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PHOSPHORUS AVAILABILITY AS AFFECTED BY THE APPLICATION OF PHOSPHATE ROCK COMBINED WITH ORGANIC MATERIALS TO ACID SOILS IN WESTERN KENYA

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SUMMARY

Most of the agricultural lands in the highlands of western Kenya are depleted of plant nutrients, particularly phosphorus. This depletion has resulted in a continued decline in crop production in the area. Recent experiments, in which direct application of indigenous phosphate rocks were evaluated, have yielded variable results, depending on the relative reactivity of the rock phosphate tested. The effectiveness of rock phosphate was generally low compared with fertilizers such as triple super phosphate. This is attributed to the relatively low solubility of the rocks as opposed to the readily water soluble phosphorus fertilizers. Phosphate rocks are available locally and are cheaper than triple super phosphate. If the solubility of these phosphate rocks could be improved, the resource-poor smallholder farmers in western Kenya would have an affordable source of phosphorus for their crops. Greenhouse and field experiments were conducted to evaluate the effects of combining different on-farm organic materials with the Minjingu rock phosphate (from Tanzania) on the availability of phosphorus to maize (*Zea mays*) in western Kenya. The greenhouse results indicated that there were significant positive linear relationships between rock phosphate application rates and (i) the Olsen-extractable soil phosphorus in the soil samples taken four weeks and nine weeks respectively after the application of the treatments; (ii) the dry matter yield, and (iii) phosphorus uptake. Results of the field experiments showed that rock phosphate combined with farmyard manure or crop residues (maize stover) generally increased the Olsen-extractable soil phosphorus, maize yields and phosphorus uptake, particularly in the first season when both the Minjingu rock phosphate and organic materials were applied, but the effectiveness of the materials and their combinations varied between the two sites. Combining Minjingu rock phosphate with the organic materials improved its relative agronomic effectiveness for maize.

INTRODUCTION

Acid soils such as the Ultisols and Oxisols in the highlands of western Kenya are deficient in phosphorus (P), an essential nutrient for plant growth and development. In these soils, P availability is reduced through adsorption by aluminium (Al) and iron (Fe) oxides and by precipitation with soluble Al and Fe. Liming of acid soils reduces P sorption and increases soil pH thereby increasing P availability. Liming is an expensive practice, however, and is less effective on high-P-fixing soils. It is seldom used by farmers in Kenya.

The low solubility of phosphate rock (PR) has discouraged its recommendation for direct use as a source of P for crops. In recent years, however, attention has been focused on its direct use, especially in developing countries (IFDC, 1978, Sanchez *et al*., 1997). The main interest is due to its relatively low cost compared with the processed fertilizers, and to its effect both in supplying P and liming soils in the long-term (Chien, 1978; Ahn, 1993). Utilization of local PR deposits minimizes importation costs and hence saves on foreign exchange. In addition, other elements in PR, such as Ca, can improve the soil chemical and physical characteristics and contribute to plant nutrition (Mnkeni *et al*., 1991).

One of the unexploited options to increase the solubility of PR is to combine it with on-farm organic material such as farmyard manure (FYM) and crop residues, which farmers, particularly resource-poor smallholders, can access easily. Depending on the amount and quality of the material used, it can influence P availability by stimulating microbial activity that can, in turn, increase mineralization of soil organic P, produce organic acids that may help to acidify and dissolve PR, and reduce P sorption (Palm *et al*., 1997). This study was conducted to: (i) compare the influence of manure and crop residues on the solubility and availability of P in the local Minjingu phosphate rock (MPR), and its uptake by maize, with that of water-soluble triple super phosphate (TSP) fertilizer; (ii) monitor the effect of the application of manure and crop residues combined with MPR on soil chemical properties, with particular emphasis on P availability; and (iii) compare the agronomic effectiveness of MPR combined with organic materials in relation to TSP.

METHODOLOGY

Greenhouse study

An experiment was conducted in a greenhouse at Uasin Gishu, Chepkoilel Campus of Moi University, Eldoret, Kenya, to evaluate the effects of different organic materials on the solubility of PR, and to determine appropriate rates to be tested in the field. The imposed treatments were MPR at 0, 25, 50, and 75 kg P ha^{-1}, combined with or without chicken manure, farmyard manure, maize stover, compost and sulphur (S) in a 4×6 factorial structure. The rate (2 t ha^{-1} air-dry weight) of application of these organic materials was decided on the basis of the availability of these materials to smallholder farmers under normal farming conditions. The S was introduced to provide an acidic environment to enhance the dissolution of PR (Bromfield, 1975). TSP at different rates was not included because past work had shown that TSP gave comparable yields to MPR (Okalebo and Woomer, 1994; Mutuo *et al*., 1999). The MPR used is a biogenic type originating from Arusha, Tanzania with 13 % total P and 3 % neutral ammonium-citrate-soluble P contents (Van Kauwenberg, 1991). Only one soil type, collected from the Chepkoilel Campus, was used. The soil in this area has a clay texture and has been classified as Rhodic Ferralsol (FAO/UNESCO, 1990). The chemical properties of the organic materials and the soil are given in Tables 1 and 2 respectively. Air-dry soil (4 kg pot^{-1}) was placed in 5 l plastic pots. The treatments were allocated and incorporated thoroughly in the pots of soil, which were then watered to field capacity. Into each pot three maize seeds were planted. Each treatment was replicated four times. The pots were arranged in a randomized complete blocks design. One week after germination, the seedlings were thinned to two plants per pot. Soil samples were taken four and nine weeks after the application

Table 1. Some chemical properties of the organic materials used in the greenhouse experiment. (FYM = farmyard manure).

Properties (%)	Organic materials			
	Maize stove	FYM	Compost	Chicken manure
Total P	0.14	0.48	0.42	1.08
Total N	0.91	1.84	2.19	3.01
Total K	2.11	0.28	1.38	1.82
Total Ca	0.30	0.62	1.76	0.80
Total Mg	0.25	0.14	0.56	0.39

Table 2. Some chemical and physical properties of surface (0 – 0.15 m) soils from the greenhouse experiment and the on-farm trials in Busia and Siaya.

Properties	Busia	Siaya	Uasin Gishu (greenhouse)
pH (H_2O, 1:2.5)	5.2	5.4	4.9
Total carbon (%)	3.2	1.7	1.3
Total N (%)	0.4	0.3	0.1
Olsen P (mg kg^{-1})	1.0	1.0	4.0
Clay (%)	34.0	20.0	46.0
Sand (%)	52.0	48.0	38.0
Silt (%)	14.0	32.0	16.0
Soil class	Loam	Loam	Clay loam
Soil order	Orthic Ferralsol	Orthic Ferralsol	Rhodic Ferralsol

of treatments and analysed for extractable P. The total biomass was harvested after nine weeks, dried to a constant weight at 65 °C and then weighed. The plant samples were analyzed for N and P contents.

Field studies

Field experiments were conducted at two smallholder farms, one sited in the Busia (lat. 0 °20′ N, long. 340 °15′ E; 1294 m asl) and the other in the Siaya (lat. 0 °03′ N, long. 340 °25′ E; 1400 m asl) districts in western Kenya. Both sites have bimodal rainfall and hence two cropping seasons per year. The soils are classified as Orthic Ferralsol (FAO/UNESCO, 1990). Air-dry soil samples from the top 0 – 0.15 m at both sites were analyzed for pH, organic carbon, extractable P, particle size, and total P and N (Table 2), while the organic materials were analyzed for total N, P, K, Ca and Mg (Table 3).

The farms were representative of the smallholder maize-based cropping systems in these two districts of western Kenya. The treatments in the field experiments were: (i) control (no organic materials); (ii) maize stover at 1 t ha^{-1}; (iii) maize stover at 2 t ha^{-1}; (iv) farmyard manure at 1 t ha^{-1}; and (v) farmyard manure at 2 t ha^{-1}. Each of these treatments received two rates (0 and 60 kg ha^{-1}) of P as MPR. The experiments (5 × 2 factorial) were laid out at each site in a randomized complete blocks arrangement with four replications. The P rate of 60 kg ha^{-1} was chosen partly on the

Table 3. Some chemical properties of the organic materials used in the field trials in Busia and Siaya. (FYM = farmyard manure).

Properties (%)	Busia		Siaya	
	Maize stover	FYM	Maize stover	FYM
Total P	0.14	0.35	0.09	0.38
Total N	0.91	0.76	0.77	1.18
Total K	2.11	1.37	1.92	1.80
Total Ca	0.30	0.61	0.27	0.65
Total Mg	0.26	0.39	0.24	0.45

basis of the greenhouse results and partly on earlier observations (Jama *et al*., 1997), which showed that P applications of 30 to 80 kg ha^{-1} gave maximum net benefits to the maize crop in most soils in western Kenya. An extra plot was included at each site specifically for the purpose of calculating the relative agronomic effectiveness (RAE) of PR. These plots received TSP, at 60 kg P ha^{-1}. Individual plot size was 5 × 5 m.

All the plots were ploughed and residues from the previous crop were removed manually before the application of treatments. The first crop was on planted 21 and 22 March 2000 at Busia and Siaya respectively. PR and organic materials were broadcast and incorporated to a depth of 0 – 0.15 m before planting. Maize seeds were sown at a spacing of 0.75 × 0.25 m with two seeds per planting hole. Two weeks later, the plants were thinned to one plant per hole to give 53 300 plants ha^{-1}. At both sites, the plots were hand weeded three times and harvested towards the end of August 2000. Soil samples were taken between 0 – 0.15 m depth when the crop was 1 m tall, at tasselling and at harvesting of the first crop. The sampling depths represent the soil layer where most organic matter is concentrated and also where a large proportion of the maize feeder roots is found. Plant tissue samples consisted of the fifth leaf from the tip when the crop was 1 m tall. Stover and grain samples were taken at harvesting of the first crop. All were analyzed for phosphorus.

After harvesting the first season's crop, all the plots were again ploughed and crop residues removed manually. In the second season, maize seeds were sown in September with no added fertilizer other than N at 40 kg ha^{-1} as urea. This was applied to all the plots, including the control. The crop was weeded twice at both sites. The experiments were harvested on 5 and 6 January 2001 at Busia and Siaya respectively. At planting and at harvesting of the second crop, soil samples were again taken at the same depth. Plant tissue and stover samples were also taken again for chemical analysis. In both seasons, grain maize yields were expressed on an air-dry weight basis.

Laboratory and data analysis

Chemical analysis of the soil and plant-material samples was carried out as outlined by Okalebo *et al*. (1993). The GENSTAT 5.32 Program, (GENSTAT, 1993) was used for statistical analysis of the data. The standard error of the differences (*s.e.d*.) was used to compare the treatment means.

Table 4. Extractable P (mg kg^{-1}) from soils treated with different rates of Minjingu phosphate rock (MPR) and their combinations with 2 t ha^{-1} each of different organic materials at four and nine weeks after treatment application.

	Four weeks					Nine weeks				
	MPR applied (kg P ha^{-1})					MPR applied (kg P ha^{-1})				
	0	25	50	75	OM mean	0	25	50	75	OM mean
Control	0.89	2.08	1.75	4.30	2.25	3.10	3.47	2.92	4.47	3.49
Chicken manure	1.04	2.48	3.47	3.03	2.50	2.74	4.11	3.56	6.75	4.29
Compost	1.25	1.74	2.49	2.60	2.02	2.19	3.92	4.84	5.25	4.05
FYM	1.14	0.97	4.22	2.76	2.27	2.28	3.92	3.47	4.65	3.58
Maize stover	0.92	2.03	1.63	4.17	2.19	1.28	3.47	4.11	3.38	3.06
Sulphur	0.90	1.44	2.53	2.57	1.86	2.19	2.83	3.28	5.57	3.46
MPR mean	1.02	1.79	2.68	3.24		2.29	3.62	3.70	5.01	
s.e.d. MPR	0.37					0.5				
s.e.d. OM	0.45					0.70				
s.e.d. MPR × OM	0.90					1.40				

OM = organic material; FYM = farmyard manure.
Relationship between MPR rates (Y) and means of extractable P (X) at four weeks, $Y = 0.031X + 1.04$; $r^2 = 0.99$; $n = 4$ and at nine weeks $Y = 0.33X + 2.42$; $r^2 = 0.92$; $n = 4$.

Mean maize grain yields realized in the MPR plots were determined for each season and for the two seasons combined. Using these values, the relative agronomic effectiveness (RAE) was determined in relation to the yields obtained in the 'extra' TSP-treated plot as follows:

$$\text{RAE}\ (\%) = \frac{\text{Yield of MPR or its combination plot} - \text{Yield of control}}{\text{Yield of TSP plot} - \text{Yield of control plot}} \times 100$$

RESULTS

Greenhouse experiment

Extractable soil P. The Olsen extractable P from soils treated with different organic materials and their combinations are given in Table 4. The extractable soil P increased linearly with the increase in the MPR rates ($r^2 = 0.99$ and $r^2 = 0.92$ for the samples taken at four and nine weeks after the treatments application, respectively) at both sampling times. The effects of combining organic materials with MPR on the extractable P were variable but the combination of chicken manure and MPR consistently produced the highest extractable P at both sampling times.

Dry matter yield. The dry matter yields (DMY) obtained with the different organic materials and their MPR treatment combinations are given in Table 5. The effects on DMY varied but, on average, chicken manure combined with MPR gave the highest ($p < 0.01$) DMY followed by the combination of FYM and MPR. Combinations of

Table 5. Treatments effects on dry matter yields and P uptake.

	Dry matter yield (g pot^{-1})					P uptake (mg pot^{-1})				
	MPR applied (kg P ha^{-1})					MPR applied (kg P ha^{-1})				
	0	25	50	75	OM mean	0	25	50	75	OM mean
Control	16.8	19.7	19.6	20.1	19.1	13	17	15	21	16.5
Chicken manure	21.5	21.8	27.9	23.7	23.7	17	18	25	23	20.8
Compost	13.2	18.4	20.6	26.8	19.8	14	19	23	21	19.3
FYM	17.4	20.0	23.0	22.0	20.6	11	17	17	27	18.0
Maize stover	18.0	15.7	18.7	24.0	19.1	18	15	18	22	18.3
Sulphur	12.3	16.9	10.6	18.2	14.5	12	13	10	21	14.0
MPR rate	16.5	18.8	20.1	22.5		14	16	18	22	
s.e.d. MPR			1.3					1.6		
s.e.d. OM			1.6					2.0		
s.e.d. MPR × OM			3.1					4.0		

OM = organic material; FYM = farmyard manure; MPR = Minjingu phosphate rock.
Relationship between PR rates (Y) and means of dry matter yield (X), Y = 0.0 77X +16.58; $r^2 = 0.98$; n = 4 and between PR rates and means of P uptake Y = 0.0104X +13.6; $r^2 = 0.97$; n = 4.

MPR with compost or maize stover produced similar DMY, to those of the control treatments. The S-treated pots had the lowest DMY. Chicken manure combined with 50 kg P ha^{-1} as MPR produced the highest DMY, while S combined with MPR at the same rate of P, produced the lowest. Increased rates of MPR with or without organic materials increased DMY linearly ($r^2 = 0.98$).

P uptake by maize. P uptake (Table 6) increased linearly with DMY and the PR applied (both $r^2 = 0.97$). A combination of chicken manure with PR gave the highest mean P uptake followed by compost, maize stover and FYM. Combining S with PR resulted in the lowest P uptake followed by the control (P without organic material in combination). Of the individual treatment combinations, S combined with PR at 50 kg P ha^{-1} and FYM combined with PR at 75 kg P ha^{-1} had the lowest and highest P uptake, respectively.

Field experiments

Soil extractable P. The effects of applying both P and organic materials on the Olsen-extractable soil P at the two field experimental sites (Busia and Siaya) are presented in Table 6. In general, the values were very low. Nevertheless, the application of P as MPR increased ($p < 0.01$) the amount of extractable P. In the control plot at the Busia site, it was increased from 1.96 mg kg^{-1} soil in the first season to 3.47 mg kg^{-1} soil in the second season. In the 60 kg P ha^{-1} plot, it increased from 3.30 mg P kg^{-1} soil in the first season to 5.01 mg P kg^{-1} soil in the second season. At the Siaya site, the corresponding values were: 1.65 to 1.99 mg P kg^{-1} soil in the control plot, and 3.15 to 4.12 mg P kg^{-1} soil in the 60 kg P ha^{-1} plot.

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Table 6. Treatments effects on soil-extractable P (mg kg^{-1}) when the maize plants were at a height of 1 m during the two seasons at the Busia and Siaya sites, 2000.

	Soil-extractable phosphorus (mg kg^{-1})											
	Busia						Siaya					
	First cropping season			Second cropping season			First cropping season			Second cropping season		
	MPR applied (kg P ha^{-1})			MPR applied (kg P ha^{-1})			MPR applied (kg P ha^{-1})			MPR applied (kg P ha^{-1})		
	0	60	OM mean	0	60	OM mean	0	60	OM mean	0	60	OM mean
Control	2.32	3.01	2.67	3.04	5.01	4.02	1.45	3.15	2.30	1.77	3.96	2.87
FYM 1 t ha^{-1}	1.84	3.19	2.51	3.46	4.02	3.74	1.96	2.79	2.38	2.46	3.75	3.10
FYM 2 t ha^{-1}	2.26	3.67	2.97	3.01	5.48	4.24	1.46	3.74	2.60	1.83	4.78	3.3
Maize stover 1 t ha^{-1}	1.62	3.66	2.64	3.19	6.19	4.69	1.47	2.87	2.17	2.00	4.15	3.07
Maize stover 2 t ha^{-1}	1.78	2.96	2.37	4.64	4.34	4.49	1.90	3.21	2.56	1.89	3.98	2.94
MPR rates mean	1.96	3.30		3.47	5.01		1.65	3.15		1.99	4.12	
s.e.d. MPR	0.24			0.68			0.31			0.24		
s.e.d. OM	0.37			1.07			0.49			0.37		
s.e.d. MPR rate × OM	0.53			1.52			0.69			0.53		

OM = organic material; FYM = farmyard manure; MPR = Minjingu phosphate rock.

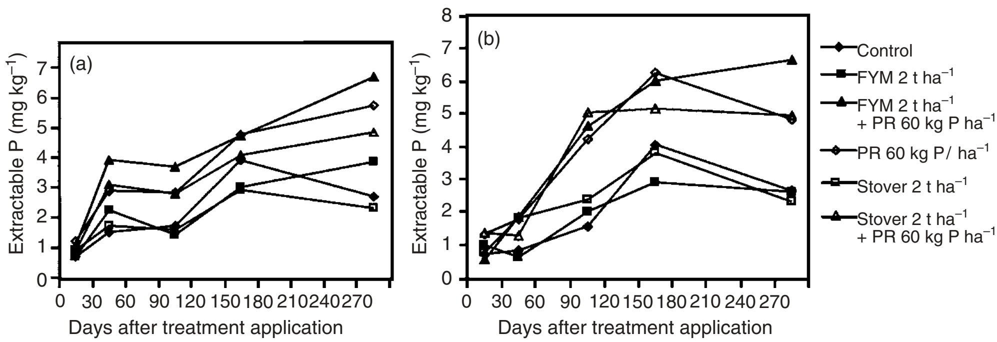

Figure 1. Effects of phosphate rock (PR), organic materials and their combinations on extractable P during the two growing season at Busia (a) and Siaya (b), in year 2000. Day zero represents original soil status.

Soil samples taken at different intervals showed that extractable soil P increased from the time the treatments were applied. This was most pronounced in the plots that received 60 kg P ha^{-1} as MPR, alone or in combination with 2 t ha^{-1} of either FYM or maize stover (Figure 1).

P content of maize plant tissue. The maize plant tissue samples taken during the first season, when the plants were 1 m tall, were analyzed for their P contents. In general, the results given in Table 7 show that application of MPR increased the plant tissue P content at both sites. In addition, the combination of organic materials with MPR

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Table 7. Treatments effects on leaf P content when the maize plants were at a height of 1 m during the first season at Siaya and Busia, 2000.

	Siaya leaf P content (%)			Busia leaf P content (%)		
	MPR applied (kg P ha^{-1})			MPR applied (kg P ha^{-1})		
	0	60	OM mean	0	60	OM mean
Control	0.21	0.28	0.24	0.16	0.19	0.17
FYM 1 t ha^{-1}	0.26	0.30	0.28	0.15	0.14	0.15
FYM 2 t ha^{-1}	0.24	0.29	0.27	0.16	0.18	0.16
Maize stover 1 t ha^{-1}	0.30	0.30	0.30	0.13	0.23	0.18
Maize stover 2 t ha^{-1}	0.28	0.33	0.30	0.17	0.19	0.18
MPR rate mean	0.26	0.30		0.18	0.18	
s.e.d. MPR		0.015			0.010	
s.e.d. OM		0.024			0.016	
s.e.d. MPR × OM		0.033			0.023	

OM = organic material; FYM = farmyard manure; MPR = Minjingu phosphate rock.

increased the tissue P contents (Busia, $p < 0.05$ and Siaya, $p < 0.001$). Some variations were observed, however. For example, the organic materials without MPR increased the tissue P content at the Siaya site but, at the Busia site, when the materials were applied at 1 t ha^{-1} the tissue P contents were lower than in the control treatment.

Maize grain yield. On average during the long-rains, the application of 60 kg P ha^{-1} as MPR increased the grain yield above that of the control by 71 and 10 % at the Busia and Siaya sites respectively (Figure 2). Application of the organic materials, with or without MPR, had variable effects on grain yields. The combination of MPR with organic materials, however, increased yields. The largest yield increase was observed at the Siaya site in the first season. Here an application of 60 kg P ha^{-1} as MPR combined with maize stover at 2 t ha^{-1} produced 67 % more grain compared with that obtained with an application of 60 kg P ha^{-1} alone. Similarly, at the Siaya site 60 kg P ha^{-1} as MPR combined with FYM at 2 t ha^{-1} gave the largest yield increase (60 %) compared with the yields obtained from the application of 60 kg P ha^{-1} alone.

From March to July 2000 (long rains), 544 mm of rain were received at Siaya compared with 794 mm at Busia. The rainfall totals for the second season (August – December 2000) at the two sites were 895 and 564 mm for Siaya and Busia respectively. The second season's crops at both sites were meant to monitor the residual effects of both P and organic material treatments, as none of the treatments was re-applied. The amount and distribution of rainfall at the two sites during the two seasons were satisfactory for maize. On average, yield levels at Busia were slightly better than in the first season. At Siaya, however, the second season's yields were very low compared with those obtained in the first season. Application of organic materials continued to give varied effects on yields but, on average, they were positive.

There were no interaction effects between P and the application of organic materials on yields at Busia in the first season. In the second season, however, where P was not

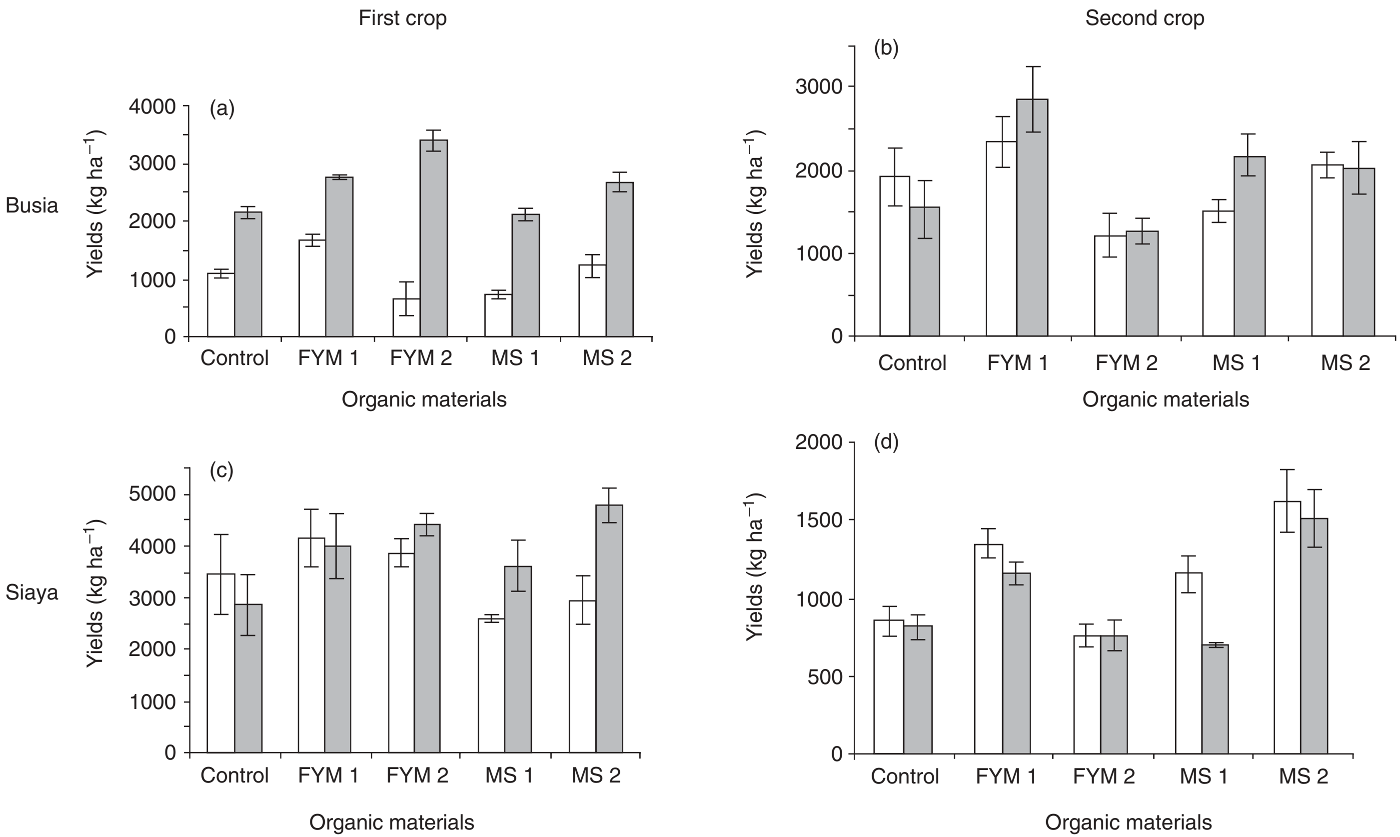

Figure 2. Maize grain yields (kg ha^{-1}) as affected by Minjingu PR and organic materials in western Kenya during the year 2000 cropping seasons; a and c = long rains; b and d = short rains. FYM 1 and FYM 2 = farmyard manure at 1 and 2 t ha^{-1} respectively; MS 1 and MS 2 = maize stover at 1 and 2 t ha^{-1} respectively; *s.e.d.*s are given as Y-error bars. □ = 0 kg P ha^{-1}; ■ = 60 kg P ha^{-1}.

Table 8. Relative agronomic effectiveness (RAE) of MPR with its combinations at Busia and Siaya.

	Busia RAE (%)		Siaya RAE (%)	
Treatments	Crop 1	Crop 1 and 2	Crop 1	Crop 1 and 2
MPR 60 kg P ha^{-1}	58	10	−136	−103
MPR 60 kg P ha^{-1} + FYM 1 t ha^{-1}	39	−31	120	71
MPR 60 kg P ha^{-1} + FYM 2 t ha^{-1}	170	128	211	272
MPR 60 kg P ha^{-1} + stover 1 t ha^{-1}	78	−0.8	33	9
MPR 60 kg P ha^{-1} + stover 1 t ha^{-1}	151	111	294	309

FYM = farmyard manure; MPR = Minjingu phosphate rock.

applied yields were highest and lowest in the treatments with 1 and 2 t ha^{-1} of organic materials respectively; the opposite was observed where P was applied. At Siaya, the interaction effects between P and organic materials on yields were observed in both seasons. In the first season, the plots that received 60 kg P ha^{-1} without organic materials (FYM or stover) gave lower yields than the plots that received only organic materials. At the rate of 1 t ha^{-1}, both organic material treatments, with or without P gave similar yields but at 2 t ha^{-1}, the plots that received 60 kg P ha^{-1} gave higher yields than those without P. Although very much reduced, similar yield trends were observed in the second season.

Relative agronomic effectiveness. The relative agronomic effectiveness (RAE) of PR combined with organic materials for maize grain yields are given in Table 8. The results indicated that combining MPR with higher rates of organic materials greatly improved the RAE of MPR compared with that of TSP at both sites. However, the application of PR alone and in combination with FYM or stover at 1 t ha^{-1} lowered the effectiveness of PR below that of TSP. The highest RAE was obtained at Siaya when PR combined with stover at 2 t ha^{-1} gave a RAE of 294 % (309 % for the combined crops 1 and 2) and PR combined with FYM at 2 t ha^{-1} gave a RAE of 211 % (272 % for the combined crops 1 and 2). At Busia, the effectiveness of PR was lower when it was combined with FYM at 2 t ha^{-1}, giving a RAE of 170 % (128 % for the combined crops 1 and 2). PR combined with stover at 2 t ha^{-1} gave a RAE of 151 % (111 % for the combined crops 1 and 2).

DISCUSSION

The soils used in the greenhouse and field studies were moderately acidic, i.e. pH 4.85, 5.23 and 5.36 for Chepkoilel (greenhouse), Busia and Siaya respectively. The soils were all very low in the Olsen-extractable soil P. Acidity and low P values are soil conditions generally recognized as potentially benefiting from the direct application of rock phosphate as P fertilizer (Khasawneh and Doll, 1978).

The observed increase in the Olsen-extractable soil P with the increase in the rates of P applied as MPR in both the greenhouse (Table 4) and field (Table 6) experiments demonstrated that: (i) the soils used had the required conditions for the direct use of PR as P fertilizer; and (ii) the Minjingu PR used is a reactive and thus effective source of P for plant growth as reported earlier (Mnkeni *et al*., 1992; Semoka *et al*., 1992; Woomer *et al*., 1997). The observed increases in the extractable soil P between sampling times, especially in the second cropping season of the field experiments when no addition of MPR was made, strongly demonstrated that MPR continued to decompose and release P (residual effect) into the soil (Mnkeni *et al*., 1992). In general, however, the Olsen-extractable soil P levels were found to be below 10 mg P kg^{-1} soil, which is considered to be a threshold for plant needs (Okalebo, 1987), even after application of the treatments. This indicates that the sites were highly depleted in plant-available P, and continuous application of the treatments would be required before the soil capital P is built up to equal or exceed the threshold level. Also, it is possible that the low extractable soil P values observed over the two seasons indicated that some released P had gone into the reserve and not into the liquid capital P (Buresh *et al*., 1997). Further, it is possible that some released P was fixed on the soil colloids in these high-P-fixing soils. It is also possible that some released P was immobilized by microbes, especially with the addition of the organic materials, thus making some released P unavailable to the crop.

The organic materials, either on their own or when combined with MPR, affected the extractable soil P differently. In the greenhouse experiment, the chicken manure treatment increased the extractable soil P more than the other treatments at both sampling times. This can be attributed to the high P content of the chicken manure compared with the other organic materials used (Table 1). Chicken manure was also found to be superior to the other organic materials in terms of quality, probably because it is rich in nutrients and can decompose fast. It is possible that decomposing manure produces organic acids (Iyamuremye and Dick, 1996), which enhance the solubility of MPR. The observed significant linear relationships between the rates of P applied as MPR and the extractable soil P and between the extractable soil P and DMY demonstrated that the soil used in the experiment was deficient in P, MPR is a reactive phosphate rock and the test crop used benefited from its application.

Although only two rates of P (0 and 60 kg ha^{-1} as MPR) were used in the field experiments, maize growth trends were similar to those observed in the greenhouse. When the treatments were applied in the first season, maize grain yields increased due to the P application at both sites. However, as was observed in the greenhouse experiment, crops performed differently when organic materials were applied either on their own or in combination with MPR. Application of FYM manure, either at 1 or 2 t ha^{-1}, produced more grain than did the other treatments at both sites. This could be due to the fine and high quality manure, hence its capacity to decompose fast and release nutrients, in comparison with coarse maize stover, which was of lower quality and took longer to decompose. It is possible, also, that the fast decomposing FYM enhanced dissolution of PR and released P for the crop to use (Palm *et al*., 1997).

The second season's crop performance tested the residual effects of the treatments applied in the first season, as the treatments were not reapplied. At the Busia site, maize grain yields compared well to those of the first season except that the average yield for the no-P plots was significantly higher than the yields for the 60 kg P ha^{-1}, the opposite of what was recorded in the first season. At the Siaya site, the maize grain yields were very low compared with those of the first season. This was attributed to an infection of maize streak virus experienced at the site during the second season, since rainfall (distribution and amount) was adequate.

The RAE at both sites improved when PR was combined with organic materials at the higher rate. This suggests that the use of Minjingu PR when combined with organic materials is a viable option for P replenishment. The soils at Siaya and Busia had clay contents of 20 % and 34 % respectively. That the RAE was better at the former site suggests that some of the P released at Busia was in the soil colloidal system and unavailable to the crop. Even after taking the above possibilities into consideration, however the RAE results showed that, because of its residual effects, the use of Minjingu PR and its combinations with organic materials was more effective than TSP.

CONCLUSIONS

The results demonstrate that the low P content in soils in western Kenya seriously limits maize yields. They suggest though that the effectiveness of PR may be enhanced by combining it with organic materials such as those commonly available on smallholder farms in western Kenya, i.e. maize stover and FYM manure. It was observed that the use of organic materials alone can increase maize yield even though the materials may not replenish all the P taken up by crops. Further research is being carried out on the economic and P sorption/desorption aspects to verify some of these findings. However, there is a need for long-term studies to evaluate the residual effect of PR and its combination with organic materials.

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