11 Application of Inorganic Phosphorus Fertilizer

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ABSTRACT

Phosphorus deficiency has been identified as a major constraint to crop production on highly weathered, low activity clay soils in the humid and subhumid zones of sub-Saharan Africa. Phosphorus deficiency is further accentuated on many of the soils, especially Ultisols and Oxisols, because of fast reversion of soluble P into insoluble forms through reactions with iron and aluminum oxides. Phosphorus fertilization is of fundamental importance for sustaining crop production, maintaining soil fertility, and enhancing the fertility of degraded soils. Recent research indicates that the application of inorganic P through soluble and relatively reactive phosphate rock (PR) sources can be effective in increasing crop production and productivity, enhancing the replenishment of N through biological fixation, and in the maintenance or improvement of the overall fertility of soils. The effectiveness of PR and the residual value of fertilizer P from soluble and rock P sources can be enhanced by amending them with locally available organic and crop residues or by the recycling of P from rock RP through leguminous crops. It is suggested that an approach in which the use of P-efficient genotypes and P management are integrated is more practical and sustainable.

Apart from water shortage, soil infertility is the major constraint to crop production throughout much of the tropical regions. According to Sanchez et al. (1997) soil fertility depletion in smallholder farms is the fundamental biophysical root cause for declining food production in sub-Saharan Africa. This implies that no matter how effectively other problems are addressed, per capita food production in Africa will continue to decline unless soil fertility depletion related problems are effectively addressed. Effective soil fertility management holds the key to enhancing food production and to effectively reverse this trend of declining productivity would require soil fertility replenishment in Africa.

Worldwide, P deficiency is the major constraint to crop production on low activity clay soils in the humid and subhumid tropics (Sanchez and Salinas, 1981). The situation is no different in West Africa, and P deficiency has been widely regarded as the major biophysical constraint to crop production on many farmlands in the humid and subhumid zone of West Africa (Mokwunye et al., 1996; Sahrawat et al., 2000). Low concentration of P combined with low P solubility limits the productivity of soils and lies at the heart of the problem of the maintenance and enhancement of soil fertility. Lack of adequate P not only limits the response to other major nutrients including N, but also affects the overall fertility and productivity of soils.

Despite extensive research on soil P, much still remains to be learned about the management of low P, low activity clay soils in West Africa. This chapter summarizes recent information on the role of inorganic P fertilizer application for maintaining and enhancing soil fertility in the humid and subhumid zones in West Africa. Included under inorganic P fertilizers are soluble P fertilizers and PR-based P sources.

LOW PHOSPHORUS STATUS OF SOILS

Acid soil-related fertility problems are common in the humid and subhumid tropical regions (Von Uexkull and Mutert, 1995). Soils are naturally acid or become acid, and the acid soil-related infertility problem is accentuated under intensified agricultural production systems. The acid soil-related infertility problem is complex and involves complex interactions of pH, toxicities of Al and Mn and deficiencies of P, Ca, and Mg (Helyar, 1991; Sumner et al., 1991; Foy, 1992). It is often difficult to separate these effects under field conditions. It has, however, been established that P deficiency is the major nutrient constraint on soils affected by acid soil-related infertility problems (Chien and Friesen, 2000; Sahrawat et al., 2000)

Phosphorus deficiency is widespread in the soils of the tropics. For example, in a study of 500 soils collected from 42 countries covering the tropical regions, the World Phosphate Institute categorized 65% as acutely deficient in P and a mere 8% were classified as not deficient in P (Kaola et al., 1988). Based on the agronomic response of crops to applied P, Sahrawat (1994) concluded that a majority of the soils in the humid and subhumid zones of West Africa were acutely deficient in available P.

Nutrient diagnostic studies made at the West Africa Rice Development Association (WARDA), along a north-south transect in Côte d'Ivoire demonstrated that as one moved from north to south, soil acidity increases and the deficiency of P becomes more important than that of N for cereals such as rice (*Oryza sativa* L.) (Sahrawat et al., 2000). These observations are in accordance with the findings that the deficiency of P is more important than that of N in the humid forest zone of West

Table 11–1. Acid soil-related constraints for upland crops in the humid zone of West Africa.

Constraints	Humid forest	Forest-savanna transition
Soil acidity	+++	+/++
P deficiency	+++	+ /++
N deficiency	++	+++
Shortened fallow	+++	+++

Source: Adapted from Sahrawat et al. (2000).
Notes: +++ = major ; ++ = important ; + = locally important.

Africa (Sahrawat et al., 1999). Yet, on soils in the savanna and savanna-forest transition zones, N deficiency is more important than P deficiency (Table 11–1). As a general rule, P deficiency becomes increasingly important from north to south on a north-south transect in West Africa.

In the humid and subhumid zones of West Africa, Alfisols, Ultisols, and Oxisols are the dominant soils (Kang and Juo, 1979; Deckers, 1993) and P deficiency has been identified as one of the major nutrient constraints for crop production and the maintenance of soil fertility. Among the various soil types, Alfisols predominate in the West African savanna, a region with an annual rainfall of 800 to 1500 mm. Ultisols are found extensively in the high rainfall regions of West Africa. Oxisols are predominant in the equatorial zone where rainfall is high (Sahrawat et al., 2000).

In general, low available P in soils is a problem throughout tropical Africa and many of the soils in the humid zone of West Africa are naturally low in P (Warren, 1992; Sahrawat et al., 2000). On acid soils, the problem is more severe as the applied P is converted to unavailable forms due to reactions with Fe and Al hydroxides (Juo and Fox, 1977; Sanchez and Salinas, 1980; Mokwunye et al., 1986; Warren, 1992; Abekoe and Sahrawat, 2001).

The reversion of soluble P to insoluble forms and P sorption is associated with, and can be predicted from, the contents of hydroxides of Fe and Al. Many of the Ultisols and Oxisols have been reported to be notorious in limiting the amount of P that is available to crops (Sanchez and Uehara, 1980; Mokwunye et al., 1986; Warren, 1992; Owusu-Bennoah et al., 1997; Abekoe and Sahrawat, 2001). The P requirements of soils to maintain a level of available P is influenced by P sorption capacity which, in turn, is related to the content of hydroxides of Fe and Al. According to the review by Warren (1992), the P requirements of soils in the tropical Africa tend to follow the order: Oxisols>Ultisols>Alfisols.

From this brief discussion, it can be generalized that while low P status is a common problem in the humid and subhumid zones of West Africa, the problem of P deficiency is more acute on the acid soils in the forests and derived savannas than on the mildly acid or nearly neutral pH soils of the Guinea savannas of the subregion. Also, it should be realized that it is more difficult to maintain a level of available P in the acid soils of the forest zone than on soils in the savanna zone and that the P requirement is higher in the case of former rather than the latter group of soils (Sahrawat et al., 2000).

INORGANIC PHOSPHORUS FERTILIZER APPLICATION FOR IMPROVING CROP YIELDS

Application of P is essential on low P status soils for overcoming the depletion of soil reserves because unlike N, P cannot be added by a biological process comparable to biological nitrogen fixation (BNF) and is, therefore more critical for keeping the soil fertile and productive.

A combination of P-efficient crops or cultivars and P fertilization practices may provide a better strategy for sustainable crop production on soils where P availability is a major constraint. Recent research has demonstrated varietal differences in P efficiency which have been reported for rice (Koyama and Chamnek, 1971; Fageria et al., 1988; Sahrawat et al., 1995a, 1997a, 1997b, 1998, 2000), maize (*Zea mays* L.) (Horst, 2000), cowpea (*Vigna unguiculata* L. Walp.) (Ankomah et al., 1995), legume cover crops (Tian et al., 1998; Kamh et al., 1999; Vanlauwe et al., 2000b), and several other crops of the tropical regions (Johansen et al., 1995; Randall, 1995). Species or varietal differences in P efficiency are especially important on soils with low P status, low P availability, and in production systems where the use of purchased inputs of P is low (Rao et al., 1999; Sahrawat et al., 2000).

Among the sources of inorganic P, soluble P sources and natural PR sources indigenous to the subregion are important. Current research on the use of PR as P source is especially emphasized in this section. In view of the importance given to the use of PR as a P source, another section covers aspects relating to improving the efficacy of PR as a P source.

Soluble Phosphorus Sources

A response of crops to added P is common on many soils of tropical Africa. Greater responses to P application have been reported for crops grown in the humid compared with the drier zones (Bationo et al., 1997). The rate of P application depends on the P requirement of the crop and the P sorption capacity of the soils (Bationo et al., 1986; Sahrawat et al., 1995a, 1995b). Several studies made on the P requirements of crops using a soluble P source such as triple superphosphate (TSP) suggest that crops may respond to a rate as small as 10 kg P ha^{-1}. For example, in a recent study Jama et al. (1997) reported that application of 10 kg P ha^{-1} as TSP on acid Alfisols in western Kenya had a significant residual effect on the maize crop in the following season. Applications of between 10 and 30 kg P ha^{-1} were highly beneficial to the maize crop.

Sahrawat et al. (1995a) determined the P response of upland rice cultivars on Ultisols low in P (2.7–2.9 mg Bray-1 P kg^{-1} of soil) in the forest zone of Côte d'Ivoire. They found that grain yields of the four upland rice cultivars tested were significantly increased by P application and the response was low at P rates higher than 60 kg P ha^{-1} (Fig. 11–1). Differences in the P responsiveness of cultivars (WAB 56-125, WAB 56-104, and WAB 56-50) and IDSA 6 were noteworthy over a range of fertilizer P applications (30–135 kg P ha^{-1}) during the 2 yr of study (Sahrawat et al., 1995a). Grain yields of the four cultivars were, however, similar when P was not applied. The rooting depths of the cultivars were increased by the application of P at the lowest application rate (30 kg P ha^{-1}).

In a 3-yr study (1993–1995), Sahrawat et al. (1997a) determined the response of four upland rice cultivars (WAB 56-104, WAB 56-125, WAB 56-50, and IDSA 6), adapted to acid soil conditions, to fertilizer P (as TSP) applied at rates of 0, 45, 90, 135, and 180 kg P ha^{-1} only once in 1993, and to the residual effect of P fertilizer in 1994 and 1995 on an Ultisol low in available P. Grain yields of cultivars were significantly increased by fertilizer P application in 1993 and by the residual effect of P fertilizer in 1994 and 1995, although the magnitude of P response decreased with time after the fertilizer was applied. The grain yield response to the residual effect of P fertilizer in 1994 was significant after P applied at rates of 135 and 180 kg P ha^{-1} for all the four cultivars and from 90, 135, and 180 kg P ha^{-1} for only two cultivars. In 1995, the response from the residual effect of P fertilizer at 135 and 180 kg P ha^{-1} was generally significant.

The results obtained on the Ultisol indicated that the applied P had reverted to insoluble P as a result of reactions with Fe and Al hydroxides, and that the residual value of fertilizer P decreased quickly, suggesting that the application of small amounts of P every year might be a better strategy than applying high rates of soluble P at any one time (Sahrawat et al., 1997a). The results reported by Sahrawat et al. (1997a) are in accordance with those reported for Ultisols and Oxisols, which have high P sorption capacity and revert soluble P into insoluble forms and decrease its availability to crops (Owusu-Bennoah and Acquaye, 1989; Sanyal and De Datta, 1991; Warren, 1992; Linquist et al., 1996, 1997). These results, however, contrast

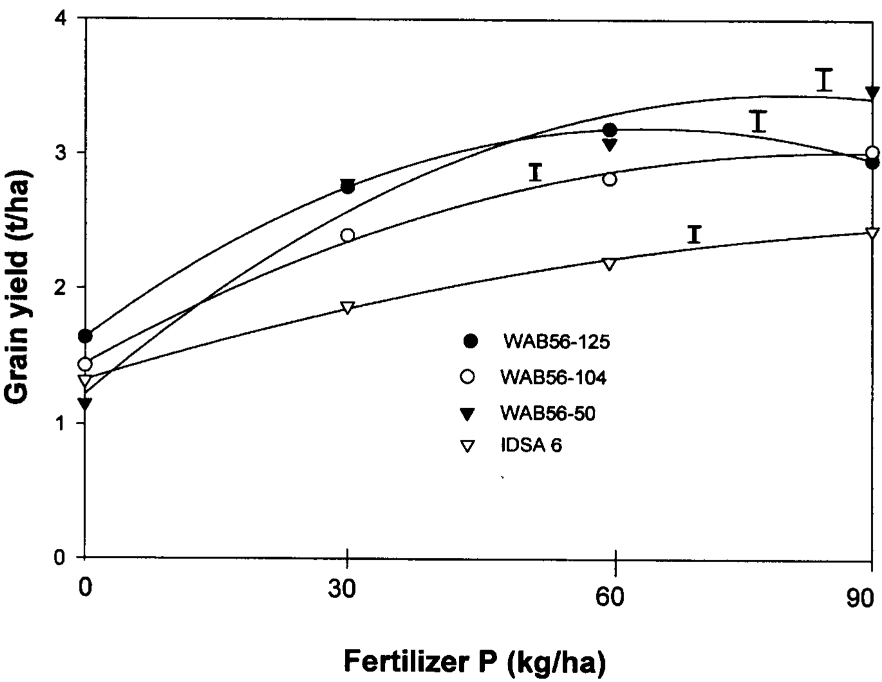

Fig. 11–1. Relationships between grain yield and fertilizer P rates (varying from 0–90 kg P ha^{-1}) of four upland rice cultivars on an Ultisol in 1992 (Sahrawat et al., 1995a). Vertical bars indicate LSD at P = 0.05 between P rates for each cultivar.

with those reported by Sahrawat et al. (1995b) for sorghum [*Sorghum bicolor* (L.) Moench] grown on a Vertisol (Typic Pellustert). They reported that the residual value of P to the succeeding crop of sorghum, even from moderate rates of applied P (10, 20, and 40 kg P ha^{-1}), was significant. More importantly, results showed that the sorghum yield and P uptake in treatments in which P was applied at 20 or 40 kg P ha^{-1} once in 2 yr was at par with, or greater than, treatments in which 10 kg or 20 kg P ha^{-1} was added every year. Ninety percent relative grain yield was achieved at about 20 kg P ha^{-1} of fresh P, and 40 kg P ha^{-1} applied once in 2 yr which satisfactorily met the P requirement of sorghum on the Vertisol (Sahrawat, 2000)

Phosphorus sorption and its reversibility or desorption play a dominant role in controlling P availability in Ultisols and Oxisols with medium- and fine-textured topsoil (Sanchez and Uehara, 1980; Abekoe and Sahrawat, 2001). These are the major soils in the humid and subhumid zones of Africa. Yet, some of the coarse-textured topsoils such as Alfisols, Ultisols, and Entisols in humid West Africa have only low to moderate P sorption capacity (Juo and Fox, 1977; Abekoe and Sahrawat, 2001). The P management strategies on the above two groups of soils will thus be different, based on the residual value of fertilizer P. For the sandy soils of semiarid West Africa, P sorption appears of minor importance (Doumbia et al., 1992).

Phosphate Rocks

In West Africa, several countries have an indigenous supply of PR. Among the West African countries, Togo (Hahotoe) and Senegal (Taiba and Thies) are significant producers of PR on the world market. In addition, Burkina Faso (Kodjari), Mali (Tilemsi), and Niger (Tahoua) have been exploiting PR in a finely ground form for local use. In addition, several other countries, Benin, Cameroon, Ghana, Guinea-Bissau, Liberia, Mauritania, and Nigeria, have PR deposits that have not been exploited. Additional deposits of PR also remain unexploited in countries which have developed PR deposits (Johnson, 1995). The P concentration in these PRs range from 10 to 17% P and their agronomic potential as judged by molar PO_4 /CO_3 ratio ranges from 4.9 to 23.0. This indicates that the West African PRs are not very reactive. Some of the most reactive PRs have a molar PO_4 /CO_3 ratio <5. The solubility of some of the PRs, as judged by ammonium citrate solubility also indicated that they have low and variable solubility (Table 11–2) (Mokwunye, 1995a).

Despite relatively low reactivity and diverse quality, the use of indigenous PRs appears attractive in terms of their lower cost and the high capital investment required for the production of soluble P sources. These, and other related issues, on the use of PRs as a source of P for various crops on diverse soils in diverse growing environments have been reviewed (Khasawneh and Doll, 1978; Hammond et al., 1986; Tandon, 1987; Bolan et al., 1990; Bolland and Gilkes, 1990; Gilkes and Bolland, 1994; Rajan et al., 1996; Buresh et al., 1997). It would appear that under the current economic situation in the subregion, the use of PR needs to be explored because if found efficacious their use would be a significant step in increasing agricultural productivity (e.g., see Kagbo, 1991; Sale and Mokwunye, 1993; Mokwunye, 1995a; Bationo et al., 1997). In addition, in the context of building soil P capital in Africa, the use of indigenous PRs as a source of capital P has been emphasized (Mokwunye, 1995b; Buresh et al., 1997; Sanchez et al., 1997).

Table 11–2. Phosphorus concentration, agronomic potential, and solubility of some West African phosphate rocks.

Phosphate rock	Total P conc.	Molar PO_4 /CO_3 ratio	Solubility†
	% P		% P
Kodjari (Burkina Faso)	10–12	23.0	0.8–1.2
Tilemsi (Mali)	13	11.2	1.8–2.0
Tahoua and Parc W (Niger)	14	4.9	0.8-1.6
Taiba and Thies (Senegal)	15–17	NA‡	NA
Hahotoe (Togo)	15–17	12.3	1.1–1.4
Sokoto (Nigeria)	15	11.5	1.4–1.6

Source: Johnson (1995), Mokwunye (1995b).
† Solubility measured in neutral ammonium citrate solution.
‡ Not available.

Another important consideration in the use of PRs is that they have a liming potential associated with its dissolution in acid soils and the release of Ca which they supply to the soil. Hellums et al. (1989) found that PRs from West Africa and South America have the potential to supply Ca to the soil during dissolution. A recent study of Indian PRs also indicated that the application of these materials can be a useful source of Ca, in addition to P, on acid soils such as Ultisols (Prakash and Badrinath, 1995).

The use of PRs as a source of P to crops, especially on acid soils in the humid and subhumid zones, appears attractive as the soils have the potential acidity to solubilize them. In some of the soils, such as Ultisols and Oxisols, the use of soluble P is effective with an application in each season but the residual effect is drastically reduced one or two seasons after the application of fertilizer P (Linquist et al., 1996, 1997; Sahrawat et al., 1997a). However, though the solubility of PR may be low initially, it improves with time in contact with acid soils (Mokwunye, 1995a ; Visker et al., 1995; Hu et al., 1997; Adediran et al., 1998).

In the past, research on the evaluation of indigenous PR in West Africa has been targeted at soils in the drier regions, which are not highly suited to the use of PRs with direct application. In this section, the latest information on the utilization of PRs on the acid soils of the humid and subhumid zones has been summarized.

Tandon (1987) listed 15 factors that can affect the yield responses to directly applied rock P to soils: soil (most importantly pH), crop, type of PR, grade of P, particle size of PR, season (wet or dry, etc.), time of application, method of application, mixing PR with single or triple superphosphate, use of organic manures, altitude (climate), treatment with microorganisms, digestion of PR with composts, use of iron pyrites or elemental S. He cited results from numerous studies made in India, emphasizing the importance of these factors under diverse crop, soil, and agroclimatic conditions. It should, however, be stressed that soil itself is the single most important factor in determining the effectiveness of PRs for direct application.

According to reviews by Khasawneh and Doll (1978), Chien and Menon (1995a), and Rajan et al. (1996), the most important factors that influence the agronomic effectiveness of PR with direct application include sources of PR, especially its solubility in citric or formic acid; soil properties (notably, pH), exchangeable Ca, soil texture, P-sorption capacity and organic matter content; management practices, especially water regime which influences soil pH, and crop species. In addition, the

Table 11–3. Effects of P placement and P source (TSP and PR) on maize yields at four sites in Malawi. Values are averaged across N sources and P rates.

	Maize yield							
	Bembeke		Mbawa		Bolero		Meru	
	TSP	PR	TSP	PR	TSP	PR	TSP	PR
	t ha^{-1}							
1991/92 season								
Point placed	4.4	2.9	4.5	3.5	5.5	4.9	7.0	5.4
Band	3.4	3.0	5.5	4.1	7.0	6.2	7.6	7.8
Placement x source interaction								
Prob.	0.17		NS		NS		0.01	
SED†	0.17						0.402	
Placement prob.	NS		0.01		0.003			
Source prob.	0.002		<0.001		0.07			
SED	0.376		0.265		0.392			
CV %	33		18		20			
1992/93 Season (residual P effects)								
Point placed	2.4	2.1	4.0	2.3	3.5	2.9	3.8	2.5
Band	2.4	2.2	4.3	3.2	3.9	3.8	4.3	4.7
Placement × source interaction								
Placement prob.								
Prob.	NS		0.21		0.25		0.01	
SED			0.396		0.340		0.372	
Placement prob.	NS		0.06		0.002			
Source prob.	NS		< 0.001		NS			
SED			0.396		0.240			
CV %	39		24		20			

Source: Wendt and Jones (1997).
† SED is standard error of the difference in means.

mineralogical composition of the PR also affects the solubility and hence its agronomic effectiveness (see also Chien and Van Kauwenbergh, 1992).

Wendt and Jones (1997) assessed the value of Malawi Tundulu PR in supplying P for maize production in Malawi. An experiment was conducted at four locations ranging from low to medium in available P, to compare the effects of Malawi Tundulu PR, a low-reactivity P source and TSP on maize yields. The soils at the experimental sites were Udic Rhodustalf (pH 5.5) at Bembeke, Oxic Haplustalf (pH 5.2) at Mbawa, Ustic Tropept (pH 6.1) at Bolero, and Ustic Tropept (pH 5.7) at Meru. Both TSP and PR were more effective when band applied, compared to the traditional point application (Table 11–3). The response to banded PR was site-specific, and was related to the P sorption capacity of the soil, with best responses occurring on soils with low-P sorption capacity. A further experiment made at two sites indicated that broadcasting PR gave greater yields than banding. The results indicate that the Tundulu PR from Malawi, applied as a band or broadcast, has the potential to replace conventional P fertilizers on some soils in Malawi.

Adediran et al. (1998) evaluated the effectiveness of Sokoto PR (indigenous to Nigeria) and Togo PR relative to SSP in laboratory, greenhouse, and field tests. Results of an incubation study for 12 wk showed that the availability of P, deter-

Table 11–4. Maize grain yield and relative agronomic effectiveness (RAE) for Minjingu phosphate rock (MRP) as compared to triple superphosphate (TSP) during two seasons on a Kandiudalf in western Kenya.

Season	Grain yield				RAE (%)
	MRP	TSP	No added P	SED†	
	t ha^{-1}				
1	3.5	3.4	1.3	0.3	107 (32)‡
3	4.8	5.6	2.2	0.3	79 (26)

Source: Mutuo et al. (1999).
† SED is standard error of the difference in means.
‡ Values in parentheses are standard deviations.

mined by Bray-1 extractable P, was greater when SSP was applied to an Alfisol (pH 6.8) than to an Ultisol (pH 5.4) or an Oxisol (pH 5.6). Yet, application of the two PRs to the Ultisol and Oxisol maintained a greater concentration of extractable P in the soil than when fertilized with SSP. In the greenhouse, with maize as the test crop, the relative agronomic effectiveness (RAE) of the two PRs was 40% of that of the SSP on the Alfisol. The Sokoto PR gave a better performance than SSP and Togo PR on the Oxisol (160% RAE) and Ultisol (100% RAE) soils. In a field study carried out for 3 yr with Sokoto PR and SSP as the P sources for maize, it was found that Sokoto PR had an RAE of 54, 83, and 107% relative to that of SSP in the first, second and third year of cropping.

These results support the hypothesis that on acid soils, the effectiveness of PR increases and that of soluble P decreases with time. For proper evaluation of the PRs, tests need to be conducted for at least 3 yr. Results from annual experiments, therefore, may not provide a correct and proper evaluation of PRs. There is also a need for a systematic research approach in the use of laboratory, greenhouse, and field tests for evaluating PRs.

In a recent study on a Kandiudalf (pH 5.1; bicarbonate-EDTA extractable P 2 mg kg^{-1} soil; organic C 14 g kg^{-1} soil) of the humid zone in western Kenya, Mutuo et al. (1999) compared the use of the relatively effective Minjingu PR from Tanzania with TSP for maize production. It was found that Minjingu PR was an effective source of P for maize production. Application of P more than doubled maize yield during the long rainy seasons (seasons 1 and 3). Maize grain yields in the short rainy season (season 2) were low and variable for all treatments due to unfavorable growing conditions. Maize yields were comparable for TSP and Minjingu PR. The relative agronomic effectiveness of the Minjingu PR averaged 107% in Season 1 and 79% in season 3 (Table 11–4). Among the soil tests evaluated, P extracted by anion resin and mixed resins appeared to be superior to bicarbonate and NaOH as a soil test for use with both TSP and rock P-treated soils.

The results reported by Mutuo et al. (1999) suggest that the use of PR of reasonable reactivity on acid soils low in bases, such as Ca, can be as effective as soluble P sources in increasing crop production. These results are in agreement with those of Scaife (1968) who found that the application of Minjingu PR gave a large response in cotton grown on an acid soil at Ukiriguru, Tanzania.

Six PR sources indigenous to West Africa were evaluated as P sources and compared to TSP for upland rice on an Alfisol low in available P (3 mg kg^{-1} Bray 1 P) at Danane in the forest zone of Côte d'Ivoire in 1997 under rainfed condition.

Table 11–5. Grain yield response of upland rice cultivar WAB 56-50 to the application of P from six phosphate sources in West Africa and triple superphosphate (TSP) on an Alfisol at Danane, Côte d'Ivoire in 1997 wet season. Phosphate rock sources were added to supply P at a rate of 200 kg P ha^{-1} and TSP was added to supply P at a rate of 60 kg P ha^{-1}.

Treatment†	Grain yield	Agronomic P efficiency
	t ha^{-1}	kg grain kg^{-1} P applied
No P added	0.96	--
Rock P (Mali)	2.54	8
Phosphate tricalcic (Senegal)	2.38	7
Phosphate d'alumina (Senegal)	2.26	7
Rock P (Togo)	2.20	6
Rock P (Burkina Faso)	2.01	5
Rock P (Niger)	1.80	4
TSP	2.36	23
LSD (0.05)	0.52	

† All treatments received a uniform application of N (100 kg N ha^{-1} as urea in three splits) and K (80 kg K ha^{-1} as KCl).

The PRs from Burkina Faso, Niger, Mali, Senegal and Togo were of highly variable reactivity and applied to supply P at a rate of 200 kg ha^{-1}. For comparison, TSP was added to supply P at a rate of 60 kg P ha^{-1}. Application of P more than doubled the grain yields of rice irrespective of P sources. In general, rock P proved inferior to TSP as a source of P (Table 11–5). Based on agronomic P efficiency, the performance of the six rock P sources varied from 17 to 35% as effective as TSP. The rock P from Mali (Tilemsi) was most effective and the one from Niger the least (Diatta et al., unpublished data, 1998).

Bationo et al. (1997) made agronomic and economic evaluations of Tilemsi rock P from Mali in farmer-managed experiments conducted over a 4-yr period (1989–1992) in three agroecological zones (rainfall ranging from 600–1200 mm) in Mali to evaluate the profitability of Tilemsi rock P in various crop production systems {pearl millet [Pennisetum glaucum (L.) R.Br.], groundnut [*Arachis hypogaea* L.], sorghum, maize and cotton [*Gossypium hirsutum* L.]} in comparison with water-soluble P fertilizers. The soils at the three sites had slightly acidic pH and were low in available P (1–14 mg Bray-1 P kg $soil^{-1}$). At each of the three sites 30 farms were studied. Marginal analyses were used to compare the various treatments using soluble P and rock P. In general, the profitability of fertilizer use decreased from the humid to the drier areas. Evidently, the yields of pearl millet and groundnut were affected by drought in the drier zones. Good responses, however, were obtained by the application of P from soluble or RP sources for crops grown in the humid zones. The results showed that the crop yields using the Tilemsi rock P were similar to those obtained with cotton- or cereal-complex imported fertilizers. The economic analysis of the results clearly demonstrated that at two out of the three sites, the financial benefit of the direct application of Tilemsi rock P was higher than for the recommended fertilizer practices. These results are in agreement with those reported by Kagbo (1991) who used the data from on-farm experiments conducted in Mali and showed that the use of indigenous of Tilemsi rock P was more profitable than the commonly used imported cotton-fertilizer, especially for maize-cotton rotations.

Another approach which has been used for utilizing rock P with direct application is based on the hypothesis that certain herbaceous and grain legumes are able to use P from rock P due to microbiological activity in the rhizosphere (Vanlauwe et al., 2000b). A cereal crop such as maize or rice could then benefit from P mineralized from the legume residues or from an improvement in the availability of P from certain P fractions (Maroko et al., 1999).

Studies by Vanlauwe et al.(2000b) indeed showed that the application of Togo rock P in a series of experiments in the savanna zone of Nigeria on neutral pH soils, low in available P, improved symbiotic properties, N accumulation, and biomass production of *Mucuna pruriens* (L.) Varutilis (Wright) Burck and *Lablab purpureus* L. The application of *Mucuna* residues significantly increased the release of P from rock P, resulting in higher values of extracted P (Olsen P) in the soil compared to the *Lablab* or maize treatments. Field experiments, conducted to study the residual effects of various plant residues on the following maize crop, showed that the application of rock P to *Mucuna* or *Lablab* increased grain yield, total N and P uptake of the following maize crop. The increases in the yield were attributed to an improved P supply to the maize indicated by higher values of Olsen P in the soil. The apparent recoveries of P from rock P by the maize crop in the legume-maize rotations were higher than in the maize-maize rotations (Vanlauwe et al., 2000a).

In a field study conducted on Ultisols in the humid zone of Côte d'Ivoire using a green manure-lowland rice cropping sequence, Attiogbevi-Somado (2000) showed that the application of Tilemsi rock P from Mali at 90 kg P ha^{-1} increased BNF by *Aeschynomene afraspera* J. Leonard. Nitrogen derived from the air (% Ndfa) was correlated to P uptake by the legume ($r = 0.97$) and nodulation ($r = 0.91$). Green manure application increased the yield and N and P uptake of the following lowland rice crop. Combining green manure with rock P tended to enhance the availability of P as indicated by the concentration of extractable P in the soil. It was suggested that the use of green manures can play an important role in improving the availability of P from unprocessed rock P with direct application.

From this discussion it can be concluded that direct application of rock P to cereal crops such as upland rice and maize can be exploited by supplying P on acid soils low in available P. Alternatively, the utilization of P from RP can be improved through the use of legumes in various rotations or as cover crops on mildy acid or non-acid, low P status soils.

AMENDING PHOSPHATE ROCKS TO IMPROVE THEIR EFFECTIVENESS

Use of indigenous rock P appears attractive in the present situation where the cost of mineral fertilizers is escalating. It is also realized that for direct application of P from phosphate rocks, their effectiveness needs to be improved by suitable amendment. Moreover, in the context of production systems that use organic inputs, organic and crop residues may be useful in improving the availability of P from both mineral and rock P sources (Iyamuremye and Dick, 1996; Buresh et al., 1997; Palm et al., 1997; Ae et al., 1990, 1995, 1996; Buerkert et al., 2000).

Organic and Crop Residues

Although the application of organic inputs alone generally cannot provide sufficient P for crop growth due to low tissue P concentration, the application of crop and organic residues can increase P availability by reducing P sorption and enhancing P solubilization. For example, in a field experiment on a Kandiudalf in western Kenya, the application of a high-quality organic source, *Tithonia diversifolia* (Hemsley) was found to increase the P status of the soil, with and without the application of TSP, with respect to resin P, bicarbonate P, microbial P, and sodium hydroxide inorganic P. The application of *Tithonia* also reduced P adsorption. This was attributed to competition for adsorption sites by organic anions produced during the decomposition of the high quality *Tithonia*, residues whereas, the application of maize stover had no effect on any of the P fractions or P adsorption (Nziguheba et al., 1998). It was concluded that a high quality organic input, such as *Tithonia* leaves, can be effective in increasing P availability in the soil.

Zaharah and Bah (1997) reported that the application of fresh leaves of *Gliricidia sepium* (Jacq.) Walp., *Acacia mangium* Willd, *Leucaena leucocephala* (Lam.) de Wit and *Senna siamea* (Lamk) Irwin and Barneby generally increased the solubility of P from less reactive PRs and depressed or did not affect the solubility from more reactive sources. Among the five PRs evaluated (North Carolina PR, Christmas Island PR, China PR, Algeria PR, and Tunisia PR) Algeria PR was the most reactive and China PR the least in the absence of green manures. Green manure application effects on the solubilization of PR were attributed directly to their effect on the supply of nutrients and release of P and indirectly by influencing P adsorption. The extent of the influence depended on green manure quality, especially the C/P ratio of the materials.

Results of a pot-culture experiment (Tian and Kolawole, 1999) showed that the incubation of plant residues in the form of *Leucaena leucocephala* (Lam.) de Wit and *Dactyladenia barteri* (Hook.f.ex Oliver) G.T. Prance and F. White leaves and maize stover with Sokoto PR (from Nigeria) increased P uptake by *Crotolaria ochroleuca* G. Don. The increase in P uptake by the test plant was found to be directly related to the polyphenol to N ratio of the plant residues incubated with PR. From these results it was suggested that the effectiveness of PR can be increased by mixing or composting the PR with low-quality plant residues (with high polyphenol to N ratio). It is known that a high polyphenol and low N concentration in plant residues slows down residue decomposition (Tian et al., 1992), thus leading to a prolonged reaction of the released organic compounds or acids with PR. Perhaps polyphenols may also influence the solubilization of P from PR by binding P into an organic P form, or polyphenols may be directly involved in the dissolution of P from PR.

The results of the studies reported by Nziguheba et al. (1998) and Tian and Kolawole (1999) provide examples on the role of diverse organic inputs in the form of plant residues of relatively high-quality (high content of N and P) and low-quality (high polyphenol to N ratio, low N and P). Future studies must focus on the role of chemical constituents in organic inputs, especially plant residues that influence P solubilization and availability in conjunction with PR.

Organic Acids

The solubility of P in PR can also be increased using microbiological methods (Bardiya and Gaur, 1974; Asea et al., 1988; Roy et al., 1999) involving the role of certain microorganisms producing organic acids that complex with metals in PR, resulting in the release of P. Kpomblekou-A and Tabatabai (1994) studied the release of P from two PRs of different reactivity using 19 low-molecular-weight organic acids. The PRs used were low reactive Kodjari PR from Burkina Faso and medium reactive North Florida PR. Results showed that the release of P from PRs by the acids was affected by chemical structure, type, and position of the functional groups of the ligands, and the concentration of the acids. The ratios of the P-released/protons added for most of the organic acids were greater than those for the mineral acids, indicating chelation of the metals associated with P in the PRs. Citric and oxalic acids were found to be more effective than sulfuric acid in releasing P from the two PRs. The P released from the low reactive Kodjari PR was greater than that released from North Florida PR. These results show differences in the ability of organic acids to release P from PRs of varying reactivity for direct application to soils. They also provide evidence to show that organic acids have potential as amendments for increasing the availability of P in PRs added to soils.

Composting with Organic Manures

Composting PRs with agricultural wastes is an age-old, accepted practice to increase solubility (Mishra and Bangar, 1986; Tandon, 1987). Such phospho-composts, prepared from the composting of PRs with organic and crop residues, typically contain low amounts of P (about 3% P) but have been reported to be effective in supplying P and increasing crop production. The use of phospho-composts thus may seem attractive in organic farming systems or in situations where farm wastes are to be used effectively (Rajan et al., 1996).

However, not all manures are best suited for solubilizing P from PR. For example, Mahimairaja et al. (1995) found that there was a low level of dissolution of PR during composting with poultry manure, although the addition of elemental S to the compost enhanced the dissolution of P from North Carolina PR. The low level of PR dissolution in poultry manure compost was mainly attributed to the high concentration of Ca^{2+} in the manure solution. A sample of well-decomposed poultry manure obtained from the University of Ghana Agricultural Research Station at Nungua, Ghana, was found to contain 0.59% P and 3.1% Ca on an air-dried wt basis (Abekoe and Agyin-Birikorang, unpublished data, 2000). These authors also found that amending the PR from Togo with poultry manure had a small effect on the apparent release of P from the PR. These results support the observation made by Mahimairaja et al. (1995) with poultry manure in New Zealand and suggest that the use of some manures may not be an attractive option if they contain high amounts of $CaCO_3$.

Sulfur

Additives such as elemental S and by-products of iron ores (iron pyrites), can be used with advantage for increasing PR solubility by providing increased acidity, with direct application (Tandon, 1987; Rajan et al., 1996). In a recent study, Sharma and Prasad (1996) showed that the application of iron pyrites (containing 22% S) to Mussoorie PR increased the effectiveness of PR from 6 to 64% as effective as diammonium phosphate (DAP) with wheat (*Triticum aestivum* L.) on a sandy loam soil with a pH of 7.4. Where these resources are indigenous or available cheaply, they certainly can be exploited with advantage for improving the effectiveness of PR.

Modified Phosphate Rock Products

Another approach which has been advanced for increasing the solubility of PRs is based on the use of lower amounts of sulfuric or phosphoric acids than normally used for making SSP or TSP, for partially acidulating PRs, resulting in the formation of a range of products termed partially acidulated phosphate rocks (PAPRs) (Schultz, 1986). Fertilizer products with improved effectiveness and chemically equivalent to PAPR can also be prepared by the process of compacting of PR with water-soluble fertilizers such as TSP or SSP (Lupin and Le, 1983).

Since the 1980s, the International Fertilizer Development Center (IFDC) has carried out comprehensive research on the production and use of PAPR and compacted products (based on PR + SSP or PR + TSP) (Hammond et al., 1986; Chien et al., 1987; Chien and Hammond, 1988; Menon and Chien, 1990; Kpomblekou et al., 1991; Chien and Menon, 1995b). Results of greenhouse evaluations and field research conducted in Asia, sub-Saharan Africa, and Latin America have shown that PAPR at 40 to 50% acidulation with sulfuric acid (H_2SO_4) or at 20% with phosphoric acid (H_3PO_4) generally approaches the effectiveness of SSP or TSP in certain tropical soils and crops.

This research has also indicated that if a PR has a high Fe_2O_3 and Al_2O_3 content, it may not be suitable for preparing PAPR because of the reversion of water-soluble P to water-insoluble P during the process of acidulation. In the case of such PRs, their compaction with water-soluble fertilizers such as TSP or SSP at a P ratio of 50:50 can be a better alternative, and has been found to be agronomically and economically attractive for utilizing relatively unreactive indigenous PRs in various developing countries (Chien and Menon, 1995b).

Chien et al. (1996) provided a quantitative estimate of the enhancement effect of water-soluble P on the availability of P from PR in a greenhouse study with maize and cowpea on a Typic Hapludult (pH 4.8). Tagged P from TSP and central Florida PR (CFPR) were used to distinguish P availability from soil, TSP, and CFPR. The effectiveness of P sources in terms of increasing dry matter yield and P uptake followed the order of TSP = (CFPR + TSP) > PR for maize and TSP = (CFPR + TSP) > CFPR for cowpea. Phosphorus uptake from CFPR in the presence of TSP was higher than P uptake when CFPR was applied alone, indicating an enhancement effect of TSP on CFPR (Table 11–6). The relative increase in P uptake from CFPR due to TSP influence was 72% for cowpea and 165% for maize.

Table 11–6. Dry matter yield, P uptake, and relative agronomic effectiveness (RAE) obtained with triple superphosphate (TSP) and central Florida phosphate rock (CFPR) P sources for maize and cowpea in a greenhouse pot study.

	Maize		Cowpea	
P source	Dry matter†	RAE	Dry matter	RAE
	g pot^{-1}	%	g pot^{-1}	%
Control	1.07	0	0.60	0
CFPR	4.10	31	3.85	55
CFPR + TSP	9.13	83	6.45	98
TSP	10.78	100	6.55	100
LSD (0.05)	1.32	--	1.22	--
	Maize		**Cowpea**	
	P uptake†	RAE	P uptake	RAE
	mg P pot^{-1}	%	mg P pot^{-1}	%
Control	1.15	0	0.79	0
CFPR	9.12	37	8.72	50
CFPR + TSP	19.93	86	15.38	92
TSP	23.00	100	16.70	100
LSD (0.05)	3.97	--	3.65	--

Source: Chien et al. (1996)
† Results averaged over five rates of P.

However, a review of research also indicates that PAPRs prepared using sulfuric acid directly by partial acidulation or by cogranulating with soluble P such as SSP may actually result in depressing rather than enhancing the dissolution of PRs. This has been attributed to the formation of $CaSO_4$ as coatings on the PR particles. Studies made using electron microscopy and energy-dispersive x-ray diffraction have shown that the $CaSO_4$ coatings indeed may delay disintegration of the PAPR granules, delaying the maximum contact with acidity in soils (Rajan et al., 1996).

PHOSPHORUS FERTILIZER APPLICATION FOR ENHANCING SOIL FERTILITY

One of the ways in which P affects nutrient cycling, crop production, and soil fertility is through the interactions between P and other nutrients (Adams 1980; Sumner and Farina 1986; Bache and Ross, 1991; Tandon, 1992; Black, 1993). However, little attention has been devoted to field research in soil fertility to study the interactions between nutrients and there is no way of verifying the large number of interactions reported from experiments made under greenhouse or solution culture conditions. The importance of an appropriate nutrient balance in crop production and in the maintenance and enhancement of soil fertility is recognized (Smaling et al., 1997). It is important to appreciate that this is clearly the recognition of the importance of nutrient interactions. Crop production and nutrient balance are the interplay of nutrient interactions which can be antagonistic or negative, additive or zero interaction, or synergistic or positive interaction. The low-activity clay soils of the humid zone in West Africa typically have low cation exchange capacity and low inherent fertility, and these soils more than others require a balanced use of plant nutrients.

Phosphorus fertilization influences soil fertility through its effects on the BNF and recycling of N through the accumulation and decomposition of organic matter in the soil. A recent review by Sanchez et al. (1997) has emphasized the importance of P status of soils in replenishing the stock of N in soils through BNF. This can be achieved either through the use of grain legumes in various cropping systems or through the use of traditional and managed fallows, and the use of organic and crop residues (Giller et al., 1997; Palm et al., 1997; Buresh and Tian, 1998; Jama et al., 1998; Kamh et al., 1999; Becker and Johnson, 1999; Attiogbevi-Somado, 2000; Vanlauwe et al., 2000a, 2000b).

It is argued that in the soils of the humid zone in West Africa, P deficiency is the major nutrient constraint for crop production as well as for the adaptation of legumes under various cropping patterns and in traditional and managed fallows that are used for replenishing N. The direct application of relatively unreactive PR to the soil may not be able to meet the immediate P requirements of the crops, but may be sufficient to raise the P status of the soil so that legumes may be able to establish themselves and help replenish the N supply. Furthermore, the supply of P is of fundamental importance for the establishment and effectiveness of the legumes in managed and natural fallows and in various cropping systems. Also, with improved P status of the soil, the quality of vegetation would favor plants that biologically fix N.

Warren (unpublished data, 1998) studied soil, natural vegetation and agronomy at two sites (Machanga and Mutuobare) in Kenya with contrasting fertility. The major difference between the sites was in P status. It was found that higher soil P was associated with the enrichment of soil organic matter by labile fractions indicated by (i) lower radiocarbon age and (ii) higher N mineralization. High soil P status thus influenced soil fertility by its direct effect on plants and by increasing the turnover of soil organic matter. It was concluded that native soil P is an important indicator of the potential of a soil. High soil P favored N_2 fixing plants, indicated by (i) the natural mix of tree species in favor of *acacias* and (ii) the better performance of cowpea crops on the soil. Furthermore, improvement of the soil P status with manure application over the previous 6 yr at the site improved the yields of cowpea, but it did not increase the legume/ cereal ratio. The results of this study have important implications and underpin the importance of soil P status as an important indicator of soil fertility and more importantly, for its improvement and rehabilitation.

Studies made on Mediterranean grasslands in West Asia showed that on marginal soils where regular cropping is not possible because of their shallow depths, steep slopes, and presence of stones, annual applications of P at low rates of 11 kg P ha^{-1}, alleviated the deficiency of P and resulted in improved pasture production. Legume production showed the greatest response to P and increased productivity by three times (Osman et al., 1991). The application of P also improved the soil organic matter status. In a long-term experiment conducted for 12 yr at Tel Hadya in northern Syria, it was observed that annual application of fertilizer P at 5 and 11 kg P ha^{-1} for a 7 yr period (1984–1990) raised the Olsen extractable P from 7 (in the control, no P treatment) to 20 and 40 mg P kg^{-1} soil in the treatments where P was added at 5 and 11 kg P ha^{-1} annually by the end of the 7th season in 1991. Application of P also improved legume and total herbage yields, and improved productivity in sheep (*Ovis aries*) grazing the pasture. Strong residual effects of fertilizer P were observed long after the initial application of P (Osman, 1997). These results demonstrate the importance of fertilizer P in enhancing the fertility status of marginal soils under grasslands.

Although the above study is from the Mediterranean region, it has been cited here as an excellent example to illustrate the underlying principle on the role of P fertilizer in enhancing the soil fertility through the use of legume crops. In the context of West Africa, the choice of legume or cover crops and P management strategy will be different but the same principle would apply in that legume species can be used to enhance soil fertility with P fertilization (e.g., see Becker and Johnson, 1999; Attiogbevi-Somado, 2000; Vanlauwe et al., 2000a, 2000b)

CONCLUSIONS AND RESEARCH NEEDS

The results discussed in this chapter demonstrate the critical importance of inorganic P fertilization in increasing crop production and maintaining soil fertility. By enhancing the role of legumes in traditional and managed fallows in various crop production systems, the application of P is equally important for improving the fertility of soils that are degraded as a result of the depletion of organic matter and nutrient reserves or the accentuation of acid soil-related problems. The application of inorganic P fertilizers is a major requirement for sustained crop production in cereals as well as for enhancing replenishment of N through biological fixation.

Among the inorganic sources of P, the role of indigenous PRs appears highly relevant and important in the West African region because of the high cost of mineral fertilizer. It is equally encouraging to note from the results discussed which clearly demonstrate that the use of relatively reactive PRs (e.g., Tilemsi RP from Mali) with direct application on acid, low P status soils in the moist savanna or humid forest zones of the region has the potential to meet the P requirements of crops as well as improving soil chemical properties and overall soil fertility.

There is a need for strategic research for developing a decision support system based on the choice of agroclimatic, soil and crop/species-related parameters that influence the efficacy of rock P as a source of P. Similarly, research on the role of P fertilizer, especially indigenous rock P, in enhancing and reclaiming the fertility of soils needs to be intensified. It is stressed that the evaluation of rock P must be based on the results of field experiments run for consecutive years as the results from single-season experiments provide only an incomplete picture and therefore incorrect results.

There is an urgent need to intensify research on enhancing the effectiveness of P from both soluble and PRs in conjunction with the use of organic inputs, especially plant materials. Organic acids seem to have a potential as amendments for increasing the availability of P from PRs applied to soils.

Due to sorption of phosphate by Fe and Al oxides, the efficacy of P and the residual value of P from soluble P sources are drastically reduced. Yet, P applied through PR has low initial solubility and availability, although results from a few studies suggest that the effectiveness of P from PR on acid soils improves with time. These results offer an opportunity for further research in the use of a combination of mineral and PR sources for sustained P supply. Equally relevant and important, is research on the integrated use of organic and inorganic P sources.

The conventional soil tests used for assessing available P with mineral P sources may not be suitable for assessing the P status of soils fertilized with P from PR. There is an obvious need to clarify this aspect through future research so that soil tests can be relied on for rational and judicious use of P from PR or a combination of mineral P and PR.

There is a continuing need for research to identify crops and genotypes that are adapted to low P soil conditions in various cropping systems. It is argued that crops or genotypes of crops bred or selected under favorable growing environments and high P soil conditions would rarely perform well and yield to their potential when grown in harsh environments and on low P soils. Results available in the literature suggest that potential exists in genetic adaptation to low P soil conditions and this should be explored and exploited for various crops in the subregion. For sustained crop production and the maintenance of soil fertility, the use of suitable crops/cultivars is essential to combine with improved crop and natural resources management practices.

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