ca | 2.11 | 2.43 | 46 |
| Mg | 2.28 | 2.86 | 44 |
| P + Mg | 2.87 | 2.72 | 52 |
| P + Ca | 2.79 | 2.79 | 51 |
| Ca + Mg | 2.12 | 2.28 | 48 |
| P + Ca + Mg | 2.98 | 2.81 | 52 |
| $LSD_{0.05}$ | 0.364 | 0.712 | 6.7 |

[a]All plants received 100 kg N ha$^{-1}$ and 80 kg K ha$^{-1}$.
[b]No P, Ca or Mg.

TABLE VII. AGRONOMIC P EFFICIENCY (APE) AND PHYSIOLOGICAL P EFFICIENCY (PPE) OF RICE CULTIVAR WAB 56-50 AS AFFECTED BY APPLICATIONS OF Ca AND Mg WITH P FERTILIZER AT MAN, CÔTE D'IVOIRE, 1994 [28]

| Treatment[a] | APE (kg grain kg$^{-1}$ P applied) | PPE (kg grain kg$^{-1}$ P uptake) |
|---|---|---|
| P | 22 | 482 |
| P + | 17 | 482 |
| P + Ca | 15 | 476 |
| P + Ca + Mg | 19 | 421 |
| $LSD_{(0.05)}$ | 4 | 64 |

[a]All plants received 100 kg N ha$^{-1}$ and 80 kg K ha$^{-1}$.

## 5. PHOSPHORUS RESPONSE AND P EFFICIENCY OF UPLAND RICE

Selection of cultivars of rice that acquire more P, or that have better efficiency of use of P, is a strategy for adaptation to harsh rainfed upland environments where acute P deficiency limits yields. In the highly weathered soils of the humid zone in West Africa, availability of P is reduced by the reaction of soluble P with Fe and Al oxides [30, 31].

Varietal differences in P efficiency are expressed when they are grown on acid, highly P-deficient soils. Despite a great deal of research on soil P worldwide, much still remains to be learned about practical aspects of management, and about P responsiveness and P efficiency of upland rice [32, 33]. Monde et al. [34] evaluated the performance of a hundred and forty-four local upland genotypes, collected in Sierra Leone, for tolerance of low available P by growing them on an upland Oxisol [pH ($H_2O$) 4.9; Bray-1 P 4.3 kg ha$^{-1}$; organic C 0.78%; CEC 10.2 cmol kg$^{-1}$) sandy loam in texture.

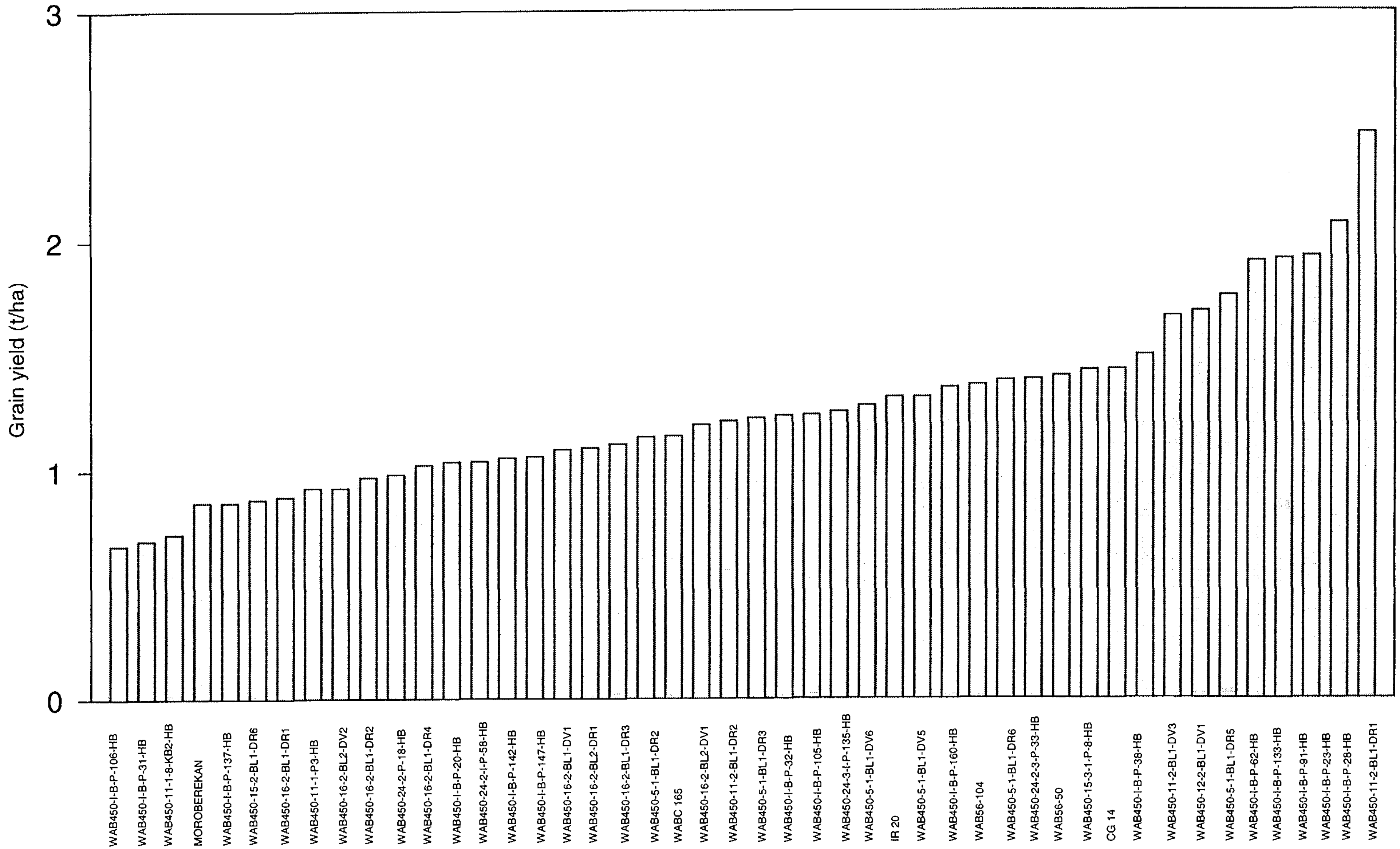


FIG. 1. Performance of 46 interspecific progenies grown on an Ultisol at Man,Côte d'Ivoire in 1996.

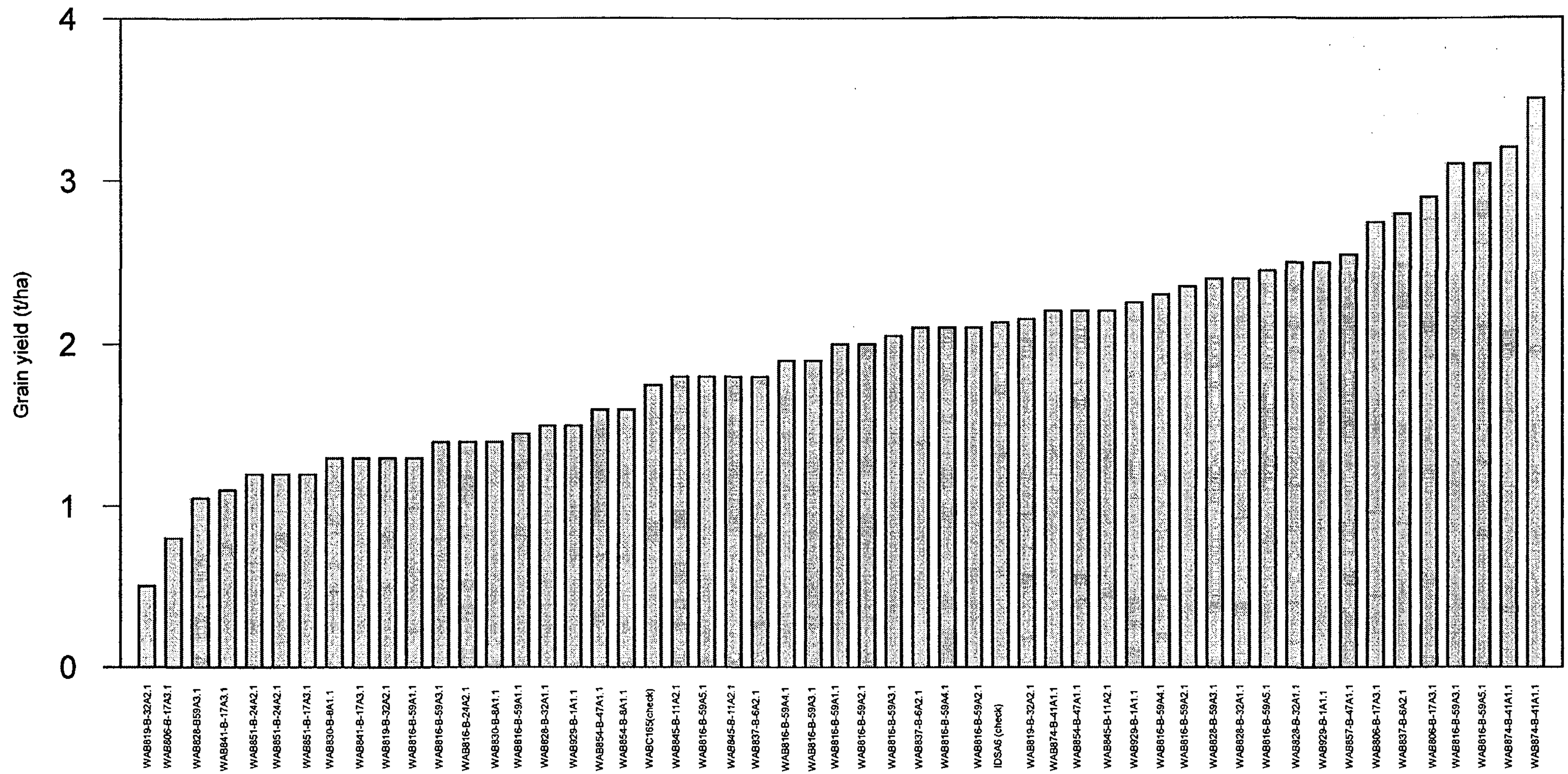


FIG. 2 . Performance of 53 interspecific progenies grown on an Ultisol at Man,Côte d'Ivoire in 1998.

TABLE VIII. NUTRIENT ELEMENT CONTENT (mg $kg^{-1}$) IN SHOOTS OF RICE CULTIVAR WAB 56-50 AS AFFECTED BY APPLICATIONS OF P, Ca AND Mg AT TILLERING, AT MAN, CÔTE D'IVOIRE, 1994 [28]

| Treatment[a] | N | P | K | Ca | Mg | Fe | Mn | Zn |
|---|---|---|---|---|---|---|---|---|
| Control[b] | 30,400 | 2,000 | 26,800 | 3,400 | 2,700 | 306 | 528 | 34 |
| P | 27,800 | 2,300 | 31,300 | 3,000 | 3,000 | 330 | 628 | 28 |
| Ca | 28,900 | 2,000 | 30,500 | 3,100 | 3,000 | 269 | 441 | 35 |
| Mg | 29,400 | 2,000 | 29,100 | 3,200 | 3,300 | 294 | 556 | 27 |
| P + Ca | 31,500 | 2,100 | 28,100 | 3,300 | 3,000 | 205 | 570 | 32 |
| P + Mg | 1,000 | 2,150 | 27,600 | 2,900 | 2,700 | 267 | 539 | 33 |
| Ca + Mg | 30,800 | 2,000 | 30,100 | 3,400 | 2,900 | 271 | 644 | 27 |
| P + Ca + Mg | 29,500 | 2,300 | 28000 | 3,500 | 2,900 | 303 | 571 | 28 |
| $LSD_{0.05}$ | 4,420 | 200 | 2,600 | 350 | 590 | 119 | 146 | 6 |

[a]All plants received 100 kg N $ha^{-1}$ and 80 kg K ha.
[b]No P, Ca or Mg.

TABLE IX. NUTRIENT ELEMENT UPTAKE (kg $ha^{-1}$) IN THE BIOMASS OF RICE CULTIVAR WAB 56-50 AS AFFECTED BY APPLICATIONS OF P, Ca AND Mg, AT MAN, CÔTE D'IVOIRE, 1994 [28]

| Treatment[a] | N | P | K | Ca | Mg | Fe | Mn | Zn |
|---|---|---|---|---|---|---|---|---|
| Control[b] | 39.6 | 3.7 | 49.4 | 5.6 | 6.9 | 0.91 | 1.21 | 0.085 |
| P | 61.0 | 6.5 | 58.1 | 9.4 | 11.4 | 1.93 | 1.70 | 0.080 |
| Ca | 48.2 | 3.3 | 56.2 | 8.0 | 9.0 | 0.90 | 2.09 | 0.080 |
| Mg | 45.2 | 4.1 | 56.2 | 8.1 | 10.3 | 1.08 | 2.14 | 0.096 |
| P + Ca | 52.9 | 5.9 | 52.8 | 8.3 | 9.9 | 1.71 | 2.31 | 0.070 |
| P + Mg | 54.1 | 6.0 | 52.8 | 6.6 | 10.9 | 2.75 | 1.61 | 0.070 |
| Ca + Mg | 48.1 | 3.9 | 45.2 | 6.9 | 8.5 | 1.21 | 1.60 | 0.093 |
| P + Ca + Mg | 59.1 | 7.1 | 59.4 | 8.2 | 11.8 | 2.24 | 2.16 | 0.090 |
| $LSD_{0.05}$ | 12.3 | 1.6 | 16.9 | 2.7 | 3.0 | 0.40 | 0.93 | 0.024 |

[a]All plants received 100 kg N $ha^{-1}$ and 80 kg K $ha^{-1}$.
[b]No P, Ca or Mg.

The cultivars received 60 kg N, 25 kg P or as appropriate, and 32 kg K $ha^{-1}$. Among the cultivars tested, thirty *O. glaberrima* and ten *O. sativa* showed tolerance of low P, using as the criterion percent relative tillers, i.e. ratio of number of tillers with no P : number with 25 kg P $ha^{-1}$ [35]. Tolerant cultivars achieved 90 to 100% relative tillers. The results showed that *O. glaberrima* varieties have greater tolerance for low available P. Tolerance for low available P was significantly correlated with tiller production ($r = 0.80$, $n = 140$), panicles $m^{-2}$ ($r = 0.58$), panicle weight ($r = 0.66$) and grain P-content ($r = 0.72$).

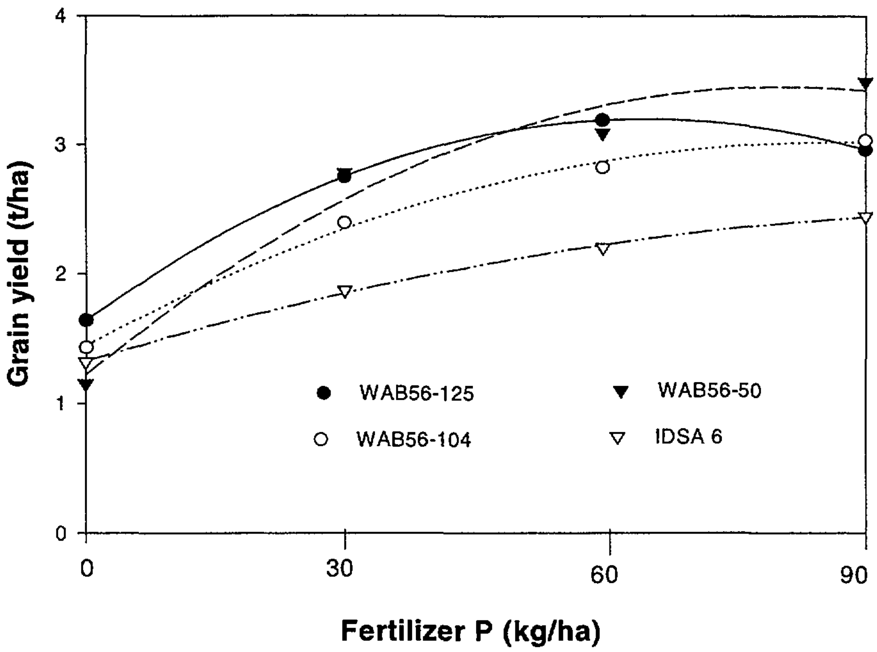


FIG . 3 . Relationships between grain yield and different fertilizer P rates of four upland rice cultivars on an Ultisol in 1992.

TABLE X. AGRONOMIC P EFFICIENCY (APE) AND PHYSIOLOGICAL P EFFICIENCY (PPE) OF FOUR UPLAND-RICE CULTIVARS AS AFFECTED BY P FERTILIZATION OF AN ULTISOL AT MAN, CÔTE D'IVOIRE, 1992 [33]

| P rate (kg $ha^{-1}$) | WAB 56-125 | WAB 56-104 | WAB 56-50 | IDSA 6 |
|---|---|---|---|---|
| | | APE (kg grain $kg^{-1}$ P applied) | | |
| 30 | 37 | 32 | 54 | 18 |
| 60 | 26 | 23 | 32 | 15 |
| 90 | 15 | 18 | 26 | 12 |
| Mean | 26 | 24 | 37 | 15 |
| | | PPE (kg grain $kg^{-1}$ P uptake) | | |
| 30 | 542 | 542 | 588 | 537 |
| 60 | 508 | 519 | 571 | 504 |
| 90 | 461 | 507 | 517 | 411 |
| Mean | 504 | 523 | 559 | 484 |

Sahrawat et al. [33] conducted field experiments in 1992 and 1993 to determine P responses and efficiencies of four promising, acid-tolerant cultivars (WAB 56-104, WAB 56-125, WAB 56-50 and IDSA 6) on an Ultisol, low in available P, at Man. The cultivars were selected from a large number of entries tested earlier for acidity tolerance. Triple superphosphate was used, at 0, 30, 60 and 90 kg P $ha^{-1}$ in 1992 and 0, 45, 90 and 135 kg P $ha^{-1}$ in 1993. The four cultivars produced similar grain yields when no P was applied.

The WAB cultivars gave better responses than did IDSA 6 to increasing rates of P (Figs. 3 and 4). The agronomic and physiological P efficiencies were higher at lower rates of P, and higher for the WAB cultivars than for IDSA 6 (Table X). The poor P efficiency of IDSA 6 was due mainly to its lower harvest index (ratio grain yield : grain plus straw yield) which was improved relatively little by P fertilization (Fig. 5). Harvest index was significantly correlated ($r^2 = 0.626$, n = 16) to P harvest index (ratio of P in grain : P in grain plus straw) (Fig. 6). Therefore, harvest index may have utility as a simple criterion for selecting for P efficiency.

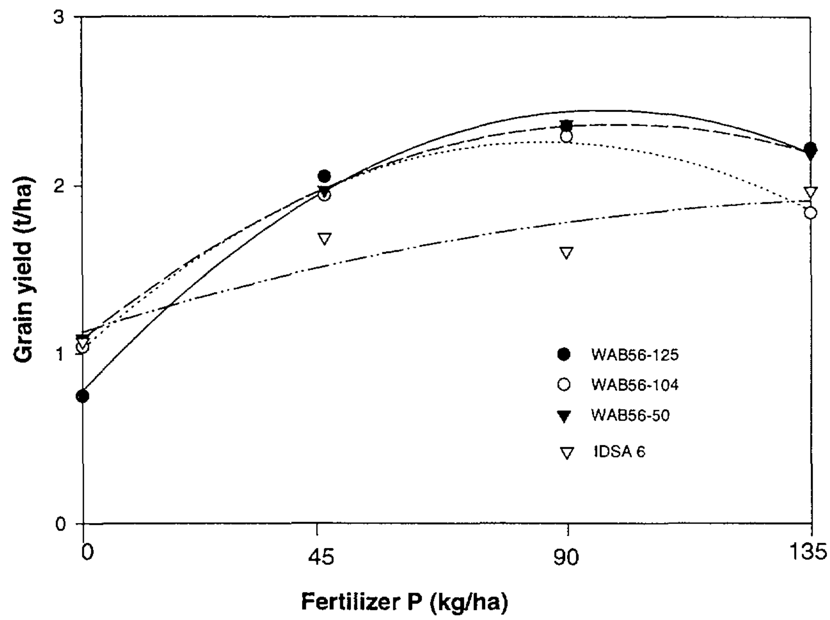


FIG. 4 . Relationships between grain yield and different fertilizer P rates of four upland rice cultivars on an Ultisol in 1993.

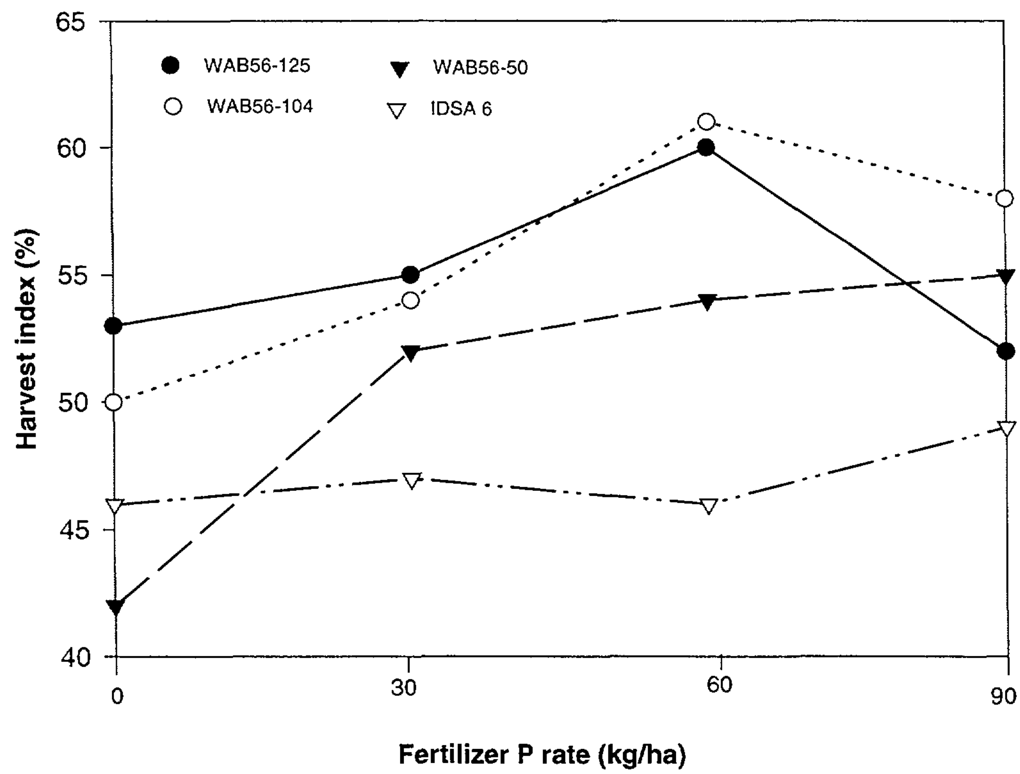


FIG. 5 . Relationships between harvest index and different fertilizer P rates of four upland rice cultivars in 1992.

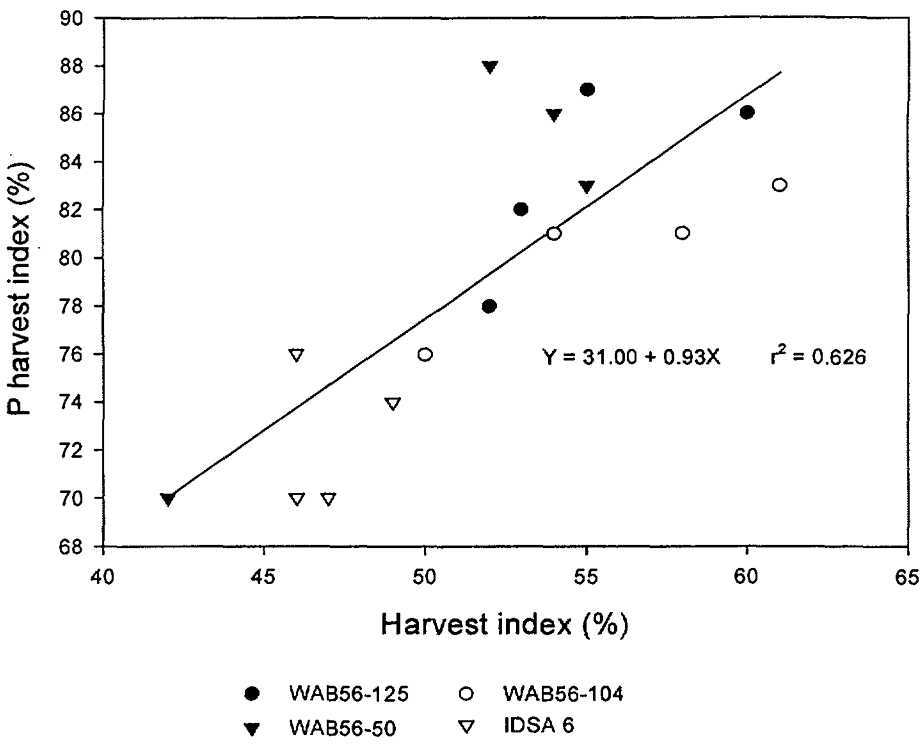


FIG. 6. Relationships between P harvest index and harvest index of four upland rice cultivars in 1992. Each point represents a mean value of four replications. The cultivars received four rates of fertilizer P at 0, 30, 60 and 90 kg P $ha^{-1}$.

In a 3-year (1993–95) study, Sahrawat et al. [36] determined the responses of the same four cultivars to 0, 45, 90, 135 and 180 kg P $ha^{-1}$ applied only in 1993. The soil at the experimental site at Man was an Ultisol low in available P. Grain yields were significantly increased by applied P in 1993, and by the residual effects of the fertiliser in 1994 and 1995, although magnitude of the responses decreased with time. The WAB cultivars showed superior cumulative agronomic and physiological P efficiencies than did IDSA 6. The amounts of total P removed in three successive crops were similar for all four cultivars although P harvest indices were 10 to 12% higher in the WAB lines than in IDSA 6. The results revealed that the differences observed in P efficiency were due to differences in internal utilization efficiency.

In 1998, the three WAB cultivars were released by the national program in Côte d'Ivoire for cultivation by farmers in the upland ecology.

## 6. CONCLUSIONS

Rice is a unique crop in that it grows well submerged and in well drained upland soils. However, its performance under acid upland conditions is greatly affected by soil and environmental constraints. Water shortage and poor fertility, and lack of well adapted cultivars are the major factors constraining productivity and yield stability. Most farmers in tropical Africa cannot afford soil amendments to adapt the cultivars that have not been selected or bred for the local environments. The discussion in this paper highlights the need to exploit genetic tolerance in rice to select and develop cultivars that are well adapted to specific upland environments. We cannot over-emphasise the fact that upland rice is a robust crop, and tolerant cultivars can perform well in acid-soil conditions. It is argued that suitable crop and nutrient-management strategies are essential not only to exploit the full potential of genetic tolerance but, more importantly, to provide the bases for sustainable rice-production system. Phosphorus nutrition is of critical importance not only for food crops such as rice and others that are part of the system, but P input is also absolutely necessary for reaping the benefits of biological $N_2$ fixation in natural and managed fallows. Finally, the approach in which genetic tolerance and nutrient management are integrated appears both practical and sustainable.

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