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ORIGINAL ARTICLE

Long-term effects of TSP and Minjingu phosphate rock applications on yield response of maize and soybean in a humid tropical maize–legume cropping system

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Abstract Crop production in sub-Sahara Africa is constrained by low soil phosphorus (P) content. A study was conducted in western Kenya to explore alternative P inputs and ways of optimizing their effectiveness and profitability. A field experiment established in 2007 studied the effects of Minjingu phosphate rock (MPR) and triple superphosphate (TSP) on maize, common beans and soybean yield. MPR and TSP were applied seasonally at a rate of 0, 12.5, 25 and 50 kg P ha^{-1} either alone or in combination. Application of P, irrespective of amount, resulted in significantly higher grain yield and total biomass for maize, common beans and soybean compared with the 0 P treatment. Applying P at 12.5 kg ha^{-1} resulted in significantly ($\rho \leq 0.05$) lower maize, common beans and soybean grain yields than all the other P rates. On the other hand, application of P at 25 kg ha^{-1} resulted in similar yields to the higher P application rates. Relative agronomic effectiveness of MPR was similar for both maize and soybeans in most seasons, confirming that MPR has high potential for direct application in these soils. Switching from no application to P applied at 12.5 and also 25 kg P ha^{-1} attracts a marginal rate of return of at least 200 %. Switching from 25 kg P ha^{-1} to any of the other options attracted MRR < 200 %. This implies that adoption of either MPR or TSP by farmers in western Kenya is profitable for maize and soybeans production, given that MRRs were above 100 % minimum acceptable rate of return which is a requirement for farmers to change from one technology to another.

Keywords Minjingu phosphate rock · Triple superphosphate · Acid soils · Maize · Soybean

Introduction

Soils in western Kenya have low inherent fertility (FAO 2001), characterized by negative nutrient balances of nitrogen (N), phosphorus (P) and potassium (K) triggered by continuous cropping without adequate restorative practices. In this region P losses are estimated at about 3–13 kg ha^{-1}. As a result of low and declining soil fertility, average maize production is <1.0 t ha^{-1} (Sanchez et al. 1997). Responses of maize to P are significant even at rates as low as 10 kg P ha^{-1} (Jama et al. 1997) indicating the importance of adding P to crops in this area. Application of P-based fertilizers is, therefore, needed seasonally to overcome P deficiency and to restore and maintain the productivity of these soils.

However, only 10–30 % of P applied as water-soluble P fertilizers is usually captured/taken up by

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plants in the year of application. Most P from the fertilizer granule is retained by the soil as adsorbed-P reaction products or residual fertilizer compounds (Bolland et al. 1988). These Kenyan soils have a significant capacity to sorb large amounts of P, thus taking the P out of the soil solution. This limits the availability of added inorganic P for plant growth and productivity in subsequent seasons.

Many smallholder farmers in the region find it increasingly difficult to afford water-soluble commercial P fertilizers such as triple superphosphate (TSP) because of high cost. This called for the need to evaluate alternative means to increase crop production such as less expensive indigenous phosphate rocks (PRs). Africa has promising PR sources such as Minjingu in northern Tanzania and Busumbu and Sukulu in eastern Uganda, both of which have high relative reactivity (van Straaten 2002). Such phosphate rocks are best suited for direct application to acid soils ($pH < 5.5$) with low Ca and P concentrations (Sanchez 1976; Rajan et al. 1996). The direct application of PR is considered a cost-effective alternative for correcting P deficiencies in these soils, mostly Eutrudox and Kandiudalfs (Braun et al. 1997).

Minjingu phosphate rock (MPR) is an ideal P fertilizer material for the highly weathered acidic soils (Buresh et al. 1997) which are widespread in western Kenya. MPR requires no further modification, apart from fine grinding. The suitability of Minjingu PR as P source for crops in P-deficient soils has been demonstrated by various authors. For example, Bromfield et al. (1981) reported a relative agronomic effectiveness (RAE) of 75 % for Minjingu PR applied to maize in a five seasons study in western Kenya. Studies on optimal TSP and MPR P recommendations under the predominant maize–legume based agricultural systems in western Kenya are few. The present investigation was undertaken in order to (1) quantify the long-term effects of different P fertilizer sources on crop productivity, (2) to assess the economic returns of these different products to farmers, and (3) develop optimal TSP and MPR recommendations relevant to maize–legume based agricultural systems.

Materials and methods

Site description

The study was conducted in Maseno, Siaya district situated at latitude 0° 25′N and longitude 33° 54′E, as long term field trial established in 2007. This site is at an altitude of 1310 m above sea level at 0° 08′ 38.9″N and 34° 25′ 27.5″E and receives a mean annual rainfall of about 1700 mm. The area has a bi-modal rainfall distribution with two cropping seasons (long rains between March and August and short rains between September and January). Temperatures range from 14 to 34 °C. The soil are Eutrodox and Kandiudalfs (Hartemink et al. 1996; USDA 1999) developed from various parent material including intermediate and basic igneous rocks and sedimentary rocks.

Experimental design and treatments

The trial was set up as a randomized block design and consisted of seven treatments with four replications. The treatments were a nil fertilizer treatment (without NPK), and all the other treatments received blanket application of N and K and combined or sole sources of P (Table 1). The omission of N and K check was informed by previous work in western Kenya (Kihara and Njoroge 2013) which demonstrated that there was no grain yield response to P alone unless N was also applied and vice versa. The nutrients N, P and K were applied in the form of urea, either TSP and MPR, and potassium chloride respectively. Phosphorus and K fertilizers were banded within the crop rows. The experiment was on-farm and researcher-managed. However, most of the operations were carried out by local farmers, following their practices.

The chemical characteristics of MPR were 12.9 % total P, 53 g kg^{-1} carbonate, 330 g kg^{-1} total calcium, 2 % citric acid soluble P and less than 1 % water soluble P. Maize (DH04), bush beans (KK8) and soybeans (SB20 from 2007 to 2010 and SB 25 in 2011) were test crops grown under maize–bush beans rotation or maize–soybeans rotation system. The high susceptibility of the soybean variety SB20 to soybean rust disease necessitated the change to SB25 a soybean rust resistant variety in 2011. The maize–bush beans rotation was present during the short rain season and maize–soybeans rotation system was present during the long rains season. Plot sizes were 6 m × 6 m in size. The crop rotations and cropping systems in this study were initiated in 2007, and remained in the same place through to 2013 (i.e., a 6-year period involving 10 cropping seasons in total). The experiment tested the effects of four rates (0, 12.5, 25 and 50 kg ha^{-1}) of P applied in two forms: a soluble form (triple

Table 1 Treatments testing P sources as implemented in western Kenya 2007–2012 period

Treatment	N	K	Application rate (P kg ha^{-1})	
			TSP	MPR
1	0	0	0	0
2	60	60	12.5	0
3	60	60	25	0
4	60	60	12.5	50
5	60	60	25	25
6	60	60	50	0
7	60	60	0	50

superphosphate-TSP) and a less soluble form (Minjingu phosphate rock-MPR; Table 1). Two treatments of TSP at 12.5 kg Pha^{-1} + MPR at 50 kg P ha^{-1} and TSP at 25 kg P ha^{-1} and MPR at 25 kg P ha^{-1} were included. This was to help verify our hypothesis that the level of plant available P from MPR will be increased with increasing proportion of TSP in the TSP–MPR mixtures.

The P fertilizers were applied by hand to the experimental plots at sowing for each season for 10 seasons.

The test crops were planted using a rope at a spacing of 75 cm × 25 cm, 45 cm × 10 cm and 45 cm × 5 cm for maize, common bean and soybean, respectively. Planting was done at the onset of rainfall between mid-February and early-March of each year for the long rains season and between late-September and early-October for short rains season. The plots were weeded at least twice per season depending on the weed intensity.

The crops were harvested from the plots at maturity. Field management and harvesting was done following standard agronomic practices. For example, a net plot of 22.5 m^2 (5 m × 4.5 m) was harvested followed by shelling/threshing, drying the different components at 60 °C for 48 h and recording the dry weight measurements.

Soil analysis

The soil was sampled at a depth of 0–15 cm, then air dried and sieved through a 2 mm sieve. Selected physical and chemical properties of the soils were determined (Table 2). Soil pH (water and 0.01 M KCl) analysed at 1:2.5 soil–solution ratio, was determined electrometrically (McLean 1965).

Soil texture was determined by the hydrometer method (Dewis and Freitas 1989). Organic carbon was determined using Walkley–Black procedure (Nelson and Sommers 1982). Potassium was determined using flame photometer, while Ca and Mg were determined using atomic absorption spectrophotometer (Chapman 1965).

Soil samples of alternating seasons were analyzed for available P using the Bray-1 method to determine the trend of soil P changes with time. Selected soil samples in alternating years thus 2007, 2009 and 2011 were air-dried, and extracted with 0.03 M NH_4F and 0.025 M HCl in a 1:20 soil–solution ratio (Bray and Kurtz 1945).

Determining economic benefits

To assess the costs and benefits associated with different treatments, the partial budget technique as described by CIMMYT (1988) was applied. Economic analysis was done using the prevailing market prices for inputs at planting and farm gate prices for outputs, at the time the crop was harvested. To reflect difference between experimental yield and the yield that farmers could expect, the yields were adjusted downwards by 10 % for farmer management and a further 5 % for small plot size (Spencer 1993). Farm gate price of output (value) at harvest (using the prices of the year 2007) was US$ 0.40 (US$ 1 = 87 Kenya shillings) kg^{-1} of maize and US$ 0.60 kg^{-1} of soybean.

Although maize stover is often used as a source of fuel–wood and livestock feed in the study area, its cost is not included in the analysis. Gross revenue was calculated by multiplying yield data with the relevant constant price. The price of maize and soybean seed planted was US$ 0.05 and US$ 0.80 kg^{-1} respectively.

Table 2 Baseline soil characteristics

Parameter	Value	
pH in water (1:2.5)	5.6	McLean (1965)
pH in KCl (1:2.5)	4.2	McLean (1965)
Exchangeable calcium (cmol$_c$ kg^{-1})	5.74	Chapman (1965)
Exchangeable magnesium (cmol$_c$ kg^{-1})	1.99	Chapman (1965)
Exchangeable potassium (cmol$_c$ kg^{-1})	0.14	Chapman (1965)
Extractable phosphorus (mg P kg^{-1})	1.19	Bray and Kurtz (1945)
Total soil organic carbon (%)	1.23	Nelson and Sommers (1982)
Total nitrogen (%)	0.12	Bremner and Mulvaney (1982)
Clay (%)	51	Dewis and Freitas (1989)
Sand (%)	22	Dewis and Freitas (1989)
Silt (%)	26	Dewis and Freitas (1989)

Farm gate cost of fertilizer was US\$ 1.50 kg^{-1} P for TSP, US\$ 5.75 kg^{-1} of P for MPR elemental P content of 8.8 % was used (van Straaten 2002), US\$ 0.60 kg^{-1} of urea and US\$ 0.75 kg^{-1} of muriate of potash. These, together with costs of labour (US\$ 1.7 day^{-1}) to plant and weed were used to calculate the total variable costs. Gross margin was calculated as the difference between gross revenue and total variable costs. Thus, the total variable cost (seed, fertilizer, labor for planting, weeding and harvesting) and gross revenue based on farm gate prices were used. To determine the treatments suitable for uptake by farmers, dominance analysis was undertaken. The treatments that were dominated (inferior), i.e., those options with lower net returns (and higher total variable costs) than other options with higher net returns and lower total variable costs (Kihara et al. 2010), were removed from further analysis. For the non-dominated treatments, marginal rate of return (MRR) for switching from the lowest to the next best alternative were calculated. The percentage (%) MRR between any pair of non-dominated treatments denotes the return per unit of investment in fertilizer expressed as a percentage. To obtain an estimate of these returns we calculate the MRR, which is given by the following formula (CIMMYT 1988):

$$MRR\ (between\ treatments\ a\ and\ b) = \frac{Change\ in\ NB(NB_b - NB_a)}{Change\ in\ TCV(TCV_b - TCV_a)} \times 100$$

where NB is net benefits and TCV is total variable costs.Thus, a MRR of 100 % implies a return of US\$ 1 on every dollar of expenditure in the given variable input.

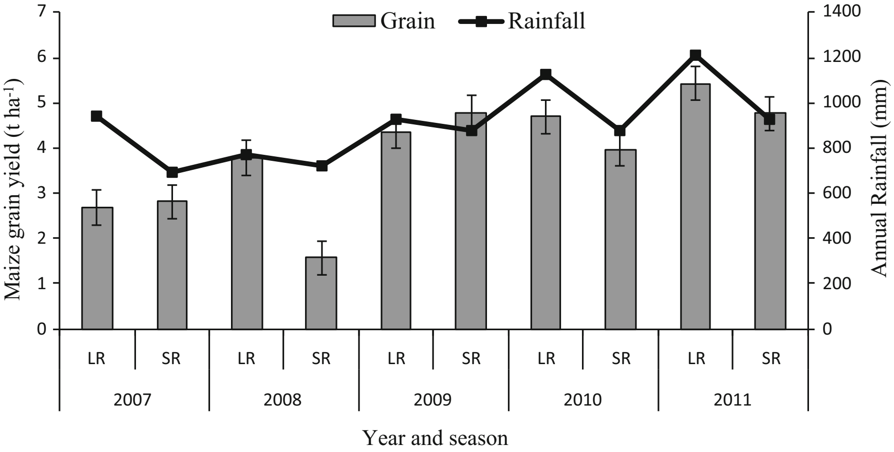
Statistical analysis

Analysis of variance was carried out using R software version 3.0.1. The mixed model procedure was used for analysis of variance between treatments allowing for analysis of random effects of replicate and fixed effects of season and P fertilizer application. Least significant differences were used to separate means. Reference to statistical significance refers to $p < 0.05$ unless otherwise noted.

The relative agronomic effectiveness (RAE) of a rock phosphatic fertilizer is defined as a ratio of the response from a phosphate rock to that from a standard phosphatic fertilizer, usually triple superphosphate (TSP; Le Mare 1991) and expressed as a percentage. In this study, the effectiveness of MPR expressed as RAE was calculated relative to the effectiveness of TSP for common beans, soybean and maize grain yield according to the procedure of Gopalakrishnan and Palaniappan (1992):

$$RAE = \frac{Grain\ yield\ in\ PR\ treated\ plot - Grain\ yield\ in\ P\ control}{Grain\ yield\ in\ TSP\ treated\ plot - Grain\ yield\ in\ P\ control} \times 100.$$

Fig. 1 Effect of long rains (LR) and short rains (SR) season mean maize grain yield across all treatments. *Error bars* refer to SE



Results

Soil characteristics

Soil analysis results summarised in Table 2 clearly demonstrate that these soils are grossly deficient in P and K. For example, 30 mg kg^{-1} (Wortmann et al. 2009) is the critical level of available Bray-1 P for the crops tested, but soils were below this threshold. The need for major nutrient inputs in these soils is evident through the significant response of the three crops to applied P.

Grain yield response to applied P as affected by season

The effect of P application on yield varied with P levels and the prevailing weather conditions in the particular growing season. For the three crops, Year and P source had significant effect on yield ($\rho \leq 0.05$) while also a significant Year × P interaction ($\rho \leq 0.001$, 0.01, and 0.05 for maize, soybeans and common beans respectively) was observed. Overall, the short rains season with rain ranging from 600 to 890 mm had the lowest maize grain yield of 1.8 t ha^{-1} compared to long rains ranging from 750 to 1200 mm with the lowest maize grain yield of 2.8 t ha^{-1}. The highest maize grain yield for the long and short rains seasons were 5.5 and 4.8 t ha^{-1}, respectively. The maize grain yield was consistently low during the short rains seasons except in 2007 and 2009 (Fig. 1).

Effect of phosphorus application and source on maize yield

Addition of P fertilizers, even at a low rate (12.5 kg P ha^{-1}) significantly increased maize, common beans and soybean yields over the nil fertilizer treatment by 100, 79 and 94 % respectively throughout the seasons (Table 3). Addition of TSP at 25 kg P ha^{-1} or more doubled the maize total biomass yield compared to the 0 P treatment and the increase was larger with time and as the P rate increased (Fig. 2). The percent increase in maize grain yield over nil fertilizer treatment after application of TSP 50 kg^{-1} and MPR 50 kg ha^{-1} was 148 and 163 % respectively. Combined application of MPR 50 kg ha^{-1} + TSP 12.5 kg ha^{-1} and MPR 25 kg ha^{-1} + TSP 25 kg ha^{-1} increased maize grain yield over nil fertilizer treatment by 146 and 160 % respectively. The application of P fertilizer at rates at 50 kg ha^{-1} although significantly better than the nil fertilizer treatment and 12.5 kg P ha^{-1}, was not different from the yield at 25 kg P ha^{-1} application rate. Further, an interesting pattern in response to P source was observed with time in the long rains seasons. Here, maize yield in 2008 increased by 13, 29, 40 and 13 % in treatments MPR (50 kg ha^{-1}), TSP (12.5 kg ha^{-1}), TSP (25 kg ha^{-1}) and TSP (50 kg^{-1}), respectively, compared with yield in 2007; and yields in 2009 were further increased by 52, 35, 54 and 59 %, respectively, compared with yield in 2008 (Fig. 2). A key result is that both biomass and grain yield were not significantly different between TSP (25 and 50 kg P ha^{-1}) and MPR (50 kg P ha^{-1}) treatments.

Table 3 Effect of applied phosphorus fertilizers and season on grain yield of maize, common beans and soybeans

Year	TSP 50	TSP 12.5 + MPR 50	MPR 50	TSP 25 + MPR 25	TSP 25	TSP 12.5	Nil fertilizer treatment	Grand mean[b]
Maize LR								
2007	2.94ab	3.02ab	3.60a	3.55a	2.42ab	2.452ab	1.74b	2.82d
2008	4.81ab	4.27ab	5.00a	4.73ab	4.16ab	3.82b	2.00c	4.11c
2009	5.21ab	5.67ab	5.94a	5.46ab	4.28ab	3.885bc	2.2125c	4.66bc
2010	5.54ab	6.27a	6.07ab	5.93ab	5.09ab	4.27b	2.22c	5.05ab
2011	6.88ab	6.49ab	6.50ab	7.33a	6.12ab	5.02b	2.52c	5.84a
Grand mean[a]	5.03ab	5.00ab	5.359a	5.29a	4.37bc	3.83c	2.03d	
Maize SR								
2007	3.80a	3.79a	3.45ab	3.29ab	2.32ab	2.21ab	1.83b	2.96c
2008	1.8625a	2.0375a	1.945a	1.605a	1.665a	1.42ab	0.98b	1.65d
2009	6.54a	6.11ab	6.11ab	6.08ab	5.56b	4.22c	1.60d	5.17a
2010	4.82a	5.21a	4.67a	4.84a	4.77a	3.52b	1.97c	4.26b
2011	6.12a	5.94ab	5.62ab	5.85ab	4.73c	4.73c	2.25d	5.03a
Grand mean[a]	5.08a	5.11a	4.81a	4.80a	4.43a	3.57b	1.81c	
Common Beans SR								
2007	1.08a	1.04ab	1.05ab	0.97ab	0.90ab	0.72bc	0.49c	0.89c
2008	0.63a	0.78a	0.71a	0.73a	0.74a	0.68a	0.39b	0.67d
2009	1.05a	1.03a	0.85ab	0.74b	0.89ab	0.67b	0.42c	0.81c
2010	1.12ab	1.37a	1.10ab	1.09ab	1.07ab	0.98b	0.53c	1.04b
2011	1.43a	1.27a	1.44a	1.42a	1.42a	1.25a	0.57b	1.26a
Grand mean[a]	0.99ab	1.04a	0.98ab	0.95ab	0.96ab	0.83b	0.46c	
Soy beans LR								
2007	1.14a	1.09ab	1.02ab	1.15a	0.95ab	0.78b	0.47c	0.94d
2008	1.63ab	1.71a	1.72a	1.73a	1.50ab	1.29b	0.93c	1.50b
2009	1.66ab	1.90a	1.77a	1.78a	1.44b	1.02c	0.46c	1.43c
2010	0.76a	0.72a	0.87a	0.67a	0.80a	0.64a	0.35b	0.69e
2011	3.14a	2.69c	2.90bc	2.99ab	2.43d	1.59e	0.63f	2.34a
Grand mean[a]	1.74a	1.68a	1.72a	1.72a	1.47a	1.07b	0.53c	

Means that were significantly different based on LSD analysis are labeled with different letters

[a] Grand mean refers to cumulative mean treatments across all seasons (years)

[b] Grand mean refers to cumulative mean seasons (years) across all treatments

Effect of phosphorus application and source on legume yield

For the legumes, Triple Super Phosphate at 50 kg ha^{-1} and MPR at 50 kg ha^{-1} increased soybean grain yield over nil fertilizer treatment by 125 and 123 % respectively. Application of $\geq$25 kg P ha^{-1} as either TSP or MPR gave a common bean grain yield increase over nil fertilizer treatment of 116 and 118 %, respectively. The increase in soybean grain yield over nil fertilizer treatment due to application of MPR 50 kg ha^{-1} + TSP 12.5 kg ha^{-1} and MPR 25 kg ha^{-1} + TSP 25 kg ha^{-1} was 114 and 123 % respectively. However, the magnitude of increase in maize and soybean yield due to application of TSP (12.5 or 25 kg ha^{-1}) + MPR (50 or 25 kg ha^{-1}) was

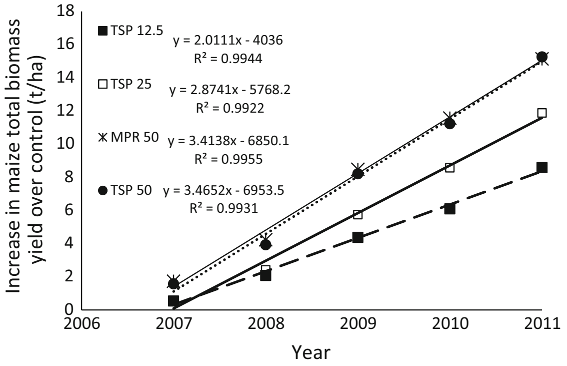


Fig. 2 Maize grain yield response on fertilizer type and rate with time

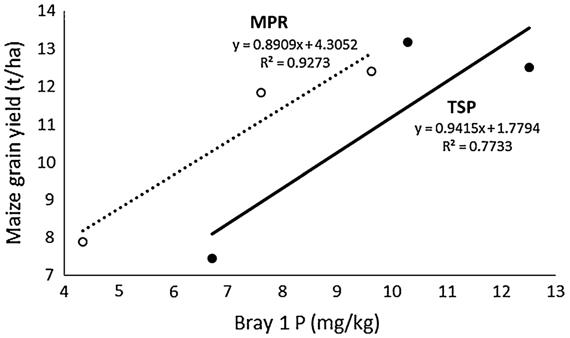


Fig. 3 The relationship between maize grain yield and extractable Bray-1 P

similar to where either TSP (50 kg ha^{-1}) or MPR (50 kg ha^{-1}), were applied. The performance of MPR or TSP applied at 50 kg ha^{-1} gave similar magnitude of increase in grain yield for the three test crops.

Bray-1 P analysis for nil fertilizer treatment was 4.59, 3.80 and 3.93, MPR at 50 kg P ha^{-1} was 4.35, 9.63 and 7.61 mg P kg^{-1} while for TSP at the same rate was 6.71, 12.51 and 10.39 mg P kg^{-1} for the years 2007, 2009 and 2011 respectively. This helps to corroborate our hypothesis that P additions in successive cropping seasons can build residual soil P fertility.

Furthermore, the correlation coefficients between Bray-1 extractable P and dry matter yield (maize) for TSP (50 kg P ha^{-1}) and MPR (50 kg P ha^{-1}) were r = 0.77** and r = 0.93** respectively (Fig. 3). However, the relationships between dry matter yield and Bray P for the two legumes were poorly correlated with coefficients of $r^2 = 0.24$ and $r^2 = 0.045$ for common beans and $r^2 = 0.0099$ and $r^2 = 0.02$ for soybeans when TSP (50 kg P ha^{-1}) and MPR (50 kg P ha^{-1}) were applied respectively.

Relative agronomic effectiveness (RAE) of P fertilizers

The RAE in Table 4 relates the effectiveness of MPR as compared to TSP the standard soluble source of P. In maize, the RAE for MPR, ranged from 91 to 155 % and 82 to 109 % at 50 kg P ha^{-1} for the long and short rains seasons respectively. In all long rains seasons except 2011, RAE of MPR was higher than 100 %. The RAE values for soybean ranged from 82 to 126 % at 50 kg P ha^{-1} with higher values being observed after first year of study. Both maize and soybean gave RAE mean of above 100 % during the long rains except 2011 for maize and 2007 and 2011 for soybeans. The same seasonal trend was observed for cumulative applications of the P fertilizers. For common bean, the effectiveness of MPR compared to TSP ranged from 69 to 98 % at 50 kg P ha^{-1}. Cumulative P application over time always gave higher grain yield in all treatments where MPR was applied than application of TSP. The grain yield due to cumulative P application followed the order MPR 50 kg P ha^{-1} > TSP 25 kg P ha^{-1} + MPR 25 kg P ha^{-1} > TSP 12.5 kg P ha^{-1} + MPR 50 kg P ha^{-1} > TSP 50 kg P ha^{-1} > TSP 25 kg P ha^{-1} > TSP 12.5 kg P ha^{-1}.

Analysis of costs and returns

Gross margins from the different P treatments varied from US$ 352 to 1536 (Table 5). Maize and soybean grown without P fertilizer (nil fertilizer treatment) had the lowest gross margin per hectare compared to plots that received P as either MPR or TSP. MPR applied at 50 kg ha^{-1} gave the highest gross margin (US$ 1536) followed by TSP 25 kg ha^{-1} + MPR 25 kg ha^{-1} (US$ 1523) while TSP 50 kg ha^{-1} > TSP at 12.5 kg ha^{-1} + MPR 50 kg ha^{-1} > TSP at 25 kg ha^{-1}. Total variable cost (TVC) was lowest (US$ 627) for nil fertilizer treatment (no P) and highest (US$ 1235) for MPR 50 kg P ha^{-1}. Overall, the treatments applied with P resulted in attractive MRR of between 190 and 260 % over the nil fertilizer treatment (Table 6). Similarly, a switch from 12.5 to

Table 4 Relative agronomic effectiveness (RAE) of Minjingu rock phosphate compared to TSP applied at 50 kg P ha^{-1} as affected by direct and cumulative application

Crop and season	Relative agronomic effectiveness (%)										
	Direct						Cumulative				
	2007	2008	2009	2010	2011	Mean	2008	2009	2010	2011	Mean
Maize (LR)	155	106	124	116	91	118.4	120	122	120	112	118.5
Maize (SR)	82	109	91	95	87	92.8	91	91	92	91	91.25
Soybean (LR)	82	114	109	126	90	104.2	98	103	106	99	101.5
Common bean (SR)	95	97	69	97	98	91.2	105	90	92	95	95

Table 5 Maize and soybean yield gross margin for TSP and MPR P fertilizers

Operations (US$)	Nil fertilizer treatment	TSP			MPR 50	MPR 25 TSP 25	TSP 12.5 MPR 50
		12.5	25	50			
Gross field benefits (maize; US$)	694	1334	1505	1720	1847	1812	1710
Gross field benefits (legume; US$)	285	575	790	935	924	924	903
Total gross field benefits (US$)	979	1909	2295	2655	2771	2736	2613
Total variable cost[a]	627	931	1059	1188	1235	1214	1233
Gross margins ha^{-1} (US$)	352	978	1236	1467	1536	1523	1379

[a] Total variable cost includes cost of seed, fertilizer, land clearing/preparation, inoculum, planting weeding and harvesting

Table 6 Marginal analysis of maize, when nil fertilizer treatment is replaced with all the other P treatments

Treatment	Marginal cost US$ ha^{-1}	Marginal net benefit	Marginal rate of return (%)
0 P	627	352	
TSP 12.5	931	978	206
TSP 25	1059	1236	201
TSP 50	1188	1467	179
TSP 25 MPR 25	1214	1523	215
TSP 12.5 MPR 50	1233	1379D[a]	×
MPR 50	1235	1536	146[b]

[a] Dominated treatments

[b] Change from TSP 50 kg ha^{-1} to MPR 50 kg ha^{-1}

25 kg P ha^{-1} attracted a MRR of 201 %. While a switch from 25 kg P ha^{-1} to higher application did attain a modest MRR increase from 146 to 190 %. From the dominance analysis only TSP 12.5 kg ha^{-1} + MPR 50 kg ha^{-1} was dominated. In other words it's a treatment that has net benefits that are less than or equal to those of a treatment with lower variable costs, suggesting it is potentially a more risky treatment than others.

Discussion

Productivity differences due to seasonal weather were expected and are in agreement with other studies (Blackwell et al. 1985; Novero et al. 1985; Turner et al. 1986). In general, biomass production for the three crops decreased with decreasing water availability (see also Blackwell et al. 1985; Turner et al. 1986). The year 2011 was the wettest (2133 mm) contributing to greater biomass production and with it, increased overall P demand by the crops.

This is evident in the observed consistent decline in Bray extractable P in 2011 where P was applied as either MPR or TSP. This was in conformity with the findings reported by McBeath et al. (2012).

A positive response to P application in western Kenya was expected because of the low soil P level (Kihara and Njoroge 2013), which in most cases is markedly less than 30 mg kg^{-1} which is below the critical threshold for maize, soybean and common bean (Cox 1992). The positive crop response to P application even at 12.5 kg P ha^{-1} indicates that soil P was very low and the potential to address the current yield gap in farmer fields through P application. However Nziguheba et al. (2002) noted that application of TSP at 10 kg P ha^{-1} gave very low soil P balances and became negative as soon as P addition was stopped. There is also the risk of nutrient mining at such low levels of P. For example, up to 11 kg of P ha^{-1} is expected to be removed through harvested crop in the plots with 12.5 kg P ha^{-1}, assuming P concentration in grain at 60 % (Henao and Baanante 1999). When further losses such as the 10 kg P ha^{-1} lost annually through erosion and runoff for systems applied with 12 kg P ha^{-1} as observed by Smaling (1993) in the same region are taken into account, the balances could be hugely negative. For smallholder agriculture to be sustainable, it is important to ensure a positive nutrient (P) balance through seasonal application of $\geq$25 kg P ha^{-1} (Nziguheba et al. 2002). Thus the seasonal additions of both MPR and TSP as in our study can contribute to building soil P (Weaver and Wong 2011) required for increased root growth to enhance the capacity of the plants to explore more soil nutrients and moisture (Rodrigriguez et al. 1998; Qiu and Isreal 1994).

Numerous studies have demonstrated that recovery of P by crops in the year of application is very low and can range from <10 up to 30 % depending on soil, crop, and management factors (Withers et al. 2005; Hedley and McLaughlin 2005). Therefore, residual P is expected to build in the soil when the removal of P by crops is lower than the fertilizer P applied. Such build-up in residual P, combined with favorable seasonal rainfall can explain the increase in maize yields with time observed in the current study, as also observed elsewhere (Sharpley 1987; Selles et al. 2011; Tisdale et al. 1993). Kalala and Semoka (2010) observed higher performance of maize by adding fresh amount of MPR or TSP to the residual P in the soil in a pot experiment. In a long-term study to determine fertilizer P use efficiency, Bolland and Gilkes (1998) showed that plant available P (Olsen P) increased in the treatments that continued to receive fertilizer P, compared to where P was withheld. Repeated P applications overcomes reduced crop P availability due to increasing fixation of P in soil with time and is in line with the observed gradual increase in Bray P with time.

MPR was able to produce equivalent yields to TSP due to the sub-humid climate, the soil characteristics and the mineralogy and chemistry of the PR source material itself (Hammond et al. 1986; Khasawneh and Doll 1978). It is well established that the extent of PR dissolution increases with the degree of carbonate substitution and Ca:P ratio of apatite in the PR (Bolland et al. 1997; Hughes and Gilkes 1986). The small crystal size, high substitution rates of carbonate for phosphate and strontium for calcium and high neutral ammonium citrate (NAC) solubility (6.2 %) of MPR can explain the high reactivity of this PR (Szilas et al. 2008). These properties place MPR among highly reactive PR, thus explaining why MPR showed the same level of effectiveness as the water-soluble TSP for this soil. In addition the positive response of the test crops to MPR was expected due to high levels of extractable Bray-1 P in the raw MPR. Chien (1996) has shown that Bray-1 soil tests can be used for estimating available P and predicting yield from soils where PR materials have been applied.

High solubility of the TSP (Sample et al. 1980) may not synchronize P release with plant uptake and could also be accompanied by transformation of released P into the NaOH–Pi pool in these high P fixing soils. In line with this observation, other authors (Savini et al. 2006; Zoysa et al. 2001) have also observed that the application of TSP increases the NaOH–Pi fraction in high P fixing soils.

Therefore the equivalence in P supply of the two sources is hypothesized to be due to: (1) reduction in the bioavailable pool of P from the standard source of P, the TSP, due to the high phosphate adsorption by soil particles and lack of synchrony with plant demand, and (2) higher bioavailable pool of P from the source presenting lower water solubility (MPR) due to higher release (adsorption sites would enhance dissolution of PR facilitating P release).

The elevated RAE at 50 kg P ha^{-1} input in seasons with higher rainfall, e.g. as observed for the long rains, demonstrate better utilization of the applied P as MPR than TSP. Furthermore, it is possible that a higher soil moisture regime during the long rains, promoted the further dissolution of MPR resulting in more available P than in short rain seasons. This is consistent with McBeath et al. (2012) who showed that more P was utilized by plants in the presence of higher rainfall. Unlike in some of the short rains season, the more uniform rainfall distribution during the long rains in our case ensured soil remained moist for most of the growing season. Such conditions allow for the dissolution reaction to occur to a sufficient extent to provide plants with P at a rate that matches their demand (Khasawneh and Doll 1978; Kanabo and Gilkes 1988; Bolland and Gilkes 1990).

Enhanced water, citrate-solubility and agronomic efficiency of phosphate rock due to mixing with water soluble fertilizers such as TSP has been observed (Chien 1996; McLean and Logan 1970; Hammond et al. 1986) and attributed to the acidity (H_3PO_4) produced when monocalcium phosphate (from TSP) undergoes hydrolysis in the soil (Chien and Hammond 1988; Chien and Menon 1995). Although such enhanced solubility was also expected in our study, this did not translate into significantly increased yield in the combined TSP + MPR treatments over sole TSP and MPR.

In our study, however, mixing MPR with soluble P fertilizer (TSP) at 1:4 and 1:1 did not result in increased RAE. This could be due to the higher P fixation potential of our study soils. It is not surprising therefore that low maize yield even after application of P in the first season of experiment were observed in our study due to possible rapid removal of phosphate from solution in these highly P fixing and deficient soils. This would also suggest a transfer of P from plant available pool extracted by Bray-1 to less available P pools. This agrees with the findings of Prochnow et al. (2006) have demonstrated that the application of soluble P to soils high in P fixing capacity decreased the available P (Bray P_1) for plant uptake.

The MPR has also been reported to provide a liming effect on acidic soils such as those in western Kenya due to its relatively high carbonate content (Nekesa et al. 2005). This could further explain the enhanced RAE effectiveness of MPR over TSP despite the MPRs less solubility. As with most acid tropical soils, soils in western Kenya usually have a low CEC and a very low base saturation (Sanchez 1976; Lal and Sanchez 1992), and therefore available soil cations status often become limiting to crop growth once low pH and P deficiency have been corrected.

The strategy of including N_2-fixing crops in the rotation cycle where PR is applied has been used to improve the effectiveness of PR and the P status of the soil/plant system (Horst et al. 2001; Kamh et al. 1999). The inclusion of soybeans and common beans in this legume–cereal cropping system may also have contributed to the enhanced MPR agronomic effectiveness during the long rains. Legumes have been shown to increase the dissolution and utilisation of phosphate rock (PR) P compared with non-legumes mainly due to rhizosphere processes (Horst et al. 2001; Kamh et al. 1999).

Economic benefits of the applied P fertilizers

Application of any rate of fertilizer whether from TSP or MPR is economically profitable in western Kenya. This is in agreement with Duflo et al. (2008) and Marenya and Barrett (2009a, b), who observed that fertilizer use is profitable in western Kenya. The MRR for a shift from 0 P to any P application were above 190 %. Small scale farmers in western Kenya would be better off if they adopted TSP or MPR application due to the acceptable MRR for both products. However, switching from 25 kg P ha^{-1} to higher application rates of at least 50 kg P ha^{-1} is not economically viable due to the <200 % MRR realized. Kihara and Njoroge (2013) recommended an application rate of 38 kg P ha^{-1} as maximum profitable rate for western Kenya. It is noteworthy that, 1 kg of P is currently priced at $ 2.05 and $ 1.50 for MPR and TSP respectively. This coupled with the bulky nature of MPR compared to TSP does not create an incentive for farmers to use this resource. To promote the use of locally or regionally available alternative fertilizer sources, like MPR, there is need for adjustment and design of regional fertilizer policy on pricing to incentivize MPR use. Further change from TSP at 12.5–25 kg ha^{-1} and from 25 to 50 kg ha^{-1} (for combined TSP + MPR) is recommended since these result in MRR of 201 and 215 %, respectively.

Conclusion

The results clearly show that, as a source of P, MPR at 50 kg P ha^{-1} can be as effective as TSP for plants grown on acid soils with relatively high P-fixing capacity. Agronomically, both application of TSP and MPR have a positive response on crop yield. Kenyan farmers could adopt TSP or MPR application due to the high MRR for both products ranging from 146 to 215 % for maize and soybeans rotation cropping system. Thus MRRs were above 100 % minimum acceptable rate of return which is a requirement for farmers to change from one technology to another. It was also found that fertilizer treatment with combined and singular application of MPR (except TSP 12.5 kg ha^{-1} + MPR 50 kg ha^{-1}) were undominated suggesting that there is a high net benefit for farmers to change from TSP to MPR. However, a farmer who is keen on high profit margin would opt for application of TSP 25 kg ha^{-1} + MPR at 25 kg ha^{-1} or TSP at 25 kg ha^{-1} which increased MRR by 215 and 206 % respectively. Finally, because soil P is a major soil constraint to crop production in western Kenya, our results provide a firm basis to explore the potential of alternative P sources for replenishment of P in these depleted soils.

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