Effect of organic and inorganic phosphorus sources on maize yields in an acid soil in western Kenya

4 authors, including:

Some of the authors of this publication are also working on these related projects:

McKnight Foundation View project

1. Integrated soil fertility management for spinach using vermicompost and tithonia diversifolia green manure in combination with urea. View project

RESEARCH ARTICLE

Effect of organic and inorganic phosphorus sources on maize yields in an acid soil in western Kenya

P. A. Opala · J. R. Okalebo · C. O. Othieno ·
P. Kisinyo

Abstract Maize production in western Kenya is commonly limited by P deficiencies and aluminum phytotoxicity. Due to high costs of imported fertilizers and lime, focus is now shifting to solutions that utilize local resources. We tested the effect of three inorganic P sources i.e., triple superphosphate (TSP), Minjingu phosphate rock (MPR) and Busumbu phosphate rock (BPR), each applied in combination with two organic materials (OMs) i.e., farmyard manure (FYM) and *Tithonia diversifolia* green manure (tithonia), or with urea on soil chemical properties related to soil acidity, P availability and maize yields for three consecutive seasons in western Kenya. The OMs and inorganic P sources were applied to provide 20 and 40 kg P ha^{-1} respectively in their combination. Where urea was used, the inorganic P sources were applied at 60 kg P ha^{-1}. Maize did not respond to application of TSP, MPR or BPR with urea in the first two seasons. However, after three seasons, maize significantly responded to application of MPR with urea. FYM was more effective than tithonia in increasing the labile inorganic P pools but it gave lower maize yields than tithonia which was more effective in reducing the exchangeable Al. It appears that the ability of an OM to lower the exchangeable Al is more important in increasing maize yields than its ability to increase P availability. The effectiveness of the inorganic P sources in increasing maize yields followed the order of their effectiveness in increasing available P, i.e., TSP > MPR > BPR, once Al phytotoxicity was reduced by application of tithonia but the difference between TSP and MPR was not significant. The extra maize yield obtained by the additional 40 kg P ha^{-1} from the inorganic P sources was, however, in most cases not substantial enough to justify their use. Economic considerations may therefore favour the use of tithonia or FYM when applied alone at 20 kg P ha^{-1} than when combined with any of the inorganic P sources used in this study at a total P rate of 60 kg ha^{-1}.

Keywords Aluminum phytotoxicity ·
Inorganic phosphorus sources · Maize yields ·
Organic materials · Phosphorus availability

Introduction

The agricultural productivity of the densely populated humid regions of western Kenya is commonly limited by low phosphorus availability and aluminum phytotoxicity. Although this problem can be mitigated by use of P fertilizers and lime, this strategy has not been effective among the smallholder farmers

P. A. Opala (✉) · J. R. Okalebo · C. O. Othieno ·
P. Kisinyo
Department of Soil Science, Moi University,
P.O. Box 1125, Eldoret, Kenya
e-mail: ptropala@yahoo.com

mainly because of its high cost. Thus in Kenya, there is growing interest in finding alternative affordable, viable and sustainable technologies to replenish soil fertility with focus shifting to solutions that utilize more local resources and less external inputs. The use of organic materials (OMs) and phosphate rock (PR) has in particular received considerable attention in recent years (Nziguheba 2007).

Farmyard manure (FYM) is the most commonly used OM in smallholder farming systems in western Kenya, but its use is constrained by its often poor quality and inadequate quantity (Probert et al. 1995). Other alternative non-traditional sources of nutrients, especially the green manures, are therefore being explored. Among such green manures, *Tithonia diversifolia* (tithonia) has been identified as a particularly promising source of N (Jama et al. 2000). However, due to its low P content (Palm et al. 2001), tithonia may need to be combined with inorganic P sources in order to supply adequate P to meet crop requirements.

The use of PRs in eastern Africa as alternatives to soluble P fertilizers is well documented. There are a number of PR deposits of variable reactivity in eastern Africa which differ greatly in their P composition and suitability as sources of P for crops (van Straaten 2002). Among such PRs, Minjingu phosphate rock (MPR) from northern Tanzania and Busumbu phosphate rock (BPR) from eastern Uganda have a great potential for use in Kenya due to their proximity (Woomer et al. 1997). These PRs are, however, not always effective in increasing crop yields because of their low solubility. Several techniques aiming to increase the solubility of PRs have, therefore, been tried in Kenya, with the potential use of organic materials (OMs) receiving considerable research attention (Waigwa et al. 2003; Kifuko et al. 2007). This approach is based on the fact that decomposing organic materials produce organic acids that solubilize P from PRs through chelating or complexing action (Kpomblekou and Tabatabai 1994).

Knowledge gaps and controversy, however, still exist as to whether combining OMs with PRs actually increases the dissolution of PRs. Emerging evidence suggests that some OMs, especially those with a high Ca content, can increase the soil pH, thereby retarding the dissolution of reactive PRs such as MPR (Ikerra et al. 2006; Smithson 1999). If this is true, then doubts must be cast at reports showing that the combination of OMs with PRs results in higher soil available P and hence higher crop yields than when the PRs are applied alone. However, if crop yields are indeed increased due to combined application of OMs with PRs, and that OMs also retard the dissolution of PRs, then the higher crop yields obtained from combined application of OMs with PRs, compared to sole application of PRs, at equivalent total P rates, cannot be due to increased soil P availability as reported by many authors (e.g., Subehia and Minhas 1993; Waigwa et al. 2003; Kifuko et al. 2007).

We hypothesized that an increase in soil pH due to addition of OMs could be important in alleviating Al phytotoxicities in acid soils, thereby enabling the crop to utilize the P from PRs more efficiently when OMs are combined with PRs than when PRs are applied alone. The objective of this study was, therefore, to evaluate the effect of three inorganic P sources i.e., MPR, BPR and triple superphosphate (TSP), applied alone or in combination with tithonia or FYM on soil pH, exchangeable Al, P availability and maize yields in an acid soil in western Kenya.

Materials and methods

Site description

The experiment was conducted at Bukura in western Kenya (0°7′N, 34°30′E) at an altitude of 1,400 m with an average annual rainfall of 1,800 mm. The rainfall is distributed over two main cropping seasons, the long rainy season, from March to July and the short rainy season from September to December. The soil was an orthic Ferralsol with the following properties: pH (H_2O) = 4.8; exchangeable acidity = 0.9 cmol kg^{-1}; total soil organic carbon = 34.9 g kg^{-1}; exchangeable Mg = 1.0 cmol$_c$ kg^{-1} and exchangeable Ca = 1.7 cmol kg^{-1}. The soil had a moderate P-fixing capacity with a soil P concentration of 0.2 mg l^{-1} corresponding to 260 mg P kg^{-1} adsorbed by the soil.

Experimental layout and management

The experiment was established in March 2006 and laid out as a randomized complete block design with three replications with plot sizes measuring 5 × 3 m. Two OMs, i.e., tithonia green manure and FYM, which represent common alternatives to inorganic P

fertilizers on smallholder farms, but vary in their chemical characteristics, were applied in combination with three inorganic P sources i.e., MPR, BPR and TSP. The OMs were applied to provide 20 kg P ha^{-1} in the combination while the inorganic P sources provided 40 kg P ha^{-1} to bring the total P rate to the area recommendation of 60 kg P ha^{-1} (FURP 1987). At the rates used in this study, the OMs provided adequate N (>80 kg N ha^{-1}) for the maize crop as per area recommendation and therefore no supplemental inorganic N fertilizer was applied. To compare the effects of these OM/inorganic P combinations with inorganic P sources applied without OMs, three treatments i.e., MPR, BPR and TSP, each applied at 60 kg P ha^{-1}, were included. The purpose of this comparison was to determine whether a substitution of 20 kg P ha^{-1} of P provided by inorganic P sources, with an equivalent amount of P from OMs plus 40 kg P ha^{-1} from inorganic P sources, could be as good as 60 kg P ha^{-1} provided solely from inorganic P sources. Urea was applied to provide N at 100 kg N ha^{-1} in all treatments without OM application. Other treatments included a control with no P input and, FYM and tithonia, each applied at a P rate of 20 kg P ha^{-1} without inorganic P source, to test the effect of applying OMs alone but at lower P rate than the recommended one.

The nutrient inputs were evenly spread within the appropriate experimental plots and incorporated to a depth of 0–0.15 m at the time of planting in each of the three seasons of experimentation. However, urea was applied at only a third of the full rate and the rest was applied 5 weeks after planting (WAP). Muriate of potash (KCl) was applied at a rate of 40 kg K ha^{-1} to all plots at the time of planting maize. Hybrid maize (HB 614D variety) was grown in the 2006 long rains season (2006 LR) and 2007 LR while the 'Duma' variety was grown in the 2006 short rains season (2006 SR) using the recommended agronomic practices of the area. Each maize crop was harvested at maturity and the maize grain yields were expressed at 13% moisture content.

Analysis of the organic materials and soils

Tithonia was obtained from the hedges bordering the experimental site while the FYM was from the Bukura Agricultural College farm. These OMs were dried and ground to pass through a 0.5 mm sieve. The quality parameters of the OMs i.e., total N, P, K, Ca, Mg, lignin and polyphenol contents were determined as described by Anderson and Ingram (1993).

In each of the three seasons, soil samples (0–0.15 m depth) were collected at 9 WAP from each plot. The soils were air-dried and prepared for chemical analyses using standard procedures. The soils' pH, exchangeable Al, extractable Olsen P and P sorption characteristics were determined at all sampling times to monitor changes in soil chemical properties. Soil pH was determined using 1:2.5 soil:water ratio (McLean 1965). Exchangeable Al was extracted using unbuffered 1 M KCl and determined by titration (McLean 1965). Available P was determined by the Olsen method as described by Okalebo et al. (2002) while the 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, x/m (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. Sequential fractionation of organic and inorganic P was performed on each of the soil treatments sampled in the 2007 LR by a modified method of Hedley et al. (1982). The following P fractions were determined; Resin extractable inorganic P (Resin-P$_i$), sodium bicarbonate inorganic and organic P (NaHCO$_3$-P$_i$ and NaHCO$_3$-P$_o$), sodium hydroxide extractable inorganic and organic P (NaOH-P$_i$ and NaOH-P$_o$) and dilute HCl extractable inorganic P (HCl-P$_i$).

Mathematical calculations and data analysis

The relative agronomic effectiveness (RAE) of the PRs compared to TSP was calculated as:

$$RAE = (Y_{PR} - Y_{control})/(Y_{TSP} - Y_{control}) \times 100$$

where Y_{PR} is maize grain yield from MPR or BPR applied at the rate of 60 kg P ha^{-1}, Y_{TSP} is maize grain yield from the TSP treatment at the rate of 60 kg P ha^{-1}, and $Y_{control}$ is maize grain yield from the control (0 P).

Analysis of variance (ANOVA) was conducted using the Genstat statistical package (GENSTAT

1993) to determine the effects of treatments on the measured soil chemical parameters and maize grain yields. The standard error of difference between means (SED) was used to compare the treatment means. Mention of statistical significance refers to $P < 0.05$ unless otherwise stated. Quantitative relationships between relevant parameters were developed by regression analyses.

Results and discussions

Characteristics of the organic materials used in the study

Tithonia contained higher amounts of C, N, Ca, Mg and K than FYM but its total P content and pH were lower than FYM (Table 1). The C:N ratios of tithonia and FYM were 13.5 and 20 respectively while the C:P ratios were 140 for tithonia and 90 for FYM. Tithonia had low lignin (<15%) while FYM had high (>15%) lignin content. Both OMs had low polyphenol content (<0.4%). Both these OMs are generally of good quality according to the classification scheme of Palm et al. (2001) and would therefore be expected to mineralize both N and P readily.

Soil pH

The soil pH was generally low, with an average of 4.75 for the control in the three seasons (Table 2). None of the treatments significantly increased the soil pH above the control in the 2006 LR. There was, however, a clear trend whereby the FYM treatments consistently gave higher pH values than the other treatments. In both the 2006 SR and 2007 LR seasons, all the FYM treatments significantly increased the soil pH above the control treatment. Tithonia was not effective in increasing the soil pH and among the tithonia treatments, it was only tithonia (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1}) which significantly increased the soil pH and this

occurred in the 2007 LR only. The increase in soil pH due to application of FYM is consistent with results reported by other workers (Whalen et al. 2000; Narambuye and Haynes 2006a, b) and can partly be attributed to the high pH of the FYM (7.7) at the time of its application. It may also be partly explained by proton exchange between the soil and the added FYM which contains some phenolic, humic-like material (Wong et al. 1998; Tang et al. 1999). Another mechanism that has been proposed to explain the increase in soil pH by such materials as FYM is the specific adsorption of humic material and/or organic acids (the products of decomposition of organics materials) onto hydrous surfaces of Al and Fe oxides by ligand exchange with corresponding release of OH^{-} as suggested by Hue et al. (1986). The failure of tithonia to significantly increase the soil pH in the present study appears to contradict findings by Cong and Merckx (2005) who reported an increase in pH due to application of tithonia in an incubation experiment. The rates of tithonia used in their study (88 t ha^{-1}) were, however, much higher compared to 5 t ha^{-1} in our study.

None of the inorganic P sources, when applied with urea, significantly increased the soil pH above the control in the first two seasons. The application of urea with the inorganic P sources is also likely to have confounded their effect on soil pH. Urea is an acidifying fertilizer and its application at a high rate (100 kg N ha^{-1}) could have slowed down the expected increase in soil pH, particularly by MPR. MPR applied with urea, however, significantly increased the soil pH by the third season of their application. The difference in effectiveness among TSP, BPR and MPR, when applied with urea, in increasing the soil pH in the third season is partially attributed to the differences in their CaCO$_3$ content. MPR was more effective in increasing soil pH likely due to its higher CaCO$_3$ content (nearly 7%) compared to 3% for BPR and 0% for TSP (van Kauwenbergh 1991; Smithson 1999). The reactivity

Table 1 Chemical composition of tithonia and farmyard manure used in the study

OM	m.c. (%)	%N	%P	%Ca	%Mg	%K	%C	pH	%Lig	%Poly
Tithonia	80	3.1	0.30	2.0	0.6	4.1	42	6.5	13	3.17
FYM	30	1.8	0.40	0.9	0.5	2.2	36	7.7	21	0.84

OM organic material, *FYM* farmyard manure, *Lig* lignin, *Poly* polyphenol, *m.c.* moisture content

Table 2 Effect of treatments on the soil pH, exchangeable Al and Olsen P at Bukura

Treatment	pH (water)			Exchangeable Al (cmol kg^{-1})			Olsen P (mg kg^{-1})		
	Season			Season			Season		
	2006 LR	2006 SR	2007 LR	2006 LR	2006 SR	2007 LR	2006 LR	2006 SR	2007 LR
Control (no P input)	4.82	4.65	4.78	0.61	0.65	0.64	5.4	5.0	3.6
Tithonia (20 kg P ha^{-1})	4.82	4.69	4.79	0.38	0.36	0.34	7.4	7.3	7.5
FYM (20 kg P ha^{-1})	4.97	4.99	5.07	0.45	0.50	0.44	7.6	9.2	9.8
MPR (60 kg P ha^{-1}) + urea	4.88	4.66	5.12	0.50	0.41	0.36	10.8	10.5	10.8
BPR (60 kg P ha^{-1}) + urea	4.78	4.64	4.85	0.61	0.56	0.64	7.4	7.4	7.3
TSP (60 kg P ha^{-1}) + urea	4.84	4.67	4.85	0.55	0.52	0.54	17.1	24.1	24.1
Tithonia (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	4.99	4.77	5.16	0.35	0.33	0.33	10.7	12.4	11.6
Tithonia (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	4.82	4.75	4.99	0.57	0.51	0.44	9.9	8.0	9.0
Tithonia (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})	4.96	4.72	4.83	0.47	0.37	0.41	15.3	20.0	17.1
FYM (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	5.05	5.00	5.13	0.37	0.42	0.38	12.1	12.7	11.3
FYM (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	5.01	4.88	5.11	0.51	0.54	0.46	9.8	11.1	10.3
FYM (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})	5.04	4.98	5.00	0.36	0.50	0.37	17.3	22.4	21.5
SED	NS	0.09	0.11	0.21	0.09	0.08	1.2	1.7	1.4
CV%	3.70	2.40	2.8	27.1	17.9	21.1	13	15	15

FYM farmyard manure, *TSP* triple superphosphate, *MPR* Minjingu phosphate rock, *BPR* Busumbu phosphate rock, 2006 LR and 2007 LR are the 2006 and 2007 long rains seasons respectively, 2006 SR is the 2006 short rains season, *SED* standard error of difference between means, *NS* not significant at $P < 0.05$

of the PR is another determinant of its ability to increase the soil pH. The dissolution of PR results in the release of hydroxyl ions and Ca^{2+} ions and consumes protons and thus, it can increase pH depending on the reactivity of the PR (FAO 2004). MPR being a reactive PR, was thus able to increase the soil pH while the unreactive BPR was ineffective in increasing the soil pH. Similar increases in pH following application of MPR have been reported by others in eastern Africa (Ikerra et al. 2006; Nekesa 2007).

Exchangeable aluminum

The most effective treatment in reducing exchangeable Al in all the seasons was tithonia applied in combination with MPR (Table 2). Farmyard manure also significantly reduced the exchangeable Al when applied alone or in combination with inorganic P

sources but its effectiveness generally tended to be lower than that of tithonia for comparable organic/inorganic input combinations. None of the inorganic P sources i.e., TSP, MPR or BPR significantly reduced exchangeable Al in the first two seasons but MPR did so in the third season of application (2007 LR).

The reduction in exchangeable Al observed due to application of FYM can partially be attributed its ability to increase the soil pH. This is consistent with other studies (e.g., Wong et al. 1998; Tang et al. 2007; Narambuye and Haynes 2006b) which reported an increase in soil pH with a concomitant decrease in exchangeable Al during decomposition of organic residues in soils. An increase in soil pH reportedly results in precipitation of exchangeable and soluble Al as insoluble Al hydroxides (Ritchie 1994) thus reducing concentration of Al in soil solution. But this mechanism cannot explain why tithonia significantly

reduced exchangeable Al relative to the control because it (tithonia) did not significantly increase the soil pH. There are, however, other mechanisms involved in the reactions of Al with OMs e.g., complex formation with low molecular weight organic acids and humic material produced during the decomposition (Haynes and Mokolobate 2001) that could explain the reduction in exchangeable Al by tithonia.

Changes in Olsen P in the soil

The Olsen P levels at the site were low ranging from 3.6 to 5.4 mg P kg^{-1} for the control treatment over the three seasons (Table 2) thus making these soils suitable for P replenishment. Addition of both organic and inorganic of P sources generally resulted in an increase in the Olsen P relative to the control but the magnitude of the increase depended on P source and the rate of P application. Averaged across the OMs, at the P application rate of 60 kg ha^{-1}, Olsen P as affected by the inorganic P sources followed the general trend; TSP > MPR > BPR in all the seasons. The higher amount of Olsen P obtained from the application of TSP compared to MPR and BPR is ascribed to the higher solubility of TSP compared to the PRs whose dissolution is usually slow (Chien et al. 1980). The higher amount of Olsen P obtained as a result of application of MPR compared to BPR can be attributed to differences in their solubility arising from varying extents of carbonate substitution in the PRs (Smith and Lehr 1966). BPR is a low carbonate-substituted variety of igneous origin with low reactivity in acids solvents, with a neutral ammonium acetate (NAC) solubility of 10% compared to 23% for MPR (McClellan 1991; van Kauwenbergh 1991). The significant increase in the Olsen P above the control by MPR indicates that the soil conditions at this site were conducive to its dissolution. Some of the factors known to increase the dissolution and subsequent release of P in PRs include, low soil pH, low exchangeable Ca and low P (Khasawneh and Doll 1978).

Combining TSP with urea, generally gave significantly higher Olsen P values compared to its combination with the OMs while combination of MPR with the OMs gave Olsen P values that were not significantly different from application of MPR with urea. However, combination of BPR with FYM or tithonia gave higher Olsen P values than its combination with urea in all the seasons although statistical significance was not always attained. Comparison of the Olsen P values from the OMs applied alone with those of the OM/BPR combinations, however, shows that their Olsen P values were very similar and in some cases, the OMs had higher Olsen P values than those of the OM/BPR combinations, suggesting that most of the Olsen P in the combinations may have been due to mineralization of the OM and not enhanced dissolution of BPR. This is in contrast to other studies (e.g., Subehia and Minhas 1993; Waigwa et al. 2003; Kifuko et al. 2007) which obtained higher levels of available P in soils treated with a combination OM and PR than with PR alone. However, the contribution of P by the OM, in the OM/PR combination, in their studies, was not considered, leading to a higher total P rate in the OM/PR combination than the sole PR application, and hence the higher amounts of available P in the combination. Our results are, however, in agreement with other recent works where total P among the treatments to be compared was the same (Smithson 1999; Savini et al. 2006). The common conclusion in these studies was that combination of PRs with OMs does not enhance the dissolution of the PRs mainly because OMs increase the soil pH and Ca levels which are negatively correlated with PR dissolution (Nziguheba 2007).

Amongst the OMs, FYM was more effective in increasing the Olsen P than tithonia likely due to the fact that FYM was applied when it had partially decomposed and hence was likely to provide more inorganic P in the short-term than tithonia which was applied as a green manure. The significant increase in Olsen P, above the control, by application of OMs alone reflects the large percentage of soluble P in both the tithonia tissues and the FYM. High levels of water soluble P in plant tissues (50–80%) have also been reported by Birch and Hood (1960). Immediate net P mineralization would also be expected to occur because both OMs had a higher P concentration (0.3% in tithonia and 0.4% in FYM) than the critical level of 0.25% required for net P mineralization (Nziguheba et al. 1998).

Phosphorus sorption

Results of the P sorption study are presented using the Langmuir sorption estimates (Table 3). The amount of P sorbed (q) was significantly lower than the

Table 3 The phosphorus sorption parameters, adsorption affinity (k), adsorption maxima (b), and P adsorbed at 0.2 mg P L^{-1} (q) obtained from the Langmuir equation for the various treatments at Bukura in the 2006 LR, 2006 SR and 2007 LR

Treatment	2006 LR			2006 SR			2007 LR		
	k (mg l^{-1})	b (mg kg^{-1})	q (mg kg^{-1})	k (mg l^{-1})	b (mg kg^{-1})	q (mg kg^{-1})	k (mg l^{-1})	b (mg kg^{-1})	q (mg kg^{-1})
Control (no P input)	3.25	681	265	1.50	930	213	1.89	863	236
Tithonia (20 kg P ha^{-1})	2.28	684	214	0.53	1,379	126	1.68	789	198
FYM (20 kg P ha^{-1})	1.68	710	178	1.26	839	166	1.95	730	204
MPR (60 kg P ha^{-1}) + urea	2.68	685	233	1.24	913	181	1.69	776	193
BPR (60 kg P ha^{-1}) + urea	5.65	590	308	1.60	949	228	3.45	703	286
TSP (60 kg P ha^{-1}) + urea	2.86	675	234	1.82	775	205	2.26	734	228
Tithonia (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	3.19	610	237	0.96	803	129	1.50	765	176
Tithonia (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	2.76	676	235	1.16	880	160	1.91	803	212
Tithonia (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})	3.60	594	242	0.93	876	134	1.34	780	162
FYM (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	2.45	719	234	0.86	923	131	1.65	755	187
FYM (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	2.62	659	224	0.91	959	142	2.29	710	220
FYM (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})	2.17	649	195	0.74	845	109	1.31	754	156
SED	0.56	32.7	21.6	0.20	136	11.8	0.24	33.4	13.1
CV%	23.4	6.1	11.4	21.3	18.0	9.0	15.5	5.4	27.2

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

control for only tithonia (20 kg P ha^{-1}), FYM (20 kg P ha^{-1}) and FYM (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1}) in 2006 LR. There were few significant differences in both the adsorption affinity and adsorption maximum among the treatments with only FYM (20 kg P ha^{-1}) significantly reducing adsorption maximum while BPR (60 kg P ha^{-1}) + urea increased it in this season. The adsorption maximum was significantly reduced by tithonia when applied in combination with MPR or TSP, and BPR when applied in combination with urea in the 2006 LR. All the treatments recorded significantly lower adsorption maxima relative to the control in the 2007 LR.

In the 2006 SR and 2007 LR, all the treatments with OMs applied alone or in combination with inorganic fertilizers significantly lowered the P sorption capacity compared to the control (Table 3). MPR was the only inorganic P source, which when applied with urea, significantly reduced P sorption in these

seasons. This is attributed to the ability of MPR to increase the soil pH and concurrently reduce the exchangeable Al in the soil. FYM when combined with TSP consistently sorbed less P than other treatments at all the sampling times.

FYM and tithonia when combined with TSP or MPR were generally more effective in reducing the P sorption capacity of the soils than when they were applied alone. This suggests that the part of the observed reduction in phosphorus sorption was due to the blocking of the P sorption sites by inorganic P provided by TSP and MPR. As observed previously by other authors (Indiati 2000; Whalen and Chang 2002), addition of P to soils decreases the soil's capacity to bind P. However, the failure of the inorganic P sources when applied alone to significantly reduce the soils' P sorption capacity point to other additional mechanisms of reduction in P sorption that were not significantly affected by inorganic

P sources. These mechanisms may include complexation and competition for sorption sites by the products of OM decomposition such as the low molecular weight organic acids (Nziguheba et al. 1998).

Soil P fractions

Labile P (Resin P, and sodium bicarbonate inorganic and organic P)

Both the resin and $NaHCO_3$ P_i were low and, in the absence of P fertilization (control), only 3 and 4% respectively, of the sequentially extracted P fractions were recovered in these (Resin and $NaHCO_3$ P_i) fractions for this treatment. The resin P values ranged from 10.6 mg kg^{-1} (control) to 45.4 mg kg^{-1} (TSP (60 kg P ha^{-1}) + urea) (Table 4). Addition of P from organic or inorganic P inputs caused a significant increase, relative to the control, in the amount of resin P

in all treatments apart from BPR (60 kg P ha^{-1}) + urea. The greatest increase in $NaHCO_3$ P_i was obtained with TSP (60 kg P ha^{-1}) + urea. The sequentially extracted $NaHCO_3$ P_i (Table 4) was 1.5–2.5 times higher than that extracted by the Olsen bicarbonate method (Table 2) due to the longer shaking period of the former. BPR (60 kg P ha^{-1}) + urea had the least amount of $NaHCO_3$ P_i (14.2 mg kg^{-1}) while TSP (60 kg P ha^{-1}) + urea had the highest (34.4 mg kg^{-1}). This is attributed to the low and slow dissolution rate of BPR which delays its entry into the labile pool of P in the soil compared to the other more soluble P sources (Savini et al. 2006).

Bicarbonate extractable P_o was higher than the resin P and $NaHCO_3$ P_i in all the treatments, except TSP (60 kg P ha^{-1}) + urea and FYM (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1}), and represented on average 9% (range 7–10%) of the sum of sequentially extracted P fractions and an average of 43% of the labile P fraction (Table 4). However, the $NaHCO_3$ P_o was

Table 4 Sequentially extracted soil P fractions at Bukura in 2007 LR as affected by organic and inorganic P sources

Treatment	Res-P (mg kg^{-1})	Bic-P$_i$ (mg kg^{-1})	Bic-P$_o$ (mg kg^{-1})	NaOH-P$_i$ (mg kg^{-1})	NaOH-P$_o$ (mg kg^{-1})	HCl-P$_i$ (mg kg^{-1})	Sum of fractions (mg kg^{-1})
Control (no P input addition)	10.6	14.8	34.7	95	188	10.2	353
Tithonia (20 kg P ha^{-1})	21.8	17.5	38.6	114	174	12.6	375
FYM (20 kg P ha^{-1})	24.0	18.6	38.7	122	211	13.1	427
MPR (60 kg P ha^{-1}) + urea	29.0	21.9	35.5	126	198	14.7	424
BPR (60 kg P ha^{-1}) + urea	18.1	14.2	32.2	106	144	41.3	359
TSP (60 kg P ha^{-1}) + urea	45.4	34.4	32.3	159	168	9.7	448
Tithonia (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	31.4	24.7	36.4	130	212	16.6	450
Tithonia (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	21.4	20.1	35.9	138	205	38.2	458
Tithonia (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})	32.4	24.2	38.3	141	191	13.6	440
FYM (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	35.7	18.3	40.2	131	174	15.1	414
FYM (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	33.9	21.0	39.5	126	199	40.8	452
FYM (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})	39.1	27.6	37.5	143	222	13.8	483
SED	4.9	2.4	NS	9.7	NS	3.9	21
CV%	17	11	10	8	10	20	5

FYM farmyard manure, *TSP* triple superphosphate, *MPR* Minjingu phosphate rock, *BPR* Busumbu phosphate rock, *Res-P* resin P, *Bic-P$_i$* bicarbonate extractable inorganic P, *Bic-P$_o$* bicarbonate extractable organic P, *NaOH-P$_i$* sodium hydroxide extractable inorganic P, *NaOH-P$_o$* sodium hydroxide extractable organic P, *HCl-P$_i$* HCl extractable inorganic P, *SED* standard error of difference between means, *NS* not significant at $P < 0.05$

unaffected by the treatments. This is consistent with results from other research using sequential extraction procedures on tropical soils (Paniagua et al. 1995). Organic P is sensitive to microbial activity and has a fast turnover rate and hence difficult to increase through addition of OMs (Tiessen et al. 1984).

Moderately labile P (NaOH P_i and NaOH P_o) and non-labile P (HCl P_i)

The largest amount of P was recovered in the moderately labile fraction and accounted for up to 79% of the sequentially extracted P fractions in the control treatment (Table 4). All the treatments except BPR (60 kg P ha^{-1}) + urea significantly increased the NaOH P_i above the control. This was likely the result of fixation of soluble inorganic P that was added with both the inorganic and organic P sources. The NaOH P_i fraction is a sink for soluble P sources and is the less readily available P that is associated with Al and Fe oxides and may thus represent P adsorption sites (Williams et al. 1980). The failure of BPR (60 kg P ha^{-1}) + urea to significantly increase the NaOH P_i fraction is partly attributed to its unreactive nature. Since BPR had not undergone substantial dissolution, as reflected in its low resin and NaHCO$_3$ P_i fractions, there was not much P_i to be adsorbed by the Al and Fe compounds. Addition of TSP at 60 kg P ha^{-1} produced the greatest net increase in NaOH P_i. The NaOH P_i fraction among the treatments with a combination of organic and inorganic P sources was not significantly different.

The NaOH-P_o fraction was on average 45% of the sum of P fractions (range 37–52%) and constituted the largest fraction of P in the studied soils, but the difference in this P fraction among the treatments was not significant. This fraction has been shown to be an important source of P in low input systems (Beck and Sanchez 1994) and the mineralization of this pool is thus likely to be responsible for provision of most of the P to the crop in the control treatment where no P inputs were applied.

No significant increase, relative to the control, occurred in the HCl P_i content except for soils treated with BPR. BPR (60 kg P ha^{-1}) + urea gave the highest (41.3 mg kg^{-1}) amounts of HCl P_i while TSP (60 kg P ha^{-1}) + urea had the least (9.7 mg kg^{-1}). The HCl P_i fraction was small and accounted for only 2–4% of the sum of P fractions

in the treatments without BPR application. The absence of major changes in the HCl P_i fraction, other than in the BPR treatments, is expected because the soil in this study was very acidic and this favours the formation of Al and Fe P_i compounds, associated with the NaOH P_i fraction, over insoluble Ca–P compounds such as hydroxyapatite which dominate the HCl P_i fraction (Iyamuremye et al. 1996; Sharply et al. 1987). The high HCl P_i in the BPR treatments confirms the unreactive nature of BPR.

Maize grain yields

The grain yields ranged from 1.9 t ha^{-1} (Control) to 5.1 t ha^{-1} (Tithonia (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})) in the 2006 LR (Table 5). In the 2006 SR grain yields were low ranging from 0.7 t ha^{-1} (BPR 60 kg P ha^{-1}) to 2.4 t ha^{-1} (Tithonia (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})). Tithonia (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1}), with a grain yield 5.3 t ha^{-1} maintained its superiority in the 2007 LR while the control had the lowest grain yield (1.3 t ha^{-1}) in this season. The variation in maize yields observed among the seasons is attributed mainly to the differences in rainfall. In the 2006 LR, the amount of rainfall received was generally high (>1,000 mm) and hence higher maize yields were obtained than in the 2006 SR when the rainfall was low (460 mm) and poorly distributed. There was little rainfall received in June and July in the 2007 LR season. This coincided with the flowering period of maize and, therefore, led to a reduction in maize yield compared to the 2006 LR season when rainfall was higher during the 2 months.

Maize did not respond to application of inorganic P sources when applied with urea in both the 2006 LR and 2006 SR. In fact, higher yields were obtained with tithonia and FYM at lower P rates (20 kg P ha^{-1}) than TSP, MPR and BPR, all applied at 60 kg P ha^{-1}, at this site. This suggests that some other factor other than soil P availability had a more profound effect on maize yields. Indeed there was no significant correlation between the Olsen P, sequentially extracted bicarbonate, resin P and NaOH P_i with maize grain yield when all treatments were used to compute the correlation coefficient (Table 6). The factor that was more important in controlling the maize yield was suspected to be Al because of the significant negative correlation ($r^2 = 0.39$) between

Table 5 Effect of phosphorus sources on maize grain yield at Bukura

Treatment	Maize grain yield (t ha^{-1})		
	2006 LR	2006 SR	2007 LR
Control (no P input)	1.9	0.8	1.3
Tithonia (20 kg P ha^{-1})	4.3	1.6	3.6
FYM (20 kg P ha^{-1})	3.2	1.4	2.5
MPR (60 kg P ha^{-1}) + urea	2.6	1.1	2.4
BPR (60 kg P ha^{-1}) + urea	2.0	0.7	1.4
TSP (60 kg P ha^{-1}) + urea	2.2	1.0	1.5
Tithonia (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	4.9	2.3	4.4
Tithonia (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	4.4	1.3	3.9
Tithonia (20 kg P ha^{-1}) + TSP (40 kg P ha^{-1})	5.1	2.4	5.3
FYM (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1})	3.2	1.4	2.7
FYM (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1})	2.9	1.0	2.4
FYM (20 kg P ha^{-1}) + TSP (40 kg P ha^{-11})	2.7	1.4	3.0
SED	0.49	0.3	0.6
CV%	18	28	13

FYM farmyard manure, *TSP* triple superphosphate, *MPR* Minjingu phosphate rock, *BPR* Busumbu phosphate rock, 2006 LR and 2007 LR are the 2006 and 2007 long rains seasons respectively, 2006 SR is the 2006 short rains season, *SED* standard error of difference between mean

exchangeable Al and grain yield (Table 6) when all the treatments were included in the correlation analysis. This relationship was stronger ($r^2 = 0.59$) when only treatments with inorganic P sources applied without OMs were used in the analysis. However, there was no significant correlation between the exchangeable Al and maize yields when treatments with tithonia or FYM were used in the analysis. Application of the OMs is likely to have reduced the levels of Al in the soil solution and hence Al phytotoxicty, thus facilitating better uptake of P by the crop. This is confirmed by the strong relationships between the Olsen P and maize yield when only the treatments with OMs were considered in the correlation analyses (Table 6). For example, 88 and 81% of the variation in maize grain yields among the tithonia treatments could be explained by resin P and Olsen P respectively. There were also strong correlations when only FYM were considered but the correlation between the labile P_i fractions with maize yield, when only the inorganic P sources applied in combination with urea were considered, was not significant. On reducing the Al phytotoxicity, P became a limiting factor and maize yield thus increased with increasing Olsen P. For example, among the tithonia treatments, both the maize yield and Olsen P followed the order; tithonia (20 kg P ha^{-1}) < tithonia (20 kg P ha^{-1}) + BPR (40 kg P ha^{-1}) < tithonia (20 kg P ha^{-1}) +MPR (40 kg P ha^{-1}) < tithonia (20 kg P ha^{-1}) + MPR (40 kg P ha^{-1}). It should be noted,

however, that besides the direct benefits of nutrient supply, and reduction of Al toxicity, OMs such as FYM and tithonia may improve other soil properties such as soil structure, soil moisture holding capacity, cation exchange capacity, microbial activity etc. which in turn influence nutrient acquisition and plant growth (Palm et al. 1997).

Among the OMs, the tithonia treatments consistently gave higher maize yields than corresponding FYM treatments. Since FYM treated soils had higher Olsen P values and lower P sorption capacities than the tithonia treated ones, FYM would be expected to be more effective than tithonia in increasing maize yields in these P-deficient soils. However, the tithonia treatments gave higher maize yields than those of FYM in all the seasons, likely due to the superiority of tithonia in reducing Al phytotoxicty, which apart from P, was the other likely constraint to maize growth in these soils.

The maize yields obtained from the application of FYM alone at only 20 kg P ha^{-1} were not significantly different from those of its combination with TSP, MPR or BPR (60 kg P ha^{-1}) in all the seasons implying that most of the maize yield in the combination was due to the effect of FYM and that maize did not benefit from the extra 40 kg P ha^{-1} provided by the inorganic P sources. The maize yields obtained when tithonia was combined with TSP or MPR (60 kg P ha^{-1}) were significantly higher than those of tithonia applied alone (20 kg P ha^{-1}) in both the 2006

Table 6 Relationships between exchangeable Al and labile and moderately labile inorganic P fractions with maize yields in the 2007 LR at Bukura

Parameter	R^2	Equation
Exchangeable Al (All treatments)[a]	0.39*	Y = −7.19 exch. Al + 6.07
Exchangeable Al (tithonia treatments)[b]	0.12 (ns)	Y = −5.06 exch. Al + 6.35
Exchangeable Al (FYM treatments)[c]	0.18 (ns)	Y = −2.22 exch. Al + 3.51
Exchangeable Al (inorganic treatments)[d]	0.59*	Y = −2.68 exch. Al + 3.15
Olsen P (All treatments)	0.02 (ns)	Y = 0.73 Olsen P + 9.87
Olsen P (tithonia treatments)	0.66***	Y = 2.52 Olsen P + 2.52
Olsen P (FYM treatments)	0.84***	Y = 0.04 Olsen P + 2.07
Olsen P (inorganic treatments)	0.03 (ns)	Y = −0.01 Olsen P + 1.94
Resin P (All treatments)	0.05 (ns)	Y = 0.02 Resin P + 2.19
Resin P (tithonia treatments)	0.77***	Y = 0.11 Resin P + 1.36
Resin P (FYM treatments)	0.44	Y = 0.03 Resin P + 1.76
Resin P (inorganic treatments)	0.01 (ns)	Y = 0.004 Resin P + 1.70
Bic P_i (All treatments)	0.04 (ns)	Y = 0.03 Bic P_i + 2.11
Bic P_i (tithonia treatments)	0.69***	Y = 0.18 Bic P_i + 0.41
Bic P_i (FYM treatments)	0.54***	Y = 0.045 Bic P_i + 1.68
Bic P_i (inorganic treatments)	0.002 (ns)	Y = 0.003 Bic P_i + 1.73
NaOH P_i (All treatments)	0.12 (ns)	Y = 0.003 NaOH P_i + 0.32
NaOH P_i (tithonia treatments)	0.49*	Y = 0.043 NaOH P_i + 1.36
NaOH P_i (FYM treatments)	0.48*	Y = 0.011 NaOH P_i + 1.35
NaOH P_i (inorganic treatments)	0.003 (ns)	Y = 0.001 NaOH P_i + 1.90

Bic P_i is the sequentially extracted bicarbonate inorganic P

[a] All the treatments were included in the regression analyses ($n = 36$)

[b] Only the treatments with tithonia, when applied alone or in combination with inorganic P sources were included in the analysis ($n = 12$)

[c] Only treatments with farmyard manure, when applied alone or in combination with inorganic P sources were included in the regression analysis ($n = 12$)

[d] Only treatments with inorganic P sources i.e., triple superphosphate, Minjingu phosphate rock and Busumbu Phosphate rock when applied with urea were included in the regression analysis ($n = 9$)

* Significant at 0.05; *** Significant at 0.001

SR and 2007 LR but not the 2006 LR. However, the combination of BPR with tithonia gave yields that were not significantly different from those obtained with tithonia when applied alone. In general, tithonia and FYM contributed more than MPR, TSP or BPR in increasing maize yields when they were applied in combination. For example, in the mixtures of OM and inorganic P sources, tithonia contributed 70–81% in increasing the maize yield obtained with mixtures while FYM contributed 95–100% during the 2006 LR and 2007 LR. It may therefore not be economically prudent to apply the additional inorganic fertilizer (40 kg P ha^{-1}) with the OMs to increase maize yields.

The RAE of MPR was >200% in all seasons indicating that although statistically significant differences in maize yields between MPR and TSP were not always attained, MPR is a potentially better source of P than TSP when both are applied in combination with urea in this acid soil. The ability of MPR to slightly increase soil pH and therefore reducing the exchangeable Al at this site compared to TSP is the likely cause of its superior performance. This is supported by the observed significant increase in grain yield above the control in the 2007 LR which coincided with a significant reduction in exchangeable Al by MPR compared to the control. In the previous two seasons, when MPR failed to significantly

reduce exchangeable Al, it also failed to significantly increase the grain yield above the control. Sinclair et al. (1993) observed that though potential increases in soil pH resulting from dissolution of PR are small, they can significantly reduce Al saturation levels in soils and consequently improve crop yields. The very low RAE of BPR (<35%) indicates that BPR is not a suitable P source for direct application in this soil.

Conclusions

There was generally little or no response to P when inorganic P sources were applied in combination with urea implying that some factor, other than P and N, was more important in governing the maize yields in this soil. The significant negative correlation that was obtained between the exchangeable Al and maize yields, suggests that Al toxicity is the likely cause of the low yields in the treatments without OM application. Tithonia which was generally more effective in reducing the exchangeable Al consistently gave higher maize yields than FYM, which was more effective in increasing P availability in the soil. Similarly, when applied with urea, MPR gave higher maize yields than TSP, despite the fact that TSP gave higher amounts of available soil P, likely due to its ability to reduce exchangeable Al. The ability of a material to reduce the exchangeable Al in soils is likely therefore to be more important, in terms of increasing maize yields, than its ability to increase P availability. Provision of 60 kg P ha^{-1} to maize, by combining tithonia or FYM at 20 kg P ha^{-1} with TSP, MPR or BPR at 40 kg P ha^{-1}, in most cases gave yields that were not substantially different from the application of the OMs alone at 20 kg P ha^{-1}. Economic considerations may therefore favour the application of tithonia or FYM alone at 20 kg P ha^{-1}, rather than combining them with the inorganic P sources applied at 40 kg P ha^{-1}, for maize production at this site.

References

Anderson JM, Ingram JSI (1993) Tropical soil biology and fertility: a handbook of methods. CAB International, Wallingford

Beck MA, Sanchez PA (1994) Soil phosphorus fraction dynamics during 18 years of cultivation on a typic Paleudult. Soil Sci 34:1424–1431

Birch HF, Hood CC (1960). Phosphorus transformations in decomposing plant residues. EAAFRO Record of Research Annual Report, KARI, Muguga, Kenya, pp 22–24

Chien SH, Clayton WR, McClellan GM (1980) Kinetic dissolution of phosphate rocks in soils. Soil Sci Soc Am J 44:260–264

Cong PT, Merckx R (2005) Improving phosphorus availability in two upland soils of Vietnam using *Tithonia diversifolia* H. Plant Soil 269:11–23. doi:10.1007/s11104-004-1791-1

FAO (2004) Use of phosphate rocks for sustainable agriculture. Fertilizer and Plant Nutrition Bulletin no. 13. Rome, Italy

Fox RL, Kamprath EJ (1970) Phosphate sorption isotherms for evaluating the requirements of soil. Soil Sci Soc Am Proc 34:902–907

FURP (1987) Fertilizer use recommendation project. Compilation of results from former fertilizer trials in Kenya. Ministry of Agriculture, Nairobi

GENSTAT (1993) Gensat 5 release 3.2 reference manual. Oxford University Press, Oxford

Haynes RJ, Mokolobate MS (2001) Amelioration of aluminum toxicity and phosphorus deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and mechanisms involved. Nutr Cycl Agroecosyst 59:47–63. doi:10.1023/A:1009823600950

Hedley MJ, Steward JWB, Chauhan BS (1982) Changes in inorganic soil phosphorus fractions induced by cultivation practices and laboratory incubation. Soil Sci Soc Am J 46:970–976

Hue NV, Craddock GR, Adams F (1986) Effect of organic acids on aluminum, toxicity in subsoils. Soil Sci Soc Am J 25:3291–3303

Ikerra ST, Semu E, Mrema JP (2006) Combining *Tithonia diversifolia* and minjingu phosphate rock for improvement of P availability and maize grain yields on a chromic acrisol in Morogoro, Tanzania. Nutr Cycl Agroecosyst 76:249–260. doi:10.1007/s10705-006-9007-0

Indiati R (2000) Addition of phosphorus to soils with low to medium phosphorus retention capacities, I. Effect on soil phosphorus sorption properties. Commun Soil Sci Plant Anal 26:1863–1872. doi:10.1080/00103629509369413

Iyamuremye F, Dick RP, Baham J (1996) Organic amendments and phosphorus dynamics: II. Distribution of soil phosphorus fractions. Soil Sci 161:436–443. doi:10.1097/00010694-199607000-00003

Jama B, Palm CA, Buresh RJ, Niang AI, Gachengo C, Nziguheba G, Amadalo B (2000) *Tithonia diversifolia* as a green manure for soil fertility improvement in Western Kenya. A review. Agrofor Syst 49:201–221. doi:10.1023/A:1006339025728

Khasawneh FE, Doll EC (1978) The use of phosphate rock for direct application to soils. Adv Agron 30:159–206. doi:10.1016/S0065-2113(08)60706-3

Kifuko MN, Othieno CO, Okalebo JR, Kimenye LN, Ndungu KW, Kipkoech AK (2007) Effect of combining organic residues with Minjingu phosphate rock on sorption and availabilty of phosphorus and maize production in acid soils of western Kenya. Exp Agric 43:51–66. doi:10.1017/S0014479706004121

Kpomblekou K, Tabatabai MA (1994) Effect of organic acids on release of phosphorus from phosphate rocks. Soil Sci 158:442–453. doi:10.1097/00010694-199415860-00006

McClellan GH (1991) Use of east and southeast African indigenous agrominerals for fertilizer production. Fert Res 30:125–126. doi:10.1007/BF01048644

McLean EO (1965) Soil pH and lime requirement. In: Black CA (ed) Methods of soil analysis, part 2. ASA, Madison, pp 199–223

Narambuye FX, Haynes RJ (2006a) Effect of organic amendments on soil pH and Al solubility and use of laboratory indices to predict their liming effect. Soil Sci 17110:754–763. doi:10.1097/01.ss.0000228366.17459.19

Narambuye FX, Haynes RJ (2006b) Short-term effects of three animal manures on soil pH and aluminum solubility. Aust J Soil Res 44:515–521. doi:10.1071/SR05062

Nekesa AO (2007). Effect of Minjingu phosphate rock and Agricultural lime in relation to maize, groundnut and soybean yields on acid soils of western Kenya. MPhil. Thesis, Moi University, Eldoret, Kenya

Nziguheba G (2007) Overcoming phosphorus deficiency in soils of Eastern Africa: recent advances and challenges. In: Bationo A, Waswa B, Kihara J, Kimetu J (eds) Advances in integrated soil fertility management in sub-Saharan Africa: challenges and opportunities. Springer, New York, pp 49–160

Nziguheba G, Palm CA, Buresh RJ, Smithson PC (1998) Soil P fractions and adsorption as affected by organic and inorganic sources. Plant Soil 198:159–168. doi:10.1023/A:1004389704235

Okalebo JR, Gathua KW, Woomer PL (2002) Laboratory methods of soil and plant analysis. A working manual, vol 2. TSBF-CIAT and SACRED Africa, Nairobi

Palm CA, Myers RJK, Nandwa S (1997). Combined use of organic and inorganic nutrient sources for soil fertility replenishment. In: Buresh RJ, Sanchez PA, Calhoun F (eds) Replenishing soil fertility in Africa. SSSA special publication no. 51. Madison, Wisconsin, pp 193–217

Palm CA, Gachengo CN, Delve CN, Cadisch G, Giller KE (2001) Organic inputs for soil fertility management in tropical agroecosystems: application of an organic resource database. Agric Ecosyst Environ 83:27–42. doi:10.1016/S0167-8809(00)00267-X

Paniagua A, Mazzarino MJ, Kass D, Szott L, Farnadez C (1995) Soil phosphorus fractions under five tropical agroecosystems on a volcanic soil. Aust J Soil Res 33:311–320. doi:10.1071/SR9950311

Probert M, Okalebo JR, Simpson RK (1995) The use of manure on smallholder farms in semi-arid Eastern Kenya. Exp Agric 31:371–381. doi:10.1017/S0014479700025540

Ritchie GSP (1994) Role of dissolution and precipitation of minerals in controlling soluble aluminum in acid soils. Adv Agron 53:47–83. doi:10.1016/S0065-2113(08)60612-4

Savini I, Smithson PC, Karanja NK, Yamasaki H (2006) Influence of Tithonia diversifolia and triple superphosphate on dissolution and effectiveness of phosphate rock in acidic soil. J Plant Nutr Soil Sci 169:593–604. doi:10.1002/jpln.200521931

Sharply AN, Tiessen H, Cole CV (1987) Soil phosphorus forms extracted by soil tests as a function of pedogenesis. Soil Sci Soc Am J 51:362–365

Sinclair AG, Johnstone PD, Smith LC, O'Connor MB, Nguyen L (1993) Agronomy modeling and economics of reactive phosphate rocks as slow-release phosphate fertilizers for grasslands. Fert Res 36:229–238

Smith JP, Lehr JR (1966) An X-Ray investigation of carbonate apatites. J Agric Food Chem 14:342–349. doi:10.1021/jf60146a004

Smithson P (1999) Interactions of organic materials with phosphate rocks and triple superphosphate. In: Buresh R, Sinclair FL (eds) Special issue on phosphorus availability, uptake and cycling in tropical agroforestry. Agroforestry Forum, vol 9, no. 4, pp 37–40

Subehia SK, Minhas RS (1993) Phosphorus availability from Udair rock phosphate as influenced by different organic amendments. J Indian Soc Soil Sci 41:96–99

Tang C, Sparling GP, McLay CDA, Raphael C (1999) Effect of short-term residue decomposition on soil acidity. Aust J Soil Res 37:561–573. doi:10.1071/S98104

Tang Y, Zhang H, Schroder JL, Payton ME, Zhou D (2007) Animal manure reduces aluminum toxicity in acid soils. Sci Soc Am J 71:1699–1707. doi:10.2136/sssaj2007.0008

Tiessen H, Stewart JWB, Cole CV (1984) Pathways of phosphorus transformations in soils of differing pedogenesis. Soil Sci Soc Am J 48:853–858

van Kauwenbergh SJ (1991) Overview of phosphate deposits in Eastern and Southern Africa. Fert Res 30:127–150. doi:10.1007/BF01048645

van Straaten P (2002) Rocks for crops: agrominerals of sub-Saharan Africa. ICRAF, Nairobi, p 338

Waigwa MW, Othieno CO, Okalebo JR (2003) Phosphorus availability as affected by application of phosphate rock combined with organic materials to acid soils in western Kenya. Exp Agric 39:395–407. doi:10.1017/S0014479703001248

Whalen JK, Chang C (2002) Phosphorus sorption capacities of calcareous soils receiving cattle manure applications for 25 years. Commun Soil Sci Plant Anal 33:1011–1026. doi:10.1081/CSS-120003870

Whalen JK, Chang C, Clayton GW, Carefoot JP (2000) Cattle manure can increase the soil pH of acid soils. Soil Sci Soc Am J 64:962–966

Williams JDH, Mayer T, Nriagu JO (1980) Extractability of phosphorus from phosphorus minerals common in soils and sediments. Soil Sci Soc Am J 44:462–465

Wong MTF, Nortcliff S, Swift RS (1998) Method for determining the acid ameliorating capacity of plant residue compost, urban waste compost, farmyard manure and peat applied to tropical soils. Commun Soil Sci Plant Anal 29:2927–2937. doi:10.1080/00103629809370166

Woomer P, Okalebo JR, Sanchez PA (1997) Phosphorus replenishment in western Kenya: from field experimentation to operational strategy. Afr Crop Sci J 3:559–570