Sustainable Agriculture Research; Vol. 4, No. 2; 2015
ISSN 1927-050X E-ISSN 1927-0518
Published by Canadian Center of Science and Education

Micro-Dosing of Lime, Phosphorus and Nitrogen Fertilizers Effect on Maize Performance on an Acid Soil in Kenya

P. O. Kisinyo[1], P. A. Opala[2], V. Palapala[1], S. O. Gudu[1], C. O. Othieno[3] & E. Ouma[1]

[1] Rongo University College, P. O. Box 103-40404, Rongo, Kenya

[2] Maseno University, Private bag, Maseno, Kenya

[3] University of Eldoret, P. O. Box 1125-30100, Eldoret, Kenya

Correspondence: P. O. Kisinyo, Rongo University College, Rongo, Kenya. Tel: 254-723-320-168. E-mail: kisinyopeter@yahoo.com; dean-agriculture@ruc.ac.ke

Received: December 18, 2014 Accepted: March 11, 2015 Online Published: March 17, 2015

doi:10.5539/sar.v4n2p21 URL: http://dx.doi.org/10.5539/sar.v4n2p21

Abstract

High cost of inorganic fertilizers and lime has precluded their use by smallholder farmers to remedy the problem of soil acidity and infertility in Kenya. To address the problem, we tested a precision technique referred to as micro-dosing, which involves application of small, affordable quantities of inorganic inputs on an acid soil in Busia County, Kenya. Experimental treatments were N-fertilizer (0 and 37.5 kg N ha^{-1}), P-fertilizer (0 and 13 kg P ha^{-1}) and lime (0, 0.77 and 1.55 tons lime ha^{-1}). 37.5 kg N and 13 kg P ha^{-1} are 50% of the recommended fertilizer rates for maize production in Kenya while 0.77 and 1.55 tons lime ha^{-1} are 25 and 50% of the actual requirement. Soil chemical changes, maize grain yield and nutrient recovery were determined. Lime and P-fertilizer significantly affected only the top-soil pH, Ca, Mg and available P, while the effects of N-fertilizer were evident on both top- and sub-soil N likely due to its faster mobility than P and lime. Grain P-fertilizer recovery efficiencies were 14 and 16-27% due to 13 kg P and 13 kg P + 0.77-1.55 tons lime ha^{-1}, respectively. N-fertilizer recovery efficiencies were 37 and 42-45% due to 37.5 kg N and 37.5 kg N + 0.77-1.55 tons lime ha^{-1}, respectively. Fertilizers applied to supply 37.5 kg N, 13 kg P and 0.77-1.55 tons lime ha^{-1} increased grain yield above the control by 134, 39 and 12-22%, respectively, therefore micro-dosing of these inputs can increase maize production on Kenyan acid soils.

Keywords: fertilizer N and P, lime, western Kenya, smallholder

1. Introduction

Agricultural production in the high rainfall areas of Kenya is constrained by soil acidity and soil fertility depletion (Kanyanjua et al., 2002). The yields of maize, which is the staple food in these regions, are very low, averaging less than 1 ton ha^{-1} against a potential of 4 tons ha^{-1}. To mitigate these constraints, many soil fertility management technologies have been attempted. These ranges from sole use of inorganic fertilizers to sole use of organic inputs (Sanginga & Woomer, 2009; Okalebo et al., 2006) but these approaches have several drawbacks which have hindered their adoption by smallholder farmers in Kenya. In particular, use of organic inputs is labour intensive, they are of often low in nutrient content and not available in sufficient quantities on smallholder farms. Inorganic fertilizers, on the other hand, are expensive and most smallholder farmers cannot afford them (Sanchez et al., 1997). However, use of fertilizers remains the key to increasing food productivity in Africa (Quinones et al., 1997).

The main problem with most of the current fertilizer management recommendations is that they target maximization of yields or profits without consideration of the agricultural risks and resource constraints faced by many smallholder households (Twomlow et al., 2010). There has been therefore growing interest to find alternative interventions that promote efficient and sustainable use of fertilizer tailored to smallholder farmers' socio-economic conditions (Nziguheba, 2007). One such technology is the use of precision technique referred to as micro-dosing, which involves the application of small, affordable quantities of inorganic inputs and seed at the time of planting or as top dressing three to four weeks after emergence (ICRISAT, 2008). For example, while the recommended N and P fertilizer rates for maize production in western Kenya are 75 kg N and 26 kg P ha^{-1} (Kenya Agricultural Research Institute (KARI), 1994), other research however suggests that farmers can increase their average yield by 50-100% by applying as little as 10 kg N ha^{-1} (Twomlow et al., 2010) therefore improving the prospects of adopting the use of fertilizers. In addition, fertilizer use efficiency could be improved by liming the acid soils to eliminate Al toxicity (Kisinyo et al., 2014), thereby resulting in a reduction in the amount of fertilizer required to achieve a target yield. Much of the work on micro-dosing of fertilizers has been conducted in semi-arid regions of Zimbabwe using mainly N fertilizers. There is need therefore to extend these evaluations in other environments, such as western Kenya, where rainfall is high and soil acidity in addition to N and P deficiencies limit crop production, to test the robustness of this technology. The objectives of this study were therefore to determine effect of micro-dosing of lime, P and N fertilizer on: i) soil chemical properties and ii) maize performance on an acid soil in Busia County, Kenya.

2. Materials and Methods

2.1 Site Description

The study was carried out in Busia County, 1300 m asl, (0°19'N & 34°12'E). The average annual rainfall is 1600 mm which is distributed over two main cropping seasons, the long rainy season which is from March to July and the short rainy season from September to December (Jaetzold & Schmidt, 1983). The initial soil properties are presented in Table 1. The soils were moderately acidic, low in organic C (< 2%), N, P and exchangeable bases (Ca, Mg and K) but high in Al saturation (> 20%) (Landon, 1991). The soil type at the site has been classified as an Orthic Ferralsol (FAO, 1988).

Table 1. Initial soil chemical and physical characteristics of the study site

Parameter	value
pH – H_2O (soil: water; 1:2.5)	5.44
Bicarbonate extractable P (mg kg^{-1})	2.44
Total N (%)	0.09
Nitrate (mg kg^{-1})	1.57
Organic C (%)	1.66
Ca (cmol kg^{-1})	3.12
Mg (cmol kg^{-1})	1.81
K (cmol kg^{-1})	0.41
Exchangeable Al (cmol kg^{-1})	1.63
Al saturation (%)	23.4
ECEC (cmol kg^{-1})	6.97
Specific gravity	2.44
Sand (%)	54
Silt (%)	30
Clay (%)	26
Soil Texture	Sandy clay loam
Soil Classification	Orthic Ferralsol

2.2 Experimental Design, Layout and Management

The study was conducted over two seasons; long and short rains in the 2008. The experiment was a 2 × 2 × 3 split-split plot laid out in randomized complete block design with N as the main plot, P as the sub-plot and lime as sub-sub plot. Two N rates, 0 representing a practice where farmers apply no fertilizer and 37.5 kg N ha^{-1}, which is half the recommended N rate for the area (KARI, 1994), were used in the main plot. P was also applied at 0 and 13 P kg ha^{-1} for similar reasons as N. Liming material containing 21% calcium oxide was applied at 0, 0.77 and 1.55 tons^{-1} ha in the sub-sub plots. The lime requirement of soil was calculated using the equation proposed by Cochrane et al. (1980). The equation aims at reducing the % Al saturation to a level that is commensurate with crop Al tolerance using the following formula:-

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

Where Al = cmol kg^{-1} soil in the original exchange complex, RAS = required % Al saturation, Ca = cmol kg^{-1} soil in the original exchange complex and Mg = cmol kg^{-1} soil in the original exchange complex. The approximate lime requirements (tons $CaCO_3$ cmol kg^{-1}) was calculated by multiplying the Ca cmol kg^{-1} by the soil specific gravity.

A RAS value of 20% was used since most maize germplasm grown in Kenya are sensitive to >20% Al saturation (Ligeyo, 2007; Kisinyo et al., 2013). Thus, the calculated actual lime requirement was 3.09 tons ha^{-1} while 0.77 tons ha^{-1} and 1.55 tons ha^{-1} represent 25% and 50% of the actual lime requirement, respectively.

Plots measuring 3.5 m by 3 m were demarcated after ploughing to the appropriate tilth in the year 2008 long rain season. Each plot was separated from the next by a spacing of 1 m. Lime was applied only once in the long rains season by evenly broadcast and thoroughly mixing it with the soil 30 days prior to planting. This was to allow for adequate time for it to react with the soil. Fertilizers phosphate as triple superphosphate and N as calcium ammonium nitrate were spot applied into the planting holes and thoroughly mixed with soil at the time of planting in each season. Nitrogen was split-applied with 30% applied at planting and the rest as a top-dress at six weeks later. Two maize seeds (hybrid 513) were planted per hill at a spacing of 75 cm by 25 cm and were thinned to one plant per hill two weeks post-emergence. Maize was managed using the recommended agronomic practices for the area and harvested at physiological maturity.

2.3 Determination of Crop Response to Lime, P and N Fertilizer Applications

The grain yield was computed using the following formulae:

$$\text{Yield per plot} = (\text{Total fresh weigh} \times \text{Sample dry weight}) / \text{Sample fresh weigh} \quad (2)$$

$$\text{Yield (kg ha}^{-1}) = (\text{Yield per plot} \times 10{,}000\ \text{m}^2)/\text{Effective area (m}^2) \quad (3)$$

where effective area is part of the plot harvested which is less the guard row and plants at the end of each row.

Plant fertilizer recovery efficiency was calculated using the following equation by Dobermman (2005):

$$\text{Nutrient recovery efficiency (\%)} = (NT - No)/\text{T} \times 100 \quad (4)$$

where NT = nutrient uptake in treated plots (kg ha^{-1}), No = nutrient uptake in control plots (kg ha^{-1}) and

T = rate of the nutrient applied (kg ha^{-1}).

2.4 Soil Sampling and Analyses

Nine sub - soil samples were taken at the experimental site in March 2008 with a soil auger at the 0-20, 20 - 40 and 40 - 60 cm soil depths in a zig - zag manner prior to treatment application. Samples from each depth were thoroughly mixed and about 1.0 kg composite sample taken to the laboratory for determination of the initial soil properties at the site. The samples were subsequently taken from each plot at appropriate intervals at the same depths to monitor changes in selected soil chemical properties due to treatment applications. The soil samples were air-dried and the ones taken before treatment applications were analysed for texture, specific gravity, pH (1: 2.5; soil: water), bicarbonate extractable P, exchangeable bases (Ca^{2+}, Mg^{2+}, K^+ and Na^+), acidity (Al^{3+} and H^+), organic carbon (%C) and total N (%N). The samples taken after treatment applications were analyzed for pH, available P, nitrates, exchangeable Ca^{2+}, Mg^{2+} and Al^{3+}. Soil specific gravity was calculated by determining the weight of solid particles per weight of equal volume of water. The grain samples were analysed for P and N contents. Detailed laboratory procedures for specific gravity determination are outlined by Smith (1981) while procedures for soil chemical and plant analyses are described by Okalebo et al. (2002).

2.5 Statistical Analysis of Data

All the maize yields data were subjected to analysis of variance (ANOVA) with the split-split plot design using General Statistics (Genstat, 2010). Means were separated using pooled standard error of difference of means (s.e.d) whenever treatment effects were significant at $p \leq 0.05$).

3. Results and Discussion

3.1 Effects of Lime on Soil pH, Ca, Mg and Al levels

Figure 1 shows the effect of lime on soil pH. Lime at the rates of 0.77 and 1.55 tons ha^{-1} took about 60 and 126 days to increase soil pH to the highest pH peaks of about 5.7 and 6.0, respectively. Lower lime rate (25% of the actual lime requirement) increased soil pH to highest peak in relatively shorter time and thereafter the pH began to decline earlier compared to where half of the requirement was applied. This was likely because Ca^{2+} ions in lower lime rate was depleted very fast, resulting in increase in soil acidity. Similar results were reported by Sanchez (1976) who found that the residual effect of lime depends on the amount of Ca^{2+} and/or Mg^{2+} ions still remaining in the liming material at any given time. In a Kenyan acid soil, 2 tons lime ha^{-1}, representing 50% of the actual lime requirement kept soil pH above 5.5 for about 2 years (Kisinyo et al., 2014). The exchangeable Ca^{2+} and Mg^{2+} increased with increasing lime rates (Figures 2 and 3) while the exchangeable Al^{3+} decreased with increasing rates of lime.

Lime had no significant effect on soil pH, exchangeable Ca^{2+} and Al^{3+} in the sub-soils (20-40 and 40-60 cm depths) (Figures 1- 4). This is attributable to the slow solubility of lime and hence low mobility within the soil (Yorst & Ares, 2007). In a similar study, very little changes in soil pH, exchangeable Ca^{2+} and Al^{3+} were reported in the sub-soil (12 -85 cm depth), $2^1/_2$ years after lime application at rates between 1.5 – 6.0 tons $CaCO_3$ ha^{-1} (Arya, 1990). Surface application of lime is not likely therefore to correct sub-surface soil acidity.

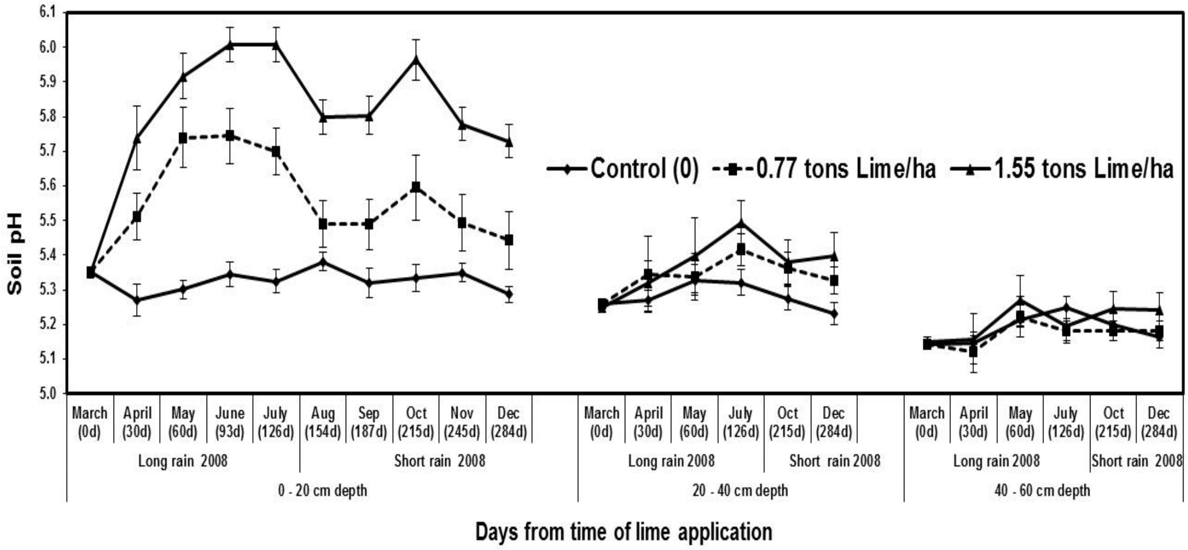

Figure 1. Effect of lime on soil pH during the cropping period; *d=days from time of lime application and error bars indicates standard error of means (SEM)*

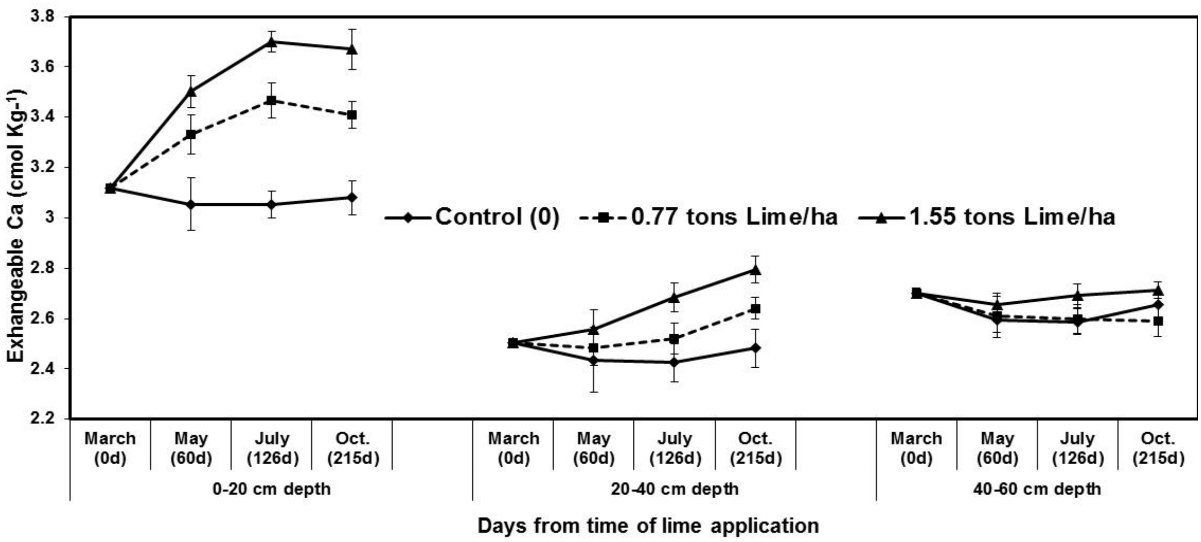

Figure 2. Effect of lime on exchangeable calcium during the cropping period

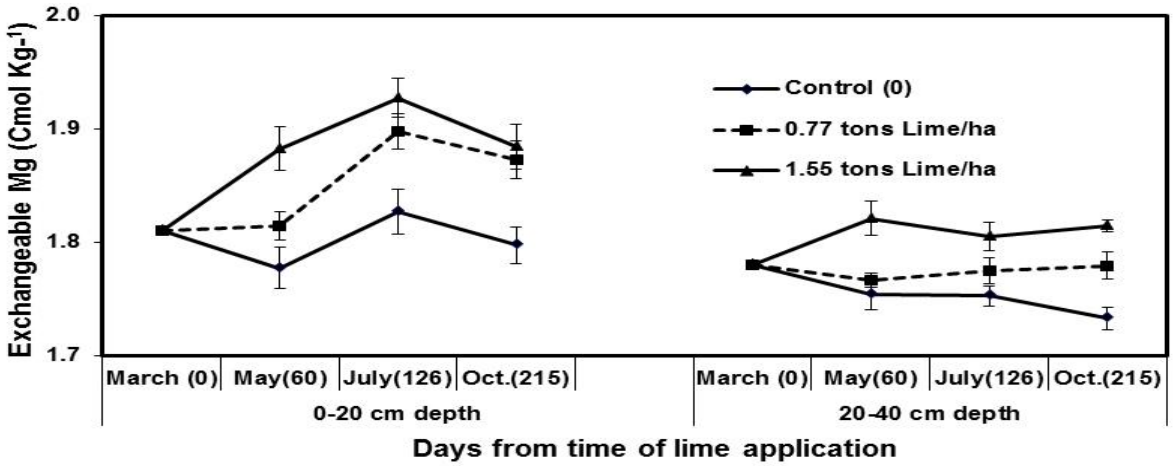

Figure 3. Effect of lime on exchangeable magnesium during the cropping period

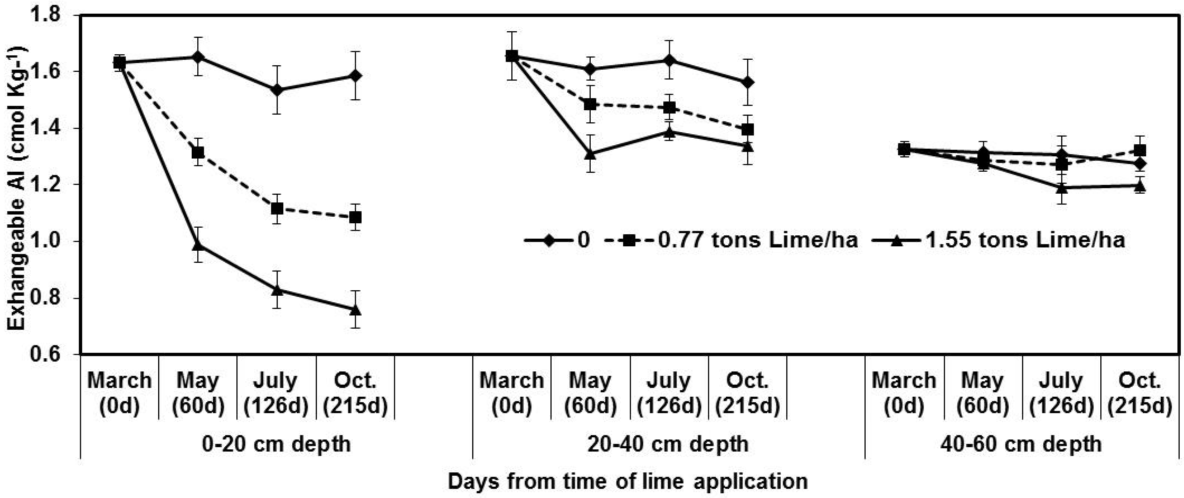

Figure 4. Effect of lime on exchangeable aluminium during the cropping period

3.2 Effects of P Fertilizer and Lime on Soil Available P

Figure 5 shows the effects of lime and P fertilizer on soil available P at the 0-20 cm depth. Generally, both P fertilizer and lime had significant effect ($p \leq 0.05$) on available P. A combined application of P fertilizer and lime increased soil available P more than the application of either of them alone. The available P reached its highest peak in about 30 days (in May) from date of its application (in April) and thereafter there was a general declining trend during the cropping season. However, in the month of October there was another peak due to a second P fertilizer application in mid-August, during the short rain planting season. The increase in soil available P as a result of liming observed in this study is consistent with others studies (Tisdale et al., 1990; van Straaten, 2002) which attributed it to reduced P sorption. Many other studies have investigated the effects of lime application on P retention and extractability, but consistent improvements in the availability of soil P have not been obtained (Mansell et al., 1984; Holford et al., 1994; Curtin & Syers, 2001). Liming is, however, often successfully applied to remedy other soil constraints such as soil acidity as was demonstrated in the present study.

Figure 6 shows the effects of P fertilizer on soil available P down the soil profile. Soil available P generally decreased down the soil profile because of the immobile nature of P. In a similar study, no significant changes in soil available P below the layer of P fertilizer incorporation in acid soils were reported (Arya, 1990). From the present study, it is evident that surface application of lime and P fertilizer applications may not correct P deficiency on acid soils.

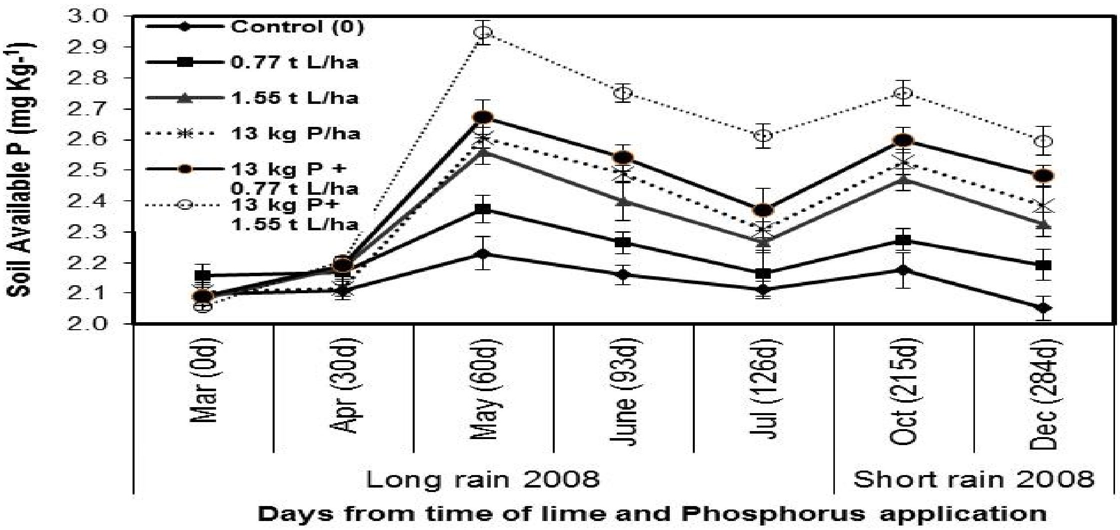

Figure 5. Effect of P fertilizer and lime on soil available P at the 0 - 20 cm soil depth during the cropping period

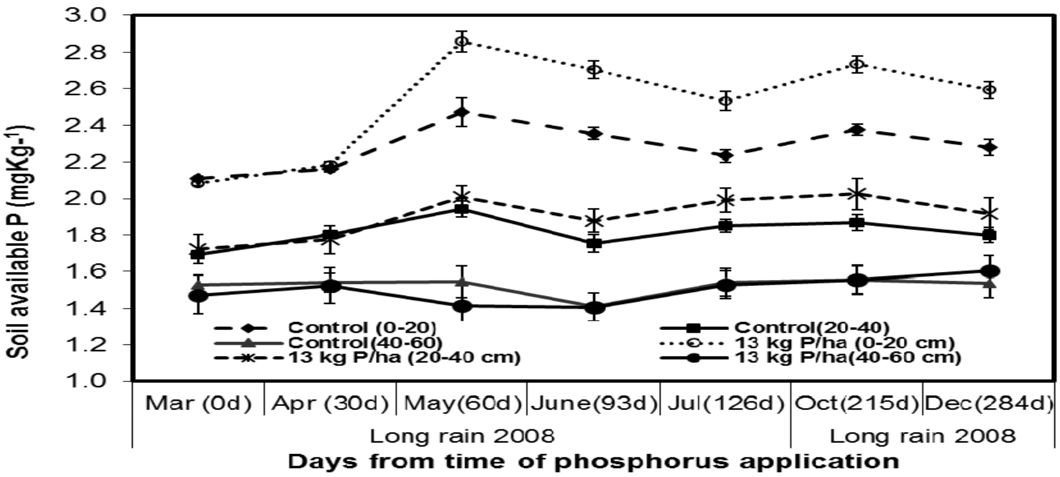

Figure 6. Effect of P fertilizer and lime on soil profile available P during the cropping period

3.3 Effect of N Fertilizer on Soil Nitrate Levels

Soil nitrate levels generally increased at the onset of rains i.e. from March to May even on plots which did not receive N fertilizer application (Figure 7). This was followed with a decline in plots which did not receive N fertilizer throughout up to July when the crop was harvested. A similar trend of increase was observed during the short rains due to N fertilizer applications. Increased nitrate levels observed on all plots at the onset of rains was likely due to the so called 'Birch effect' attributed to rapid mineralization of killed microbial biomass and labile organic matter released on drying and also to rapid nitrification of NH_4^+-N accumulated during the dry season (Birch, 1958; Seneviratne & Wild, 1985). The effect of N fertilizer on nitrate levels down the soil profile was more pronounced than that of lime on soil pH, exchangeable Al^{3+}, Ca^{2+} and Mg^{2+} and also that of P fertilizer on soil available P reported above in Figures 1 to 6. This was because unlike phosphate, Ca^{2+} and Mg^{2+} ions, nitrate ions are very mobile within the soil and are therefore easily leached by rainfall water down the soil profile (Giller et al., 1997).

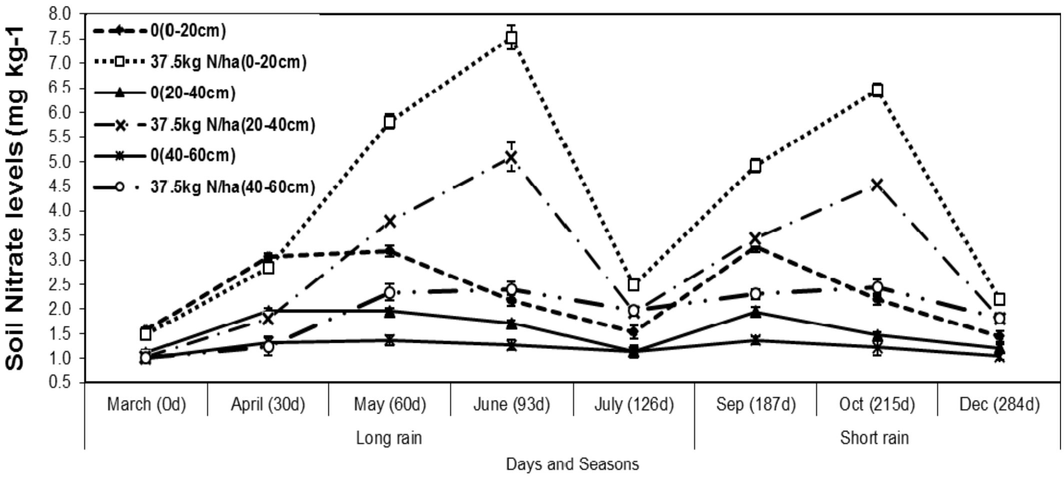

Figure 7. Effect of N fertilizer on soil profile nitrate levels

3.4 Effect of Lime on Phosphorus and Nitrogen Fertilizers Recovery Efficiency

Table 2 shows the effect of lime on grain P and N fertilizer recovery efficiencies. Lime increased both grain P and N fertilizers recovery efficiencies, which increased with increase in rates of lime. The mean grain P fertilizer efficiencies were about 14, 16 and 27 % due to 13 kg P, 13 kg P + 0.77 tons lime and 13 kg P + 1.55 tons lime ha^{-1}, respectively. The average annual N fertilizer recoveries were about 37, 42, and 45% due to 37.5 kg N, 37.5 kg N + 0.77 tons lime and 37.5 kg N + 1.55 tons lime ha^{-1}, respectively. In acid tropical soils, only about 10-20% of the applied P fertilizer is normally recovered by plants in the year of application due to high P sorption by Al and Fe sesquioxides (Keerthisinghe, 2001). P fertilizer recoveries of between 18 to 31% have been reported on Nigerian acid soils (Fofana et al., 2007). Thus, P fertilizer recoveries in this study are within the range normally reported in tropical acid soils. Nitrogen fertilizer recovery efficiencies were also within the range of 30-70% normally recovered by crops (Bock, 1984). Micro-dosing lime increased P and N fertilizers recovery efficiencies primarily by restoring soil pH to levels that are favourable for plant growth and microbial activity. It also eliminated toxic elements and ensured the availability of essential elements. Under such optimal growth conditions crops are able to absorb and use fertilizers more efficiently (Adams & Martin, 1984). Therefore, it is evident from this study that higher N and P fertilizer recovery efficiencies in acid soils can be achieved through micro-dosing lime.

Table 2. Effect of lime on the grain P and N fertilizers recovery efficiency (%)

Phosphorus fertilizer	recovery efficiency			Nitrogen fertilizer	recovery efficiency		
Treatments	LR	SR	Mean	Treatments	LR	SR	Mean
13 kg P ha^{-1}	13.6	14.2	13.9	37.5kg N ha^{-1}	37.6	36.2	36.9
13 kg P ha^{-1} +0.77 tons lime ha^{-1}	15.7	16.4	16.1	37.5kg N ha^{-1}+ 0.77 tons lime ha^{-1}	42.7	40.9	41.8
13 kg P ha^{-1}+1.55 tons lime ha^{-1}	26.3	26.9	26.6	37.5kg N ha^{-1} + 1.55 tons lime ha^{-1}	46.4	43.9	45.2
Mean	18.5	19.2		*Mean*	42.2	40.3	

3.5 Effects of N, P Fertilizers and Lime on Maize Grain Yield

The maize grain yield data is presented in Table 3. The highest mean annual grain yield increase above the control of 134% was obtained with the application of 37.5 kg ha^{-1} N, followed by 13 kg P ha^{-1} (39%) and lime (12-22%). The increased maize grain yield due to lime, N and P fertilizers application reported in this study confirm work by several authors that soil N, P deficiencies and acidity limit maize production in these soils. In similar studies in Kenyan highland acid soil, 50% of the recommended N fertilizer rate and 25-50% of the actual lime requirement increased maize grain yield by about 106 and 13-27%, respectively (Kisinyo, 2011) while Opala et al. (2007) observed significant responses to application of only 6 kg P ha^{-1}. Similarly, in Zimbabwe, 33-50% of the recommended N fertilizer rate increased maize grain yield and adoption of fertilizer use by SHF

(ICRISAT, 2008). Combinations of any two or three of the inputs i.e. lime, P and N, had more effect on maize yield than any one of them applied alone likely due to synergism.

Table 3. Effects of N, P fertilizers and lime on maize grain yield (tons ha^{-1})

Treatments		Long rain					Short rain				
N kg ha^{-1}	P kg ha^{-1}	Control	0.77 t lime ha^{-1}	1.55 t lime ha^{-1}	Mean for P	Mean for N	Control	0.77 t lime ha^{-1}	1.55 t lime ha^{-1}	Mean for P	Mean for N
0	0	0.474	0.595	0.641	0.570	0.857	0.569	0.614	0.730	0.638	0.905
	13	0.950	1.171	1.309	1.143		1.007	1.179	1.329	1.171	
37.5	0	1.667	1.874	1.973	1.838	2.013	1.763	1.876	2.017	1.885	2.112
	13	2.009	2.181	2.372	2.187		2.139	2.333	2.544	2.338	
Mean Lime		1.355	1.275	1.455			1.369	1.500	1.655		
CV%		3.7					3.2				
s.e.d$_{(0.05)}$ *N*		0.016					0.015				
s.e.d$_{(0.05)}$ *P*		0.020					0.005				
s.e.d$_{(0.05)}$ *lime*		0.021					0.012				
s.e.d$_{(0.05)}$ *N*P*		0.010					0.016				
s.e.d$_{(0.05)}$ *N*Lime*		ns					ns				
s.e.d$_{(0.05)}$ *P*Lime*		0.024					ns				
s.e.d$_{(0.05)}$ *N*P*Lime*		0.031					0.026				

t = tons & ns= not significant.

4. Conclusion

Lime increased soil pH, exchangeable Ca^{2+} and Mg^{2+} and reduced exchangeable Al^{3+} which resulted to increased soil available P. Both lime and P fertilizer significantly increased soil available P of the top but not sub-soil due to their slow mobility. Surface applications of lime and P fertilizer cannot therefore adequately correct sub-soil acidity and P deficiency. However, the effect of N fertilizer on soil nitrate levels was significant in the sub-soil because nitrate ions are very mobile within the soil profile and are therefore easily leached by rain water. Micro-dosing of lime increased recovery efficiency of N and P fertilizers and therefore, has the potential to increase nutrient recovery necessary for high crop yields. Application of small amounts of lime and fertilizers P and N significantly increased maize grain yield suggesting that micro-dosing has the potential to increase maize production on Kenyan N and P-deficient acid soils. However, there may be need for further economic evaluation because farmers make their decisions on whether or not to adopt a technology based on economic considerations.

Acknowledgements

We are grateful to The McKnight Foundation for funding the research work. We are also very thankful to the farmer, Mr. Peter Omitto for allowing us to conduct the research on his farm.

References

Adams, F., & Martin, J. B. (1984). Liming effects on nitrogen use and efficiency. In R. O. Hauck (Ed.), *Nitrogen in Crop Production* (pp. 416-424). American Society of Agronomy, Madison.

Arya, L. M. (1990). *Properties and Processes in upland acid soils in Sumatra and their management for crop production*. Winrock Intl. Inst. of Agri. Dev., Raleigh.

Birch, H. F. (1958). The effect of soil drying on humus decomposition and nitrogen availability. *Plant Soil, 10*, 9-31. http://dx.doi.org/10.1007/BF01343734

Bock, B. R. (1984). Efficient use of nitrogen in cropping systems. In R. O. Hauck (Ed.), *Nitrogen in Crop Production* (pp. 272-292). American Society of Agronomy, Madison.

Cochrane, T. T., Salinas, J. G., & Sanchez, P. A. (1980). An equation for liming acid mineral soils to compensate crop aluminium tolerance. *Tropical Agriculture (Tinidad), 57*, 33-40.

Curtin, D., & Syers, J. K. (2001). Lime-induced changes in indices of soil phosphate availability. *Soil Science Society of America Journal, 65*, 147-152. http://dx.doi.org/10.2136/sssaj2001.651147x

Dobermman, A. (2005). Nitrogen use efficacy-state of the art. IFA International Workshop on Enhanced Efficiency Fertilizers, Frankfurt, Germany, June 28-30. Retrieved Spetember 11, 2010 from http://soilfertility.unl.edu/Matrials%20to%20included/nitrogen%20use520state%20of%20the%20art_Dobermman.pdf

FAO. (1988). Revised legend of the FAO-UNESCO soil map of the world. Food and Agriculture Organization of the United Nations, Rome.

Genstat. (2010). *The GenStat Teaching Edition.* GenStat Release 7.22 TE, Copyright 2008, VSN International Ltd.

Giller, K. E., George, C., Ehaliatis, C., Adams, E., Sakala, W. D., & Mafongoya, P. L. (1997). Building soil nitrogen capital in Africa. In P. J. Buresh et al. (Eds.), *Replenishing soil fertility in Africa* (pp. 151-192). SSSA special publication no. 51. Madison. Wisconsin.

Fofana, B., Wopereis M. C. S., Bationo, A., Breman, H., & Mando, A. (2007). Millet nutrient use efficiency as affected by natural soil fertility, mineral fertilizer use and rainfall in the West African Sahel. *Nutrient Cycling in Agroecosystems, 81*, 25-36. http://dx.doi.org/10.1007/s10705-007-9146-y

Holford, I. C. R. (1983). Effects of lime on phosphate sorption characteristics and soluble phosphate of fifteen acid soils. *Australian Journal of Soil Science, 21*, 333-342. http://dx.doi.org/10.1071/SR9830333

ICRISAT. (2008). *Micro Doses, Mega Benefits. Promoting Fertilizer Use in Semi – Arid Zimbabwe*. A manual for extension staff. FAO, Rome.

Jaetzold, R., & Schmidt, H. (1983). F*arm management handbook of Kenya, Vol. IIA Western Kenya and Vol. II B (Central Kenya):* Natural conditions and farm management information. Ministry of Agriculture/GAT Nairobi and GTZ/Ashburn.

Kanyanjua, S. M., Ireri, L., Wambua, S., & Nandwa, S. M. (2002). Acid soils in Kenya: Constraints and remedial options. *KARI Technical Note No.11.*

KARI. (1994). Fertilizer use recommendations. Vol. 1-22. *Fertilizer Use Recommendations Project.* Kenya Agricultural Research Institute, Nairobi Kenya.

Keerthisinghe, G., Zapata, F., Chalk, P., & Hocking P. (2001). Integrated approach for improved P nutrition of plants in tropical acid Soils. In W. J. Horst et al. (Eds), *Plant nutrition – Food security and sustainability of agro-ecosystems* (pp. 974-975). Netherlands: Springer.

Kisinyo, P. O., Othieno, C. O., Gudu, S. O., Okalebo, J. R., Opala, P. A, Maghanga, J. K., … Ogola, B. O. (2013). Phosphorus Sorption and Lime Requirements of Maize Growing Acids Soil of Kenya. *Sustainable Agriculture Research, 2*, 116-123. http://dx.doi.org/10.5539/sar.v2n2p116

Kisinyo. P. O. (2011). *Constraints of soil acidity and nutrient depletion on maize (Zea mays L.) production in Kenya.* Ph.D. Thesis. Moi University.

Kisinyo, P. O., Othieno, C. O., Gudu, S. O., Okalebo, J. R., Opala, Ng'etich W. K., Nyambati, R. O., … Opile, W. R. (2014). Immediate and Residual Effects of Lime and Phosphorus Fertilizer on Soil Acidity and Maize Production in Western Kenya. *Experimental Agriculture,* 50, 128-143. http://dx.doi.org/10.1017/S0014479713000318

Landon, J. R. (1991). *Booker Tropical Soils Manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics* (pp. 133-137). New York: John Wiley & Sons Inc.

Ligeyo, D. O. (2007). *Genetic analysis of maize (Zea mays L.) tolerance to aluminium toxicity and low phosphorus stress and development of synthetics for use in acid soils of western Kenya.* Ph. D. Thesis. Moi University.

Mansell, G. P., Pringle, R. M., Edmeades, D. C., & Shannon, P. W. (1984). Effects of lime on pasture production on soils in the North Island of New Zealand. 3. Interaction of lime with phosphorus. New Zeal. *Journal of Agriculture Research, 27*, 363-369. http://dx.doi.org/10.1080/00288233.1984.10430637

Nziguheba, G. (2007). Overcoming phosphorus deficiency in soil1511s of Eastern Africa: recent advances and challenges. In A. Bationo et al. (Eds.), *Advances in integrated soil fertility management in sub-Saharan Africa: challenges and opportunities* (pp. 49-160). New York: Springer.

http://dx.doi.org/10.1007/978-1-4020-5760-1_13

Okalebo, J. R., Gathua, K. W., & Woomer, P. L. (2002). *Laboratory methods of soil analysis: A working manual*. (2nd ed.). TSBR-CIAT and SACRED Africa, Nairobi, Kenya.

Okalebo, J. R., Othieno, C. O., Woomer, P. L., Karanja, N. K., Sesmoka, J. R. M., Bekunda, M. A., … Mukhwana, E. J. (2006). Available technologies to replenish soil fertility in East Africa. *Nutrient Cycling in Agroecosystems, 76*, 153-170. http://dx.doi.org/10.1007/s10705-005-7126-7

Opala, P. A., Jama, B. J., Othieno, C. O., & Okalebo, J. R. (2007). Effect of phosphate fertilizer application methods and nitrogen on maize yields in western Kenya. An agronomic and economic evaluation. *Experimental Agriculture, 43*, 477-487. http://dx.doi.org/10.1017/S0014479707005315

Quinones, M. A., Borlaug, N. E., & Dowswell, C. R. (1997). A fertilizer-based green revolution for Africa.. In P. J. Buresh et al. (Eds.), *Replenishing soil fertility in Africa* (pp. 81-95). SSSA special publication no. 51. Madison. Wisconsin.

Sanchez, P. A. (1976). *Properties and management of soils in the tropics*. New York, USA: John Willey and Sons, Inc.

Sanchez, P. A., Shepherd, K. D., Soule, M. J., Place, F. M., Buresh, P. J., Izac, A-M. N., … Woomer, P. L. (1997). Soil fertility replenishment in Africa: An investment in Natural resource capital. In R. J. Buresh , P. A. Sanchez & F. Calhoun (Eds.), *Replenishing soil fertility in Africa.* (pp. 1-46). SSSA special publication no. 51. Madison.

Sanginga, N., & Woomer, P. L. (2009). *Integrated Soil Fertility Management in Africa: Principles, Practices and Development Processes*. Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture, p. 263. Nairobi, Kenya.

Seneviratne, R., & Wild, A. (1985). Effect of mild drying on the mineralization of soil nitrogen. *Plant Soil, 84*, 175-179. http://dx.doi.org/10.1007/BF02143181

Smith, M. J. (1981). *Soil Mechanics. Longman Scientific and Technical*, (4th ed.). England, UK.

Tisdale, S. L., Nelson, W. L., & Beaton. J. D. (1990). *Soil fertility and fertilizers*. New York: Macmillan.

Twomlow, S., Rohrbach, D., Dimes, J., Rusike, J., Mupangwa, W., Ncube B., … Maphosa, P. (2010). Micro dosing as a pathway to Africa's Green Revolution: Evidence from broad scale on-farm trials. *Nutrient. Cycling in Agroecosystems, 88*, 3-15. http://dx.doi.org/10.1007/s10705-008-9200-4

van Straaten, P. (2007). *Agrogeology: the use of rocks for crops*. Enviroquest Limited, 352 River Road, Cambridge, Ontario N3C 2B7 Canada, p. 440.

Yorst, R. S., & Ares, A. (2007). Phosphorus and lime requirement of tree crops in tropical acid soils: A review. *Journal of Tropical Forest Science, 19*, 176-185.