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Comparison of effects of phosphorus sources on soil acidity, available phosphorus and maize yields at two sites in western Kenya

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The effects of farmyard manure (FYM), *Tithonia diversifolia* (tithonia) and urea when applied alone or in combination with Minjingu phosphate rock (MPR), Busumbu phosphate rock (BPR) or triple superphosphate (TSP) on soil acidity, P availability, maize yields and financial benefits were evaluated at Bukura and Kakamega in western Kenya. A reduction in exchangeable acidity and Al was observed in most tithonia- and FYM-treated soils, but not with inorganic P sources when applied in combination with urea. The effectiveness in increasing available soil P followed the order; TSP > MPR > BPR among inorganic P sources, and FYM > tithonia among organic materials at both sites. At Bukura, a site higher in both available P and Al saturation compared with Kakamega, maize did not respond to inorganic P sources applied in combination with urea. Maize, however, responded when inorganic P sources were applied in combination with FYM or tithonia at this site. At Kakamega, maize responded to TSP but not to MPR or BPR when applied with urea. Application of TSP in combination with tithonia gave the highest maize yields at both sites. Of the tested technologies, only FYM when applied alone at Bukura was economically attractive.

Keywords: maize yields; phosphorus availability; phosphorus sources; soil acidity

Introduction

Western Kenya is dominated by Ferralsols, Acrisols and Nitisols whose agricultural productivity is commonly limited by low availability of phosphorus, with 80% of the soils across farms in this region being reported as severely P-deficient (Jama et al. 1998). The situation is exacerbated by the high acidity of these soils with a possibility of aluminum phytotoxicity. On such P-deficient soils, use of other nutrient inputs is not usually effective unless P limitations are overcome. Management of P deficiency requires addition of organic or inorganic fertilizers or their combinations. Sole use of organic inputs to supply adequate P to meet crop requirements is, however, not a practical option due to their low P content (Palm et al. 2001). Phosphorus must, therefore, be added to P-depleted soils in concentrated forms either as P-containing fertilizers or phosphate rocks (PRs). The use efficiency of inorganic soluble phosphate fertilizers applied to soils with moderate to high P-fixation capacity, such as soils of western Kenya, is reduced by P-fixation (Buresh et al. 1997), while

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the effectiveness of PRs is often limited by their low solubility. The challenge then is to identify cost-effective practices that are able to increase the use efficiency of applied P inputs to these soils. The potential use of locally available organic materials (OMs) to reduce P fixation and enhance availability of applied inorganic P inputs has, in particular, received considerable research attention in recent years in eastern Africa (Ikerra et al. 2006; Kifuko et al. 2007; Opala et al. 2007).

The use of PR as an alternative P source to manufactured soluble phosphate fertilizers is well documented (Khasawneh and Doll 1978). Along with its Ca and Mg constituents, PR assumes a significant role as a potential tool for sustaining soil productivity by reducing soil acidity through its liming effect (Anetor and Akinrinde 2007). However, early studies with PRs produced results that have been reported as erratic and sometimes conflicting, leading to confusion and disagreement on the utilization of PRs (Khasawneh and Doll 1978). There has, however, been renewed interest in the use of PRs in Kenya's neighbours such as Minjingu phosphate rock (MPR) from northern Tanzania and Busumbu phosphate rock (BPR) from eastern Uganda, especially when applied in combination with OMs as alternatives to costly mineral P fertilizers and lime. The objective of this study was, therefore, to determine the effects of farmyard manure (FYM) and *Tithonia diversifolia* (tithonia), when applied alone or in combination with MPR, BPR or triple superphosphate (TSP), on soil P changes, soil acidity, maize yields and financial benefits in acid soils of western Kenya .

Materials and methods

Site description

The field experiment was conducted in March to July 2007 at Bukura and Kakamega in western Kenya. The sites were chosen on the basis of their contrasting soil characteristics, with Bukura having a lower pH than Kakamega but higher in exchangeable acidity, Al and available P (Table 1). Bukura is 1400 masl, 0°30'N latitude and 34°30'E longitude, with an average annual rainfall of 1700 mm and a daily average temperature of 22°C, whereas Kakamega is 1330 masl, 0°08'N latitude and 34°22'E longitude with an average annual rainfall of 1900 mm and a daily average temperature of 21°C.

Soil analysis

Soil samples (15 cm depth) were collected at the beginning of the study from the two sites for characterization of initial soil properties and again at 9 weeks after planting of maize from each plot to determine treatment effects on selected soil chemical properties. The soils were air-dried, prepared and analysed using standard procedures as described by Okalebo et al. (2002). In brief, soil pH was determined using a glass electrode pH meter at 1:2.5 soil/water ratio. Exchangeable acidity and exchangeable Al were extracted using unbuffered 1 M KCl and determined by titration. The basic cations (Ca, Mg and K) were extracted using ammonium acetate at pH 7. Exchangeable Ca and Mg in the extract were determined using atomic absorption spectrophotometry and exchangeable K was determined by flame photometry. Organic C was determined by Walkley and Black sulfuric acid-dichromate digestion followed by back titration with ferrous ammonium sulfate (Nelson and Sommers 1982). Total N and P were determined by digesting 0.3 g of

Table 1. Initial surface (0–20 cm) soil properties at the study sites.

Parameter	Bukura	Kakamega
pH (H ₂ O) (1:2.5)	4.80	5.10
Exchangeable acidity (cmol _c kg ⁻¹)	0.88	0.35
Exchangeable Al (cmol _c kg ⁻¹)	0.63	0.13
Ca (cmol _c kg ⁻¹)	1.94	2.1
Mg (cmol _c kg ⁻¹)	1.01	1.8
K (cmol _c kg ⁻¹)	0.12	0.2
ECEC (cmol _c kg ⁻¹)	3.95	4.85
Al saturation (%)	22	7.2
Organic C (%)	3.2	2.7
Total N (%)	0.3	0.3
C:N ratio	10.6	9.0
Total P (%)	0.04	0.03
Olsen P (mg kg ⁻¹)	5.6	2.5
P sorbed at 0.2 mg P L ⁻¹	260	45
Sand (%)	52	54
Silt (%)	18	28
Clay (%)	30	18
Soil classification	Orthic Ferralsol	Ferralic Cambisols

Note: ECEC, effective cation-exchange capacity.

the soil sample in a mixture of Se, LiSO₄, H₂O₂ and concentrated H₂SO₄. The N and P contents in the digests were determined colorimetrically. Available P was determined by the Olsen method (Olsen et al. 1954), which involved extracting soil P with 0.5 M NaHCO₃ (pH 8.5); the 6-day equilibration method of Fox and Kamprath (1970) was used to determine the P sorption characteristics of the soils.

Non-linear regression using the Genstat statistical package (GENSTAT, 1993) was used to fit the P adsorption data to the non-linear form of the Langmuir equation;

$$q = kbc/(1 + kc),$$

where c (mg P L⁻¹) is the equilibrium concentration, q (mg P kg⁻¹) is the amount P adsorbed per unit mass of adsorbent, b (mg P kg⁻¹) is the P adsorption maximum and k (mg L⁻¹) is the constant related to the energy of adsorption.

Experimental layout and management

The treatments consisted of three inorganic P sources; TSP, MPR and BPR each applied in combination with FYM, tithonia or urea in a randomized complete block design with three replications. Other treatments included a control with only urea applied (no P), and FYM and tithonia, each applied alone. FYM and tithonia were applied to supply 20 kg P ha⁻¹ in treatments where they were used either alone or in combination with inorganic P sources. The inorganic P sources were applied to provide 40 kg P ha⁻¹ in OM/inorganic P source combinations. However, when they were used in combination with urea, they were applied at 60 kg P ha⁻¹. Tithonia had 3.0% N, 0.3% P, 3.8% K, 42% C, pH 6.5, whereas FYM had 1.8% N, 0.4% P 1.2% K, 36% C, pH 7.7. Both PRs were ground to pass through a 0.15-mm sieve. The

BPR was of igneous origin, had 12% P with a neutral ammonium acetate (NAC) solubility of 10%, whereas MPR was biogenic, and had 13% P with an NAC of 23%.

Where used, urea was applied at 100 kg N ha^{-1} . All nutrient inputs were uniformly broadcast on the plots and then incorporated into the top soil (0-15 cm) using a hand hoe prior to planting of maize. Urea at 100 kg ha^{-1} was split applied in plots without tithonia or FYM, one third at planting and two-thirds at 5 weeks after planting. Potassium was applied at the time of planting as muriate of potash (KCl) at a rate of 60 kg K ha^{-1} . The intention was to supply sufficient amounts of N and K to ensure that the two nutrients were not limiting factors on plant growth while studying the P effects. The rates of tithonia and FYM that were applied provided $> 80 \text{ kg N ha}^{-1}$, which was considered adequate to meet the N needs for the maize crop and hence no inorganic N was applied to plots with tithonia or FYM. After the application of treatments, two maize seeds (Hybrid 614D) were planted per hill at a spacing of $75 \times 25 \text{ cm}$, and were thinned to one plant per hill 2 weeks after planting. Maize was grown using recommended agronomic practices and harvested at maturity. Data were subjected to analysis of variance using the Genstat statistical package (GENSTAT, 1993) and treatment means were compared using the standard error of difference between means at $p < 0.05$.

Economic analysis

In order to evaluate soil amelioration endeavour from an economic point of view, costs and financial benefits of each treatment were compared using partial budgeting, which included only costs and benefits that varied from the control treatment (CYMMYT 1988). To determine the adoption potential of the tested nutrient inputs, a benefit-cost ratio (BCR), calculated as value of additional maize yield after application of the nutrient inputs divided by cost of nutrient inputs to achieve this, was used (FAO 1989). The costs of maize and inorganic fertilizers were determined through a market survey of the area. Tithonia was costed in terms of labour involved in harvesting, transporting and incorporating it into the soil (Mucheru-Muna et al. 2007). Amounts of labour for fertilizer application, FYM and harvesting and application of tithonia were determined from observation of the performance of the specific activities in each season (Table 2)

Results

Soil pH, exchangeable acidity and exchangeable aluminum

The effects of treatments on the soil pH at Kakamega and Bukura are given in Table 3. Soil pH was not significantly affected by application of nutrient inputs at both sites. There was a clear trend, however, whereby FYM treatments consistently gave higher pH values than the other treatments. The exchangeable acidity at Kakamega was low compared with that at Bukura. A significant reduction in exchangeable acidity, compared with the control, was observed in all treatments with tithonia and FYM at the Kakamega site. A similar trend was observed at Bukura although the reduction was not always significant. None of the inorganic P sources applied in combination with urea significantly reduced exchangeable acidity at both sites. There were no significant treatment effects on exchangeable Al at Kakamega where the levels of exchangeable Al were generally low. However at Bukura, with higher levels

Table 2. Values used for cost–benefit analysis (USD).

Parameter	Kakamega	Bukura
Price of TSP kg^{-1}	0.54	0.62
Price of MPR kg^{-1}	0.27	0.35
Price of BPR kg^{-1}	0.23	0.31
Price of urea kg^{-1}	0.46	0.54
Transport of fertilizers to the farm 100 kg^{-1}	1.75	1.75
Labour for applying fertilizer per hectare	1.67	1.67
Price of FYM $100 \text{ kg}^{-1\text{a}}$	0.80	0.80
Cost of application of FYM $\text{ha}^{-1\text{a}}$	26	26
Cost of cutting and application of 6.7 t ha^{-1} of tithonia ^a	605	605
Price of maize kg^{-1}	0.32	0.32
Price of maize stover 100 kg^{-1}	15	12

Note: ^a Values of farmyard manure (FYM) and tithonia are expressed on dry matter basis. Cost of application includes cost for collection and transport of materials within the homestead. TSP, triple superphosphate; MPR, Minjingu phosphate rock; BPR, Busumbu phosphate rock

of exchangeable Al, significant reductions in exchangeable Al were observed with the most effective treatment being tithonia when applied in combination with MPR.

Changes in Olsen P and P sorption

The results of changes in Olsen P in the soils, as influenced by the treatments, are summarized in Table 4. Addition of P from both organic and inorganic sources generally resulted in increase in Olsen P relative to the control. The magnitude of increase in Olsen P depended on the soil type, P source and rate of P application. The Kakamega site had lower Olsen P values than Bukura. Application of P sources increased Olsen P above the control for all the treatments at both sites except for the following treatments: tithonia applied alone at Bukura, FYM applied with BPR at Kakamega, and BPR applied with urea at both sites. Application of tithonia alone gave Olsen P values that were not significantly different from those obtained with its combination with the PRs at 60 kg ha^{-1} at Kakamega. Combination of TSP with tithonia or FYM (60 kg P ha^{-1}) always gave higher Olsen P values compared with the sole application of the two OMs at 20 kg P ha^{-1} at both sites. At Bukura, application of tithonia or FYM alone gave significantly lower Olsen P values compared with when they were combined with MPR or TSP, but not BPR. Combining the PRs with tithonia or FYM gave higher Olsen P values than when PRs were combined with urea. However, when the TSP was combined with tithonia or FYM, it gave lower amounts of Olsen P than when it was combined with urea at Kakamega, but not Bukura where FYM + TSP gave higher amounts of Olsen P.

Results of the P sorption are presented in Table 4 and focus only on adsorbed P, which is of more agronomic relevance than adsorption maxima and affinity, which are not presented. The P sorption capacity of the Kakamega soil was low with a mean of 37 mg P kg^{-1} of P sorbed at 0.2 mg P L^{-1} for control treatment. None of the P sources had significantly reduced the amount of P sorbed at this site at the end of the experiment. At Bukura, the P sorption capacity of the control (269 mg P kg^{-1})

Table 3. Effect of inorganic and organic materials on soil pH and exchangeable acidity at Kakamega and Bukura.

Treatment	pH		Exchangeable acidity (cmol _c kg ⁻¹)		Exchangeable Al (cmol _c kg ⁻¹)	
	Kakamega	Bukura	Kakamega	Bukura	Kakamega	Bukura
1. Control (no P input addition)	5.26	4.82	0.39	0.85	0.13	0.61
2. Tithonia (20 kg P ha ⁻¹)	5.22	4.82	0.25	0.64	0.10	0.38
3. FYM (20 kg P ha ⁻¹)	5.38	4.97	0.25	0.67	0.10	0.45
4. MPR (60 kg P ha ⁻¹) + urea	5.30	4.88	0.30	0.73	0.10	0.50
5. BPR (60 kg P ha ⁻¹) + urea	5.24	4.78	0.39	0.81	0.10	0.61
6. TSP (60 kg P ha ⁻¹) + urea	5.20	4.84	0.32	0.79	0.10	0.55
7. Tithonia (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	5.37	4.99	0.23	0.66	0.10	0.35
8. Tithonia (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	5.28	4.82	0.23	0.65	0.10	0.51
9. Tithonia (20 kg P ha ⁻¹) + TSP (40 kg P ha ⁻¹)	5.21	4.96	0.28	0.67	0.13	0.36
10. FYM (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	5.47	5.05	0.20	0.71	0.10	0.37
11. FYM (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	5.42	5.01	0.24	0.79	0.13	0.57
12. FYM (20 kg P ha ⁻¹) + TSP (40 kg P ha ⁻¹)	5.37	5.04	0.26	0.63	0.10	0.47
SED	NS	NS	0.05	0.09	NS	0.21
CV%	2.5	3.70	18.1	15.8	25.6	27.1

Note: FYM, farmyard manure; TSP, triple superphosphate; MPR, Minjingu phosphate rock; BPR, Busumbu phosphate rock. NS, not significant; SED, standard error of difference between means; CV%, coefficient of variation.

Table 4. Effect of treatments on soil available Olsen P at Kakamega and Bukura.

Treatments	Olsen P (mg kg ⁻¹)		P sorption (mg kg ⁻¹)	
	Kakamega	Bukura	Kakamega	Bukura
1. Control (no P input addition)	2.6	5.4	37	269
2. Tithonia (20 kg P ha ⁻¹)	4.2	7.0	30	192
3. FYM (20 kg P ha ⁻¹)	3.8	7.8	32	236
4. MPR (60 kg P ha ⁻¹) + urea	4.1	10.8	32	261
5. BPR (60 kg P ha ⁻¹) + urea	3.4	7.4	39	285
6. TSP (60 kg P ha ⁻¹) + urea	8.2	17.1	32	223
7. Tithonia (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	4.8	10.7	38	222
8. Tithonia (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	4.7	9.3	38	255
9. Tithonia (20 kg P ha ⁻¹) + TSP (40 kg P ha ⁻¹)	7.5	15.3	29	207
10. FYM (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	4.9	12.1	32	229
11. FYM (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	3.3	9.8	30	238
12. FYM (20 kg P ha ⁻¹) + TSP (40 kg P ha ⁻¹)	8.1	17.3	29	175
SED	0.6	1.2	NS	30
CV%	15	13	13	16

Note: FYM, farmyard manure; TSP, triple superphosphate; MPR, Minjingu phosphate rock; BPR, Busumbu phosphate rock; SED, standard error of difference between means; CV%, coefficient of variation; NS, not significant.

was much higher than that at Kakamega and would be classified as medium according to Juo and Fox (1977). The amount of P sorbed was significantly lower than the control for only three treatments at this site; tithonia when applied alone or in combination with TSP, and FYM applied in combination with TSP. Application of BPR with urea increased the amount of P adsorbed although statistical significance was not achieved.

Maize grain yields

The grain yield data are presented in Table 5. There was no significant response by maize to application of the inorganic P sources when applied in combination with urea at Bukura. At Kakamega, maize responded to application of TSP but not MPR or BPR when applied in combination with urea compared with the control. All the treatments with tithonia applied alone or in combination with PRs or TSP increased yields above the control at both sites. The highest maize yields at both sites were obtained with tithonia when applied in combination with TSP. FYM significantly increased grain yields above the control when combined with TSP or MPR but not when combined with BPR at both sites. Among the OM/inorganic P source combinations, only tithonia when combined with TSP increased yields significantly above that of the application of the sole tithonia at the Kakamega site. At Bukura, none of the OMs/inorganic P fertilizer combinations gave yields that were significantly higher than the sole application of the OMs despite having an additional 40 kg P ha⁻¹.

Table 5. Effect of P sources on maize grain yield at Bukura and Kakamega.

Treatment	Total P (kg ha ⁻¹)	Grain yield Mg ha ⁻¹	
		Kakamega	Bukura
1. Control (no P input addition)	0	2.6	1.9
2. Tithonia (20 kg P ha ⁻¹)	20	4.2	4.3
3. FYM (20 kg P ha ⁻¹)	20	3.5	3.2
4. MPR (60 kg P ha ⁻¹) + urea	60	3.4	2.6
5. BPR (60 kg P ha ⁻¹) + urea	60	2.4	2.0
6. TSP (60 kg P ha ⁻¹) + urea	60	3.9	2.2
7. Tithonia (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	60	4.7	4.9
8. Tithonia (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	60	4.1	4.4
9. Tithonia (20 kg P ha ⁻¹) + TSP (40 kg P ha ⁻¹)	60	5.4	5.1
10. FYM (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	60	3.7	3.2
11. FYM (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	60	2.7	2.7
12. FYM (20 kg P ha ⁻¹) + TSP (40 kg P ha ⁻¹)	60	3.8	2.9
SED		0.50	0.49

Note: FYM, farmyard manure; TSP, triple superphosphate; MPR, Minjingu phosphate rock; BPR, Busumbu phosphate rock; SED, standard error of difference between means.

Economic analyses

The highest added costs were obtained with the tithonia treatments while the least costs were obtained with FYM treatments (Table 6).

Tithonia applied with TSP gave the highest net financial benefits while BPR applied with urea had the least at both sites (Table 7). The net benefits for the OM/inorganic P combinations appeared to be site specific and depended on the input combination. For example, at Kakamega, combining tithonia with TSP or MPR resulted in net benefits that were higher than the sole use of TSP, MPR or application of tithonia alone. However, combining tithonia with BPR at this site led to lower net benefits than sole application of tithonia. At Bukura, however, combining tithonia with any of the inorganic P sources resulted in net benefits that were higher than the sole application of the tithonia or inorganic P sources. The benefit cost ratios (BCRs) for all treatments, apart from those with FYM were, however, generally low (<2). The highest BCR at Kakamega (1.1) and Bukura (4.5) were obtained with FYM applied with MPR and FYM alone respectively.

Discussion

The increase in soil pH due to application of FYM is consistent with results reported by other studies and can be attributed to several factors such as liming effects of FYM, proton exchange between the soil and added FYM, which contains some phenolic, humic-like material, and specific adsorption of humic material onto hydrous surfaces of Al and Fe oxides by ligand exchange with corresponding release of OH⁻ (Narambuye and Haynes 2006). The failure of tithonia to significantly increase soil pH in the present study is inconsistent with findings by Cong and Merckx (2005) who reported an increase in pH due to application of tithonia. However, they used very high rates of tithonia (88 t ha⁻¹) compared with 6 t ha⁻¹,

Table 6. Effect of phosphorus sources and organic materials on added costs (USD ha⁻¹).

Treatment	Fertilization cost ^a		Labor cost ^b	Total added costs	
	KK	BK		KK & BK	KK
1. Control (no input addition)	–	–	–	–	–
2. Tithonia (20 kg P ha ⁻¹)	0	0	605	605	605
3. FYM (20 kg P ha ⁻¹)	0	0	26	72	72
4. MPR (60 kg P ha ⁻¹) + urea	276	295	3	279	298
5. BPR (60 kg P ha ⁻¹) + urea	250	270	3	253	273
6. TSP (60 kg P ha ⁻¹) + urea	298	344	2	300	346
7. Tithonia (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	108	108	607	715	715
8. Tithonia (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	91	91	607	698	698
9. Tithonia (20 kg P ha ⁻¹) + TSP (40 kg P ha ⁻¹)	122	141	606	728	747
10. FYM (20 kg P ha ⁻¹) + MPR (40 kg P ha ⁻¹)	154	154	28	182	182
11. FYM (20 kg P ha ⁻¹) + BPR (40 kg P ha ⁻¹)	137	137	28	165	165
12. FYM (20 kg P ha ⁻¹) + TSP (40 kg P ha ⁻¹)	168	187	27	195	214

Note: KK, Kakamega; BK, Bukura; FYM, farmyard manure; TSP, triple superphosphate; MPR, Minjingu phosphate rock; BPR, Busumbu phosphate rock. ^a Added fertilizer costs; ^b added labour costs.

Table 7. Net financial benefits (USD ha⁻¹) and benefit–cost ratio.

Treatment	Kakamega		Bukura	
	Net benefit	BCR	Net benefit	BCR
1. Control (no input addition)	–	–	–	–
2. Tithonia (20 kg P ha ⁻¹)	–2	–0.03	144	0.23
3. FYM (20 kg P ha ⁻¹)	35	0.50	323	4.50
4. MPR (60 kg P ha ⁻¹) + urea	1	0.03	–51	–0.17
5. BPR (60 kg P ha ⁻¹) + urea	–329	–1.3	–248	–0.90
6. TSP (60 kg P ha ⁻¹) + urea	146	0.50	–228	–0.65
7. Tithonia 20 kg P ha ⁻¹ + MPR (40 kg P ha ⁻¹)	58	0.08	327	0.47
8. Tithonia 20 kg P ha ⁻¹ + BPR (40 kg P ha ⁻¹)	–145	–0.20	172	0.25
9. Tithonia 20 kg P ha ⁻¹ + TSP (40 kg P ha ⁻¹)	300	0.41	405	0.54
10. FYM 20 kg P ha ⁻¹ + MPR (40 kg P ha ⁻¹)	194	1.10	223	1.22
11. FYM 20 kg P ha ⁻¹ + BPR (40 kg P ha ⁻¹)	–130	–0.79	100	0.61
12. FYM 20 kg P ha ⁻¹ + TSP (40 kg P ha ⁻¹)	139	0.71	138	0.64

BCR, benefit–cost ratio; FYM, farmyard manure; TSP, triple superphosphate; MPR, Minjingu phosphate rock; BPR, Busumbu phosphate rock.

on dry weight basis, in our study. Although it has been reported (Ikerra et al. 2006) that MPR can increase soil pH, in the present study its application in combination with urea, which is an acidifying fertilizer, could have slowed down the expected increase in soil pH. The reduction in exchangeable acidity and Al observed due to application of FYM can partially be attributed to its ability to increase the soil pH

results in precipitation of exchangeable and soluble Al as insoluble Al hydroxides (Narambuye and Haynes 2006; Tang et al. 2007). However, this mechanism cannot apply for tithonia, which did not increase the soil pH. Complex formation of Al with low molecular weight organic acids produced during the decomposition of OMs such as tithonia may explain the reduction in exchangeable acidity and Al (Haynes and Mokolobate 2001).

Combining PRs with tithonia or FYM gave higher Olsen P values than when PRs were combined with urea. However, when TSP was combined with tithonia or FYM, it gave lower amounts of Olsen P than when it was combined with urea. This may suggest that tithonia and FYM were enhancing the dissolution of PRs, but retarding the availability of P from TSP. However, closer examination of the data reveals that tithonia and FYM were unlikely to have enhanced the dissolution of PRs and that combining these two OMs with PRs has no advantage in terms of increasing Olsen P compared with their application with urea. For example, at Bukura, applying tithonia alone (20 kg P ha^{-1}) resulted in an Olsen P of 7.0 mg kg^{-1} , which is 65% that obtained with its combination with MPR (10.7 mg kg^{-1}). Because tithonia was applied at 20 kg P ha^{-1} as proportion of total rate of 60 kg P ha^{-1} , it would be expected theoretically to contribute to only 33% of Olsen P in the combination. In this example, MPR when combined with urea had an Olsen P of 10.8 mg kg^{-1} , which was $>100\%$ of the $10.7 \text{ mg P kg}^{-1}$ obtained from the combination of tithonia and MPR. Application of PRs in combination with OMs did therefore not result in synergy in terms of increasing Olsen P. The likely reason why PRs when combined with tithonia and FYM gave higher Olsen P levels compared with their combination with urea, is that both tithonia and FYM were generally more effective in increasing Olsen P compared with PRs and therefore a portion of the insoluble PRs (20 kg P ha^{-1}) was substituted by more available P from tithonia or FYM in the combinations. However, when combined with urea, all the 60 kg P ha^{-1} was from low soluble PRs and thus lower Olsen P levels were observed. However, TSP when combined with urea, gave higher Olsen P levels compared with its combination with tithonia or FYM. In this case, TSP was more effective in increasing Olsen P compared with tithonia and FYM whose P is mostly in organic forms initially. Therefore, substituting a portion of TSP (20 kg P ha^{-1}) in the combination with tithonia or FYM yielded less Olsen P than when TSP was applied at the full rate of 60 kg P ha^{-1} . If cost was not a limiting factor, then replenishing soil P using TSP in combination with urea would be a more appropriate strategy as it results in more available P than when applied in combination with tithonia or FYM. Likewise, if availability and cost were not a constraint, then it would be better to apply tithonia or FYM alone than combining them with MPR or BPR. The combination of BPR with any of the OMs gave Olsen P levels that were very similar to or sometimes lower than those of the OMs applied alone. This can be attributed to nonreactive nature of BPR and also its high Fe content (Savini et al. 2006) which tended to increase P sorption. Therefore, most of the extractable P in the combinations is likely to have been contributed by the OMs with insignificant contributions from BPR.

P sorption capacity of the soil at Kakamega was low compared with that at Bukura likely due to the lower content of exchangeable Al and higher soil pH at Kakamega. FYM and tithonia when applied in combination with TSP were more effective in reducing P-sorption than when they were applied alone at Bukura. This suggests that the part of observed reduction in P adsorbed was due to the blocking of

P sorption sites by inorganic P. As observed previously by other authors (e.g. Whalen and Chang 2002), addition of P to soils decreases the soil's capacity to bind P. However, the failure of inorganic P sources when applied alone to significantly reduce P sorption point to other additional mechanisms of reduction in P sorption that were not significantly affected by inorganic P sources. These may include complexation and competition for sorption sites by products of OM decomposition such as low molecular weight organic acids (Nziguheba et al. 2002; Guppy et al. 2005).

Apart from the treatments with application of tithonia, the maize grain yields were generally higher in Kakamega than Bukura for comparable treatments, although the Olsen P values were higher at Bukura. On the basis of Olsen P alone, this was unexpected.

Three possible reasons can, however, be advanced for the higher yields at Kakamega. (1) Because of the lower P sorption capacity at Kakamega, the soil at this site was able to maintain higher P levels in soil solution over a longer time as compared with the Bukura soil with relatively high P sorption capacity soil. This is in conformity with findings of Mokwunye (1977) that it is the level of P in solution rather than the total labile P in the soil that determines plant utilization of P. This is confirmed by this study where we found no significant correlation between Olsen P and maize yields at both sites. It appears that each site had its own critical Olsen P levels for maize growth. According to Curtin and Syers (2001), soils can differ substantially in the level of P maintained in the soil solution at a given Olsen P value and consequently, Olsen P values for optimum growth can vary from soil to soil. The critical Olsen P level for maize growth (10 mg P kg^{-1}) proposed by Okalebo et al. (2002) may, therefore, not be applicable to all soils and appropriate field calibration in the soils for which the Olsen P test will be used is therefore necessary (Warren 1992).

(2) Al toxicity is likely to have constrained maize growth at Bukura, but not at Kakamega. Initial soil characterization showed that the soil at Kakamega had a lower level of Al saturation (7.2%) compared with that of Bukura (22%). According to Farina and Chanon (1991), the critical levels of Al saturation for some susceptible maize varieties, above which Al toxicity would occur, is $\sim 20\%$. The crop at Bukura is thus likely to have experienced Al toxicity while that at Kakamega did not, (3) a combination of both '1' and '2' as explained above.

The combination of TSP with OMs, gave higher maize yields than combination of OMs with MPR or BPR because of higher solubility of TSP. Presumably, OMs were able to reduce Al toxicity through fixation and allow maize to respond better to applied inorganic P input where they were used in combination. This could also partly explain why tithonia treatments gave higher yields at Bukura than Kakamega. Tithonia, having been the most effective material in reducing exchangeable Al, likely removed Al toxicity at Bukura and allowed maize to utilize the available P, which was higher at this site compared with Kakamega.

The added costs of using tithonia were very high because of its bulkiness. At the rate of 20 kg P ha^{-1} used in this study, almost 30 t ha^{-1} of fresh tithonia biomass were applied thus greatly increasing cost of labour for its collection and application. Added costs for use of FYM were relatively lower than tithonia's because of its higher P content and lower moisture, hence the FYM applied was less bulky. The other advantage of FYM, which it shared with tithonia, compared with inorganic P sources, was its ability to provide N in addition to P thus making use of FYM less costly than inorganic P sources, which had to be combined purchased urea to provide N. Although tithonia applied with TSP had the highest added costs, it

recorded the highest net benefits at both sites because it produced the highest yield increases above the control. All the BPR treatments at Kakamega had negative net financial benefits because BPR generally tended to depress maize yields at this site. Tithonia applied alone at this site also had negative net benefits because of very high labour costs, which were not offset by the additional maize yield accruing from its use. However at Bukura, tithonia applied alone gave positive benefits because of its ability to produce a very large increase (126%) in yield over the control. The decision by farmers to adopt nutrient inputs depends on their profitability but as a general rule, a BCR of at least 2:1 is attractive to farmers (FAO 2006). BCRs in the present study were generally low and only FYM when applied alone at 20 kg P ha⁻¹ met this criterion at Bukura.

Conclusions

None of the nutrient inputs significantly affected soil pH but tithonia and FYM reduced exchangeable acidity and Al, especially at the Bukura site. Combination of TSP, MPR or BPR with OMs did not result in synergism in terms of increased available P. Use of TSP, MPR or BPR in combination with urea was not agronomically effective at Bukura where the Al saturation was high, but maize responded to them when they were applied in combination with OMs at this site. OMs are likely to have reduced Al toxicity at this site and allowed maize to respond better to applied inorganic P input where they were used in combination. At Kakamega, where Al saturation was low, maize responded to TSP when combined with urea but the response to PRs was not significant. At Kakamega, none of the tested technologies was economically attractive, whereas at Bukura only FYM when applied alone at 20 kg P ha⁻¹ achieved a benefit:cost ratio of 2 and most likely this treatment should be used among the tested nutrient sources and combinations. Differences in response by maize to different P inputs at the two sites indicate that P recommendations for maize cannot easily be transposed among diverse soils of western Kenya.

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