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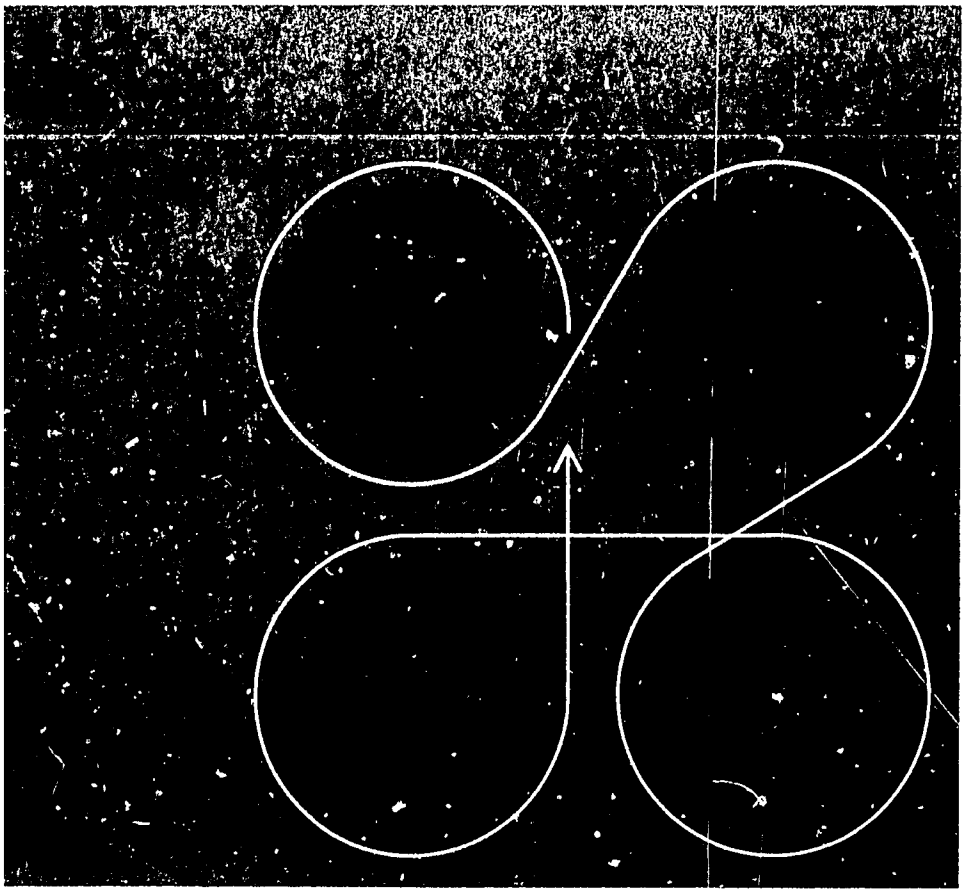

PHOSPHORUS RESPONSE ON OXISOLS AND ULTISOLS

A summary of cooperative projects carried out by
Centro de Pesquisa Agropecuaria dos Cerrados, Planaltina, Brazil
University of Puerto Rico, Rio Piedras, Puerto Rico
Soil Research Institute, Kumasi, Ghana
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NEW YORK STATE COLLEGE OF AGRICULTURE AND LIFE SCIENCES
A STATUTORY COLLEGE OF THE STATE UNIVERSITY
AT CORNELL UNIVERSITY, ITHACA, NEW YORK

With modern methods of travel and communication shrinking the world almost day by day, a progressive university must extend its campus to the four corners of the world. The New York State College of Agriculture and Life Sciences at Cornell University welcomes the privilege of participating in international development — an important role for modern agriculture. Much attention is being given to efforts that will help establish effective agricultural teaching, research, and extension programs in other parts of the world. Scientific agricultural knowledge is exportable.

A strong agriculture will not only provide more food for rapidly growing populations in less-developed countries, but also a firmer base upon which an industrial economy can be built. Such progress is of increasing importance to the goal of world peace.

This is one in a series of publications designed to disseminate information concerned with international agricultural development.

Donald Fisher

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Phosphorus Response on Oxisols and Ultisols*

Edited by Douglas J. Lathwell†

ABSTRACT

Experiments were carried out on representative Ultisols and Oxisols of Puerto Rico, Brazil, Ghana, and Peru to define crop response to fertilizer phosphorus, to measure relative efficiency of various methods and rates of application, and to estimate the residual effect of fertilizer phosphorus. These soils are deficient in available phosphorus in their native state and require fertilizer phosphorus for optimum crop yield when first brought into production. They vary widely in their phosphorus requirements, and the initial application needed varies from as little as 40 kg P_2O_5/ha to as much as 1000 kg P_2O_5/ha. Once the initial deficiency is corrected, maintenance applications of from 20 to 60 kg P_2O_5/ha will provide adequate phosphorus for optimum crop growth. The residual effect of initial broadcast applications of fertilizer phosphorus was always high. Liming of these soils apparently increases the availability of soil phosphorus for several crops at least, probably as a result of increased microbial decomposition of soil organic matter.

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CONCLUSIONS AND RECOMMENDATIONS

The Ultisols and Oxisols with which we have worked are, in their native state, deficient in available phosphorus. Most, if not all of them, require fertilizer phosphorus for optimum crop yield when first brought into production. These soils vary widely in their phosphorus requirements, and the rates required to achieve 70 to 80 percent of maximum yield in the first crop vary from as little as 40 kg P_2O_5/ha on some of the Ultisols with coarse-textured surface horizons of Peru and Ghana to as much as 500 to 1000 kg P_2O_5/ha on the Oxisols with clayey-textured surface horizons of the Cerrado of Brazil. The initial application should be broadcast and incorporated into the soil. Methods are being developed and used for predicting how large the initial fertilizer phosphorus application should be, although further calibration with field response on a wide range of soils remains to be done. From a practical standpoint, the amount of fertilizer phosphorus required for the initial application is closely related to soil texture—the finer the texture, the higher the initial requirement.

If economic conditions dictate, the deficiency on soils with a high phosphorus requirement can be corrected over several years rather than by a single application. On these soils, 80 to 100 kg P_2O_5/ha applied as a band application for 4 to 5 years will serve to correct the deficiency. If the fertilizer phosphorus is banded, the yield of the first crop, however, will probably be lower than if it is broadcast. Once the initial deficiency is corrected, maintenance applications of from 20 to 60 kg of P_2O_5/ha will provide adequate phosphorus nutrition for annual food crops.

A combination of an initial broadcast and a band treatment on soils with a high adsorption capacity may be more efficient than either method of application alone. Much work remains, however, to define the most suitable long-term fertilizer phosphorus practices on various soils and for different cropping combinations.

In several experiments, annual crops responded less to fertilizer phosphorus when lime was added, apparently because enhanced mineralization of organic phosphorus increased the availability of soil phosphorus. Because these observations apply only to the first one or two crops in a cropping sequence, the longer-term responses to combined lime and fertilizer management remain to be evaluated, and long-term practices have yet to be developed.

Soil tests will be useful in following the phosphorus status of these soils under cultivation. The measurement of soil phosphorus for predicting responses in the experiments reported here was about equally well estimated by the 0.05N HCl plus 0.025N H_2SO_4 and the $NaHCO_3$ methods. Although these and possibly other methods may require further calibration for different crops and other soils, they appear preferable to attempting to characterize only the concentration of phosphorus in soil solution. The concentration in solution was found to be analytically more difficult

to estimate and may be more dependent on additional estimates of quantity and capacity factors to adequately characterize the phosphorus-supplying system.

The results from all locations have demonstrated the high residual effects of fertilizer phosphorus on a wide range of Oxisols and Ultisols. In all experiments, the residual effect of a high initial broadcast application or several band applications of fertilizer phosphorus has been great. The long-lasting residual effect of fertilizer phosphorus on Ultisols and Oxisols is illustrated by the experience in Puerto Rico, where a long history of fertilizer phosphorus use has made it difficult to locate field sites that are potentially responsive to phosphorus. The residual effect is important, and, consequently, fertilizer phosphorus management on these soils is not greatly different from other important agricultural soils. The Ultisols and Oxisols on which we have worked, then, are not an infinite sink for fertilizer phosphorus; but, instead, previously applied fertilizer phosphorus contributes significantly to the phosphorus nutrition of plants grown on them. Thus, initial fertilizer phosphorus application, although large and expensive, needs to be prorated over several years and looked upon as an initial capital investment much the same as an irrigation or drainage system.

The relative value of untreated natural phosphates and processed forms such as superphosphate has not been clearly defined. Results to date with annual crops like maize, soybeans, and upland rice are not particularly promising. The unprocessed natural rocks, however, have proved to be reasonably good sources of phosphorus for such forage grasses as *Panicum maximum* and *Brachiaria decumbens* which may be more tolerant of soil acidity than the annual food crops. Ordinary superphosphate has some advantages over concentrated superphosphate because it furnishes sulfur and additional calcium. A processed source such as superphosphate should be used in maintenance applications.

Suggestions to improve the efficiency of fertilizer phosphorus or to reduce the rate of decline of soil test phosphorus have focused primarily on minimizing contact of fertilizer phosphorus with the soil and restricting contact with the volume of soil where active, absorbing roots are present. Although this approach may provide additional improvements in fertilizer phosphorus efficiency, substantially more information about the location and activity of the root system is required. The long-term potential exists for increasing food crop production by developing cultivars that can thrive in the presence of low amounts of available soil phosphorus.

INTRODUCTION

Ultisols and Oxisols are generally very deficient in phosphorus. Unless fertilizer phosphorus is added, it is not possible to sustain high yields of food crops. The purpose of this report is to summarize the results obtained from field experiments carried out in Puerto Rico, Brazil, Peru, and Ghana to measure crop response to added fertilizer phosphorus. The specific objectives of these experiments were to determine the amounts and placement of fertilizer phosphorus required for optimum production, to evaluate long-term and residual effects of fertilizer phosphorus on crop yields, and to relate soil properties to fertilizer phosphorus requirements and crop response. The goal of such a research program is to develop a set of general fertilizer phosphorus recommendations that can be used by the individual farmer in growing food crops.

Phosphorus reactions in highly weathered soils

The clay fraction of the soils studied is dominated by iron oxides, gibbsite, kaolinite, and amorphous oxides of iron and aluminum (Weaver, 1974; Tyler, 1975; Lopes, 1977). Consequently, the surface potential of these materials remains constant while the surface charge varies (van Raij and Peech, 1972). Many of these soils have a low effective cation exchange capacity and are generally acid and quite infertile. Lopes (1977) showed that these soils are highly reactive to phosphorus and that "total Al_2O_3", along with clay content, is strongly correlated with phosphorus reactivity. Thus, he concluded from a practical standpoint that sand content is a useful index of the phosphorus requirement of these soils, since the requirement decreases as sand content increases. On the basis of his studies, Adams (1977) concluded that the most consistent predictor of reactivity of soils to phosphorus is its content of amorphous aluminum. Kamprath (1972) concluded that the largest amounts of phosphorus are fixed by amorphous hydrated oxides of iron and aluminum, followed by gibbsite, goethite, and kaolinite. The more crystalline the material, the smaller is its fixation capacity.

Methods to evaluate phosphorus requirements

Many chemical tests have been devised over the years to measure the quantities of soil phosphorus available to plants. When used properly, many of these tests are helpful in separating soils that are apt to respond to fertilizer phosphorus additions from those that are not likely to do so. These tests, however, do not provide information about the amount of fertilizer phosphorus required. Fox and Kamprath (1970), therefore, considered a capacity factor, which is a measure of the amount of phosphorus required to maintain a given level of phosphorus in solution. They proposed the use of sorption isotherms to estimate the phosphorus requirements of soils. The approach used is to determine how much phosphorus must be added to a soil to obtain the level of phosphorus in the soil

solution that maintains optimum plant growth. This procedure differs from that using the adsorption maxima by emphasizing the amount of phosphorus in the soil solution rather than the degree of saturation of the sorbing complex. A phosphorus concentration of 0.2 ppm in the soil solution has been used as a standard to estimate fertilizer requirements (Beckwith, 1965; Fox and Kamprath, 1970; Fox, Plucknett, and Whitney, 1968). More recently, Fox et al. (1974) showed that the soil solution level for adequate growth under field conditions varied among species and stage of growth. While work with phosphorus sorption is encouraging, it is clear that an understanding of plant requirements for phosphorus as well as soil properties affecting phosphorus availability is required for proper use of phosphorus isotherms. Yost (1977) has suggested that desorption isotherms may be a more useful index of phosphorus availability since, in fact, as the plant removes phosphorus from solution, it is being desorbed from the soil surfaces.

The double acid solution (0.5N HCl + 0.025N H_2SO_4) of Mehlich and the modified 0.5N $NaHCO_3$ method of Olsen (Hunter, 1974) are widely used in Latin America to extract phosphorus from soils to establish correlations between soil test levels and response to fertilizer phosphorus. These methods have been used with reasonable success in many areas (Kamprath, 1972).

Crop response

Crop response to fertilizer phosphorus is common on Ultisols and Oxisols, especially when fertilizer phosphorus is first applied to them. Kamprath (1972) has summarized much of the response to phosphate fertilization in tropical America. In many experiments, significant responses to phosphorus fertilization were observed. Depending on the crop, recommended rates ranged from 60 to 240 kg P_2O_5/ha. Of particular concern on these soils are strategies to maximize efficiency of applied phosphorus. Broadcasting or banding or combinations have been used in various soils. Of equal importance are the residual effects of fertilizer phosphorus. Few studies on the highly weathered soils to evaluate the long-term effect of fertilizer phosphorus have been made. Younge and Plucknett (1966) showed that large broadcast applications of phosphate on an Oxisol in Hawaii maintained forage yields for nearly 10 years. On an Ultisol from North Carolina, Kamprath (1967) showed that large initial applications of fertilizer phosphorus had a marked residual effect on the yield of corn 7 to 9 years after application. A combination of a large broadcast plus an annual band application resulted in the highest yields. The extractant 0.05N HCl plus 0.025N H_2SO_4 reflected the added fertilizer phosphorus.

CROP RESPONSE TO APPLIED PHOSPHORUS

Rate and placement experiments

Field experiments were established in Puerto Rico, Brazil, and Ghana to define response curves for applied fertilizer phosphorus on representative Ultisols and Oxisols and to compare the efficiency and estimate the residual effect of banded and broadcast fertilizer phosphorus. The soils on each experimental site in Puerto Rico were Orthoxic Palehumults (Humatas and Torres series). The soil at the experimental site in Brazil was classed as a Typic Haplustox. The soils of the two sites in Ghana were classified as Typic Paleudults. The soil on one extrapolation site in Brazil is marginal between a Haplustox and an Acrustox, and on the other site, an Acrustox.

Brazil experiments at Centro de Pesquisa Agropecuaria dos Cerrados (CPAC). The study involving rates and methods of application of fertilizer phosphorus was carried out on the CPAC station. The experimental site was cleared of regrowth from a previously cleared area of cerradao vegetation. As far as was known, this site had received no fertilizer phosphorus and was typical of those surveyed by Lopes (1977) where 99 percent of all samples were extremely deficient in available phosphorus. When no fertilizer phosphorus was applied to this site, crop growth was a complete failure. Selected chemical properties of this Dark Red Latosol (Haplustox) are given in table 1. A detailed description of the site, treatments imposed, and data collected for the first five crops of the experiment are given by Yost (1977). The treatments used and the maize grain yields are given in table 2. Yield alone will be considered in this discussion.

The broadcast applications of fertilizer phosphorus were made once only in November 1972, just before the first crop was planted. The addition of 1280 kg of P_2O_5 has supplied sufficient phosphorus to pro-

Table 1. Some selected chemical properties of the Dark Red Latosol (Haplustox) used in the phosphorus rate and placement experiment

Depth	*C*	*N*	*Exchangeable cations*		*Al saturation*	*Soluble P (double acid)*
			Ca+Mg	*Al*		
cm	%		*me/100 g*		%	*µg/gm*
0–10	1.8	0.21	0.4	1.9	83	1
10–35	1.2	0.08	0.2	2.0	91	1
35–70	0.9	0.05	0.2	1.6	89	1
70–150	0.7	0.05	0.2	1.5	88	1

Source: Yost, 1977.

Table 2. Grain yields from 7 consecutive maize crops grown on Dark Red Latosol (Haplustox) to measure influence of rate and placement of fertilizer phosphorus on grain yields

P_2O_5 applied			*Grain yields*							
Broadcast	*Banded**	*Total applied 1972–77*	*1972–73*	*1973*	*1973–74*	*1974*	*1974–75*	*1975–76*	*1976–77*	*Avg.*
kilograms per hectare										
0	80	320	2,415	5,080	3,080	6,030	4,490	2,270	1,335	3,530
0	160	640	3,855	6,575	3,415	8,075	5,860	4,730	2,710	4,890
0	320	1,280	4,795	8,430	4,190	9,040	6,890	6,910	4,855	6,435
80	80†	640	4,585	6,005	2,565	6,485	5,790	4,980	4,195	4,945
320	80	640	6,660	7,330	3,335	7,225	5,400	3,720	2,475	5,165
160	0	160	5,235	3,270	880	1,785	1,650	660	450	1,990
320	0	320	6,275	5,690	2,210	3,425	3,000	1,890	885	3,340
640	0	640	6,795	7,480	2,975	6,440	4,820	3,890	2,555	4,995
1,280	0	1,280	7,960	8,540	3,870	9,035	6,250	6,190	4,670	6,645
2,000 (May '73)	0‡	2,080	2,265	9,550	4,560	9,020	6,600	6,970	5,325	7,005
Average of banded treatments§			3,690	6,695	3,560	7,715	5,745	4,635	2,965	4,950
Average of broadcast treatments§			7,010	7,235	3,020	6,300	4,690	3,990	2,705	4,995

*Banded treatments were discontinued after fourth crop.
†The 80 kg P_2O_5 banded was continued on all crops.
‡This treatment received 80 kg P_2O_5 banded on first crop.
§Averages calculated using treatments that received 320, 640, and 1280 total P_2O_5, either banded or broadcast.

duce nearly optimum yields in seven successive maize crops over the course of the experiment. Yields from smaller broadcast treatments, however, showed a general decline in yield (fig. 1). Further, the lower the initial broadcast rate, the greater was the decline in yields. Whereas the effects of the 160-kg treatment had largely dissipated by the end of the sixth and seventh crops, the residual effect of the 640-kg rate remained substantial even through the seventh crop. By the seventh crop, yields from the 320-kg rate had fallen to only about 20 percent of the 1280-kg rate. After the first crop, a higher broadcast rate was established, but the higher rate was not greatly superior to the 1280-kg treatment.

When the yields from band applications of fertilizer phosphorus are

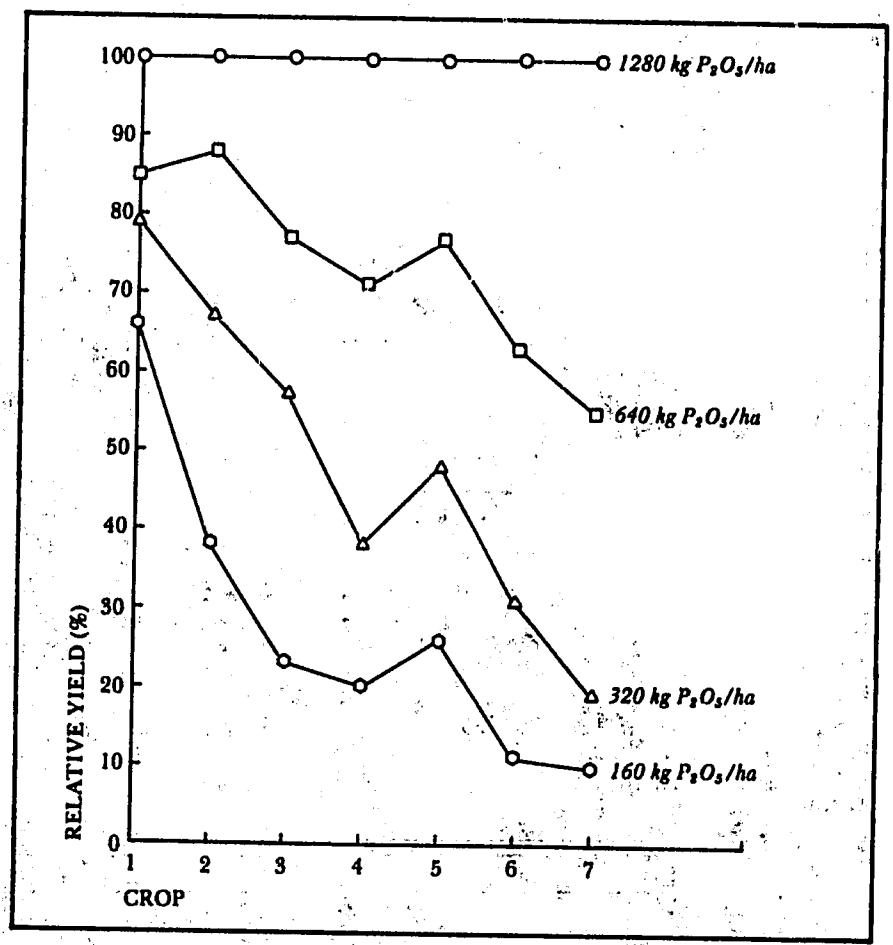

Figure 1. Relative yields of 7 successive maize crops treated with broadcast P at different rates.

compared for the first four crops, the 80-kg P_2O_5 rate averaged 62 percent as much yield and the 160-kg P_2O_5 rate averaged 82 percent as much yield as the 320-kg P_2O_5 rate (fig. 2). When the banded phosphorus applications were discontinued after the fourth crop, the residual effect of the 80- and 160-kg rates declined rapidly relative to the residual effect of the 320-kg rate.

A combination of an initial 320-kg P_2O_5 broadcast treatment and repeated band application of 80 kg P_2O_5 to each of the first four crops exceeded the yield of the highest band treatment in the first crop. In the second through the seventh crops, however, the yields of the combination treatment were similar to the yields produced by the repeated banding of

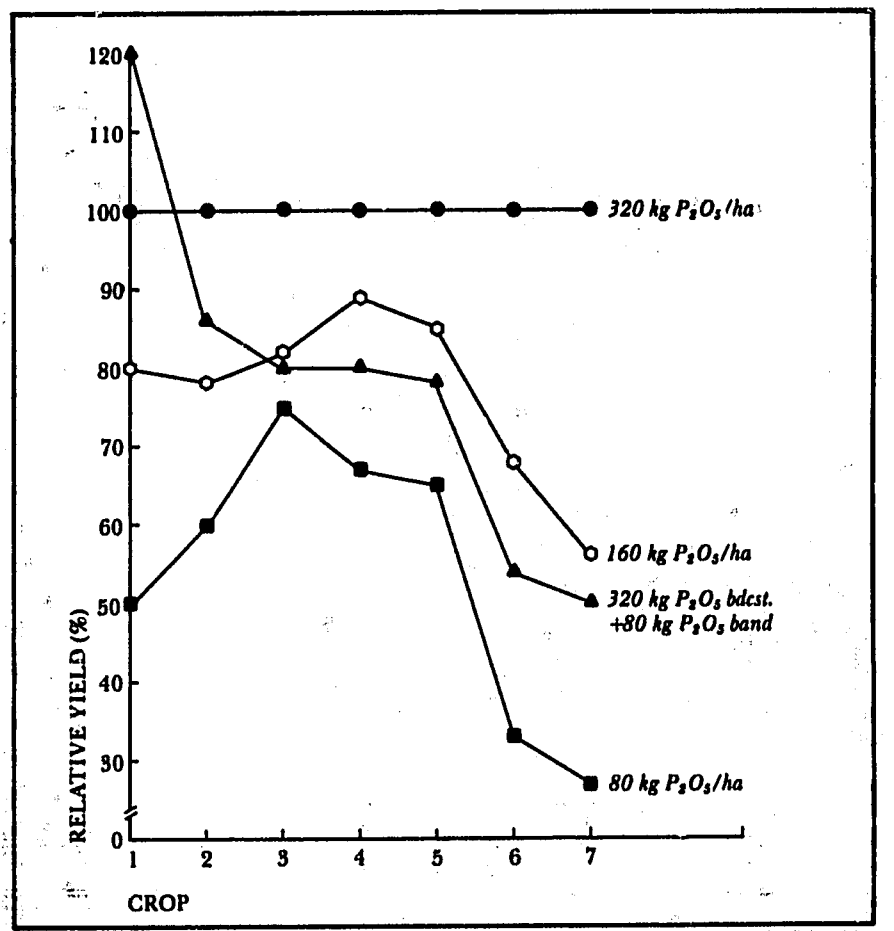

Figure 2. Relative yields of 7 successive maize crops with band treatments of P applied at various rates to the first 4 plantings.

80 kg P_2O_5 to each of the first four crops. The yields from the combination treatment were higher than those produced by only the repeated banding of 80 kg, indicating a substantial and surprisingly constant residual effect of the initial 320 kg P_2O_5 broadcast.

Except for the first crop, 320 kg P_2O_5 banded for each of the first four crops produced yields equal to the highest broadcast treatments. Thus, the highest band treatment applied to four consecutive crops supplied sufficient phosphorus to produce maximum yields through at least the seventh crop. These results show the cumulative effects from band application in building up soil levels of phosphorus.

In the first crop, all treatments that received only banded fertilizer phosphorus yielded significantly less than those treatments that received the same amount of broadcast fertilizer phosphorus (160 and 320 kg P_2O_5, table 2). With repeated band application to subsequent crops, however, the relative position changed, and the banded treatments yielded

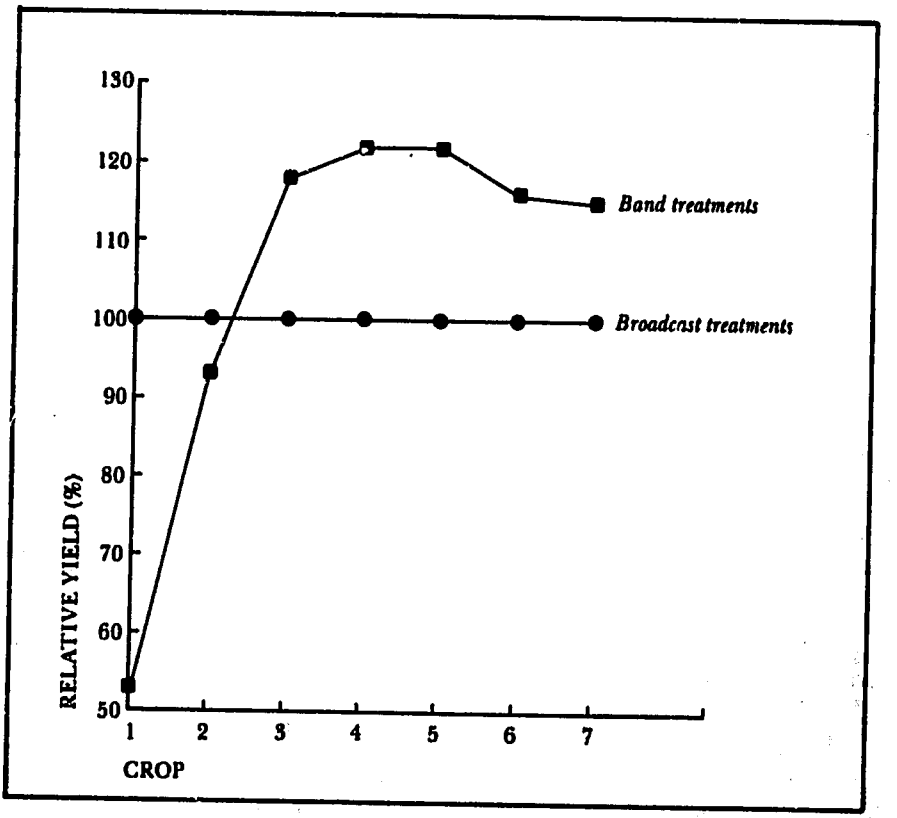

Figure 3. Comparative yields from banded fertilizer phosphorus and total P_2O_5 broadcast treatments applied at the same rates. Averaged treatments were 320, 640, and 1280 kg P_2O_5 for both methods.

more than the same amount of fertilizer phosphorus broadcast initially. A comparison of equal quantities of applied fertilizer phosphorus in the third through the seventh crops shows that the averaged yields of the all-banded treatments were about 120 percent of the averaged yields of the all-broadcast treatments (fig. 3). This difference occurred because yields from the low rates of broadcast phosphorus fell off more rapidly than yields from the low rates of banded phosphorus, even though both were residual treatments after the fourth crop.

Of particular interest are the treatment that received 320 kg P_2O_5 broadcast initially and 80 kg P_2O_5 banded with each of the first four crops and the treatment that received 80 kg P_2O_5 broadcast and 80 kg P_2O_5 banded with each of the seven crops (fig. 4). The yields for the first five crops obtained with the first treatment were about 85 percent of those obtained with the 1280 kg P_2O_5 broadcast, and yields of the last two crops fell off rather rapidly. With the treatment that received only the 80 kg broadcast and 80 kg P_2O_5 to each subsequent crop, yields of the first four crops were about 70 percent of those obtained with 1280 kg P_2O_5 broadcast. With the last three crops, however, the yields were nearly 90 percent of those obtained with 1280 kg P_2O_5 broadcast. Thus, high yields have been produced over the course of the experiment from rather modest applications of fertilizer phosphorus to this soil with a high phosphorus requirement.

To compare the effect of various rates and application methods on fertilizer phosphorus utilization, Yost (1977) measured the amount of

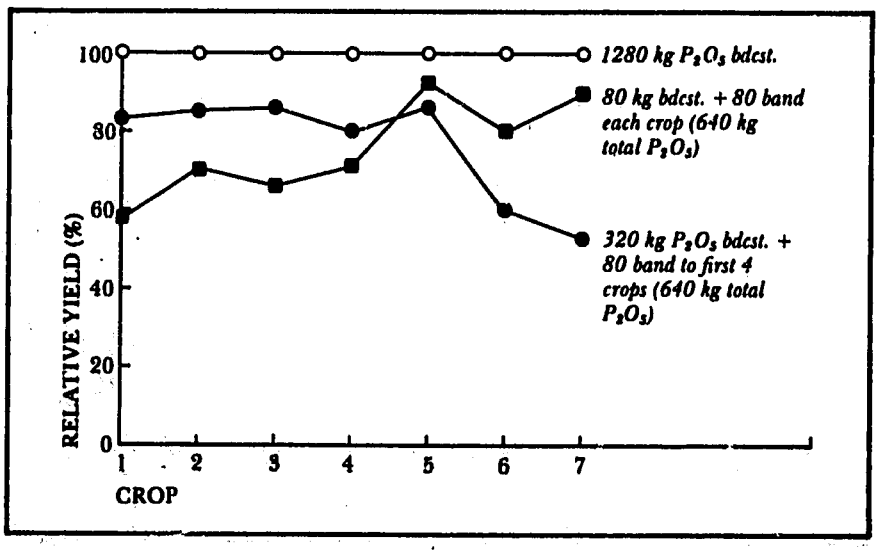

Figure 4. Relative yields of broadcast-plus-band treatments and broadcast-only treatments.

phosphorus absorbed in plant tops by the first five crops. A particularly important and valid assumption is that this soil supplies only insignificant amounts of phosphorus. He showed that while large amounts of fertilizer phosphorus are required for high yields of the initial crop, significant amounts of fertilizer phosphorus are recovered by five crops. The amount of fertilizer phosphorus removed increased nearly linearly with increasing rate of initial application. This obviously continues through at least seven crops as shown in table 2.

Application rate also has an important effect on residual phosphorus availability as measured by the double-acid method (Vettori, 1969). It was found that 640 kg P_2O_5/ha broadcast raised the double-acid soil test level of phosphorus well above the critical value of 10 μg P/g, while 320 kg P_2O_5/ha raised the soil test phosphorus level to a value approaching the critical level (table 3). Yost (1977) showed that the level of soil test phosphorus declined more rapidly with time as the application rate increased, however, suggesting that more phosphorus was transformed into nonextractable forms at higher application rates. As shown in table 3, the higher double-acid values and relative yields of crop 5 with the band applications of fertilizer phosphorus suggest that more plant-available P remained in the soil when band applications were made than when applications were broadcast.

An extrapolation experiment on the Red-Yellow Latosol (Haplustox–Acrustox) soil on the CPAC station was begun in November 1973 comparing broadcast and banded fertilizer phosphorus. The characteristics of this soil are given in table 4. Three consecutive maize crops were grown on the experiment. In the second and third crops the plots were split, and both sorghum and maize were grown (table 5). Yields were good on this experiment, with the high rate of broadcast fertilizer

Table 3. Influence of phosphorus rate and application method on double-acid soil test values and on yields of maize (2nd and 5th crops) grown on Dark Red Latosol

Total P_2O_5 applied		*Double acid P*		*Relative yield*	
Broadcast	*Band**	*Crop 2*	*Crop 5*	*Crop 2*	*Crop 5*
kg/ha		*μg/gm*		*%*	
	320		5.9		72
320		7.4	5.1	67	46
	640		14.2		94
640		19.5	9.0	88	77
	1,280		28.4		110
1,280		55.8	21.9	100	100

Source: Yost, 1977.
*Total applied to first 4 crops.

phosphorus giving the largest yields for the first two maize crops. By the third crops, however, the combination of a more modest initial broadcast rate plus an annual band application was out-yielding the broadcast for first-crop-only treatment with both maize and sorghum. While both crops responded to the addition of lime, the sorghum crops did better. The results from this experiment are generally consistent with the experiment on the Dark Red Latosol.

A second extrapolation experiment was established on a clayey-textured Red-Yellow Latosol (Acrustox) at the Agua Limpa farm of the University of Brasilia. In these experiments, one crop of beans (*Phaseolus vulgaris*) was grown as the test crop, with several varieties being used. The chemical properties of the soil given in table 6 are similar to the loamy Red-Yellow Latosol in the other extrapolation experiment. The main difference is the higher clay content of the soil at the Agua Limpa site. The design of the experiment was similar to the previously described experiments (table 7). Three levels of fertilizer phosphorus were broadcast, and one banded treatment was made. Yield increased significantly with all varieties as the broadcast application of fertilizer phosphorus increased from 160 to 2060 kg P_2O_5/ha. Perhaps the most important result is the relatively good yield that resulted from the banded application of 160 kg P_2O_5/ha. Although maximum yield was obtained with 2060 kg/ha of P_2O_5 broadcast, over 70 percent of this maximum yield was obtained by banding only 160 kg/ha of P_2O_5. The yield from the banded fertilizer phosphorus compared with the high broadcast rate was markedly better than the response shown by maize in the first experiment discussed. Whether this difference was attributable to species, soil, or other factors was not ascertained.

Table 4. Some chemical properties of the Red-Yellow Latosol (Haplustox – Acrustox) used in the phosphorus extrapolation experiment

Depth	*pH*	*Exchangeable cations*		*Al saturation*	*Soluble P (double acid)*
		Ca+Mg	*Al*		
cm		*me/100 g*		%	*µg/g*
0–15	4.65	0.17	0.56	77	1
15–30	4.65	0.14	0.42	75	1
30–45	4.60	0.13	0.31	70	1
45–60	4.75	0.12	0.17	59	1

Table 5. Crop yields from 3 crops grown on Red-Yellow Latosol (Haplustox-Acrustox) from different rates and placement of fertilizer phosphorus

P_2O_5 applied					Lime treatment		Grain yield						
Broad-cast	Band (annually)			Total applied	Rate	Depth	73–74 Crop 1	74–75 Crop 2		75–76 Crop 3		Average	
	1	2	3				Maize	Maize	Sorghum	Maize	Sorghum	Maize	Sorghum
kg/ha					t/ha	cm	kg/ha						
400	100	50	50	600	0	—	4,510	5,850	3,560	7,650	5,630	6,005	4,595
400	100	150	150	800	4	0–30	5,500	7,140	8,080	8,350	7,960	6,995	8,020
400	0	0	0	400	4	0–30	5,110	6,670	7,330	6,340	5,950	6,040	6,640
2,000	0	0	0	2,000	4	0–30	6,040	8,900	8,080	8,090	7,680	7,675	7,880

Table 6. Some chemical properties of Red-Yellow Latosol (Acrustox) at the Agua Limpa site (Brasilia)

Depth	pH (H_2O)	Exchangeable cations		Al saturation	Available P (double acid)
		Ca+Mg	Al		
cm		me/100 g		%	µg/g
0–7	4.80	0.30	0.58	66	tr.
7–22	4.75	0.28	0.51	65	tr.
22–42	4.85	0.20	0.28	58	tr.
42–58	5.05	0.12	0.11	48	tr.
58–90	5.40	0.13	0.04	23	tr.

Table 7. Yield of several varieties of dry beans (*Phaseolus vulgaris*) on the Red-Yellow soil (Acrustox) as influenced by rate and placement of fertilizer phosphorus

P_2O_5 added		Bean yields				
Broadcast	Band	Rico 23	Carioca	Rosinha	Roxinho	Average
kilograms per hectare						
160	0	695	665	860	600	705
400	0	1,300	1,515	1,360	1,140	1,330
2,060	0	2,060	2,250	1,940	1,460	1,930
0	160	1,425	1,580	1,520	1,165	1,425

Puerto Rico experiments. The first experiment on a Humatas soil at the University of Puerto Rico Corozal substation consisted of ten treatments as shown in table 8. Sorghum was planted in November 1970 and harvested in April 1971. Typical moderate yields were obtained in this winter season cropping. The average yield for all plots was about 2700 kg/ha of grain, and yields did not differ significantly among treatments. Likewise, a maize crop which followed sorghum gave no response to any of the fertilizer phosphorus treatments. In January 1972, plantains were planted on this site to measure response to both fertilizer nitrogen and phosphorus. Earlier work (Caro-Costas et al., 1964) had shown that plantains are responsive to applied phosphorus on this soil. Yields of plantains obtained in the experiment were extremely high by any previous standards. Although variability in the experiment was substantial, yields tended to increase with phosphorus treatment in both the initial crop and the first ratoon crop. Yield trends were the same for fertilizer phosphorus applied at planting time and from the residual treatments.

Because little response was obtained on the first Torres site, a second site on a Torres soil was selected, and a series of nine consecutive crops was grown from November 1971 to July 1976. Selected chemical properties of this soil are given in table 9. Five crops grown on the second site were maize; the third crop was upland rice, the fourth was soybeans, and the last was dry beans (table 10). The seventh crop was lost before harvest time. Yields varied considerably among treatments, even though soil of the site was reasonably uniform. Other factors, such as disease affecting certain crops, undoubtedly contributed to the variability. In the first crop,

Table 8. Yield of sorghum and plantain as influenced by rate and placement of fertilizer phosphorus on the Humatas clay

P_2O_5 treatment		*Sorghum yield*	*P_2O_5 added*	*Plantain yields**	
Broadcast	*Band*	*1970*	*1972*	*1973*	*Ratoon*
kg/ha				*t/ha*	
0	22.5	2,810	55	51.14	28.37
0	45.0	2,370			
0	90.0	2,840			
0	180.0	2,550			
360	22.5	2,450	110	49.29	36.55
90	0	2,980			
180	0	2,730	0	54.72	40.21
360	0	2,550			
1,120	0	2,500	0	49.09	36.48
0	0	3,500	0	37.11	31.33

Source: del Valle et al., 1978.

*Treatments received 335 kg N/ha on each crop. Where yields are omitted, crops received variable amounts of N, so that only these 5 treatments can be compared for phosphorus effects.

response to phosphorus was significant, with some advantage for the band P treatments (fig. 5). Yields from 90 kg P banded were as high as from 1120 kg P broadcast ahead of planting. In the second crop, treatment had no effect on maize yields. On the third crop, rice, the band phosphorus treatments were omitted, and there was no response to phosphorus application. Yields, however, were low, and disease apparently further reduced yields on the experiment. The yields of soybeans in crop 4 were high, with no differences among treatments. From the fifth through the eighth crop, yields from the banded P treatments, which were applied to each crop, were superior to the broadcast treatments (fig. 5). Increases in yield from band treatments were modest compared with the phosphorus control on the latter crops. Except for the first maize crop, throughout the course of the experiment the broadcast treatments were

Table 9. Some selected chemical properties of Torres clay used in phosphorus rate and placement experiment

Soil depth	*pH*	*O.M.*	*CEC*	*Exchangeable cations*				*Al saturation*
				Ca	*Mg*	*K*	*Al*	
cm		%		*me/100 g*				%
0–15	4.7	4.25	13.0	2.15	0.65	.78	3.15	47
15–30	4.8	2.30	10.6	1.75	0.34	.55	3.37	56
30–60	4.6	0.88	9.8	2.02	0.42	.40	4.03	59
60–90	4.7	0.42	9.7	2.36	0.49	.19	4.10	57
90–120	4.6	0.35	9.7	2.07	0.45	.21	4.94	64

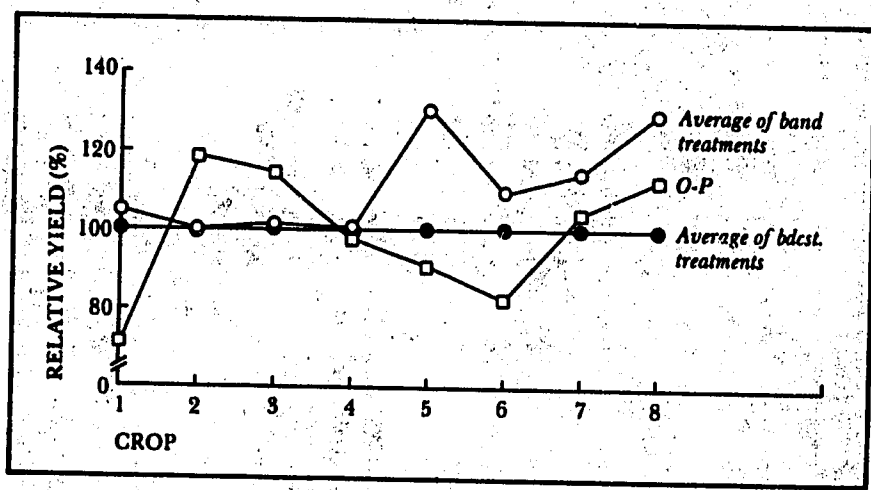

Figure 5. Yields of the phosphorus control treatment and the average of the 4 band fertilizer phosphorus treatments compared with the average of the 4 initial broadcast fertilizer phosphorus treatments on Torres soil.

not greatly different from the control. The maize yields on the phosphorus control plots, however, were high compared with yields obtained on the experiments at the CPAC in Brazil where the crop was a failure without added fertilizer phosphorus.

It should be pointed out that these two sites in Puerto Rico were selected after considerable effort to locate soils where a response to fertilizer phosphorus could reasonably be expected. Whereas the previously uncultivated soils of the Brazilian cerrado were almost always extremely low in available phosphorus, it was not possible to locate cultivated soils in Puerto Rico that were extremely deficient. Many of the agricultural soils of

Table 10. Crop yield from 8 consecutive crops on Torres soil to measure rate and placement of fertilizer phosphorus on crop yield

P_2O_5 treatment			*Yields of grain**							
Broadcast	*Band†*	*Total P_2O_5 applied*	*1971 –72 Maize*	*1972 Maize*	*1972 –73 Rice*	*1973 Soybeans*	*1973 –74 Maize*	*1974 Maize*	*1975 Maize*	*1975 –76 Beans*
kilograms per hectare										
0	22	180	3,190	4,980	1,315	3,475	3,860	3,020	4,680	1,850
0	45	360	3,195	5,235	1,775	3,830	4,050	3,320	3,780	1,750
0	90	720	3,790	4,660	1,485	3,500	4,540	3,080	3,660	1,540
0	180	1,440	4,135	4,585	1,520	4,230	5,815	3,840	3,900	1,670
360	22	540	3,695	5,500	1,440	3,480	3,765	2,885	3,960	1,680
90	0	90	3,235	4,930	1,540	3,310	2,940	2,685	3,890	1,230
180	0	180	3,260	5,150	1,505	3,580	3,585	2,475	3,430	1,120
360	0	360	3,460	4,980	1,450	3,645	4,010	3,405	3,060	1,230
1,120	0	1,120	3,700	4,445	1,510	4,380	4,205	3,520	3,520	1,650
0	0	0	2,425	5,795	1,735	3,680	3,140	2,480	3,630	1,490

Source: del Valle et al., 1977.
*1974–75 maize crop was lost before harvest.
†Band treatment applied to each crop except rice.

Puerto Rico have been intensively cropped to sugar cane and tobacco, both of which receive heavy dressings of phosphate fertilizers. These soils have been cropped for 50 years or more and may well have received as much as 10,000 kg/ha, or more, of P_2O_5 over that time (Abruna, personal communication). The difficulty in finding sites that were potentially responsive to fertilizer phosphorus and the lack of really substantial response on the field sites illustrates the high residual effects of fertilizer phosphorus that can be expected on the Ultisols and Oxisols.

Ghana experiments. Experiments similar to those in Puerto Rico and Brazil were started in two locations in Ghana in 1975. The same combinations of broadcast and band treatments except at lower rates were used in these experiments (tables 11 and 12). The site at the Kwadaso station on the Kumasi soil had been cleared from secondary forest the year before the experiment was established. The site at Huhunya was cleared from scrub savanna before the experiment was established. Both sites were variable because of previous burning and termite activity. They were, however, representative of the soil conditions encountered in West Africa. Little or no fertilizer phosphorus had ever been applied to either site, as far as was known. Two crops of maize per year were planted, one in the major rainy season beginning in late March and the other in the second or minor rainy season beginning in September. The minor rainy season crop was lost at Kwadaso in 1975, and the major and minor rainy season crops at Huhunya were lost in 1977 because of extreme drought at the sites. In the minor rainy season, stem borer has been a serious problem.

Yield increases in Kumasi soil approached 1000 kg/ha as a consequence of phosphorus fertilization. Response to fertilizer phosphorus

Table 11. Yield of maize on the Kumasi soil as influenced by rate and placement of fertilizer phosphorus

P_2O_5 treatment			*Yields*						
Broad-cast	*Band*	*Total applied*	*1975*		*1976*		*1977*		*Mean*
			Major	*Minor*	*Major*	*Minor*	*Major*	*Minor*	
Kilograms per hectare									
0	40	160	5,235		5,580	1,770	4,060	695	3,470
0	60	240	5,830		5,740	1,600	3,720	760	3,530
0	80	320	5,615		5,140	1,500	3,690	770	3,345
0	100	400	5,540		5,730	1,400	3,270	490	3,285
240	60	480	5,755		4,760	1,600	3,440	650	3,240
160	0	160	5,710		4,990	1,340	2,870	450	3,070
240	0	240	5,940		5,210	1,330	3,060	495	3,205
320	0	320	5,690		5,800	1,740	3,500	655	3,470
400	0	400	5,735		5,460	1,400	3,380	565	3,305
0	0	0	4,795		4,710	600	2,390	315	2,560

increased with time. Neither method of application nor rate had any influence on yield. While yields obtained in this experiment were not as great as those obtained at other locations, they were generally quite high for this region. It should be noted that major season maize yields declined, particularly between the second and third crops. The third major season crops were all residual phosphorus treatments, however, and this may have been responsible for the yield decline. The third minor season crop at Kwadaso yielded only 18 percent and 17 percent of the major season crop with banded and broadcast phosphate applications, respectively. The low crop yield was due mainly to drought coupled with severe stem borer infestation and streak, to which the maize crop is susceptible in the minor season. These results and field observations suggest that an alternative crop should be sought for the minor season in the humid zone of Ghana.

On the Bedeasi soil at the Huhunya site, a significant response to fertilizer phosphorus was obtained, even though the yields were somewhat lower than at Kwadaso. The initial broadcast treatment had some advantages over band treatments applied to each crop. Again, for maximum usefulness of this experiment, additional crops would be needed. The annual rainfall of the Huhunya area is about 1200 mm, but the distribution tends to be erratic so that crop yields are frequently reduced by drought. It should be noted, however, in the minor rainy season of 1976, grain yield was very low without fertilizer phosphorus.

These experiments show that response to fertilizer phosphorus will increase on these soils as cropping continues. Data from this location, like the others, indicate substantial residual effects of fertilizer phosphorus. The influence of rates on these experiments was not evident over the

Table 12. Yield of maize on the Bedeasi soil as influenced by rate and placement of fertilizer phosphorus

P_2O_5 treatment			*Yields*				
Broad-cast	*Band band*	*Total applied*	*1975*		*1976*		*Mean*
			Major	*Minor*	*Major*	*Minor*	
kilograms per hectare							
0	40	160	3,330	3,040	2,130	1,560	2,515
0	60	240	3,605	3,130	2,300	920	2,490
0	80	320	3,395	3,190	2,630	1,880	2,775
0	100	400	3,240	2,890	2,620	1,280	2,510
240	60	480	3,455	3,160	2,080	1,520	2,555
160	0	160	3,580	2,980	2,980	1,060	2,650
240	0	240	3,575	3,360	3,490	1,700	3,030
320	0	320	3,365	3,130	3,460	1,480	2,860
400	0	400	3,300	3,280	3,920	1,560	3,015
0	0	0	1,805	1,950	1,210	100	1,265

period of observation; thus, the data suggest that relatively small quantities of fertilizer phosphorus are sufficient for maximum yield under the conditions of these experiments. The longer-term effectiveness of these residual treatments, of course, can only be determined by subsequent cropping.

Continuous cropping experiments, Peru. The main thrust of the research program at Yurimaguas was to provide a viable alternative to shifting cultivation on the Ultisols in the Amazon jungle. The research has been directed at evaluating effects of land-clearing methods on soil properties and crop yields and selecting the most practical cropping sequences and fertilizer requirements for sustained crop production. Thus, selected treatments were used to evaluate responsiveness of these soils to fertilizer phosphorus. Some of the properties of the Yurimaguas soil (Typic

Table 13. Chemical properties of Yurimaguas series used in cropping experiment

Sample depth	*pH*	*Exchangeable cations*		*Al saturation*
		*Ca+Mg**	*Al*	
cm		*me/100 gm*		*%*
0–5	3.8	1.44	1.17	45
5–13	3.7	0.13	2.14	94
13–43	3.9	0.13	2.82	96
43–77	4.0	0.08	2.73	97
77–140	4.1	0.10	4.19	98
140–200	4.9	0.14	3.51	96

Source: Tyler, 1975.
*Includes K and Na; in lower horizons these constitute 30 to 40 percent of bases.

Table 14. First year phosphorus response of several crops, cropping system experiment on the Yurimaguas soil, Yurimaguas, 1973

Treatment N-P_2O_5-K_2O	*Yield*			
	Rice	*Cassava*	*Guinea grass*	*Soybeans*
kg/ha		*t/ha*	*t (4 cuts)/ha*	*kg/ha*
Burned				
50-400-50	2,560	29.1	18.98	845
50-0-50	2,350	21.9	14.97	590
Bulldozed				
50-400-50	1,660	22.0	12.86	275
50-0-50	1,250	12.5	6.19	100

Paleudult) are given in table 13.

The yields presented in this analysis were derived from a continuous cropping experiment in which several cropping sequences were introduced on land that had been cleared either by traditional methods of slash and burn or by bulldozing. Several fertility treatments were imposed after the first crop grown in the sequence, including treatments with and without fertilizer phosphorus (table 14). All four of these crops responded to the fertilizer phosphorus applied. Yields were higher on the burned than on the bulldozed plots. The response to phosphorus, however, was greater on the bulldozed plots than on the burned plots, illustrating the effect that ash residue in the burned plots had on the phosphorus fertility status of the soil (Seubert, 1975; Seubert et al., 1977).

In subsequent additions to the continuous cropping experiment, long-term cropping systems were developed, including continuous rice cropping and a rotation of rice–maize–soybeans. In these two cropping systems, a complete fertilizer treatment including 230 kg P_2O_5/ha was broadcast on all plots. Beginning with the second crop in the sequence, one series was carried without any further additions of fertilizer phosphorus to evaluate the residual effects of the initial application of fertilizer phosphorus. In both cropping systems and in each of the three experimental areas (table 15), the residual effect of the initial fertilizer phosphorus application remained high. Initial land clearing on all three areas was by slash-and-burn method. The results obtained here are consistent with the other experiments reported previously: when these areas are first brought into cultivation, a substantial response to fertilizer phosphorus is obtained, but the residual effect of the added phosphorus remains significant over an extended cropping period.

Table 15. Residual effects of fertilizer phosphorus on continuous and rotating cropping systems, Yurimaguas, 1973–75

*Location and fertilizer treatment**	*Continuous Rice*		*Maize-Soybeans-Rice*			
	No. of crops	*Avg. yield*	*No. of crops*	*Yield of maize*	*Yield of soybeans*	*Yield of rice*
		kg/ha		*kg/ha*		
Clearing 1						
Complete	6	2.01	8(3+4+1)	1.32	1.48	3.01
Residual	6	1.85	8(3+4+1)	1.35	1.67	2.95
Clearing 2						
Complete	4	2.60	5(2+2+1)	2.20	1.95	2.54
Residual	4	2.64	5(2+2+1)	2.08	1.53	2.94
Clearing 3						
Complete	2	2.36	2(1+1)	0.69	1.80	
Residual	2	2.39	2(1+1)	0.70	1.69	

*Complete treatments received N–P_2O_5–K_2O each crop. Residual treatments received N–P_2O_5–K_2O on first crop and only N and K_2O on succeeding crops.

Lime--Phosphorus experiments

Ghana. Two experiments were carried out in Ghana to study the effects of lime on yield response of food crops to phosphorus applications. One was at Kwadaso on the Asuansi soil series (Ultisol), and the other was at Aiyinasi on the Basachia soil series (Oxisol). The site at Kwadaso had been cropped for a number of years, whereas the site at Aiyinasi was cleared from secondary forest vegetation which had grown up after previous cropping. Some chemical properties of the two soils are given in table 16. Maize was grown during the major rainy season and cowpeas were grown during the minor rainy season at both sites in both 1976 and 1977. The fertilizer phosphorus treatments shown in tables 17 and 18 were applied only to the major crop of maize. The treatments were banded with the seed at Kwadaso, while at Aiyinasi the fertilizer phosphorus treatments were broadcast and incorporated into the soil. Yield data for cowpeas was obtained only at the Aiyinasi site for the 1977 minor season crop.

For the 1976 major season, maize grain yield was increased by both lime and phosphorus at Aiyinasi, but only phosphorus had a significant effect at Kwadaso (tables 17 and 18). At both sites the response to applied phosphorus was greatest at zero lime and lowest when 4 t/ha lime was applied. At zero lime, the added fertilizer phosphorus produced yield increases of about 50 and 170 percent over yields obtained from the control plots at Kwadaso and Aiyinasi, respectively. The increases were reduced to about 4 and 5 percent, respectively, at the 4-t/ha lime rate. When averaged over lime rates, response to fertilizer phosphorus was confined to the two highest rates on the Asuansi soil (Kwadaso site), while on the Basachia soil (Aiyinasi site) response was greatest to the first increment of added phosphorus but continued to the highest rate. Grain yields were limited at Kwadaso by drought conditions which prevailed from two weeks after silking to the end of the season.

In 1977, grain yields of maize were increased by both lime and phosphorus at both sites. At Kwadaso, grain yields increased up to the highest rate of fertilizer phosphorus added. At Aiyinasi, however, the largest yields were obtained with the first increment of added fertilizer phos-

Table 16. Chemical properties of Asuansi and Basachia soils used in lime and phosphorus experiments

Sample depth	*Soil pH*		*Exchangeable cations*		*Al saturation*
	H_2O	*$CaCl_2$*	*Ca+Mg*	*Al*	
cm			*me/100 gm*		*%*
Asuansi					
0–25	5.4	4.9	1.85	0.09	4
Basachia					
0–15	4.5	4.2	0.98	0.41	29
15–30	4.2	3.9	0.47	0.90	66

phorus. The effectiveness of applied fertilizer phosphorus decreased with increasing lime rate except for the upswing at the 4-t/ha rate compared to the 2-t/ha rate. No explanation for the upswing in 1977 is apparent. Grain yields were limited at Aiyinasi by drought and by damage from birds and insects.

On the Asuansi soil, the organic matter content of the plots ranged from 1.1 to 2.4 percent and averaged 1.6 percent in the 0–25-cm zone.

Table 17. Maize yields as influenced by various combinations of lime and phosphorus on Asuansi soil at Kwadaso

Lime rate	*P_2O_5 rate (kg/ha)*					
	0	*25*	*50*	*75*	*100*	*Avg.*
t/ha	*yields in kg/ha*					
1976 major season						
0	1,070	890	1,430	1,610	2,500	1,500
1	1,430	1,430	1,610	2,140	1,960	1,715
2	1,340	1,430	1,250	1,610	1,610	1,450
4	1,960	1,610	1,780	2,320	2,500	2,035
Avg.	1,450	1,340	1,520	1,920	2,140	
1977 major season						
0	1,040	2,100	2,150	2,350	3,190	2,165
1	1,860	2,270	2,820	2,910	2,760	2,525
2	2,550	2,560	2,780	3,160	2,970	2,805
4	2,370	2,780	3,350	3,240	3,460	3,080
Avg.	1,955	2,430	2,775	2,915	3,095	

Table 18. Maize yields as influenced by various combinations of lime and phosphorus on Basachia soil at Aiyinasi

Lime rate	*P_2O_5 rate (kg/ha)*					
	0	*25*	*50*	*75*	*100*	*Avg.*
t/ha	*yields in kg/ha*					
1976 major season						
0	1,050	2,630	2,920	2,900	2,830	2,470
1	1,380	2,790	3,100	3,130	3,440	2,770
2	2,230	2,700	2,990	3,200	3,610	2,950
4	3,080	3,010	3,420	3,060	3,330	3,180
Avg.	1,935	2,780	3,010	3,070	3,300	
1977 major season						
0	715	1,515	1,550	2,160	1,430	1,340
1	910	1,965	1,915	1,415	1,780	1,600
2	1,525	1,735	1,880	1,855	2,165	1,830
4	1,635	1,610	2,555	2,740	2,330	2,175
Avg.	1,195	1,705	1,975	2,045	1,845	

The bulk of determinations, however, were between 1.4 and 1.8 percent. The extractable phosphorus content of the soil using the methods of Greweling and Peech (1965) was about 1 ppm, which is in the low range. The organic matter content of the Basachia soil averaged 2.0 percent in the surface 0–15-cm zone and 1.7 percent in the 15–30-cm zone. The variation from plot to plot was small at this site. The extractable phosphorus content of the soil was about 1 ppm, again in the low range. The marked reduction in phosphorus response where lime was added may be due to the mineralization of organic phosphorus in these soils as a consequence of the added lime. The response to phosphorus in the absence of lime is predictable since the extractable phosphorus is in the low range. The organic matter content of both of these soils is sufficiently low, however, that the lime effect on apparent mineralization and enhanced phosphorus availability would not be expected to be a long-lived phenomenon.

The yield of cowpea grain at Aiyinasi in the 1977 minor rainy season shows the same trends as the two maize crops grown in the major rainy seasons of 1976 and 1977 (table 19). Yield increased substantially as a result of phosphorus application. The addition of lime reduced the response to phosphorus but not to the extent that it did in the previous two maize crops.

Peru. Because pasture production is one alternative in the cropping program at the Yurimaguas site in Peru, an experiment to determine the optimum rates of lime and phosphorus for Guinea grass production was carried out. The average yield of 14 cuttings shows a strong response to additions of fertilizer phosphorus (table 20). Because harvests were made at approximately 8-week intervals, the 14 cuttings were made over a 2-year period. Fertilizer phosphorus was applied only when the experiment was established in October 1973. Seasonal variations in yield resulted in varied response among cuttings. On this soil, the lowest rate of P_2O_5 was as effective as any of the higher rates, except possibly on the zero-lime treatment. Yield from liming increased substantially when no

Table 19. Cowpea grain yields in the 1977 minor season as influenced by various combinations of lime and phosphorus applied to maize grown in the 1976 and 1977 major rainy season on the Basachia soil at Aiyinasi

Lime rate	*P_2O_5 rate (kg/ha)*					
	0	*25*	*50*	*75*	*100*	*Avg.*
t/ha	*yields in kg/ha*					
0	480	750	790	1,060	870	790
1	490	970	830	870	1,190	870
2	720	870	870	1,070	1,250	960
4	700	950	880	1,140	930	880
Avg.	600	890	850	1,040	1,060	

fertilizer phosphorus was applied (table 20). Yield from liming increased only modestly when fertilizer phosphorus was applied. Consequently, response to additions of fertilizer phosphorus was lower on the limed treatments. This is consistent with the results of the Ghana experiments and may have involved mineralization of organic phosphorus. The residual effect of the fertilizer phosphorus remained high throughout the experiment. On the basis of these results, the most reasonable treatment for sustained pasture production is the combination of 2 tons of lime/ha and 60 kg P_2O_5/ha. If, however, lime was not available, nearly maximum yields could be obtained with higher application rates of fertilizer phosphorus alone. Nothing was gained by the higher lime or phosphorus rates, indicating that these soils require very modest amounts of fertilizer phosphorus. How frequently fertilizer phosphorus would need to be applied was not provided by this experiment.

Phosphorus source experiments

Brazil. Additional studies were made in Brazil to explore sources of phosphorus other than superphosphate for species that can tolerate high exchangeable aluminum and low soil phosphorus. Since a natural rock phosphate (Araxá rock phosphate) is found in the Cerrado region in Brazil, the use of rock phosphates, unprocessed except for grinding, is an attractive alternative. Rock phosphate sources may be more available in unlimed acid soils if aluminum-tolerant species can be grown. Since pasture for extensive beef cattle grazing is one major potential use for developed cerrado, the response of perennial grass *Brachiaria decumbens* was tested using ordinary superphosphate, rock phosphates, and a magnesium–silicate–phosphate combination at three lime rates. The phosphorus sources were:

- Ordinary superphosphate (20 percent citrate-soluble P_2O_5),
- Thermofosfato: Araxá rock phosphate heated with $MgSiO_3$ containing 19 percent total P_2O_5 of which 18 percent is citrate soluble,
- Hiperfosfato: Moroccan rock phosphate containing 30 percent P_2O_5

Table 20. Yield of Guinea grass as influenced by lime and phosphorus rates, Yurimaguas soil*

Lime rate	*P_2O_5 rate (kg/ha)*					
	0	*57.5*	*115*	*230*	*460*	*Avg.*
t/ha	*yields in t/ha*					
0	1.99	2.64	3.16	3.03	3.60	2.88
2	2.86	3.47	2.99	3.38	3.33	3.21
3.5	2.73	3.48	3.09	3.52	3.28	3.22
Avg.	2.52	3.20	3.08	3.31	3.40	

Source: Lopez, 1978.
*Average over 14 cuttings.

of which 25 percent is citrate soluble,

- Araxá rock phosphate: a natural rock phosphate found in the Cerrado containing 28 to 30 percent total P_2O_5, of which about 5 percent is citrate soluble.

The liming rates were 0, 3, and 4.5 t $CaCO_3$/ha, whereas the phosphate sources were applied before the first crop was planted at rates of 0, 86, 345, and 1380 kg total P_2O_5/ha. No further applications were made except for one treatment where 85 kg P_2O_5/ha as ordinary superphosphate was surface broadcast annually. The forage was established in February 1974, and ten harvests were made over the period to June 1977.

In the unlimed plots, the thermofosfato source reduced the exchangeable aluminum from about 70 percent saturation to essentially zero at the highest rate and increased exchangeable calcium and magnesium content about sevenfold, or from about 0.6 me to about 4 me/100 gm soil. The 345-kg P_2O_5 rate reduced aluminum saturation from about 70 percent to about 50 percent. The hiperfosfato rock also had a liming effect, as it reduced the aluminum saturation from about 70 percent to 20 percent at the highest rate. The unaltered Araxá rock, however, had little effect on the exchangeable aluminum, calcium, and magnesium levels in the soil.

The yields obtained with these materials are given in table 21 and show that a significant response to phosphorus was obtained with each material. Further, yield increased substantially over the course of the experiment with increasing rates of P_2O_5. The response to annual applications of 85 kg P_2O_5/ha superphosphate was very high over the last eight cuttings, and yields approached, or exceeded, those of the best treatments. Both the

Table 21. Yield of Brachiaria as influenced by source and rate of phosphorus*

Source of phosphorus	*Rate P_2O_5*	*Yield*
	kilograms per hectare	
OSP	85	1,485
	345	3,140
	1,380	3,895
Thermofosfato	85	1,325
	345	3,120
	1,380	4,080
Araxá rock	85	810
	345	2,265
	1,380	3,290
Hiperfosfato	85	1,310
	345	3,160
	1,380	3,815
OSP	85 (Annual total = 25.5 kg)	3,505
Control	0	765

*Average from 10 cuttings at 3 lime rates over 3 years.

thermofosfato material and the hiperfosfato materials were equal to superphosphate. This is not surprising, however, since both of these materials contained a fair proportion of citrate-soluble phosphorus. The Araxá source was inferior to the other sources, particularly at the lowest rate and in the early cuttings. The Araxá rock improved as a source of phosphorus over the course of the experiment, and in later cuttings yields approached or exceeded those obtained with other sources. It may therefore be a particularly useful source of phosphorus for the perennial forage crops in the cropping patterns of the Cerrado. Cost of material should favor the Araxá rock over the processed materials and make it competitive economically for pasture situations. If, however, the higher overall yields obtained and, in particular, the higher yields obtained in the early cuttings are important, then the processed materials have an important advantage.

Peru. In Peru, a source of rock phosphate (Fosbayovar) is available and has the potential to substitute for processed phosphate materials. It is about 30 percent P_2O_5, and 25 percent of the total P_2O_5 contained in the rock is citrate soluble. Fosbayovar was tested at Yurimaguas on the pasture grass *Panicum maximum* (Guinea grass) along with several other unprocessed materials and ordinary superphosphate at a single rate of 460 kg P_2O_5/ha. This experiment was done as part of the lime × phosphorus experiment reported in table 20. One application of the materials was made at the beginning of the experiment. No lime was applied with the rock phosphate sources. As shown in table 22, all of the rock sources were effective in supplying phosphorus for Guinea grass. The yields from the rock phosphate sources were from 86 to 91 percent of those from the superphosphate averaged over the 14 cuttings (28 months). The relative amounts of phosphorus supplied by the rock sources and by superphosphate did not change over the course of the experiment. The residual effects of all of the materials were high, but superphosphate maintained

Table 22. Yield of Guinea grass as influenced by phosphorus source on Yurimaguas soil*

Phosphorus source†	*Dry matter produced/cutting*	*Relative yield*
	t/ha	%
Ordinary superphosphate	3.60	100
Fosbayovar rock	3.09	86
North Carolina rock	3.27	91
Florida rock	3.21	89
Morocco rock	3.20	89
Control, O–P	1.99	55

Source: Lopez, 1978.
*Average of 14 cuttings.
†All materials applied at rates of 460 kg total P_2O_5/ha.

its relative superiority. With this forage crop, which is fairly tolerant of soil acidity, the rock sources performed relatively well; and the Fosbayovar rock probably would cost less per unit of forage produced than would the processed materials, which cost more per unit of P_2O_5.

In a second experiment, Guinea grass was used to evaluate Fosbayovar rock, with five rates of the material tested at three lime rates (table 23). A total of ten cuttings were made between June 1973 and October 1975. Response was substantial to the first phosphorus rate with no lime in this experiment, and yields tended to increase as the rate of fertilizer phosphorus application increased.

The addition of lime gave higher yields both with the control phosphorus treatments and with the rock-source treatments. The phosphorus response was greater at the zero-lime level than at the 1-ton rate even though the yields were higher at the 1-ton lime level, again indicating possible mineralization of organic phosphorus. The Fosbayovar rock had strong residual effects. Higher rates of both lime and phosphorus produced slightly greater yields all through this experiment. If this source is to be used, then modest rates (200–250 kg P_2O_5/ha) at the 1-ton lime rate seem to be most reasonable and economical. Neither the long-term residual effects of these applications nor the effectiveness of Fosbayovar rock as compared with superphosphate can be deduced from this experiment.

In another experiment with annual food crops — maize, rice, and soybeans —, the Fosbayovar rock was compared with triple superphosphate. When the soil was unlimed (RP treatments), it was extremely acid and the aluminum saturation was very high (table 24). Soil pH increased modestly and aluminum saturation decreased substantially where the soil had been limed (TSP treatments). A marked response to fertilizer phosphorus was obtained in this experiment (table 25), and although crop yields were generally low, probably because of previous soil management, rock phosphate was decidedly inferior to superphosphate as a phosphorus source. Even the additional high rates of rock applied before the soybean crop was planted did little to improve the performance of the

Table 23. Guinea grass yields using Fosbayovar rock phosphate as a phosphorus source and the influence of lime on phosphorus response*

Lime rate	*P_2O_5 rate (kg/ha)*					
	0	*115*	*230*	*460*	*920*	*Avg.*
t/ha	*yield per cutting in t/ha*					
0	1.52	2.07	1.99	2.15	2.29	2.00
1	1.85	1.94	2.27	2.29	2.34	2.14
2	—	2.14	2.43	2.56	2.67	2.45
Avg.	1.69	2.05	2.23	2.33	2.43	

*Average of 10 cuttings over 28 months.

Fosbayovar rock. It is likely, then, that these crops were reflecting lack of tolerance to soil acidity rather than an insufficiency of phosphorus, a conclusion that is supported by the analyses for soluble phosphorus reported in table 24. Aluminum-tolerant species or varieties might improve the performance of the rock phosphate. Other experiences (Barnes and Kamprath, 1975) indicate that liming extremely acid soils further reduces the plant-available phosphorus in rock phosphates. At the CPAC in Brazil, tests of various sources of rock phosphates on rice and soybeans have shown that 8 kg of P_2O_5 from rock are required to equal 1 kg P_2O_5 from superphosphate (CPAC annual reports). The prospect of efficiently using unprocessed rock phosphates as fertilizers for annual food crops is not encouraging.

Table 24. Some soil chemical properties of P source experiment, on Yurimaguas soils*

P treatment		*Soil pH*	*Exchangeable cations*		*Al saturation*	*Soil test P (Olsen)*
Source	*Rate*		*Ca+Mg*	*Al*		
	kg/ha		*me/100 gm*		*%*	*ppm*
RP†	60	4.1	1.1	2.7	71	6
RP†	120	4.0	1.0	2.9	74	8
RP†	480	4.3	1.5	2.3	60	27
TSP‡	60	4.6	2.7	1.4	34	5
TSP‡	120	4.6	2.8	1.6	36	9

Source: Villachica, 1978.
*Samples taken after rice crop was harvested but before treatments were applied to soybean crop.
†Unlimed.
‡1.4 t/ha lime applied before first crop was planted.

Table 25. Yields of food crops as influenced by source and rate of fertilizer phosphorus, Yurimaguas soil

Source	*Rate P_2O_5**		*Yield*		
	Before planting				
	Maize	*Soybeans*	*Maize*	*Rice*	*Soybean*
	kg/ha				
Rock phosphate†	60	480	55	330	300
Rock phosphate	120	750	145	160	380
Rock phosphate	480	1,000	940	605	705
TSP	60	60	965	1,520	1,185
TSP	120	120	1,310	1,620	1,240
O–P	0	0	0	350	860

Source: Villachica, 1978.
*Rock phosphate treatments were unlimed. TSP treatments received 1.4 t/ha and 1.0 t/ha lime before maize and soybeans were planted, respectively.
†Fosbayovar rock (Peru).

SOIL CHARACTERIZATION

Sorption isotherms

As part of the soil characterization studies made in conjunction with the field experiments, a substantial body of data, collected by means of the sorption isotherm method, to estimate the phosphorus requirements of these soils has been accumulated. Table 26 presents a summary of data collected by Lopes (1977), Adams (1977), and Weaver et al. (1975), estimating the quantity of the phosphorus comparing the procedure of Kamprath and Fox (1970) with a modification of the procedure of Olsen and Watanabe (1957). Lopes (1977) measured the phosphorus required to maintain several levels in solution. In the other studies, only the amount needed to maintain 0.1 ppm phosphorus in solution was determined. The soils from Brazil vary widely in how much phosphorus is needed to maintain any given solution concentration. Average amounts do not differ among soil groups, however, although there is a wide range of values within each group. The quantity of phosphorus required to maintain a solution concentration of 0.1 ppm in the soils of Puerto Rico is about the same as that required in the soils of Brazil. In these samples, the amount required to provide from 0.05 ppm to 0.20 ppm phosphorus in solution ranges from about 15 to 20 percent of the phosphorus adsorption maximum.

The results from the Ghana soils and the values reported for two soil samples from Peru are obviously much lower than those of either Brazil

Table 26. Quantities of phosphorus required to give various solution concentrations in several Brazil, Ghana, Puerto Rico, and Peru soils*

Soils	*Amounts of P required to give solution concentration*					
	0.05 ppm		*0.10 ppm*		*0.20 ppm*	
	Avg.	*Range*	*Avg.*	*Range*	*Avg.*	*Range*
	ppm					
Brazil						
Red-Yellow Latosol	196	51–479	259	60–642	293	71–738
Red Latosol	195	69–406	234	83–484	282	95–576
Dark Red Latosol	208	72–498	257	85–595	301	101–717
Puerto Rico						
Oxisols			334	0–616		
Ultisols			276	50–425		
Ghana						
Kumasi (Ultisol)			47	35–61		
Peru						
Yurimaguas (Ultisol)			12			
Pucallpa (Ultisol)			65			

*Sources: Lopes, 1977; Weaver, Fox, and Drosdoff, 1975; Adams, 1977; NCSU Annual Report, 1975.

or Puerto Rico. Without question, according to the phosphorus sorption data, much less fertilizer phosphorus is required to maintain a given level of solution phosphorus in the soils from the experiments made in Ghana and Peru than in the soil samples from Brazil and Puerto Rico. This is borne out by comparing the results from the field trials in Brazil with those in Ghana where much less fertilizer phosphorus was required to give maximum response. Indeed, extremely small quantities of sorbed phosphorus were required to maintain 0.1 ppm solution concentration for the soils studied in both Ghana and Peru. The criteria stated by Juo and Fox (1977) indicate that all of the soils—including those of Brazil and Puerto Rico and those of Ghana and Peru—used in the field experiments reported here fall into the low- or medium-phosphorus sorption groups.

Lopes (1977) made a thorough study of the influence of other soil parameters on the phosphorus sorption maxima and the amount of sorbed phosphorus required to maintain various solution concentrations. Although a whole series of soil properties were strongly related to phosphorus sorption by the cerrado soils of Brazil, the sand or clay content were among those most highly correlated, with the sand content negatively correlated and the clay content positively correlated. The summary of his data in table 27 shows that the quantities of sorbed phosphorus required to maintain 0.05 and 0.20 ppm phosphorus in solution in surface soils under cerrado vegetation clearly increases as the clay content increases. On the basis of these data (tables 26 and 27), the initial phosphorus requirement of soils with a clay fraction dominated by kaolinite and/or hydrous oxides can be estimated directly from its clay content. Smyth (1976) has shown that lime and fertilizer phosphorus applications reduce subsequent phosphorus sorption by these soils. Thus, if it is necessary to lime these acid soils, their phosphorus requirements should be measured after the liming material has been applied and allowed to react. Otherwise, the phosphorus requirements will be overestimated.

Weaver et al. (1975) found that only the amounts of amorphous or noncrystalline aluminum oxides were significantly correlated with the

Table 27. Quantities of sorbed phosphorus required to give 0.05 and 0.20 ppm phosphorus in solution in surface soil samples (0–20 cm) under cerrado vegetation in Brazil as influenced by clay content

Percentage of clay content	*Amount of P required to give solution concentration*	
	0.05 ppm	*0.20 ppm*
<18	89	110
18–35	151	219
35–60	263	377
>60	298	453

Source: Lopes, 1977.

phosphorus adsorption parameters. Adams (1977) showed also that the most consistent predictors of reactivity of soils to phosphorus were the amounts of amorphous aluminum measured by dilute HCl, acid oxalate, or 5 percent Na_2CO_3 extraction. Both Weaver et al. and Adams concluded that iron oxides were not a reliable indicator of soil reactivity to phosphorus. In agreement with Lopes, they concluded that clay content was the most easily measured reliable variable. Pope (1976) concluded that surface area of the whole soil was the best single indicator of phosphate adsorption over the entire group of soils he studied. From their West African studies, Juo and Fox (1977) concluded that specific surface area of the sesquioxides was most responsible for phosphorus adsorption in soils of that region. Again, one is led to conclude that sand and/or clay content is the most practical measure of the quantity of phosphorus required to maintain a given phosphorus solution concentration.

Soil tests to estimate phosphorus requirements

Although the experiments carried out in this research program were not designed specifically to provide soil test correlation information, the data collected in certain experiments demonstrates the usefulness of soil tests in predicting the need for fertilizer phosphorus. The two following examples show that soil tests can be used to characterize the phosphorus status of different soils with widely varying management.

Continuous cropping experiments, Yurimaguas. As part of the program to develop soil and crop management practices required for continuous crop production, land-clearing methods were compared. Burning the plant residue in slash-and-burn cropping is a traditional method that has supplied plant nutrients to the soil. Seubert (1975) showed that the extractable phosphorus by the modified Olsen procedure (Hunter, 1974) increased with time up to 6 months and then declined, probably because of crop removal. Two treatments of the fertilizer phosphorus had extremely high levels of extractable phosphorus and extensive residual effects. Extractable phosphorus increased in the lower depths and in all horizons in the bulldozed plots, probably because microbial activity, which increased when the soil was disturbed, caused organic phosphorus to mineralize. Burning also raised the soil phosphorus above critical levels, so that a substantial fertilization effect was observed. Extractable phosphorus levels on the burned treatment, however, had already fallen to about the critical level at the 10-month sampling period.

The rate and placement experiment, CPAC, Brazil. Yost (1977) in his studies used the sorption isotherm method as well as both the double-acid extract and the Olsen procedure to estimate the available phosphorus levels in the Dark Red Latosol of the CPAC phosphorus experiment. As has been shown previously (table 2), maximum yields of maize over seven crops were obtained with 1280 kg P_2O_5/ha. This treatment resulted in an initial concentration of about 0.05 μg P/ml in the soil solution, as measured by the technique of Fox and Kamprath (1970). The sorption

isotherm procedure, as well as the double-acid soil test, was used to estimate fertilizer phosphorus requirements for subsequent maize crops following the initial fertilizer applications made before the first maize crop was planted. The sorption procedure estimated that fairly large amounts of fertilizer phosphorus would have to be added to maintain 0.05 ppm P in solution even though yields were already near the maximum. The double-acid soil tests, however, indicated sufficient phosphorus supply in the soil, and this was substantiated by the yields obtained.

Yost (1977), using the procedure of Fox and Kamprath (1970) as well as a modified procedure using 0.001 M $CaCl_2$ with slow continuous shaking, found lower quantities of sorbed phosphorus were required to maintain the various levels of phosphorus in solution. Based on field data, the values obtained by the modified procedure were more realistic. These results suggest that variations in procedure can affect results. In addition, characterization of the soil solution is affected by pH, ionic strength, and type of cation. This makes interpretation of results difficult.

Yost (1977) also analyzed samples from the Red-Yellow Latosol extrapolation experiment after the second crop using the double-acid procedure. The procedure reflected rather well the addition of fertilizer phosphorus. Based on the results from the two experiments at the CPAC, Yost (1977) concluded that both the double-acid and the 0.5N $NaHCO_3$ methods of extracting soil phosphorus provided reliable estimates of critical levels, 10–15, 6–10 μg P/g, respectively.

Plant adaptation to phosphorus stress

The experiments discussed thus far have been based on the concept of modifying the soil environment, in this instance adding fertilizer phosphorus, to meet plant needs for optimum production. An alternative approach for achieving optimum production is to adapt plants to thrive in the presence of limited supplies of essential nutrients. This is not a new idea, as has been pointed out by several authors (Wright, 1976); and breeding of wheat varieties for mineral stress tolerance has been underway in Brazil since 1919 (da Silva, 1976). More recently, however, concerted efforts have been made to select crop plants that tolerate adverse soil conditions, usually toxic levels of soluble aluminum, and low levels of soluble phosphorus.

As part of the research program at the CPAC, Salinas (1978) measured the differential response to phosphorus of several crop plants important in the Cerrado area. He showed that differential tolerance to low available phosphorus existed among varieties of wheat, maize, sorghum, rice, and beans. With the exception of maize, varieties tolerant to Al stress were also tolerant to P stress, and those sensitive to Al stress also were sensitive to P stress. His study shows the potential to select plant species or varieties of certain species that are productive at low levels of available soil phosphorus. By using plant breeding in combination with screening techniques, it should be possible to identify tolerant species and varieties.

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