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Phosphorus Sorption and Lime Requirements of Maize Growing Acid Soils of Kenya

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Abstract

In Kenya, maize (*Zea mays* L.) is mainly grown on acid soils in high rainfall areas. These soils are known for low available phosphorus (P), partly due to its sorption by aluminium (Al) and iron oxides. The study determined soil P sorption, lime requirements and the effects of lime on soil pH, Al levels and available P on the main maize growing acids soils in the highlands east and west of Rift Valley (RV), Kenya. Burnt lime containing 21% calcium oxide was used. The soils were strongly to extremely acid (pH 4.85-4.07), had high exchangeable Al^{3+} (> 2 cmol Al kg^{-1}) and Al saturation (> 20% Al), which most maize germplasm grown in Kenya are sensitive to. The base cations, cation exchange capacity and available P (< 10 mg P kg^{-1} bicarbonate extractable P) were low, except at one site in the highlands east of RV indicative with history of high fertilizer applications. Highlands east of RV soils had higher P sorption (343-402 mg P kg^{-1}) than the west (107-258 mg P kg^{-1}), probably because of their high Al^{3+} ions and also the energies of bonding between the soil colloids and phosphate ions. Highlands east of RV also had higher lime requirements (11.4-21.9 tons lime ha^{-1}) than the west (5.3-9.8 tons lime ha^{-1}). Due to differences in soil acidity, Al levels and P sorption capacities within and between highlands east and west of RV, blanket P fertilizer and lime recommendations may not serve all soils equally well.

Keywords: acid soils, phosphorus sorption, lime requirements

1. Introduction

Acid soils are widespread and occupy about 4 billion ha of the total world soils (von Uexkull & Mutert, 1995) with 58% of the land area suitable for agricultural production inhabited by 73% of the world's population. They occupy 29 and 13% of the total land areas in the sub-Saharan Africa (SSA) and Kenya, respectively (Eswaran et al., 1997; Kanyanjua et al., 2002). Soil acidity is associated with hydrogen (H), aluminium (Al), iron (Fe) and manganese (Mn) toxicities and corresponding deficiencies of the available P, molybdenum (Mo), calcium (Ca), magnesium (Mg) and potassium (K) (Giller & Wilson, 1991; Jorge & Arrunda, 1997). High levels of exchangeable Al^{3+} and Fe^{3+} in tropical acid leads to P sorption through their reaction with phosphate ions to form insoluble compounds (Tisdale et al., 1990). In acid soils with a pH < 5.0, Al minerals hydrolyze to form octahedron hexahydrate (Al^{3+}) and mononuclear hydroxides ($Al(OH)^{2+}$ and $Al(OH)_2^{+}$) which are responsible for P sorption (Kinraide, 1991; Kochian, 1995). Other factors responsible for P sorption include the type of clay minerals, clay content, soil type and soil organic matter (Tisdale et al., 1990). The predominant clay minerals responsible for P sorption in tropical acid soils are kaolinite, gibbsite, goethite, Al and Fe oxides (Buresh et al., 1997; Obura, 2008; Tisdale et al., 1990; Uehabra & Gillman, 1981). Also soils with high clay fractions sorb more P than sandy soils due to their large surface area exposed for P sorption (Tisdale et al., 1990; Warren, 1992).

High P sorption in acid soils make crops to utilize only about 10-25% of the P fertilizer applied (Bahl & Singh, 1986). Because of its importance, several tests have been developed for soil available P determination; however, they do not provide information on soil P sorption capacities (Fixen & Grove, 1990). Therefore, P sorption isotherms which relate P concentration in soil solution to soil sorbed P have been developed to predict P fertilizer requirements for crops (Beckwith, 1965; Fox & Kamprath, 1970). The most widely used model to predict relationships between fixed and solution P is the Langmuir equation (Cabrera et al., 1977; Ryden & Syers, 1975). The model implies that P sorption takes place in a soil monolayer such that any increase in soil P above P sorption maximum does not increase its sorption. Knowledge on the soil P sorption capacities is important for accurate prediction of soil P fertilizer requirement necessary for optimum plant growth in acid soils such as those found in the highlands east and west of RV region, Kenya.

Most maize (*Zea mays* L.) growing areas in Kenya have acid soils (Muhammad & Underwood, 2004). Unfortunately, most improved maize germplasm and landraces used by farmers are sensitive to high Al (> 20% saturation), found in many Kenyan acid soils (Ligeyo, 2007; Schulze & Santana, 2003). In these soils, Al toxicity (often > 20% Al saturation) and low P (often < 5.0 mg P kg^{-1}) reduce maize grain yield by 16 and 28%, respectively (Obura, 2008; Ligeyo, 2007; Schulze & Santana, 2003). Therefore, use of lime is highly recommended to enhance food production in the Kenyan acid soils (Kanyanjua et al., 2002). Lime contains Ca and /or Mg compounds that displace H^+, Fe^{3+} and Al^{3+} ions from soil colloids. This reduces P sorption in acid soils resulting to increase in soil available P (Tisdale et al., 1990; van Straaten, 2007). In Kenya, lime recommendations are meant to completely neutralize soil acidity to pH 7.0 (Kanyanjua et al., 2002). This requires large amounts of lime and has been a hindrance to its adoption, especially by smallholder farmers (SHF). This study intended to determine rates of lime required to reduce Al toxicity to levels that maize germplasm grown by farmers in the Kenyan acid soils can tolerate, while reducing soil P sorption. The study objectives reported herein determined: I) soil P sorption capacities, ii) lime requirements and iii) effect of lime on soil pH, available P and Al level on the main maize growing acid soils in the highlands east and west of RV regions, Kenya.

2. Materials and Methods

2.1 Location of the Study Sites

Sites were selected to represent major agro-ecological environments with acid soils where the staple food crop, maize, is grown in the Kenyan highlands east and west of RV (Kanyanjua et al., 2002; Sombrous et al., 1982). Highlands east of RV sites were at Lavatory (00^o 25'S and 37^o 30'E), Kingman (00^o 40'S and 36^o 56'E) and Kerugoya (00^o 28'S and 35^o 15'E). West of RV sites were at Sega (0^o 15'N and 34^o 20'E), Bumala (00^o 19'N and 34^o 12'E) and Kuinet (00^o 37'N and 35^o 18'E). Sega, Bumala, Kuinet and Lavatory soils were orphic Acrisols, orphic Ferralsols, chromic Ferralsols and humic Andosols, respectively. Kangema and Kerugoya soils were both ando-humic Nitisols (Jaetzold & Schmidt, 1983). Prior to this study, Sega and Bumala were under continuous crop cultivation for over twenty years without inorganic fertilizer inputs. Kuinet was formerly under wattle trees and thereafter three years of continuous maize cropping, with an application of 19 kg P ha^{-1} as diammonium phosphate and 43 kg N ha^{-1} as urea per year. Lavatory and Kangema sites were under continuous crop cultivation for over twenty years with inorganic fertilizer inputs. Kerugoya site was a maize farm near a tea plantation and the farmer was applying high rates of P and N fertilizers meant for tea plants.

2.2 Soil Sampling, Preparation and Characterization

Soil samples were taken from SHF fields at the six sites (Lavatory, Kingman, Kerugoya, Sega, Bumala and Kuinet). Nine sub-samples were taken with a soil auger at the 0-20 cm soil depth in a zig-zag manner. They were thoroughly mixed and about 1.0 kg composite sample packed in a polythene bag. The samples were air-dried, ground and passed through a 2 mm sieve. They were analyzed for texture, specific gravity, pH (1:2.5 (soil: water)), available P, exchangeable bases (Ca^{2+}, Mg^{2+}, K^{2+} and Na^+) and acidity (Al^{3+} and H^+). Detailed laboratory procedures are described in Okalebo et al. (2002) and Smith (1981).

2.3 Soil P Sorption Determination

Soil P sorption characteristics were determined through incubation and continuous centrifugation processes for six days using the method described by Fox and Kamprath (1970). Non-linear regression using the General Statistics (GenStat, 2010) package was used to fit the P adsorption data to non-linear form of the Langmuir equation given below:

$$X = kbc/(1 + kc) \quad (1)$$

where, X = amount of P sorbed per gram of soil (mg P kg^{-1}), b = adsorption maximum (mg P kg^{-1} soil), c = final supernatant solution P concentration (mg L^{-1}), k = a constant related to the energy of bonding between soil phosphate ions and the surface of soil particles.

For lime treatments, 100 g soil samples were weighed into 200 ml polythene bags and each thoroughly mixed with equivalent weights of lime requirement values in section 3.3. The samples were incubated for 30 days at approximately field water holding capacity to allow for lime to react with the soils after which they were once again air-dried for laboratory P sorption studies together with unlimed samples.

2.4 Determination of Soil Lime Requirements

Lime requirements of the soils were calculated using the equation of Cochrane et al. (1980). The equation aims at reducing the % Al saturation to a level that is commensurate with crop Al tolerance given as:

$$\text{Ca (cmol kg}^{-1}\text{ soil)} = 1.5[\text{Al} - \text{RAS (Al + Ca + Mg)}/100] \qquad (2)$$

where Al = cmol kg^{-1} soil in the original exchange complex, RAS = Required percentage Al saturation, Ca = cmol kg^{-1} soil in the original exchange complex, Mg = cmol kg^{-1} soil in the original exchange complex. The approximate lime requirements (tons $CaCO_3$ ha^{-1}) were calculated by multiplying the Ca cmol $kg^{-1}$by the soil specific gravities.

A RAS value of 20% was used. Soil characterization data in Table 1 was used for lime requirement determinations. Burnt lime containing about 21% calcium oxide was used in this study.

2.5 Statistical Analysis

All the generated data were subjected to analysis of variance (ANOVA) with the General Linear Model using General Statistics (GenStat, 2010). The standard error of difference between means (s.e.d) was used to compare the treatment means at statistical significance level of $p \leq 0.05$.

3. Results and Discussion

3.1 Initial Soil Characteristics of the Study Sites

Table 1. Initial soil chemical and physical characteristics

Sampling Sites	Sega	Bumala	Kuinet	Lavatory	Kangema	Kerugoya
Soil pH†	4.65±0.04	4.62±0.03	4.55±0.03	4.07±0.02	4.69±0.05	4.85±0.02
P (mg kg^{-1})‡	2.13±0.02	2.74±0.02	4.48±0.06	6.08±0.04	6.00±0.03	23.18±0.06
Ca (cmol kg^{-1})	2.75±0.01	3.15±0.04	2.69±0.02	1.35±0.03	2.30±0.02	1.95±0.01
Mg (cmol kg^{-1})	1.10±0.02	2.05±0.03	0.89±0.04	0.10±0.02	1.35±0.01	1.40±0.03
K (cmol kg^{-1})	0.45±0.01	0.37±0.01	0.74±0.02	0.27±0.03	0.33±0.01	0.42±0.01
Al (cmol kg^{-1})	2.07±0.03	2.01±0.03	2.24±0.04	4.29±0.05	3.32±0.02	2.71±0.02
ECEC (cmol kg^{-1})	6.37±0.04	7.58±0.05	6.56±0.02	6.01±0.04	7.30±0.04	6.48±0.05
Al Saturation (%)	32.50±0.56	26.52±0.37	34.15±0.62	71.38±0.49	45.48±0.24	41.82±0.53
Specific Gravity	2.39±0.04	2.33±0.02	2.29±0.01	1.74±0.02	1.82±0.01	1.90±0.02
Sand (%)	56	56	58	70	66	64
Clay (%)	30	28	24	8	14	8
Silt (%)	14	16	18	22	20	28
Textural Class	Sand clay loam	Sand clay loam	Sand clay loam	Sand loam	Sand loam	Sand loam

† = 1: 2.5 (soil: water), ‡ = bicarbonate extractable P and ECEC = effective cation exchange capacity.

Table 1 shows the initial soil chemical and physical characteristics of the study sites. Soils of Sega, Bumala, Kuinet Kangema and Kerugoya were strongly acid (pH 4.55-4.85) while Lavatory was extremely acid (pH 4.07) (Kanyanjua et al., 2002). Soils from both regions had high Al levels unsuitable for maize production. Although there are no acceptable critical levels of exchangeable Al^{3+}, values > 2.0 cmol Al kg^{-1}, are considered excess for many crops (Landon, 1984). The percent Al saturations of the soils were also high (26.52%-71.38%), since > e high level 20% Al saturation are unsuitable for most maize germplasm grown by farmers in Kenya (Ligeyo, 2007). Highlands east of RV soils had higher exchangeable Al^{3+} (2.71-4.29 cmol Al kg^{-1}) than west of RV (2.01-2.24 cmol Al kg^{-1}). All the sites had low CEC (6.01-7.58 cmol kg^{-1}) and exchangeable Ca (1.35-3.15 cmol kg^{-1}), since CEC < 15 cmol kg^{-1} and exchangeable Ca^{2+} < 4.0 cmol kg^{-1} are considered low (Landon, 1984). All the soils were P deficient (2.13-6.08 mg P kg^{-1}), except Kerugoya (23.18 mg P kg^{-1}). Bicarbonate extractable P levels < 10 mg P kg^{-1} are considered inadequate for healthy plant growth (Okalebo et al., 2002). Normally, farmers growing tea such as in Kerugoya apply compound NPK fertilizers meant for tea to other crops which increases soil available P in such farms. Acid soils with high levels of Al, low base cations and soil available P such as reported in this study are characteristics of highly weathered, common in SSA (Kanyanjua et al., 2002; van Straaten, 2007; Landon, 1984). West of RV Kenya soils have higher clay content (24-30%) and higher specific gravity (2.29-2.39) than highlands east of RV of 8-14% and 1.74-1.90, respectively. Low specific gravities in the highlands east of RV are characteristics of soils formed from recent volcanic ash (Jaetzold & Schmidt, 1983).

3.2 Soil P Sorption Capacities

Table 2 presents Langmuir parameters of the study sites and Figure 1 shows P sorption isotherms. Soils of the highlands east of RV had higher P sorption (343-402 mg kg^{-1} soil) than those of west (107-258 mg kg^{-1} soil) (Table 2 and Figure 1). According to Buresh et al. (1997) P sorption levels of 0-100, 100-400 and > 400 mg P kg^{-1} are classified as low, moderate and high, respectively. Therefore, highlands east of RV had moderate to high P sorption, while soils of the west had moderate P sorption. Earlier studies have also reported similar magnitudes of P sorption in some of the Kenyan acid soils (Kifuko et al., 2007; Obura, 2008; Opala, 2009). The differences observed in P sorption capacities between highlands east and west of RV were due to differences in exchangeable Al^{3+} and clay minerals (Obura, 2008; Jaetzold & Schmidt, 1983). Higher P sorptions in the highlands east compared to west of RV was due to their high exchangeable Al^{3+} which reacted with more phosphate ions to form insoluble compounds (Tisdale et al., 1990). The highlands east of RV soils consists predominantly of gibbsite minerals with larger surface area for P sorption compared to kaolinite found in west of RV (Jaetzold & Schmidt, 1983; Obura, 2008; Tisdale et al., 1990; Sanchez, 1976). Soils of the highlands east of RV had higher energies of bonding between soil phosphate ions and the surface of soil particles (k) than west of RV soils hence their higher P sorption. High correlations between energies of bonding and P sorption such as in this study have been reported in Pakistan soils (Chaudhary et al., 2003). The current study revealed that the recommended P fertilizer of 26 kg P ha^{-1} for maize production (Kenya Agricultural Research Institute, 1994) was not adequate for optimum maize production at all these sites. This was because it could only supply at most 11.6 mg kg^{-1} which was much below soils P sorption capacities of 107 to 402 mg P kg^{-1} (Figure 1) required to obtain the recommended solution concentration of 0.2 mg L^{-1} that is considered adequate for most crops (Beckwith, 1965).

Table 2. Langmuir P sorption parameters of some Kenyan acid soils

Sites	a) Without lime			b) With lime		
	q (mg kg^{-1})	b (mg kg^{-1})	k (mg L^{-1})	q (mg kg^{-1})	b (mg kg^{-1})	k (mg L^{-1})
Sega	258.04±4.51	589.70±7.55	3.89±0.09	92.64±6.13	695.00±5.69	0.77±0.05
Bumala	106.83±6.14	956.00±5.20	0.63±0.11	73.71±4.17	805.00±9.17	0.50±0.07
Kuinet	138.60±5.86	818.00±10.02	1.02±0.10	69.21±6.86	794.00±9.85	0.47±0.03
Lavatory	401.91±7.00	655.00±9.00	7.94±0.06	161.45±6.66	605.00±9.50	1.82±0.08
Kangema	343.36±6.56	602.30±8.50	6.63±0.15	126.29±7.22	653.00±9.54	1.15±0.03
Kerugoya	388.43±6.11	610.90±6.66	8.73±0.06	120.17±6.72	660.00±8.61	1.11±0.05

q = P sorbed per unit soil mass at equilibrium concentration of 0.2 mg L^{-1}, b =adsorption maximum (mg kg^{-1}) and k = a constant related to the energy of bonding between soil phosphate ions and the surface of soil particles (mg L^{-1}).

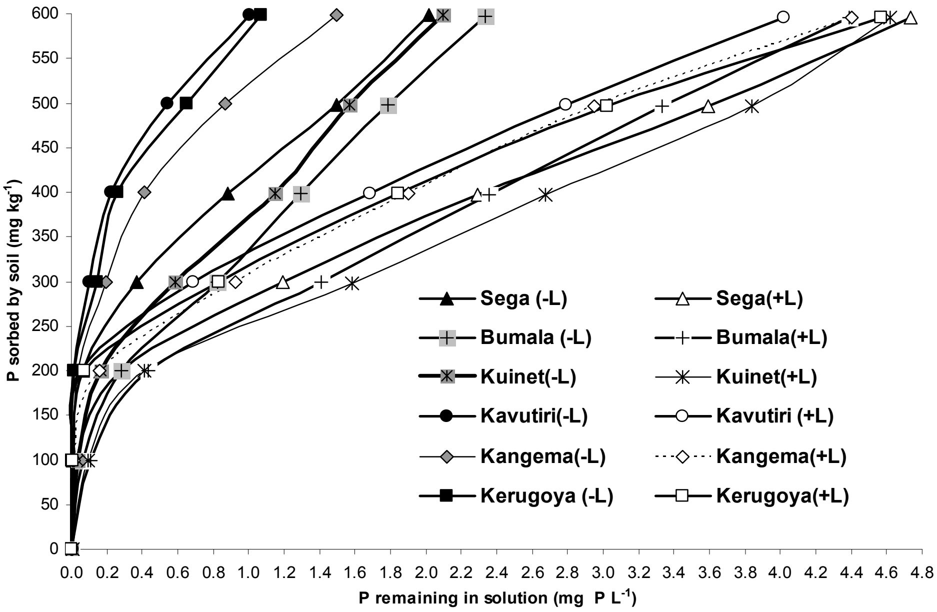

Figure 1. Phosphorus sorption isotherms of the study sites

-L = without lime and +L = with lime.

3.3 Soil lime requirements and Its Effect on Soil pH, Al Levels and Available P

Highlands east RV had higher lime requirements (11.35-21.85 tons ha^{-1}) than the west (5.28-9.84 tons ha^{-1}). Lime significantly ($p \leq 0.05$) reduced exchangeable Al^{3+} and increased soil pH and available P (Table 3). Highlands east of RV had higher requirements than the west probably due to its higher levels of exchangeable Al^{3+} requiring more Ca^{2+} ions to neutralize compared to west. Lime increased soil pH because of the likely displacement of Al^{3+}, H^{+} and Fe^{3+} ions by Ca^{2+} ions it contains. This led to the observed reduction in P sorption at all the sites. Similar studies have reported increased soil pH, available P, reduction in Al levels and P sorption in acid soils due to lime application (Bado et al., 2004; Kamprath, 1984; Kanyanjua et al., 2002; Moody et al., 1998; The et al., 2006). Therefore, lime application is important for the management of soil acidity related constraints in the main maize growing areas of Kenya.

Table 3. Lime requirements, effect of lime on soil pH, available P and exchangeable Al^{3+}

Sites	Lime requirement (tons ha^{-1})	Soil pH (1:2.5; soil: water)		Exchangeable Al^{3+} (cmol kg^{-1})		Available P (mg kg^{-1})‡	
		Control	With lime	Control	With lime	Control	With lime
Sega	8.43	$4.76\pm0.24_b$	$6.78\pm0.14_a$	$2.28\pm0.04_a$	$0.01\pm0.06_b$	$1.11\pm0.13_c$	$2.17\pm0.03_b$
Bumala	5.28	$4.69\pm0.36_b$	$6.55\pm0.12_a$	$2.16\pm0.06_a$	$0.02\pm0.07_b$	$1.80\pm.015_d$	$2.49\pm0.11_c$
Kuinet	9.84	$4.60\pm0.16_b$	$6.81\pm0.20_a$	$2.42\pm0.05_a$	$0.13\pm0.06_b$	$2.48\pm0.15_c$	$3.43\pm0.15_b$
Lavatory	21.85	$4.05\pm0.13_b$	$6.80\pm0.15_a$	$4.08\pm0.07_a$	$0.22\pm0.07_b$	$3.98\pm0.12_d$	$5.11\pm0.14_c$
Kangema	14.00	$4.73\pm0.23_b$	$6.89\pm0.18_a$	$3.59\pm0.06_a$	$0.19\pm0.08_b$	$5.56\pm0.11_c$	$7.39\pm0.82_b$
Kerugoya	11.35	$5.03\pm0.12_b$	$6.79\pm0.16_a$	$3.18\pm0.08_a$	$0.17\pm0.04_b$	$17.72\pm0.15_d$	$19.34\pm0.42_c$
Mean	11.79	4.64	6.77	2.95	0.12	5.44	6.66
CV %		2.2		5.3		3.2	
s.e.d(lime)		0.02		0.03		0.05	
s.e.d(sites)		0.01		0.02		0.09	

‡= bicarbonate extractable P.

4. Conclusion

The studied soils were strongly to extremely acid, had low base cations, CEC and available P with corresponding high Al levels and P sorptions. Soils of the highlands east of RV had higher P sorption and lime requirements compared to the west due to their higher exchangeable Al^{3+} and energies of bonding between the soil colloids and phosphate ions. The recommended P fertilizer rate of 26 kg P ha^{-1} for maize production in Kenya seemed inadequate to replenish soil P due to its high sorption in these soils. Lime increased soil pH and available P due to reduction in Al levels and P sorption. Therefore, lime application is important for the management of P deficient acid soils found in the different maize growing areas of Kenya. Due to the differences in soil acidity, Al levels and P sorption capacities within and between highlands east and west of RV, blanket P fertilizer and lime recommendations may not serve all soils favourably.

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