

**PHOSPHORUS RETENTION AND THE INTERACTIVE EFFECTS OF  
PHOSPHORUS, LIME AND TILLAGE ON MAIZE IN ACID SOILS OF THE  
KENYA HIGHLANDS**

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## EXTENDED ABSTRACT

Maize (*Zea mays*) is the most important food crop in Kenya. However, its productivity is greatly constrained across the Kenya highlands. Soil acidity and low available phosphorus (P) are among the major hindrances to maize production in acid soils of the Kenya highlands. A survey, greenhouse experiment and field trials were carried out to assess the extent of soil acidity, soil nutrient levels and common soil management practices by farmers that contribute to the poor growth performance of maize in the Kenya highlands. The study also sought to evaluate the interactive effects of tillage, P and lime on maize yields in the acid soils of the Kenyan Highlands. The survey was carried out in nine counties across the Kenya highlands namely: Meru, Embu, Kirinyaga, Nyeri, Kiambu, Nyandarua, Siaya, Busia and Eldoret. Soil acidity and nutrient levels were determined on soil samples taken from the study sites, while farmers' practices were established by administration of a structured questionnaire. Phosphorus adsorption rates and lime requirements of the soils were also evaluated. The adsorption data were fitted into the Langmuir and Freundlich adsorption equations and the relationships between sorbed P and soil properties determined by correlations. Evaluation of the interactive effects of lime, phosphorus and aluminium was carried out by establishment of a greenhouse pot experiment at Waruhiu Farmers Training Centre, Githunguri - Kiambu. Extremely acidic (pH 4.48) and strongly acidic (pH 4.59) soils were used for the study. Four lime (CaO) rates and phosphorus (Ca (H<sub>2</sub>PO<sub>4</sub>)<sub>2</sub>) rates were used. The liming rates were: 0, 2.2, 5.2 and 7.4 tonnes ha<sup>-1</sup> for the extremely acidic soil and 0, 1.4, 3.2, and 4.5 tonnes ha<sup>-1</sup> for the strongly acidic soil. Phosphorus application rates were: 0, 0.15,

0.30 and 0.59 g P kg<sup>-1</sup> soil for the extremely acidic soil and 0, 0.13, 0.26, and 0.51 g P kg<sup>-1</sup> for strongly acidic soil. The experiments were a 4<sup>2</sup> factorial laid down in a Randomized Complete Block Design (RCBD) and replicated three times. After the greenhouse experiment, field experiments were carried out during the 2014 long rains and 2014/15 short rains in Waruhiu Farmers Training Centre, Githunguri, Kiambu County. The objective of the study was to assess the interactive effects of tillage, P and lime in the management of soil acidity, P-uptake and maize growth performance. Tillage practices evaluated included: ploughing, strip tillage and use of hand hoe while fertilizer lime combinations included: DAP + lime (DAPL), TSP + lime (LP), TSP alone (P) and lime alone. The experiment was laid down in the Randomized Complete Block Design (RCBD) with split plot arrangement. Lime and P rates applied were 3.2 tonnes ha<sup>-1</sup> and 52kg P ha<sup>-1</sup>, respectively. Data collected included: maize plant height, number of leaves, internode interval, P-uptake at 30 days after emergence and at tasseling stage, grain yield, and soil chemical characteristics. Information gathered through personal interview via questionnaires revealed that most farmers (>96%) were not aware of the soil acidity problems and management strategies. The farmers also lacked sources of information about new technologies or innovations and < 37% were members of farmers' training groups. Additionally, among the 4% who were aware of soil acidity, only less than 8% had ever tested their soils for soil acidity. Farmers who had applied lime on their farms at least once were also < 3% in all sites. On the basis of overall soil fertility management, >80% of the farmers in the research area applied both fertilizer and manure in their farms, with the majority using diammonium phosphate (DAP), calcium ammonium nitrate (CAN) and farmyard manure. However, a negative

balance was identified between livestock keeping and fertility management, with <8% of the farmers returning crop residues back to the farm. Correlation analysis showed that there were significant relationships ( $P \leq 0.05$ ) between farmer education level, farmer training groups, fertilizer usage and crop yields. It is, therefore, concluded that more farmers' awareness is critical for effective management of acid soils in the Kenya Highlands. Soils in all the study sites were strongly to extremely acidic (pH 4.83 - 3.76), had high exchangeable Al ( $>2$  cmol Al  $\text{kg}^{-1}$ ), and high Al saturation ( $> 20\%$  Al), which most maize germplasm grown in Kenya are sensitive to. The cation exchange capacity was low ( $\text{CEC} < 15$  cmol  $\text{kg}^{-1}$ ) in Siaya, Busia and Eldoret while available P was low ( $<10$  mg P  $\text{kg}^{-1}$  Bray 1) for all sites. The P-adsorption data showed that average maximal adsorbed P of the soils were high (1383- 2238 mg  $\text{kg}^{-1}$  soil) while SPR varied from 189.43 mg P  $\text{kg}^{-1}$  in Eldoret to 529.76 mg P  $\text{kg}^{-1}$  in Nyeri. Freundlich P adsorption isotherms were found to have the best fit for all the tested soils ( $r^2 = 0.882 - 0.990$ ). Additionally, analysis of the interaction between P adsorption maxima and soil properties revealed that there was a positive relationship between P adsorption maxima and clay content, extractable P, exchangeable acidity and aluminium saturation. Conversely, organic matter and electrical conductivity negatively correlated with P adsorption maxima. Greenhouse pot experiments revealed that there existed good lime-Al-P interactions in acid soils of the Kenya Highlands. The interactions significantly ( $P \leq 0.05$ ) increased soil pH, extractable P, Ca, plant P uptake and maize yields. The interactions were also found to negatively affect exchangeable Al, oxalate Al, dithionate Al and P adsorption levels in the soils. Use of 7.4 tonnes  $\text{ha}^{-1}$  lime for the extremely acidic soils and 4.5 tonnes  $\text{ha}^{-1}$  for the strongly acidic soils significantly reduced exchangeable Al and

standard phosphate requirement (SPR) by > 70% compared to lower lime rates. Similarly, use of 0.59 mg P kg<sup>-1</sup> soil reduced SPR of the soil by 40% while 0.51 g P kg<sup>-1</sup> reduced SPR by > 73% in strongly acidic soils. It was, however, observed that there was no significant difference between combination of 7.4 tonnes ha<sup>-1</sup> with either 0.59 g P kg<sup>-1</sup> or 0.3 g P kg<sup>-1</sup> in extremely acidic soils or combination of 4.5 tonnes ha<sup>-1</sup> with either 0.51 g P kg<sup>-1</sup> or 0.26 g P kg<sup>-1</sup> in strongly acidic soils. This shows that the lower lime and P rates can be efficient in the management of soil P in these soils. Analysis of the relationship between lime and P availability showed that liming significantly ( $P \leq 0.05$ ) and positively correlated with soil pH, available P, exchangeable Ca, Langmuir maximum adsorption constant and Langmuir constant related to binding energy. Lime also negatively correlated with SPR and exchangeable Al. It was, therefore, concluded that lime and P positively interact to reduce Al and P adsorption in acid soils in the Kenya highlands. Further research is, however, required to evaluate the short and long term effects of the lime-P interaction on crop yields, availability of other plant nutrients and the soil environment under field conditions. Results from field experiment revealed that tillage-P- lime interactions significantly ( $P \leq 0.05$ ) increased soil pH, available P, CEC, Ca, maize growth, maize plant P-uptake and yields, and reduced soil exchangeable Al. Plough-LP interactions significantly ( $P \leq 0.05$ ) led to > 90% increase in soil pH, extractable P, CEC, Ca, and > 90% reduction of exchangeable Al as compared to the control. Plough-DAPL interactions on the other hand also led to > 96% increase in soil CEC and extractable P. Similarly; plough-DAPL and plough-LP interactions significantly ( $P \leq 0.05$ ) increased maize plant height, P- uptake, drymatter yields and grain yields. Plough-DAPL or LP interactions significantly

increased grain yields by > 70% as compared to the control treatment. Integrating plough with either DAPL or LP was, therefore, found to be effective in the management of soil acidity for increased maize production in Kiambu in the Kenya highlands. Further research is, however, required to ascertain the longterm effects of the integration on maize production, soil acidity and overall soil fertility status of the soils in the Kenya highlands.

## DECLARATION

### Candidate's Declaration

This dissertation is my own original work, done within the registration period, and has not been submitted nor being concurrently submitted in any other institution.

Esther Mwende Muindi

Signature ..... Date .....

### Supervisors' Approval

We confirm that the work reported in this dissertation was carried out by the candidate under our supervision and has been submitted for examination with our approval as university supervisors.

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## TABLE OF CONTENTS

<b>EXTENDED ABSTRACT .....</b>	<b>ii</b>
<b>DECLARATION .....</b>	<b>vii</b>
<b>COPYRIGHT .....</b>	<b>viii</b>
<b>ACKNOWLEDGEMENTS .....</b>	<b>ix</b>
<b>DEDICATION .....</b>	<b>x</b>
<b>TABLE OF CONTENTS .....</b>	<b>xi</b>
<b>LIST OF TABLES .....</b>	<b>xviii</b>
<b>LIST OF FIGURES .....</b>	<b>xxii</b>
<b>LIST OF APPENDICES .....</b>	<b>xxiv</b>
<b>CHAPTER ONE.....</b>	<b>1</b>
<b>1.0 GENERAL INTRODUCTION.....</b>	<b>1</b>
1.1 Maize production in Kenya .....	1
1.2 Role and importance of phosphorus in plant nutrition .....	2
1.3 Forms of phosphorus in soils .....	3
1.3.1 Organic phosphorus in soils .....	3
1.3.2 Inorganic phosphorus in soils.....	4
1.3.2.1 Calcium and magnesium phosphates .....	5
1.3.2.2 Iron and aluminium phosphates .....	7
1.3.2.3 Soil solution P .....	8
1.4 Phosphorus dynamics in soils .....	8
1.4.1 Phosphate retention by soils .....	9

1.4.1.1	Phosphate adsorption by soils .....	10
1.4.1.2	Precipitation.....	11
1.5	Phosphate adsorption isotherms .....	12
1.5.1	The Langmuir equation.....	13
1.5.2	The Freundlich equation .....	15
1.5.3	The Temkin adsorption equation .....	16
1.6	Factors affecting P sorption by soils .....	17
1.6.1	Soil pH .....	17
1.6.2	Ionic strength and composition of the soil solution .....	18
1.6.3	Organic matter .....	18
1.6.4	Clay mineralogy .....	19
1.6.5	Free iron and aluminum.....	20
1.6.6	Soil calcium carbonate.....	20
1.6.7	Effect of temperature .....	21
1.6.8	Effect of time.....	21
1.7	Fate of P in acid soils.....	22
1.8	Strategies and approaches to manage acid soils.....	23
1.8.1	Liming.....	23
1.8.2	Application of organic soil amendments .....	25
1.8.3	Tillage .....	27
1.8.4	Time and method of application of P-fertilizers .....	29
1.9	Phosphate - lime interactions in acid soils .....	30
1.10	The residual effects of lime .....	31
1.11	Attempts made to improve maize production in the acid soils of Kenya.....	32

1.12 OBJECTIVES .....	36
1.12.1 General objective .....	36
1.12.2 Specific objectives .....	36
1.13 HYPOTHESES .....	36
1.14 REFERENCES.....	37
<b>CHAPTER TWO.....</b>	<b>61</b>
<b>2.0 SOIL ACIDITY AND NUTRIENT STATUS OF SOME ACID SOILS</b>	
<b>OF THE KENYA HIGHLANDS .....</b>	<b>61</b>
ABSTRACT .....	61
2.1 INTRODUCTION .....	62
2.2 MATERIALS AND METHODS.....	66
2.2.1 Location of the study sites .....	66
2.2.2 Soil sampling, preparation and characterization .....	66
2.2.3 Administration of the questionnaire.....	67
2.2.4 Data analysis.....	67
2.3 RESULTS .....	68
2.3.1 Chemical and physical properties of the soils from the nine study sites .....	68
2.3.2 Characteristics, perceptions and practices of farmers as captured from the questionnaire administration. ....	69
2.3.2.1 General information about respondents gender and education levels ..	69
2.3.2.2 Membership to farmers training groups .....	70
2.3.2.3 Seasonal choice of type of crop to grow.....	71
2.3.2.4 Soil acidity perceptions or awareness among farmers.....	71

2.3.2.5	Soil acidity management through liming.....	72
2.3.2.6.	Fertilizer and manure application.....	72
2.3.2.7	Manure types and sources.....	73
2.3.2.8	Crop residues utilization by the farmers .....	74
2.3.3	Relationship between farmers' responses and soil chemical properties.....	75
2.4	DISCUSSION .....	76
2.4.1	Soil characterization.....	76
2.4.2	Characteristics, perceptions and farmers' practices.....	77
2.5	CONCLUSIONS.....	79
2.6	REFERENCES .....	81
<b>CHAPTER THREE .....</b>		<b>89</b>
<b>3.0 PHOSPHATE SORPTION BY ACID SOILS OF THE KENYA</b>		
<b>HIGHLANDS.....</b>		<b>89</b>
ABSTRACT	.....	89
3.1	INTRODUCTION .....	90
3.2	MATERIALS AND METHODS.....	92
3.2.1	Location of the study sites .....	92
3.2.2	Soil sampling, preparation and characterization .....	92
3.2.3	Phosphate sorption isotherms .....	92
3.2.4	Statistical analysis .....	93
3.3	RESULTS .....	94
3.3.1	Phosphate adsorption by the soils .....	94

3.3.2 Fitting the adsorption data to the Langmuir and Freundlich equation models .....	95
3.3.3 Relationship between adsorption and soil properties .....	97
3.4 DISCUSSION .....	98
3.5 CONCLUSION .....	101
3.6 REFERENCES .....	102
<b>CHAPTER FOUR .....</b>	<b>108</b>
<b>4.0 INTERACTIVE EFFECTS OF LIME, ALUMINIUM AND PHOSPHORUS IN ACID SOILS OF THE KENYA HIGHLANDS .....</b>	<b>108</b>
ABSTRACT .....	108
4.1 INTRODUCTION .....	109
4.2 MATERIALS AND METHODS .....	112
4.2.1 Experimental layout, design and crop husbandry .....	112
4.2.2 Laboratory analysis .....	114
4.2.3 Maize crop growth data collection .....	114
4.2.4 Statistical analysis .....	115
4.3 RESULTS .....	115
4.3.1 Initial soil physical and chemical characteristics .....	115
4.3.2 The interactive effects of lime, Al and P on soils chemical properties. ....	116
4.3.3 The interactive effects of lime, Al and P on the growth of maize .....	122
4.3.4 The interactive effects of lime, Al and P on phosphorus adsorption by the two acid soils .....	127
4.4 DISCUSSION .....	131

4.4.1	Soil chemical and physical characteristic of the soils.....	131
4.4.2	The interactive effects of lime, Al and P on soil chemical properties .....	132
4.4.3	The interactive effects of lime, Al and P on growth of maize .....	133
4.4.4	The interactive effects of lime, Al and P on soil phosphorus adsorption ..	134
4.5	CONCLUSIONS.....	134
4.6	REFERENCES.....	136
<b>CHAPTER FIVE.....</b>		<b>144</b>
<b>5.0 INTERACTIVE EFFECT OF TILLAGE, PHOSPHORUS AND LIME</b>		
<b>    IN ACID SOILS OF KIAMBU COUNTY, KENYA. ....</b>		<b>144</b>
ABSTRACT .....		144
5.1	INTRODUCTION .....	145
5.2	MATERIALS AND METHODS.....	147
5.2.1	Experimental design, layout and crop husbandry .....	147
5.2.2	Soil Characterization.....	148
5.2.3	Data analysis.....	149
5.3	RESULTS .....	149
5.3.1	Initial soil chemical and physical characteristics .....	149
5.3.2	Effects of tillage-P-lime interactions on chemical properties of acid soils	149
5.4	DISCUSSION .....	153
5.5	CONCLUSIONS.....	155
5.6	REFERENCES.....	157

<b>CHAPTER SIX.....</b>	<b>163</b>
<b>6.0 THE INTERACTIVE EFFECTS OF TILLAGE, PHOSPHORUS</b>	
<b>AND LIME ON GROWTH AND PHOSPHORUS UPTAKE</b>	
<b>BY MAIZE .....</b>	<b>163</b>
ABSTRACT .....	163
6.1 INTRODUCTION .....	164
6.2 MATERIALS AND METHODS.....	166
6.2.1 Experimental design, layout and crop husbandry .....	166
6.2.2 Effect of tillage-P-lime interaction on maize growth .....	166
6.2.3 Effect of tillage-P-lime interactions on P-uptake and maize yields.....	166
6.2.4 Data analysis.....	167
6.3 RESULTS .....	167
6.3.1 Effects of tillage-P-lime interaction on maize growth.....	167
6.3.2 Effects of tillage-P-lime interaction on maize plant P-uptake. ....	169
6.3.3 Effects of tillage-P-lime interaction on maize yields.....	171
6.4 DISCUSSION .....	172
6.5 CONCLUSIONS.....	174
6.6 REFERENCES.....	176
 <b>CHAPTER SEVEN .....</b>	 <b>181</b>
<b>7.0 GENERAL CONCLUSIONS AND RECCOMENDATIONS.....</b>	<b>181</b>
<b>8.0 APPENDICES.....</b>	<b>183</b>

## LIST OF TABLES

Table 2.1:	Description of the study areas.....	66
Table 2.2:	The chemical and physical properties of the soils from the nine study sites.....	69
Table 2.3:	Respondents gender and education levels.....	70
Table 2.4:	Factors determining fertilizer and manure choice in the Kenya Highlands. ....	74
Table 2.5:	Correlations between farmers soil manangement practices and soil chemical properties.....	76
Table 3.1:	Maximal P adsorbed and standard phosphorus requirement (SPR) of the soils from the nine sites.....	95
Table 3.2:	Regression equations with $R^2$ value for soils in the nine sites.....	96
Table 3.3:	Parameters of the fitted Langmuir and Freundlich adsorption equations.....	97
Table 3.4:	Correlation between soil properties and the Langmuir and Freundlich adsorption parameters.....	98
Table 4. 1:	Actual amounts of phosphorus and lime added to the acid soils....	113
Table 4.2:	Physicochemical properties of the two soils prior to the pot experiment.....	116
Table 4.3:	Effect of lime-Al-P interactions on the pH (water) of the acid soils.....	117
Table 4.4:	Effect of lime-Al-P interactions on extractable phosphorus ( $\text{mg kg}^{-1}$ ) of the two acid soils. ....	117

Table 4.5:	Effect of lime-Al-P interactions on exchangeable calcium ( $\text{cmol kg}^{-1}$ ) of the two acid soils. ....	118
Table 4.6:	Effect of lime-Al-P interactions on CEC ( $\text{cmol kg}^{-1}$ soil) of two acid soils.....	118
Table 4.7a:	Effect of lime-Al-P interactions on exchangeable aluminium ( $\text{cmol kg}^{-1}$ ) of the two acid soils. ....	119
Table 4.7b:	Effect of lime-Al-P interactions on aluminium saturation (%) of the two acid soils. ....	119
Table 4.7c:	Effect of lime-Al-P interactions on exchangeable acidity ( $\text{cmols kg}^{-1}$ soil) of the two acid soils. ....	120
Table 4.8a:	Effect of lime-Al-P interactions on oxalate aluminium ( $\text{Al}_o$ ) ( $\text{cmol kg}^{-1}$ ) of the two acid soils. ....	120
Table 4.8b:	Effect of lime-Al-P interactions on dithionate aluminium ( $\text{Al}_d$ ) ( $\text{cmol kg}^{-1}$ ) of the two acid soils. ....	121
Table 4.9a:	Effects of lime-Al-P interactions on oxalate iron ( $\text{Fe}_o$ ) and dithionate iron ( $\text{Fe}_d$ ) ( $\text{cmol kg}^{-1}$ ) of the two acid soils. ....	121
Table 4.9b:	Effects of lime-Al-P interactions on dithionate iron ( $\text{Fe}_d$ ) ( $\text{cmol kg}^{-1}$ ) in two acid soils.....	121
Table 4.10:	Relationship between soil pH, P, exchangeable acidity, exchangeable aluminium and lime in the two acid soils. ....	122
Table 4.11:	Effect of lime-Al-P interactions on maize plant height (cm) in the two acid soils. (averaged over 5 sampling period) .....	122
Table 4.12:	Effect of lime-Al-P interactions on number of leaves per maize plant in the two acid soils (averaged over 5 sampling period) .....	123

Table 4.13:	Effects of lime-Al-P interactions on P concentration (%) in maize tissues 35 days after emergence.....	126
Table 4.14:	Effect of lime-Al-P interactions on maize dry matter (tonnes ha <sup>-1</sup> ) 35 days after emergence .....	127
Table 4.15:	Effect of lime-Al-P interaction on standard phosphorus requirement (SPR) in extremely acidic soils of the Kenya Highlands .....	130
Table 4.16:	Effect of lime-Al-P interaction on standard phosphorus requirement (SPR) in strongly acidic soils of the Kenya Highlands .....	131
Table 4.17:	Relationship between standard phosphate requirement, lime application and Langmuir equation constants of the acid soils of the Kenya Highlands.....	131
Table 5.1:	Some baseline physical and chemical properties of the soil at the study site .....	149
Table 5.2:	Effect of tillage-P-lime interaction on pH of acid soils of Kiambu .....	150
Table 5.3:	Effect of tillage-P-lime interaction on extractable P (mg kg <sup>-1</sup> ) in acid soils of Kiambu .....	151
Table 5.4:	Effect of tillage-P-lime interaction on cation exchange capacity (CEC) (cmol kg <sup>-1</sup> ) in acid soils of Kiambu .....	151
Table 5.5:	Effect of tillage-P-lime interaction on exchangeable Ca (cmol kg <sup>-1</sup> ) in acid soils of Kiambu .....	152

Table 5.6:	Effect of tillage-P-lime interaction on exchangeable magnesium ( $\text{cmol kg}^{-1}$ ) in acid soils of Kiambu .....	153
Table 5.7:	Effect of tillage-P-lime interaction on exchangeable Al ( $\text{cmol kg}^{-1}$ ) in acid soil of Kiambu.....	153
Table 6.1:	Effect of tillage-P-lime interactions on height (cm) of maize grown in acid soils of Kiambu.....	167
Table 6.2:	Effect of tillage-P-lime interactions on number of maize leaves in acid soils of Kiambu. ....	168
Table 6.3:	Effect of tillage-P-lime interactions on internode interval of maize plants grown in acid soils of Kiambu.....	168
Table 6.4:	Effects of tillage-P-lime interactions on percent silking of maize planted in acid soils of Kiambu. ....	169
Table 6.5:	Effects of tillage-P-lime interactions on percent (%) tasseling of maize grown in acid soils of Kiambu.....	169
Table 6.6:	Effects of tillage-P-lime interactions on P- uptake ( $\text{mg kg}^{-1}$ ) by maize grown in acid soils of Kiambu 30 days after emergence. ....	170
Table 6.7:	Effects of tillage-P-lime interactions on P-uptake at tasseling stage of maize grown in acid soils of Kiambu.....	170
Table 6.8:	Effects of tillage-P-lime interactions on dry matter yield ( $\text{tonnes ha}^{-1}$ ) of maize grown in acid soils of Kiambu. ....	171
Table 6.9:	Effects of tillage-P-lime interactions on grain yield ( $\text{tonnes ha}^{-1}$ ) of maize grown in acid soils of Kiambu. ....	172

## LIST OF FIGURES

Figure 2.1:	Percentage of farmers in each site who are members of some training groups .....	70
Figure 2.2:	Criterion applied by farmers when choosing the type of crop to plant per season in the nine sites.....	71
Figure 2.3:	Percentage of farmers having soil acidity knowledge and had tested their soils in the nine sites. ....	72
Figure 2.4:	Percentages of farmers applying lime in their farms at the nine sites .....	72
Figure 2.5:	Percentages of farmers applying manures or fertilizers in their farms at the nine sites.....	73
Figure 2.6:	Sources and types of manures applied by farmers at the nine sites..	73
Figure 2.7:	Disposal of crop residues by farmers from the nine sites. ....	75
Figure 3.1:	Phosphate adsorption isotherms of the soils from nine sites .....	94
Figure 3.2:	Langmuir adsorption isotherms for soils in the nine sites .....	95
Figure 3.3:	Freundlich adsorption isotherms for soils in the nine sites .....	96
Figure 4.1:	Effects of liming on heights of maize plants planted in extremely acidic soils (LSD bars inserted) .....	123
Figure 4.2:	Effects of liming on heights of maize plants planted in strongly acidic soils (LSD bars inserted) .....	124
Figure 4.3:	Effects of liming on number of leaves from maize planted in extremely acidic soils (LSD bars inserted) .....	124

Figure 4.4:	Effects of liming on maize plant leaves in strongly acidic soils (LSD bars inserted).....	125
Figure 4.5:	Effects of liming on leaf area index of maize planted in extremely acidic soils (LSD bars inserted) .....	125
Figure 4.6:	Effects of liming on leaf area index of maize planted in strongly acidic soils (LSD bars inserted) .....	126
Figure 4.7:	Phosphate adsorption isotherm of extremely acidic soil treated with different phosphate fertilizer rates (Error bars inserted).....	128
Figure 4.8:	Phosphate adsorption isotherm of the strongly acidic soil treated with different phosphate fertilizer rates (Error bars inserted).....	128
Figure 4.9:	Phosphate adsorption isotherm of extremely acidic soil treated with different rates of lime (Error bars inserted).....	129
Figure 4.10:	Phosphate adsorption isotherm of strongly acidic soil treated with different rates of lime (Error bars inserted). .....	130

## LIST OF APPENDICES

Appendix 2.1: Interview Questionnaire .....	183
Appendix 4.1: Analysis of variance of plant height in green house experiment....	185
Appendix 4.2: Analysis of variance of number of leaves in green house experiment.....	185
Appendix 4.3: Analysis of variance of dry matter in green house experiment. ....	185
Appendix 5.1: Analysis of variance of soil pH in soils during long rains .....	185
Appendix 5.2: Analysis of variance of soil pH in soils during short rains .....	186
Appendix 5.3: Analysis of variance of soil available P during short rains .....	186
Appendix 5.4: Analysis of variance of soil CEC during long rains .....	186
Appendix 5.5: Analysis of variance of soil CEC during short rains .....	187
Appendix 5.6: Analysis of variance of soil exchangeable Al during long rains .....	187
Appendix 5.7: Analysis of variance of soil exchangeable Al during short rains ..	187
Appendix 5.8: Analysis of variance of dry matter yield during short rains.....	188
Appendix 6.1: Analysis of variance of average maize grain yield.....	188
Appendix 6.2: Average monthly rainfall (mm) at Waruhui farmers Training Centre, Githunguri .....	188

## CHAPTER ONE

### 1.0 GENERAL INTRODUCTION

#### 1.1 Maize production in Kenya

Maize is the primary staple food in Kenya (Wekesa *et al.*, 2003; Schroeder *et al.*, 2013). It is both a staple food and cash crop for small-scale farmers (Government of Kenya, 2009) and it is estimated to account for approximately 20% of the total agricultural production, 25% of the agricultural employment, and 15% of the national GDP (Ayaga, 2003). According to the Government of Kenya (2009), maize contributes about 68% of daily per capita cereal consumption, 35% of the total dietary energy consumption and 32% of the total protein consumption, amounting to a per capita consumption of about 98 kg yr<sup>-1</sup>. Thus, Kenya's national food security is strongly linked to sustainable production of adequate quantities of maize to meet the increasing domestic demand (Odendo *et al.*, 2001). Additionally, the country has 1.6 million hectares under maize production and there is limited scope for further expansion since most of the arable land is already under cultivation of other crops (Makokha *et al.*, 2001; Kibaara, 2005). Therefore, future increase in maize production can be achieved by intensification (improving yield per hectare) rather than by extensification (expanding production area). The intensification can be achieved through clear understanding of soil fertility and application of new farming technologies, which is adoption of the integrated soil fertility and plant nutrient management approaches, principles and strategies.

The average maize yield in Kenya is about 1.8 tonnes ha<sup>-1</sup> compared to the possible potential yield of over 6 tonnes ha<sup>-1</sup> (Makokha *et al.*, 2001; Government of Kenya,

2010). Additionally, average yields of below 0.5 tonnes ha<sup>-1</sup> per season are common in the western parts of the country (Nekesa *et al.*, 1999). The low maize yields have been largely attributed to low quality seeds, soil fertility decline and degradation, and poor agronomic practices (Wesonga *et al.*, 2008; Wambugu *et al.*, 2012). The yield potential of  $\geq 6$  tonnes ha<sup>-1</sup> could be achieved through the adoption of improved agronomic practices, use of hybrid maize varieties and appropriate soil fertility management practices by small-scale maize producers who account for 70% of the country's maize production (Muthamia *et al.*, 2001; Dixit *et al.*, 2011).

## **1.2 Role and importance of phosphorus in plant nutrition**

Next to nitrogen, phosphorus (P) is the second most important macronutrient as an essential plant nutrient (Srinivasan *et al.*, 2012). It is a key nutrient for higher and sustained agricultural productivity (Scervino *et al.*, 2011) and which limits plant growth in many soils. Phosphorus forms an important component of the organic compound adenosine triphosphate (ATP), which is the energy currency that drives all biochemical processes in plants (Brady and Weil, 2008). It is also an integral component of nucleic acids, coenzymes, nucleotides, phosphoproteins, phospholipids and sugar phosphates as well as intermediates of signal transduction events (Khan *et al.*, 2010; Plaxton and Lambers, 2015). Phosphorus is involved in an array of processes in plants such as photosynthesis, respiration, nitrogen fixation, flowering, fruiting, and maturation (Brady and Weil, 2008; Xiang *et al.*, 2012; Plaxton and Lambers, 2015). Plant dry matter may contain up to 0.5% phosphorus (Brady and Weil, 2008).

However, phosphorus deficiency in soil is the most common nutritional stress in many regions of the world, affecting 42% of the cultivated land in the world (Liu *et al.*, 1994). The P deficiency is caused either by low P content in the soils parent materials or by transformations of P added to soils to forms not available to plants. The P deficiency results in poor plant root formation, slow development, poor seed set and fruit formation hence, low and poor crop yields (Brady and Weil, 2008; Khan *et al.*, 2013).

### **1.3 Forms of phosphorus in soils**

Soil P exists in various chemical forms including inorganic P (Pi) and organic P (Po). These P forms differ in their behaviour, fate in soils (Hansen *et al.*, 2004; Turner *et al.*, 2007) and availability to plants (Brady and Weil, 2008).

#### **1.3.1 Organic phosphorus in soils**

The amounts of organically held phosphorus (Po) vary greatly among soils. It occurs from traces in aridisols to several hundred mg kg<sup>-1</sup> in histosols. It is estimated to range between 7 to 1056 P mg kg<sup>-1</sup> of soil or 20-80% of P in soils worldwide (Campbell and Racz, 1975; Richardson, 1994). Decomposing plant and animal products, along with the soil microflora and fauna, provide a significant store and source of Po in agricultural systems (Stutter *et al.*, 2012). It is generally assumed that soil Po is derived directly or after biochemical transformations of organic matter both among soils and within the soil profile (Cunha *et al.*, 2007; Zaia *et al.*, 2008). Added P from phosphate fertilizers can also be converted to organic forms (immobilized) (Holford, 1997; Brady and Weil, 2008; Syers *et al.*, 2008) especially where there is

no enough P in the soil, whereby microorganism convert the Pi to Po to incorporate it into their living cells.

Soil Po exists mainly in stabilized forms as inositol phosphates and phosphonates, and active forms as orthophosphate monoesters, and organic polyphosphates (Condrón *et al.*, 2005; Nash *et al.*, 2014; Plaxton and Lambers, 2015). The Po can be released when roots or phosphate secretions undergo decomposition and mineralization (George *et al.*, 2006; Rita *et al.*, 2013) mediated by soil microorganisms. As proposed by McGill and Cole (1981), mineralization can be divided into two processes: a) biochemical mineralization in which inorganic phosphorus (Pi) is released from organic compounds through phosphatase exoenzymes, regulated by P demand; and b) biological mineralization, which is the release of Pi from organic materials during carbon oxidation by soil organisms, regulated by energy demand. These processes are highly influenced by the soil moisture status, soil temperature regime, surface soil physical and chemical properties (Turner *et al.*, 2007).

### **1.3.2 Inorganic phosphorus in soils**

Inorganic phosphorus (Pi) occurs mainly as  $\text{H}_2\text{PO}_4^-$  and  $\text{HPO}_4^{2-}$  adsorbed onto the surfaces of oxides and hydroxides of Fe or Al, organic matter or bound to Ca (Olibone and Rosolem, 2010). The adsorption of P in soils depends on soil pH and clay minerals (Duputel *et al.*, 2013). However, most Pi occurs in the clay fraction as salts of orthophosphoric acid. Phosphorus forms insoluble compounds with iron and aluminium at low pH, more soluble compounds with calcium and magnesium at pH values near neutrality, and insoluble compounds with calcium at higher pH values (Tisdale *et al.*, 1985; Brady and Weil, 2008; Shen *et al.*, 2011). There is a wide range

of solubility of these various phosphate compounds and their availability to crops is optimal within the soil pH range of about 6.0 to 6.5 for most agricultural soils. The  $P_i$  compounds are grouped as calcium or magnesium-bound and iron and aluminium-bound (Brady and Weil, 2008).

### 1.3.2.1 Calcium and magnesium phosphates

Calcium or magnesium phosphate compounds are not found in soils at low soil pH but are stable, insoluble and dominant in neutral or alkaline soils (Brady and Weil, 2008; Shen *et al.*, 2011). They occur in soils in several forms and the most important forms are:

- a)  $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$ , monocalcium phosphate, which is the water-soluble component of superphosphate that is transformed to less soluble products.
- b)  $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$  and  $\text{CaHPO}_4$ , dicalcium phosphate, both hydrated and the unhydrated forms that are slightly soluble in water.
- c)  $\text{Ca}_8\text{H}_2(\text{PO}_4)_6 \cdot 5\text{H}_2\text{O}$ , octacalcium phosphate.
- d)  $\text{Ca}_3(\text{PO}_4)_2$ , tricalcium phosphate.
- e)  $\text{Ca}_{10}(\text{PO}_4)_6 \cdot (\text{OH})_2$  (hydroxyapatite) and  $\text{Ca}_{10}(\text{PO}_4)_6\text{F}$  (fluorapatite), and
- d)  $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$  (struvite) which is alkaline and water-soluble (Tisdale *et al.*, 1985; Kruse *et al.*, 2015).

Dicalcium phosphate ( $\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$ ), octacalcium phosphate ( $\text{Ca}_8\text{H}_2(\text{PO}_4)_6 \cdot 5\text{H}_2\text{O}$ ) and hydroxyapatite ( $\text{Ca}_{10}(\text{PO}_4)_6 \cdot (\text{OH})_2$ ) are the principal crystalline phosphates which have been identified in soils (Tisdale *et al.*, 1985). The native phosphorus in soils originated largely from disintegration and transformation of

rocks containing the mineral apatite,  $\text{Ca}_{10}(\text{PO}_4)_6(\text{F,Cl,OH})_2$ . Apatite has also been reported as a common soil mineral by Shipp and Matelski (1960). However, the apatite in its primary form does not supply phosphate to plants, because of its low solubility and rate of solubilization (Brady and Weil, 2008). On the contrary, hydroxyapatite ( $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ ) has been reported to be a stable form of Pi over a wide range of soil pH values (Tisdale *et al.*, 1985) hence it is ability to supply phosphate to plants.

The phosphorus found in calcareous soils does not correspond to any one mineral species (Hagin and Tucker, 2012). It may be controlled by octacalcium phosphate in some soils or by hydroxyapatite in other soils (Hagin and Tucker, 2012; Webber and Mattingly, 1970). The hydroxyapatite in soil invariably contains some carbonate ions while the presence of octacalcium phosphate has been reported in soils limed or fertilized with phosphates (Webber and Mattingly, 1970). Baifan and Yichu (1989) classified Pi in calcareous soils as follows: calcium phosphate in the form of dicalcium phosphate, octacalcium phosphate and apatite types. On the contrary, Syers *et al.* (1972) and Hooker *et al.* (1980) suggested the fractionation of inorganic phosphorus in calcareous soils as a series of calcium phosphates with complex physico-chemical reactions and varying availability to plants for growth.

The availability of P from various inorganic compounds was further compiled by Tisdale *et al.* (1985). It was revealed that struvite ( $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ ) had the highest P availability as compared to mono or dicalcium phosphates. In soils containing large quantities of magnesium, a number of insoluble magnesium phosphate compounds

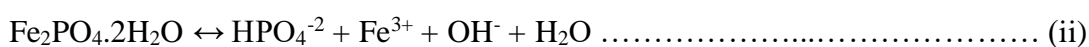
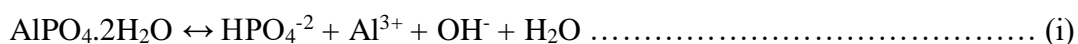
such as dimagnesium phosphate trihydrate ( $\text{MgHPO}_4 \cdot 3\text{H}_2\text{O}$ ), trimagnesium phosphate ( $\text{Mg}_3(\text{PO}_4)_2$ ) and/or struvite ( $\text{MgNH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$ ) may form (Webber and Mattingly, 1970; Tisdale *et al.*, 1985). However, these magnesium phosphates are more soluble than dicalcium phosphate and octacalcium phosphate, hence results in greater availability of P for plant uptake.

### **1.3.2.2 Iron and aluminium phosphates**

A number of aluminum and iron phosphate minerals occur in soils (Tisdale *et al.*, 1985). The most common aluminum phosphates in soils are wavellite [ $\text{Al}_3(\text{PO}_4)(\text{OH})_3 \cdot 5\text{H}_2\text{O}$ ] and variscite ( $\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$ ) (Brady and Weil, 2008; Oelkers and Valsami-Jones, 2008; Kruse *et al.*, 2015). Although variscite is dominant in slightly acidic soils, it dissolves incongruently at high pH values, leading to formation of a more basic solid phase of aluminum hydroxy phosphate (Taylor and Gurley, 1964). The aluminium hydroxyl phosphates so formed controls phosphorus concentration in solution in acid soil by forming a surface complex on variscite. However, in pure systems, where the pH of the equilibrium solution is less than 3.1, the solubility product of variscite controls the phosphorus concentration in solution (Chakravarti and Talibudeen, 1962).

Although variscite ( $\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$ ) and strengite ( $\text{FePO}_4 \cdot 2\text{H}_2\text{O}$ ) are the least soluble compounds at low soil pH (Tisdale *et al.*, 1985; Kruse *et al.*, 2015), strengite is the most common iron phosphate in soils. According to Chakravarti and Talibudeen (1962), strengite coexists with hydrated iron oxide ( $\text{Fe}_2\text{O}_3 \cdot 2\text{H}_2\text{O}$ ) at pH 3.8 to 6.7 in the tropics and in the pH range of 3.8 to 4.2 in temperate soils. Strengite also

crystallizes rapidly when iron phosphate is formed. Less crystalline aluminium phosphate has greater surface area which is favorable for release of phosphorus into the soil solution. Therefore, under very acid conditions minerals of the variscite and strengite groups are precipitated from their soluble forms (Brady and Weil, 2008) according to the following reactions.



### 1.3.2.3 Soil solution P

Soil solution P refers to the phosphorus fractions or phosphate ionic species dissolved in the soil solution and it is always in equilibrium with the labile P (Fageria, 2008). Phosphorus concentrations in the soil solutions are low, normally ranging from 0.001 to about 1 mg P L<sup>-1</sup>, with an average of about 0.05 mg P L<sup>-1</sup> (Wood, 1998). The phosphorus taken up by plant roots and mycorrhizal hyphae are mainly the H<sub>2</sub>PO<sub>4</sub><sup>-</sup>, HPO<sub>4</sub><sup>2-</sup> or PO<sub>4</sub><sup>3-</sup>, depending on the pH of the soil (Mengel *et al.*, 2001; Shinjiro, 2003). The dominant inorganic P species in the soil solution below pH 7.2 is the H<sub>2</sub>PO<sub>4</sub><sup>-</sup> while HPO<sub>4</sub><sup>2-</sup> and PO<sub>4</sub><sup>3-</sup> are dominant at pH values between 7.2 and 12.1, and 10.0 and 14.0, respectively (Shinjiro, 2003).

## 1.4 Phosphorus dynamics in soils

Primary P minerals like apatites, strengite and variscite are very stable and the release of P in soil solution from these minerals by weathering in acid soils is generally low (Shen *et al.*, 2011). In contrast, secondary P minerals including calcium (Ca), iron (Fe), and aluminium (Al) phosphates vary in their dissolution rates, depending on the size of the mineral particles and soil pH (Pierzynski *et al.*,

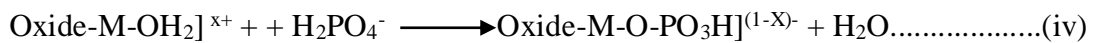
2005; Oelkers and Valsami-Jones, 2008). With increasing soil pH, solubility of Fe and Al phosphates increases but solubility of calcium phosphates decreases until pH values above 8 where it starts to increase (Hinsinger, 2001). The parent material of soil P is primarily calcium phosphates, mostly the fluorapatite [ $\text{Ca}_5(\text{PO}_4)_3\text{F}$ ], with chloride (Cl), hydroxyl ( $\text{OH}^-$ ), or carbonate ( $\text{CO}_3^{2-}$ ) sometimes replacing the F. This  $\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})$  is the raw material used in the manufacture of P fertilizers (Black, 1993). Weathering processes cause bases, silicates and carbonates to be lost from the soil, concentrates the Fe and Al, and releases P into the soil solution (Shinjiro, 2003).

The released P can be available to the soil solution as soluble inorganic P and / or reverted back to organic P through immobilization by living organisms in the soil. The soluble P can also be sorbed onto surfaces of secondary minerals and become part of the soil P pool referred to as labile P (Condon *et al.*, 2005). Additionally, the labile P can be desorbed, returned to the soil solution or transformed into more thermodynamically stable forms of P referred to as non-labile P (Novais and Smyth, 1999; Rheinheimer and Anghinoni, 2001).

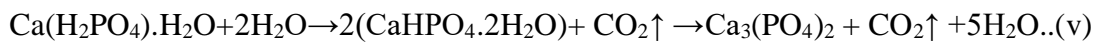
#### **1.4.1 Phosphate retention by soils**

The types of reactions that are responsible for P retention by soils differ from soil to soil and are closely related to soil pH (Brady and Weil, 2008). In acid soils, these reactions involve mainly Al, Fe and Mn oxides, or their ionic forms or hydrous oxides (Scheffe *et al.*, 2007; Brady and Weil, 2008). The aforementioned soil components retain P through ligand exchange, adsorption and precipitation reactions as shown in equations (iii) and (iv) (Sample *et al.*, 1980; Scheffe *et al.*, 2007). In

alkaline and calcareous soils, the reaction involves precipitation of calcium phosphate minerals (Equation v) or adsorption onto iron impurities on surfaces of carbonates and secondary clay minerals (Sample *et al.*, 1980; Brady and Weil, 2008; Devau *et al.*, 2010).



where M = Al or Fe .



Where: Monocalcium phosphate is soluble and tricalcium phosphate is insoluble.

#### 1.4.1.1 Phosphate adsorption by soils

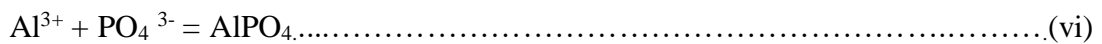
In acid soils, adsorption of P occurs principally via the formation of an inner-sphere complex between orthophosphate anions (such as  $\text{H}_2\text{PO}_4^{2-}$ ), and a metal cation or metal oxyhydroxide (such as Fe and Al) (Rhue and Harris, 1999; Sims and Pierzynski, 2005; Wang *et al.*, 2013). The orthophosphate ion then undergoes ion exchange with  $\text{OH}^-$  or  $\text{H}_2\text{O}$  groups on the soil particle surface, with a coordinate covalent bond formed between the P atom and the metal cation (Rhue and Harris, 1999; Sims and Pierzynski, 2005).

The a fore mentioned reactions or transformations lead to decreased point of zero charge (PZC). According to Reddy *et al.* (1999), once all surface sites are occupied by P adsorption, the P begins to diffuse into the particle via absorption. The adsorption processes are temperature dependent, pH controlled, and process rates decrease with time (Barrow, 1984; Wang *et al.*, 2013). The Al and Fe oxides occur as

amorphous Al and Fe in flooded soils and/or as crystalline terrestrial soils (Sah *et al.*, 1989; Fresse *et al.*, 1992). However, the amorphous oxides of Al and Fe often exhibit greater reactive surface areas than crystalline forms for P sorption (McKeague and Day, 1966; Rhue and Harris, 1999). This makes oxalate extractable Fe and Al tests useful in extraction of poorly crystalline oxyhydroxides of Fe and Al rather than the crystalline forms which are not associated with P sorption (Rayment and Lyons, 2011).

#### 1.4.1.2 Precipitation

Precipitation processes involve the removal of P from solution through the reaction of the P with Al (Equation vi), Fe and Ca cations to form new solid precipitates (Rhue and Harris, 1999; Brady and Weil, 2008).



Reactions with calcite surfaces involve initial adsorption of small amounts of P, which can be followed by precipitation of Ca-bound P (Cole *et al.*, 1953). Cations such as Na, K, and Mg can also affect P adsorption, as they can displace Ca, from the exchange complex thereby freeing up Ca to sorb P (Roborage and Corey, 1979). Precipitation of P as insoluble Ca-bound P (Equation vii) is the dominant transformation reaction in wetland soils and sediments at pH values greater than 7 (Faulkner and Richardson, 1989).



### 1.5 Phosphate adsorption isotherms

A phosphate adsorption isotherm is a graphical presentation for describing the adsorption of P by, or desorption of P from the soil solid phase as a function of the P equilibrium concentration in the soil solution at constant temperature and pressure (Olsen and Watanabe, 1957; Ahmed *et al.*, 2015; Kruse *et al.*, 2015). According to Bache (1964) and Olsen and Khasawneh (1980), an isotherm from a plot of phosphate retained against different equilibrium P concentrations can be divided into three regions. The regions correspond to three distinct stages in soil - phosphate interactions. The first region corresponds to low phosphate addition, resulting in practically complete adsorption or a negligible fraction of the added phosphate remaining in the equilibrium solution; the adsorption isotherm rises steeply and remains close to the Y-axis. The second region is a strongly curved portion of the isotherm which is convex to the Y-axis and adsorption varies logarithmically with the equilibrium phosphate concentration. The third portion occurs at medium to high phosphate concentrations (precipitation), where, the adsorption varies linearly with the amounts of P in the equilibrium solution. At higher level of this region, the slope of the line is small and, for most soils, the isotherms tend to be more or less parallel to the X-axis.

The adsorption reaction between phosphate and soils has been described mathematically using several adsorption equation models. They include: Langmuir equation (Bolster and Hornberger, 2007; Jiao *et al.*, 2008), Freundlich equation (Bolster and Hornberger, 2007; Jiao *et al.*, 2008), Temkin equation (Ioannou *et al.*, 1994; Ahmed *et al.*, 2008) and Elovich equation (Olsen and Watanabe, 1957; Fox and Kamprath, 1970; Dimirkou and Ioannou, 1998). Among these equations, the

Langmuir and Freundlich equations are the most commonly used to describe the relationship between equilibrium P and P sorbed by tropical soils (Hussain *et al.*, 2003; Kruse *et al.*, 2015). Sorption parameters derived from these equations can predict the maximum P sorption capacity (K<sub>max</sub>) and the P adsorption energy and are, therefore, useful in the evaluation of soil fertility and other P management parameters (Henry and Smith, 2003) in relation to P.

### 1.5.1 The Langmuir equation

The Langmuir equation was developed by Langmuir in 1916 on the assumption that gas-molecules are sorbed onto solid surfaces as a monolayer, with a constant and specific energy of adsorption. It was first used by Olsen and Watanabe (1957) to describe phosphate adsorption in soils. In its linear form, the Langmuir equation can be written as:

$$C/X = 1/Kb + C/b \dots \dots \dots \text{(viii)}$$

where, C = equilibrium concentration of phosphate in solution ( $\mu\text{g P/ml}$ ), X= mass of phosphate adsorbed ( $\mu\text{g}$ )/ mass of soil (g) K= adsorption maximum ( $\mu\text{g P g}^{-1}$  soil), b is a constant related to the binding energy of the soil. A plot of C/X against C should give a straight line, from which the adsorption maximum, K, the inverse of the slope and the constant b, can be calculated. The equation follows three principles, namely (i) the energy of adsorption is constant, hence uniform sites of adsorption and lack of interaction between adsorbed molecules for the gases but for soil ions; (ii) adsorption is on localized sites, which implies no translational motion of adsorbed ions in the plane of the surfaces, and (iii) the maximum adsorption possible corresponds to a complete mono ionic layer (Holford *et al.*, 1974).

The Langmuir equation was derived based on theoretical grounds and it contains parameters which have physico-chemical significance (Olsen and Watanabe, 1957; Holford *et al.*, 1974) representing the extensive (adsorption capacity) and intensive (affinity) properties of the adsorbent for the adsorbate (Holford, 1982). However, deviations from the expected linearity (curvilinearity) have been reported at high phosphate additions (Olsen and Watanabe, 1957). This problem was resolved by assuming that the type of adsorption occurred at low equilibrium concentration where a mono ionic layer can be expected (Olsen and Watanabe, 1957; Rennie and McKercher, 1959). However, the development of a multi-surface Langmuir-type equation by (Holford *et al.* 1974) and Goldberg (2005) under higher equilibrium concentrations has somewhat overcome these deviations

Rajan and Fox (1975) and Ryden and Syers (1975) used the two-term Langmuir relationship to obtain improved fit and understanding of the P –adsorption and soil-phosphate interaction. This has been considered appropriate for phosphate adsorption studies since P is retained in soils by surfaces with different affinities for phosphate. According to Holford *et al.* (1974), the two-surface Langmuir equation gives meaningful estimates of phosphate adsorption capacity compared to the simple Langmuir equation. However, the only parameters considered in all the models are the equilibrium concentration "C" and the retained phosphate "X", either in the original form or in the modified form by taking into account the phosphate already adsorbed, as suggested by Olsen and Watanabe (1957), Bache and William (1971), Fitter and Sulton (1975) and Mendoza *et al.* (1990). The multi-surface Langmuir equation model has the form:

$$X = [K_1 b_1 P / (1 + b_1 P)] + [K_2 b_2 P / (1 + b_2 P)] + \dots [K_n b_n P / (1 + b_n P)] \dots \dots \dots (ix)$$

where,  $X$  = mass of phosphate adsorbed ( $\mu\text{g}$ ) / mass of soil (g)  $K$  = adsorption maximum ( $\mu\text{g P g}^{-1}$  soil),  $b$  is a constant related to the binding energy of the soil,  $P$  is the equilibrium gas pressure.

### 1.5.2 The Freundlich equation

Freundlich equation was the first model to be used in describing phosphate retention in soil (Russell and Prescott, 1916; Siebers and Leinweber, 2012). Barrow (1978) advocated that the adsorption data from dilute solution could be fitted to the Freundlich equation of the form:  $x/m = aC^b$ ..... (x)

It was later modified to:  $x/m = KfC^{(1/n)}$  ..... (xi)

Where,  $x/m$  is the amount of P adsorbed / sorbed ( $\text{mg kg}^{-1}$  soil),  $C$  is the concentration of P in soil solution at equilibrium (EPC) ( $\text{mg L}^{-1}$ ),  $Kf$  is the proportionality constant ( $\text{mg kg}^{-1}$ ), that is extent of sorption = antilog (Y-intercept). The constant  $Kf$  is also interpreted as the amount of sorbed P that would sustain a unit P concentration in equilibrium solution (Hussain *et al.*, 2003). The  $1/n$  is the slope of the curve when  $\log(x/m)$  vs.  $\log C$  is plotted; while “ $a$ ” and “ $b$ ” are constants which represent the intercept (P sorption maximum) and slope (bonding energy) of sorption isotherms, respectively (Hussain *et al.*, 2003). The equation is normally used in its logarithmic form:  $\text{Log } X = 1/n \text{ Log } C + \text{Log } a$  ..... (xii)

hence, a plot of  $\log X$  against  $\log C$  should give a straight line.

The equation was originally empirical, without any theoretical physico-chemical foundation and no significance could be attached to the adsorption coefficients (Olsen and Watanabe, 1957; Holford, 1982; Arshad *et al.*, 2000). This implied that the energy of adsorption decreased exponentially as the fraction of covered surface is

increased (amount of adsorption) and because of this it has not been possible to compare quantitatively adsorption data for soils obtained from plots of the Freundlich equation because the equations were assumed to be empirical and treatments assumed to be theoretical (Arshad *et al.*, 2000). However, some workers suggested that the intercept and slope of a linear Freundlich plot could be used to compare phosphate adsorption in soils, but it has a limitation in that it does not predict the maximum adsorption capacity (Kuo and Lotse, 1974; Holford, 1982). Despite its limitations, the equation gives better fit to phosphate adsorption isotherms in most soils than the most widely used Langmuir equation and the more complex two-surface Langmuir equation (Fitter and Sutton, 1975; Niang *et al.*, 2002).

### 1.5.3 The Temkin adsorption equation

The derivation of the Temkin isotherm assumes that the reduction of the heat of sorption is linear rather than logarithmic, as implied in the Freundlich equation (Aharoni and Ungarish, 1977).

According to Anghinoni *et al.* (1996), the Temkin equation has generally been applied in the following form:  $X/m = a + B \ln C$ ..... (xiii)

where  $X/m$  = mass of adsorbed P ( $\mu\text{g g}^{-1}$  soil),  $C$  = the equilibrium P concentration ( $\mu\text{g ml}^{-1}$ ),  $B$ - P-buffering capacity ( $\mu\text{g g}^{-1}$  soil) and “a” = Temkin constant. A plot of  $X/m$  against  $\ln C$  gives a straight line if the adsorption process fits the model. The values of “a” and  $B$  are obtained from the intercept (a) and the slope (B), respectively.



### **1.6.2 Ionic strength and composition of the soil solution**

Both organic and inorganic anions in the soil solution compete with phosphate for adsorption sites to varying extents. This results in either adsorption of added phosphate or desorption of retained phosphate in conformity to the anion exchange mechanisms. Weakly held inorganic anions such as nitrate and chloride are of little significance, whereas specifically adsorbed anions like hydroxyl, sulphate and molybdate are competitive. The strength of bonding of the anions with the adsorption surface determines the competitive ability of that anion. For example, sulphate, even though considered to be a specifically adsorbed anion, is unable to desorb much phosphate (Zhang *et al.*, 1987) because of the affinity for colloidal surfaces. Additionally, divalent cations enhance P sorption more than monovalent cations (Lauchli and Bielecki, 2012). For example, clays saturated with  $\text{Ca}^{2+}$  retain greater amounts of P than those saturated with monovalent cations like  $\text{Na}^+$  (Moshi *et al.*, 1974).

### **1.6.3 Organic matter**

There are two principal mechanisms by which organic matter may affect the adsorption and hence availability of phosphorus in soils: (a) negatively charged organic matter adsorbs or complexes cations such as Al and Fe in acid soils and Ca in calcareous soils (Haynes and Mokolobate, 2001; Brady and Weil, 2008) and hence reduces their activities in solution and their role in P sorption and / or precipitation or (b) presence of organic acids such as humic acid, fulvic acid, and citric acid on the surface of (hydr)oxides could inhibit phosphate adsorption through site competition, electrostatic effects, and steric hindrance (Borggaard *et al.*, 2005; Weng *et al.*, 2008).

According to Tisdale *et al.* (1985) and Fink *et al.* (2014), the existing correlation between phosphate and organic matter. This increase is attributed to the ability of humic molecules to adhere to sorbing surfaces and masking of fixation sites hence preventing them from interacting with phosphate ions in solution (Brady and Weil, 2008). Organic acids produced by plant roots and microbial decay can also serve as organic anions which compete with P for positively charged sites. Other organic compounds can also entrap reactive Al and Fe in stable organic complexes called chelates hence their unavailability for reaction with phosphorus (Brady and Weil, 2008).

#### **1.6.4 Clay mineralogy**

Numerous studies show that aluminosilicate clay minerals play an important role in P sorption by soils (Fox and Kamprath, 1970; Hadgu *et al.*, 2014). Generally, clay minerals possessing high anion exchange capacity have a high affinity for phosphate ions. The clay content of a soil also has great impact on phosphate adsorption. Soils containing large quantities of clay would adsorb more phosphate than those with less clay content. Generally, the layer silicate clay minerals of the 1:1-type minerals (kaolinites) are made up of one tetrahedral (silica) sheet and one octahedral (alumina) sheet, while 2:1 type minerals (montmorillonite) are characterised by an octahedral sheet sandwiched between two tetrahedral sheets (Brady and Weil, 2008). The 1:1 clays with low  $\text{SiO}_2/\text{R}_2\text{O}_3$  (sesquioxide) ratios have therefore higher phosphate adsorption capacity than 2:1 clays (montmorillonite) with high  $\text{SiO}_2/\text{R}_2\text{O}_3$  (sesquioxide) ratios (Tisdale *et al.*, 1985; Brady and Weil, 2008). The high amount of P fixed by 1:1 clays is probably due to the higher amounts of hydrated oxides of iron

and aluminium associated with kaolinitic clays (Tisdale *et al.*, 1985). Kaolinite has large number of exposed hydroxyl groups in the gibbsite layer that can be exchanged for P (Haynes, 1983; Tisdale *et al.*, 1985). In addition, kaolinite develops pH dependent charges on its edges which can enter into adsorption reactions with P (Hayne, 1983).

### **1.6.5 Free iron and aluminum**

Oxides and hydroxides of Al and Fe play a significant role on P availability and sorption properties. According to Hadgu *et al.* (2014) and Mnthambala *et al.* (2015), oxides of Fe and Al positively correlate with P adsorption maxima. The high value of P adsorption maxima in cases of soil containing high contents of oxides of Fe and Al might be due to formation of their respective metal phosphates (Brady and Weil, 2008; Wang *et al.*, 2013). The sorption of inorganic phosphate of soils with pH less than 7.0 is closely related to the amount of reactive Fe and Al compounds (Syers *et al.*, 1977). It has also been reported that about 1 cmol Al kg<sup>-1</sup>soil, when completely hydrolyzed, can sorb up to 102 mg P L<sup>-1</sup> from the soil solution (Tisdale *et al.*, 1990). The amorphous hydrous metal oxides of Fe and Al have, however, been reported to sorb relatively greater amounts of P than their crystalline counterparts (McLaughlin *et al.*, 1981). This is because the amorphous hydrous metal oxides have more exposed sites for reaction as compared to the crystalline metal oxides.

### **1.6.6 Soil calcium carbonate**

Availability of P in soil solution in calcareous soils is dictated by both adsorption and precipitation mechanisms (Wandruszka, 2006). According to Cole and Olsen (1959),

solubility of P in calcite suspensions is controlled by a dicalcium phosphate solid phase. The initial attachment involves chemisorption of P onto dicalcium phosphate (Avnimelech, 1980) followed by octacalcium phosphates which are of low energy (Holford and Mattingly, 1975). The initial process is relatively rapid, followed by approximately a two - hour induction period, then precipitation (Amer *et al.*, 1985). Phosphorus sorption on all carbonates is, however, dictated by surface characteristics, especially surface area and zeta potential (Cole and Olsen, 1959). According to Woodruff and Kamprath (1965), the possible reactions leading to P fixation in calcareous soils are: (a) Precipitation of relatively insoluble calcium phosphate such as octacalcium phosphate, hydroxyl apatite and carbonate apatite, favoured by high calcium activity and high pH. (b) Fixation of P by clays saturated with calcium.

### **1.6.7 Effect of temperature**

Temperature affects the equilibrium between phosphate solution and adsorbed P and the rate of transfer from adsorbed, to firmly adsorbed phosphate (Barrow, 2006). High temperatures slightly increase the molar solubility of compounds such as apatite, hydroxyapatite, octacalcium phosphate, variscite and strengite. It may also stimulate biological activity which enables phosphate to be released from organic residues (Kuo and Lotse, 1974; White and Taylor, 1977). This can be attributed to increased mobility and rate of chemical reactions.

### **1.6.8 Effect of time**

Phosphorus adsorption by soils and many soil components follows an initial fast reaction followed by a much slow reaction (Wang *et al.*, 2013). The adsorption

reaction involving exchange of phosphate for anions and ligands on the surfaces of iron and aluminum oxides are extremely rapid (Tisdale *et al.*, 1985; Wang *et al.*, 2013). The slower continuing adsorption reactions involve either a diffusive penetration or chemisorption of surface - adsorbed phosphorus into micropores or aggregates of soil particles (Nilsson *et al.*, 1992) or precipitation of a phosphorus compounds for which the solubility product has been exceeded (Veith and Sposito, 1977). The slow reaction also involves a shift in the forms of phosphorus held at the surface from more loosely bound to more tightly bound forms, which may take months or years.

### **1.7 Fate of P in acid soils**

In acidic soils, P can be adsorbed dominantly by Al/Fe oxides and hydroxides, such as gibbsite, hematite, and goethite (Parfitt, 1989). Phosphorus is first adsorbed on the surface of clay minerals and Fe or Al oxides by forming various complexes. The non - protonated and protonated bidentate surface complexes may coexist at pH 4 to 9, while the protonated bidentate inner sphere complex is predominant under acidic soil conditions (Luengo *et al.*, 2006; Arai and Sparks, 2007). Clay minerals and Fe / Al oxides have large specific surface areas, which provide large numbers of adsorption sites. The adsorption of soil P can be enhanced with increasing ionic strength of the soil solution. Phosphorus may also be occluded in nanopores that frequently occur in Fe / Al oxides, and thereby become unavailable to plants (Arai and Sparks, 2007).

As a result of adsorption, precipitation and / or conversion to organic forms, only 10-30% of the phosphate mineral fertilizer applied to soils can be recovered by the crop grown after fertilization (Holford, 1997; Syers *et al.*, 2008). The remaining P stays in the soil and may be used by crops in the subsequent years depending on the dynamic

equilibrium between the adsorbed P level and P in the soil solution. Because of the low P solubility and desorption, only a small proportion of phosphate ions exists in the soil solution for plant uptake even under optimum fertilization. This makes P recovery from P fertilizer to be lower compared to other nutrient containing fertilizers (Holford, 1997).

## **1.8 Strategies and approaches to manage acid soils**

Crop production in acid soils with Al toxicity and low soil available P can be improved by use of lime, fertilizers with a liming effect, organic materials, crop germplasms tolerant to Al toxicity and /or low soil available P, and modified tillage practices (Pavinato *et al.*, 2009; Opala, 2011; Kisinyo, 2011; Ouma *et al.*, 2013).

### **1.8.1 Liming**

Liming modifies the physical, chemical and biological characteristics of soil through its direct effect on amelioration of soil acidity ((Kanyajua *et al.*, 2002; The *et al.*, 2006). It also plays an indirect role of mobilization of plant nutrients, immobilization of toxic heavy metals and improvement of soil structure (Haynes and Naidu, 1998). Physical amelioration of lime occurs through flocculation of colloid particles which leads to changes in surface potential and charge densities (Bolan *et al.*, 2003).

The chemical amelioration of lime entails reduction of chemical problems associated with soil acidity (Bolan *et al.*, 2003). Use of agricultural lime containing Ca and /or Mg compounds such as  $\text{CaCO}_3$  and  $\text{CaCO}_3 \cdot \text{MgCO}_3$  respectively to acid soils increase  $\text{Ca}^{2+}$  and /or  $\text{Mg}^{2+}$  ions in the soil solution. It also increases the soil pH, thereby reducing the activities / concentrations of  $\text{Al}^{3+}$  and  $\text{Fe}^{3+}$ ,  $\text{H}^+$ ,  $\text{Mn}^{4+}$  and  $\text{Fe}^{3+}$

ions in the soil solution. Aluminium in soils is bound in the form of Al-hydroxy compounds like  $\text{AlOH}^{2+}$  and  $\text{Al(OH)}_2^+$ , which tend to polymerise to species such as  $\text{Al}_6(\text{OH})_{15}^{3+}$  (Hsu and Rich, 1960). As the pH increases, the surface becomes increasingly negative hence increasing electrostatic repulsion and decreasing electrostatic potential (Haynes, 1982), thus reducing P sorption and increasing the concentration of  $\text{HPO}_4^{2-}$  in the soil solution (Kamprath, 1984; The *et al.*, 2006; Van Straaten, 2007) leading to increased available P for plant uptake (Kanyajua *et al.*, 2002; Kisinyo, 2011).

In addition to neutralization of soil acidity, lime enhances root development, water and nutrient uptake, which are necessary for improved crop yields (Raij and Quaggio, 1997; Van Straaten, 2007; The *et al.*, 2006). Studies conducted worldwide have shown that liming improves crop yields in acid soils. For example, Ngane *et al.* (2012) evaluated the potentials of some cement byproducts as liming materials for acid soils in Cameroon and found that they increased maize yields by 67.2%. Similarly, Kabambe *et al.* (2011) observed that liming acid soils and the subsequent residual effects of lime significantly increased maize and beans yields. However, Kisinyo *et al.* (2013) reported that the efficiency of lime depends on soil type and level of acidity, hence the need to critically study the lime - soil components interactions.

Several studies have shown that lime reduces Al toxicity, increases soil pH, Ca, Mg, uptake of N and P, thus improving crop productivity in Kenyan acid soils (Kanyajua *et al.*, 2002; Kisinyo, 2011; Opala *et al.*, 2010a, b). Nekesa *et al.* (1999) reported increased soil pH and available P in western Kenya acid soils by agricultural lime containing 21% calcium oxide (CaO). In a four - year experiment, Kisinyo (2011)

reported increased soil pH, maize grain yield, P use efficiency and reduction in exchangeable  $\text{Al}^{3+}$  in acid soils of the highlands of Kenyan Rift Valley. Higher rates of lime (4 and 6 tonnes  $\text{ha}^{-1}$ ) increased and maintained higher soil pH, available P and grain yield compared to lower rates (2 tonnes  $\text{ha}^{-1}$ ). Gudu *et al.* (2005) also reported maize grain yield increase of 0.77 to 6.18 tonnes  $\text{ha}^{-1}$  per tonne of applied lime.

### **1.8.2 Application of organic soil amendments**

Use of organic amendments such as manure has been proposed as a good alternative to liming to reduce Al toxicity in acid soils (Haynes and Mokolobate, 2001; Ch'ng *et al.*, 2014). The Organic materials (OMs) interact with P in soils in a variety of ways that potentially influences P sorption and release reactions. Direct and indirect mechanisms have been proposed for the increase of soil available P as a result of the addition of OM (Guppy *et al.*, 2005). It is hypothesized that organic acids produced during decomposition of crop residues prevent precipitation of phosphates by iron (Fe) and aluminium (Al) oxides out of the soil solution (Le Mare *et al.*, 1987) and, as a result, P concentration in the equilibrium solution increases. Competition for P-sorption sites between P and the released organic acids as well as complexation of Fe and Al oxides/ hydroxides by organic acids have been suggested as the key factors controlling the reduction of soil P sorption capacity and increasing P availability (Haynes and Mokolobate, 2001; Tang *et al.*, 2007). Ch'ng *et al.* (2014) further indicated that some organic amendments have affinity for Al and Fe which enables long term chelation of Al and Fe, instead of P, hence availing P for plant use.

Many researchers have documented the effects of organic matter (OM) on soil acidity, Al toxicity and increase in soil available P in acid soils. In western Kenya, Opala *et al.* (2010a) demonstrated that *Tithonia diversifolia* (tithonia) green manure was effective in increasing maize yield due to its ability to reduce exchangeable Al in soils without necessarily increasing the soil pH. This was attributed to the ability of tithonia manure to form complexes with Al. However, in the same study, farmyard manure (FYM) increased the soil pH but it was less effective in decreasing the exchangeable Al<sup>3+</sup> as compared to tithonia. It was, therefore, concluded that the ability of an organic material to reduce Al toxicity was related to its ability to complex the Al through organic acids produced during its decomposition. The tithonia green manure was, therefore, more effective because of its ability to release large quantities of organic acids like oxalic and tartaric acids, as compared to the well decomposed FYM which had lost most of the organic acids. Ikerra *et al.* (2006) in Tanzania also reported large quantities of organic acids in soils treated with tithonia as compared to soils treated with FYM. Similarly, on testing the effects of a range of organic materials of diverse composition commonly found on smallholder farms on maize dry matter production on two acid soils in Kericho, Kenya, Opala *et al.* (2014) reported that manures of high quality increased maize dry matter yields above the control and were generally superior to lime applied alone or in combination with TSP. This confirmed earlier observations by Opala *et al.* (2013) that some organic materials such as tithonia could substitute lime as an amendment for soil acidity.

Apart from decreasing Al and Fe ions, soil organic matter can increase plant P uptake by decreasing bulk density and increasing porosity, thereby improving root growth

and proliferation hence exploration and effective nutrient uptake (Nelson and Janke, 2007). Organic P pool increases with increasing organic matter. Organic P compounds such as inositol phosphates, nucleic acids, and phospholipids present in organic matter can be decomposed, resulting in P mineralization, thereby increasing P availability and acting as a P source for subsequent crops.

There are, however, some challenges in the use of OM to manage acid soils and replenish soil fertility. Plant P availability does not always increase following incorporation of plant residues (Somado *et al.*, 2007). This is because the magnitude of the effect of plant residues on soil P availability depends on the organic residues' quality, especially the C: P ratio (Zaharah and Bah, 1997), as well as on the soil characteristics (Nwoke *et al.*, 2004). Due to their low P contents, large amounts of organic residues have to be applied, thus increasing labour costs (Jama *et al.*, 1997; Kisinyo *et al.*, 2006). Additionally, the cost incurred by use of nutrient - rich organic materials like tithonia, *Calliandra*, or maize stover cannot be offset by the subsequent crop yield increases (Jama *et al.*, 1997; Opala *et al.*, 2007; 2010b; Nyambati and Opala, 2014).

### **1.8.3 Tillage**

Tillage practices can significantly influence the productivity and sustainability of modern farming systems. Robson and Taylor (1987) and Li *et al.* (2007) argued that tillage practices could alter nutrient dynamics via three processes: (a) mixing nutrients through the soil matrix and altering their availability to crop (b) changing the soil physical environment and, (c) affecting soil biological activity. No till or minimum tillage systems allow the accumulation of organic materials on the surface, which supply energy, carbon skeletons and electrons for growth and development of

microorganisms (Pavinato *et al.*, 2009) hence increase in biomass and eventually microbial P. Accumulated Po in the undisturbed rhizosphere may also result in high microbial activity; hence build up of more stable Po fractions (Kamh *et al.*, 1999). Additionally, minimal soil disturbance may promote increased populations of microorganisms and plant roots, thereby increasing synthesis and exudation of phosphatase enzymes and leading to enhanced transformation of Po into plant - available Pi (Rosolem *et al.*, 2014).

The effect of tillage practices on soil P dynamics within the soil profile has been explained differently by different authors. Sellers *et al.* (1997) attributed accumulation of P in the surface soil under zero-tillage to lack of physical disturbance that mixes fertilizer P thoroughly within the plough layer. On the other hand, Bolland and Brennan (2006) argued that tillage practices which mix the topsoil increase availability through mixing the previously applied P, and thus improving the effectiveness of P fertilizer for subsequent crops. There are, therefore, no consistent reports on the effect of tillage on the availability of soil P.

Although incorporation of lime into soil ameliorates soil acidity, the lime applied in the surface soil layer has little impact on subsurface acidity. This is because vertical mobility of lime is limited to only about 13 mm per year on fine - textured soils, hence taking several years to reach a considerable depth (Wortmann *et al.*, 2003). Since soils with subsurface acidity require liming down to 30 cm depth or deeper, thus, deep tillage to incorporate lime in the subsurface layers of acid soils may be appropriate in the alleviation of the subsurface acidity problem which, so far, has received little attention.

#### **1.8.4 Time and method of application of P-fertilizers**

Efficient plant use of phosphorus from P - fertilizers is important from an economic view point and the conservation of the world's phosphate resources. Phosphorus recovery from P fertilizer by crops can be improved through proper method of P fertilizer placement. In soils that have high P fixing capacities, band application enhances P recovery as compared to broadcasting (Balemi and Negisho, 2012). Banding below the level of seed placement at the time of planting has the added advantage of placing the fertilizer in immediate contact with the emerging radical and seminal roots during seedling establishment (Cook *et al.*, 1991). This concentrates the P fertilizer in a small soil volume and saturates the P binding sites, lowering the buffering capacity of the soil, thereby increasing concentration of phosphate ions in the soil solution and furthering diffusion toward the root. Rudd and Barrow (1973) reported that the combination of drilling in bands and application at sowing gives the best yield responses from single super phosphate (SSP) [ $\text{Ca}(\text{H}_2\text{PO}_4)_2$ ].

Although the timing application of P fertilizer may not influence P uptake and efficiency as much as it does with nitrogen fertilizer, the longer the phosphorus is in contact with soil, the greater the fixation that occurs. For annual crops, P application at planting time is important but top dressing is not usually effective. Unlike annual crops, top - dress application of P to perennial crops is very important. This is because annual crops will complete their life cycle without full utilization of the top - dressed P, unlike the perennial ones.

### **1.9 Phosphate - lime interactions in acid soils**

The common reason given for liming acid soils was to increase availability of soil P, Ca, Mg, pH and microbial activities (The *et al.*, 2006; Kisinyo, 2011). It is well established that in strongly acid soils, Al toxicity can have a substantial inhibitory effect on the uptake and translocation of P by plants (Chen and Barber, 1990). Haynes (1984) noted that the effects of liming on Al toxicity and P deficiency could be difficult to delineate. It was further noted that liming soils high in exchangeable and soluble Al increased plant P uptake by decreasing Al, rather than by increasing P availability *per se*. This might be attributed to reduced Al toxicity, which led to improved root growth (Friesen *et al.*, 1980).

The pH-dependence of surface potential is sensitive to factors such as exchangeable cation composition and ionic strength of the soil solution (Barrow, 1984), both of which change when lime is applied. Adsorption - desorption reactions that regulate the concentration of P in the solution can be influenced by liming through change in soil pH (Holford *et al.*, 1975; Agbenin, 1996) and the ionic species in the soil solution. When pH is increased, the proportion of the divalent phosphate ion adsorbed on to the soil colloidal complex is increased. This change in phosphate speciation with the increased pH attributed to liming promotes adsorption but, at the same time, surface electrostatic potential becomes more negative as pH increases, thus lowering the anion exchange capacity (AEC).

Liming may also accelerate P mineralization from organic sources due to increased rates of microbial activity in the soil (Bolan *et al.*, 2003), but the practical significance of this effect remains unclear because of the difficulty in measuring P

mineralization rates. Prediction of the net effect of lime on P availability on the various soil chemical and biochemical changes upon liming is therefore, tricky.

Lime - phosphorus interactions have been reported by many authors via their effects on P adsorption (Holford *et al.*, 1975; Agbenin, 1996) and P release using various chemical extractants and uptake by plants (Fernandes and Coutinho, 1999; Curtin and Syers, 2001). Studies using chemical extractants showed that the quantity of extractable P attributable to liming was influenced by the nature of the extractant (Curtin and Smillie, 1984; Curtin and Syers, 2001). Other studies quantified the so-called P-sparing effect of lime under field conditions and found it to produce effects of practical significance (Tillman and Syers, 1982; Mansell *et al.*, 1984). Unfortunately, field situations where liming might result in significant reductions in fertilizer P requirements could not be predicted. It was, therefore, concluded that because of the scarcity and unpredictability of important P-sparing effects, it would seem unwise to recommend to farmers to reduce fertilizer P inputs after lime has been applied. In summary, published information on lime-phosphate interactions suggests that, once pH is high enough to eliminate Al or Mn toxicity (pH 5.5), liming will not have a consistent effect on soil P (Bolan *et al.*, 2003; Mekonnen *et al.*, 2014).

### **1.10 The residual effects of lime**

Lime reduces the levels of exchangeable  $\text{Al}^{3+}$ ,  $\text{Fe}^{3+}$  and  $\text{Mn}^{4+}$  in acid soils and increases the levels of the exchangeable basic cations (The *et al.*, 2006). Additionally, lime is known to have longer residual effects on various soil properties of acid soils compared to other soil amendments such as organic and inorganic materials. High application rates of lime have also been found to have prolonged

residual effects as compared to low rates of lime applications (Sanchez, 1976; Kisinyo *et al.*, 2014). This can be attributed to continued amelioration of soil acidity by liming materials remaining in the soils.

### **1.11 Attempts made to improve maize production in the acid soils of Kenya**

Various attempts have been made towards understanding the extent of occurrence and behavior of the Kenya acid soils. According to Kanyajua *et al.* (2002), acid soils occupy 13% of the Kenyan agricultural land. Most of these soils are found in the Kenyan highlands where most agricultural production is carried out (Jaetzold and Schmidt, 1983; Obura, 2008; Kisinyo, 2011).

Previous studies have indicated that soils in these areas have low levels of exchangeable bases, low P and high levels of exchangeable aluminium in soil solution (Kanyajua *et al.*, 2002; Obura, 2008; Kisinyo *et al.*, 2009; Kiiya *et al.*, 2010). The available P levels of the acid soils of the western highlands of Kenya were observed by Kisinyo *et al.* (2009) to be as low as 2 - 5 mg P kg<sup>-1</sup> soil, which are far below the optimal range (10 - 15 mg P kg<sup>-1</sup> soil) required for high crop productivity when other growth factors are optimal. The low P availability has been limiting crop yields; for example, maize grain yield reductions of between 28 to 50 % have been recorded from smallholder farms in the western highlands of Kenya (Kisinyo *et al.*, 2009).

Several approaches have been employed to ameliorate the soil acidity problem in the Kenya highlands. They include: use of organic amendments, lime, fertilizer P and breeding programmes to obtain improved maize germplasms tolerant to soil acidity (Ligeyo, 2007; Ouma *et al.*, 2013; Kisinyo *et al.*, 2014). Use of organic amendments has been tested by Haynes and Mokolobate (2001) and Opala *et al.* (2010a, b; 2014). Organic amendments like *Tithonia diversifolia* green manure were found to be

effective in increasing maize yields (Opala *et al.*, 2010a, b). This was due to its ability to reduce exchangeable  $\text{Al}^{3+}$  but without necessarily changing the soil pH. However, in the same study, farmyard manure (FYM) increased soil pH without decreasing the exchangeable  $\text{Al}^{3+}$ . The effectiveness of the combination of rock phosphate and FYM has also been tested by Okalebo *et al.* (2006), Savini *et al.* (2006) and Kifuko *et al.* (2007). It was, however, reported that combination of rock phosphate with high quality manures gave better results compared to combination with low quality manures (Ikeera *et al.*, 1994).

In recent studies, Kenyan maize and sorghum germplasms tolerant to Al toxicity and with high nutrient use efficiencies have been identified (Ligeyo, 2007; Matonyei, 2010; Too, 2011; Ouma *et al.*, 2013). These elite materials provide a good foundation for breeding for cultivars tolerant to Al toxicity and with enhanced P use efficiency. However, there is no commercial maize or sorghum varieties currently available in the market for farmers' use because the performance tests on the elite materials have not been finalized (Ligeyo, 2007). There is, therefore, need for alternative methods of ensuring the available varieties which are susceptible to Al toxicity produce optimally.

Several studies have shown that lime reduces Al toxicity, and increases soil pH, available P, Ca, Mg, and uptake of N and P, thus improving crop productivity of the Kenyan acid soils (Kanyajua *et al.*, 2002; Opala *et al.*, 2010a, b; Kisinyo, 2011). Nekesa *et al.* (2007) reported increased soil pH and available P in western Kenya acid soils where lime containing 21% calcium oxide (CaO) was used. Similarly, in a four year liming experiment in western Kenya, Kisinyo *et al.* (2014) reported

increased soil pH, available P, maize grain yields, P use efficiency and reduction in exchangeable Al through liming. Although a lot of research on lime have been carried out in the western highland acid soils, limited research has been carried in the eastern highland acid soils. The soils in the eastern highlands are dominated by gibbsite minerals with large surface area for P adsorption compared to kaolinite found in the west (Sanchez, 1976; Jaetzold and Schmidt, 1983; Tisdale *et al.*, 1990; Obura, 2008). There is, therefore, the need to conduct detailed and intensive studies on these soils as attempts to improve the productivity of these soils, specifically through lime and P applications, and tillage.

Use of P fertilizers has been documented to increase soil available P in P deficient tropical acid soils (The *et al.*, 2006; Kisinyo, 2011). In Kenya, the Kenya Agricultural Research Institute (KARI) recommended the rate of 26 kg P ha<sup>-1</sup> for maize production in the country. Research carried out in the western highlands of Kenya has showed that the recommended rates are inadequate to raise soil available P to the critical level ( $\geq 10\text{mg P kg}^{-1}$  soil bicarbonate extractable P) required for healthy maize growth. Working on western Kenya acid soils, Kisinyo (2011) reported that soil available P was improved when 52 kg P ha<sup>-1</sup> were applied as compared to the recommended 26 kg P ha<sup>-1</sup>. Similar increases of soil available P due to P application in western Kenya acid soils has been reported by Opala *et al.* (2007). Limited research has been carried out on the acid soils in the eastern highlands whose P sorption capacities have been documented by Obura (2008) to be higher than those in the west. There is, therefore, need to investigate the P requirements of the acid soils in the eastern highlands.

Specific studies geared on delineating the interaction between phosphate and lime in the acid soils of the Kenya highlands is scanty. There is, therefore, need of carrying out some studies which will help to understand particular relationships and interactions between Al - P and lime in acid soils in Kenya. This information will be helpful in understanding the reactions behind any given acid amelioration processes and phosphorus sparing effects in Kenyan soils.

Although a lot of research has been carried out on acid soil amelioration practices in the western part of Kenya (Kisinyo, 2011, 2013, 2014; Opala *et al.*, 2010 a, b), crops yields have continued to be low. The fertility status of most soils in the area has also remained wanting. There is, therefore, the need of raising farmer awareness of the new technologies and current levels of fertilizer or nutrient applications for soil fertility improvement for increased crop production.

Tillage practices have been reported to influence P availability for plant uptake both directly and indirectly (Robson and Taylor, 1987; Li *et al.*, 2007). Acidity can also affect both surface and subsurface soils. The relationship between different tillage methods and P availability in acid soils has not been investigated in Kenya. Additionally, the relationship between liming and deep tillage to enhance P availability to crops where sub-soil acidity is a problem has not been established. Thus, evaluating the effects of integrating tillage, liming and phosphorus fertilizer use as a strategy for soil acidity amelioration for increased maize yields in the Kenya Highlands is paramount.

## **1.12 OBJECTIVES**

### **1.12.1 General objective**

The overall objective of the study was to improve phosphorus availability for increased maize yields in Kenya highlands under different liming and tillage practices.

### **1.12.2 Specific objectives**

The specific objectives of the study were:

- i) Characterization of the acidity and nutrient status of acid soils of the Kenya Highlands.
- ii) Determination of the phosphate sorption characteristics of acid soils of the Kenya Highlands.
- iii) Determination of the interactive effect of lime, Al and phosphorus in acid soils of the Kenya Highlands.
- iv) Determination of the interactive effect of tillage, phosphorus and lime on soil acidity and maize yields in Kiambu County, Kenya.

## **1.13 HYPOTHESES**

- i) Soils in the Kenya highlands are acidic and deficient of nutrients.
- ii) Soils in the Kenya highlands have high phosphate sorption capacity.
- iii) Properties of acid soils of the Kenya highlands are influenced by lime - Al - phosphorus interaction.
- iv) A tillage-phosphorus-lime interaction improves maize yields and reduces soil acidity.

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## CHAPTER TWO

### 2.0 SOIL ACIDITY AND NUTRIENT STATUS OF SOME ACID SOILS OF THE KENYA HIGHLANDS

#### ABSTRACT

Declining soil fertility attributed to soil acidity is a major soil productivity problem in sub-Saharan Africa. A study was carried out in nine counties across the Kenya highlands namely, Meru, Embu, Kirinyaga, Nyeri, Kiambu, Nyandarua, Siaya, Busia and Eldoret where the problems associated with soil acidity are prominent. The study aimed at assessing the extent of soil acidity, soil plant nutrient levels and common management practices observed by farmers. Soil acidity and nutrient levels were determined in the laboratory, while farmers' practices were established by administration of structured questionnaires. The soils from all the study areas were extremely acidic (pH 3.8 - 4.5), had high exchangeable Al ( $>2$  cmol Al  $\text{kg}^{-1}$ ), and Al saturation ( $> 20\%$  Al) which most maize varieties grown in Kenya are sensitive to. The exchangeable bases were low in Siaya, Busia and Eldoret while available P was low ( $<10\text{mg P kg}^{-1}$  Bray 1 P) for all sites. From the information gathered through personal interview via questionnaires,  $<37\%$  of the farmers were attached to a farmers training group in all study sites; among them,  $<4\%$  were aware of soil acidity problems and  $<8\%$  had carried out a nutrient analysis of their soils. The percent of all the farmers in all sites who had applied lime at least once on their farms, was  $<3\%$ . Most farmers ( $>80\%$ ) used both fertilizer and manure on their farms, with the majority using DAP, CAN and farmyard manure. On cultural soil fertility management, choice of subsequent crop was dictated by sustainability rather than cropping system like rotation. There was a negative relationship between livestock

keeping and soil fertility management, with <30% of the farmers returning crop residues back to the farm. Most of them fed crop residues to their livestock. Only 8% of the farmers incorporated crop residues into the soil. There was a significant ( $P \leq 0.05$ ) positive correlation between education level and fertilizer use in crop production. Farmer's age and maize yield negatively correlated with each other. Additionally, farmers' training programmes and frequencies positively influenced choice of fertilizers and levels of application. Training is therefore one of the most significant issue affecting soil fertility management in the Kenya highlands. To further enhance the understanding of soil acidity and fertility management in Kenya highlands, farmers' training should be prioritized. Appropriate strategies and approaches to soil acidity and soil fertility management should also be established.

**Key words:** *fertilizers, soil fertility, soil fertility management, soil acidity, Kenya highlands, farmers training.*

## **2.1 INTRODUCTION**

Soil acidity is a major problem for agricultural productivity worldwide (Van Straaten, 2007; Brady and Weil, 2008). Acid soils account for about 4 billion ha of the total world land area (Von Uexkull and Mutert, 1995) which is 30% of the total world land area and 58% of land suitable for agriculture, inhabited by 73% of the world's population. Most acid soils are found in South and North America, Asia and Africa, attributed to extensive weathering and leaching. The acid soils occupy 29% of the total land area in the sub-Saharan Africa (SSA) zone and 13% of the Kenyan land area (Eswaran *et al.*, 1997; Kanyajua *et al.*, 2002). Soil acidity is associated with hydrogen (H), aluminium (Al), iron (Fe), and manganese (Mn) and their high concentrations in the soil solution and exchange complex, toxicities to plant roots

(Giller and Wilson, 1991; Brady and Weil, 2008). It is also associated with corresponding deficiencies of plant available P, molybdenum (Mo), calcium (Ca), magnesium (Mg), and potassium (K) (Giller and Wilson, 1991; Jorge and Arruda, 1997) which negatively affect soil fertility and productivity.

The agricultural sector is the backbone of the Kenyan economy (GOK, 2011). It contributes 25% of the total GDP and employs about 75% of the national labour force (MAFAP, 2013). Although Kenya's food policy emphasizes self-sufficiency, food insecurity is a big problem (Ombaka, 2014). More than 10 million Kenyans (nearly one third of the population) are chronically food insecure (GOK, 2011; MAFAP, 2013) due to declining food production and ununiform distribution of agricultural products. Crop production in Kenya has been on the decline over the years, leading to importation of food (MAFAP, 2013). The low food production has been attributed to declining soil fertility, poor crop management practices, poor post harvest handling procedures (Nyoro *et al.*, 2007) and uneven and inadequate natural precipitation. Depletion of plant nutrients from soils is greatest when no or only minimal quantities of nutrient inputs are added to the soils under crop production (Smaling *et al.*, 1997) to replenish those removed by plants or through crop harvests. Studies carried out in Kenya indicate that the amount of chemical fertilizers used for maize production by most farmers is below the recommended rates (Ruigu and Schuler, 1990; Mugunieri *et al.*, 1997). This is attributed either to the lack of knowledge on the effects of fertilizers on crop yields or lack of capital due to the low income status of the farmers and lack of the appropriate agricultural inputs.

Maize (*Zea mays* L.) is the staple food crop for the majority of Kenyans (Wesonga *et al.*, 2008). However, maize production has been declining over the years (Sigunga

and Wandahwa, 2011). Both commercial and small-scale farmers are involved in maize production but in most areas the production is constrained by low soil nitrogen and phosphorus availability and high soil acidity (Sanchez, 2002; Muhammad and Underwood, 2004, Kiiya *et al.*, 2010, Obura *et al.*, 2010; Kisinyo, 2011) and inadequate natural precipitation in some areas. Phosphorus availability in acid soils is greatly influenced by aluminium ion concentration in the soil. Unfortunately, most improved maize germplasms and landraces used by Kenyan farmers are sensitive to high Al saturation (>20% saturation) and exchangeable Al (>2 cmol kg<sup>-1</sup>), common in many acid soils of the Kenya highlands (Schulze and Santana, 2003; Ligeyo, 2007). Use of calcitic (CaCO<sub>3</sub>) and dolomitic (CaCO<sub>3</sub>.MgCO<sub>3</sub>) liming materials which ameliorate Al toxicity, raising soil pH and promoting increased base saturation and soil extractable P (Brady and Weil, 2008; Kisinyo *et al.*, 2013; Kisinyo 2014a and b) is, therefore, important in management of P in these soils.

Soil acidity and fertility can also be managed through the use of tolerant plant germplasms; improved agronomic, cultural and biological practices and use of inorganic fertilizers. Some of these management practices are known to farmers, who undertake them routinely within their farming protocols. However, some of the relevant management practices are not undertaken due to various reasons including lack of credit to purchase the required inputs, lack of knowledge on the importance of lime, lack or inavailability of improved crop varieties tolerant to soil acidity constraints and inadequate amount of organic materials (Kisinyo *et al.*, 2014a). Several studies have been undertaken in Kenya to assess the best management practices for soil acidity amelioration. Smaling *et al.* (1992), Palm *et al.* (1997), Jama *et al.* (1997) and Opala *et al.* (2013) reported that intergrated plant nutrient

management (IPNM) by combining inorganic and organic fertilizers improves maize yields. Additionally, Ligeyo (2007), Matonyei (2010) and Ouma *et al.* (2013) reported some success in the development of P - use efficient maize germplasms which are tolerant to Al toxicity in acid soils.

The many studies undertaken on soil acidity and fertility status in Kenya have concentrated on nutrient management issues (Opala *et al.*, 2011; Opala *et al.*, 2013; Kisinyo *et al.*, 2013). Limited research has focused on farmers' knowledge, attitudes and current adoption levels of the management recommendations. Farmers' knowledge of the causes of the problem and potential solutions is often the first step towards identifying and designing appropriate strategies for any successful management practice. In addition, their perception of how well a technology performs is understandably one of the key factors influencing their decision to adopt new technologies (Ajayi *et al.*, 2007; Kumbhar *et al.*, 2015). It is also generally recognized that the technology adoption process may be hindered by failure to incorporate views and perceptions of intended users during the design or development process. For the effective adoption of soil fertility management, soil fertility gaps identification and addressing of farmers' views and perceptions is paramount. The information generated would be useful in guiding future soil acidity management programme designs for the Kenya highlands. Therefore, the objective of the research was to evaluate the current soil acidity and fertility status of selected Kenya highlands soils and the current soil fertility management practices as an approach to enhanced and sustainable maize production in the Kenyan highlands.

## 2.2 MATERIALS AND METHODS

### 2.2.1 Location of the study sites

Sites were selected to represent the major agro-ecological areas with acid soils in the Kenyan highlands where the staple food crop, maize, is grown east and west of the Rift Valley (Sombroek *et al.*, 1982; Kanyanjua *et al.*, 2002). The study sites had been under continuous crop cultivation for years with minimal attention to the state of the art maize production practices. Descriptions of the selected sites are shown in Table 2.1. From the information in Table 2.1, Meru, Embu, Kirinyaga, Nyeri, Kiambu and Nyandarua represented the highlands east of the Great Rift Valley while Siaya, Busia and Eldoret represented the highlands west of the Great Rift Valley.

**Table 2.1: Description of the study areas**

County	Site	GPS of sites		Elevation (m)	Soil Type
Meru	Kaguru	00 05 S	037 39 E	1460	Humic Nitisols
Embu	Kavutiri	00 25 S	037 30 E	1700	Ando- humic Nitisols
Kirinyaga	Inoi	01 04 S	036 47 E	1539	Ando- humic Nitisols
Nyeri	Chehe	00 25 S	037 10 E	1920	Nitisols
Kiambu	Githunguri	01 03 S	036 45 E	1720	Nitisols
Nyandarua	Magumu	00 46 S	036 35 E	2691	Eutric Nitisols
Eldoret	Turbo	00 38 N	035 10 E	1835	Chromic Acrisols
Siaya	Sega	00 13 N	034 14 E	1228	Orthic Acrisols
Busia	Bumala	00 16 N	034 12 E	1248	Orphic Ferralsols

Soil type information sourced from FURP, 1988.

### 2.2.2 Soil sampling, preparation and characterization

Soil samples were randomly taken from cultivated farmers' fields from the nine study sites. Nine point samples were taken with a soil auger at the 0-15 cm, 15-30 cm and 30-50 cm soil depth in a zigzag manner at each experimental site. The point soil samples were thoroughly mixed and about 1.0 kg composite sample from each site was packed in polythene bags. The samples were air-dried, ground and passed

through a 2 mm sieve and subsequently analyzed for various soil properties. Soil pH was measured in 1:2.5 soil 0.01 M CaCl<sub>2</sub> suspensions (Hendershot *et al.*, 1993) and extractable P determined by the Bray 1 method (Kuo, 1996). Organic carbon (% C), total nitrogen (% N), CEC, exchangeable bases, exchangeable acidity, micronutrients and particle size were analyzed according to the procedures described by Okalebo *et al.* (2002).

### **2.2.3 Administration of the questionnaire**

A systematic sampling procedure (Banning *et al.*, 2012) was used to select farmers in the nine study sites to respond to the questionnaire as presented in Appendix 2.1. The farmers were selected at a distance of 500 meters apart resulting in a sample size of 20 farmers per site and 180 for the whole study (9 counties). Data was obtained from sampled farmers through interviews and structured questionnaires. The Farmers' survey was undertaken in October/December, 2013, using a single - visit survey approach (Thompson, 1997). Data collected included information on farmers' socio - economic status, soil acidity and fertility management practices.

### **2.2.4 Data analysis**

The social data was coded and analyzed by using the SPSS software, version 17 (SPSS, 2008). Descriptive analysis was applied whereby frequencies of scores were computed. Dependency tests were also conducted to find out if there were any relationships between the various variables addressed by the questionnaires.

## 2.3 RESULTS

### 2.3.1 Chemical and physical properties of the soils from the nine study sites

Some of the chemical and physical properties of the composite soil samples from the nine counties are as presented in Table 2.2. The pH, hence the soil reaction of the nine composite soil samples ranged from 3.7 - 4.5 rated as extremely acidic ( $\text{pH} < 4.5$ ) (Table 2.2). The % aluminium saturation was high ( $> 20\%$  Al) for soils from all the sites, with Nyeri soils having the highest aluminium saturation levels (59.7 %) while Nyandarua had the lowest (28.5 %). Likewise, exchangeable aluminum levels were high ( $> 2 \text{ cmol kg}^{-1}$ ), with Embu having the highest ( $3.7 \text{ cmol kg}^{-1}$ ) and Nyandarua the lowest ( $2.0 \text{ cmol kg}^{-1}$ ). The soil CEC was  $> 15 \text{ cmol kg}^{-1}$  soil in all sites except in Siaya and Nyeri. All the soils had low amounts of Bray 1 P ( $< 15 \text{ mg kg}^{-1}$ ). Exchangeable Ca was also adequate ( $> 4 \text{ cmols kg}^{-1}$ ) in all sites except Nyeri and Meru. The western highlands had greater percent clay and higher % base saturation than those of the eastern highlands. The % OC was low ( $> 2\%$ ) in western highlands compared to eastern highlands. Zinc was highest in kiambu ( $4.8 \text{ mg kg}^{-1}$ ) and lowest in Busia ( $1.1 \text{ mg kg}^{-1}$ ) while Iron was highest in Siaya ( $56.6 \text{ mg kg}^{-1}$ ) and lowest in Kiambu ( $32 \text{ mg kg}^{-1}$ ). The textural class of soils in the western highlands was clay while the textural class of the eastern highlands varied from sandyloam, loam, clay loam to clay.

**Table 2.2: The chemical and physical properties of the soils from the nine study sites.**

Site / Property	Kirinyaga	Meru	Embu	Nyandarua	Kiambu	Nyeri	Siaya	Busia	Eldoret
pH <sub>CaCl2</sub>	4.5	4.1	3.9	4.0	3.8	3.7	4.1	4.1	4.3
T.Nitrogen (%)	0.8	0.6	1.0	0.3	0.2	0.3	0.1	0.1	0.1
Carbon (%)	8.9	7.9	8.7	5.1	2.6	2.7	1.2	1.5	1.6
P (mg kg <sup>-1</sup> )	10.2	8.9	9.3	9.7	5.7	9.8	4.1	1.1	2.8
Ca (cmol kg <sup>-1</sup> )	5.9	3.8	6.1	6.4	6.8	3.0	6.2	7.2	6.0
K (cmol kg <sup>-1</sup> )	0.9	1.2	1.1	1.1	0.2	0.2	0.4	0.3	0.6
Mg (cmol kg <sup>-1</sup> )	0.9	1.4	0.8	1.8	1.9	0.7	1.4	1.6	1.1
Na (cmol kg <sup>-1</sup> )	0.1	0.3	0.4	0.7	0.2	0.2	0.9	0.9	0.6
Al (cmol kg <sup>-1</sup> )	2.7	2.6	3.7	2.0	2.1	3.3	2.2	2.3	2.3
Al Saturation (%)	36.4	37.4	33.7	28.5	31.6	59.7	31.2	29.4	32.7
CEC (cmol kg <sup>-1</sup> )	15.3	16.0	17.9	15.5	15.0	13.1	14.8	19.1	17.7
BS (%)	22.7	29.3	38.1	41.1	26.0	12.5	61.6	54.3	51.6
Fe (mg kg <sup>-1</sup> )	38.5	37.7	44.5	50.8	32.0	42.0	56.6	38.0	52.0
Zn (mg kg <sup>-1</sup> )	1.5	2.2	3.1	3.6	4.8	2.0	2.0	1.1	1.4
PSD*									
Clay (%)	14.3	51.7	49.0	22.3	50.3	28.3	58.3	56.3	57.3
Silt (%)	27.3	21.3	26.7	39.3	16.7	16.0	17.0	21.0	13.0
Sand (%)	58.3	27.0	24.3	38.3	33.0	55.7	24.7	22.7	29.7
Textural class	SL	Clay	CL	Loam	SL	SL	Clay	Clay	Clay

\*particle size distribution; SL-sandy loam; CL-clay loam

### **2.3.2 Characteristics, perceptions and practices of farmers as captured from the questionnaire administration.**

#### **2.3.2.1 General information about respondents gender and education levels**

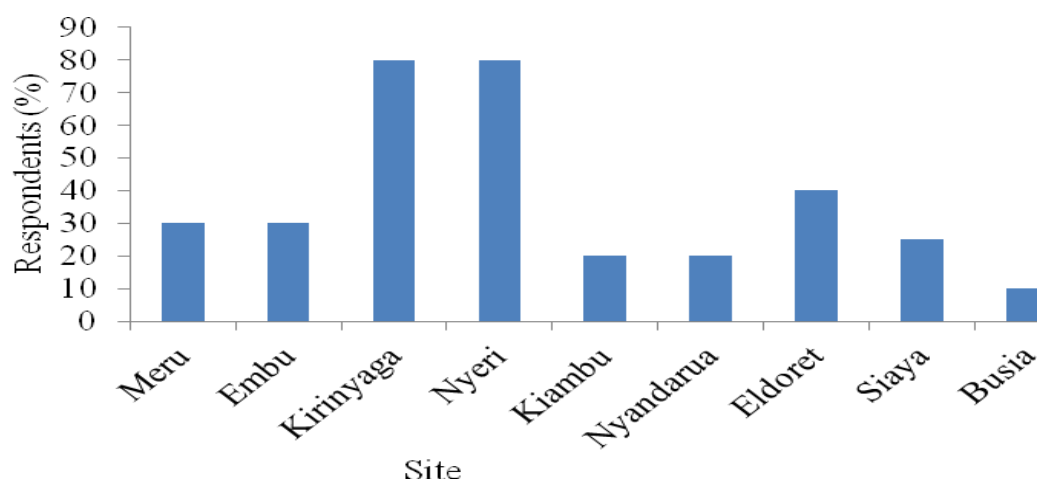
More than 50% of the respondents were men apart from Kiambu and Nyandarua (Table 2.3). The education level of the respondents varied greatly from site to site. More than 50% of the respondents in Meru, Embu, and Siaya had only attained primary school education, while in Kirinyaga and Nyeri most of the respondents had tertiary education level.

**Table 2.3: Respondents gender and education levels**

County	Gender (% of respondents)		Education Level (% of respondents)		
	Female	Male	Primary	Secondary	Tertiary
Meru	33.3	66.7	60	25	15
Embu	33.3	66.7	60	25	15
Kirinyaga	33.3	66.7	10.5	36.8	52.6
Nyeri	33.3	66.7	10.5	36.8	52.6
Kiambu	55	45	45	25	20
Nyandarua	55	45	45	25	20
Eldoret	30	70	21.1	42.1	26.3
Siaya	45	55	52.6	15.8	15.8
Busia	40	60	26.3	36.8	36.8

### 2.3.2.2 Membership to farmers training groups

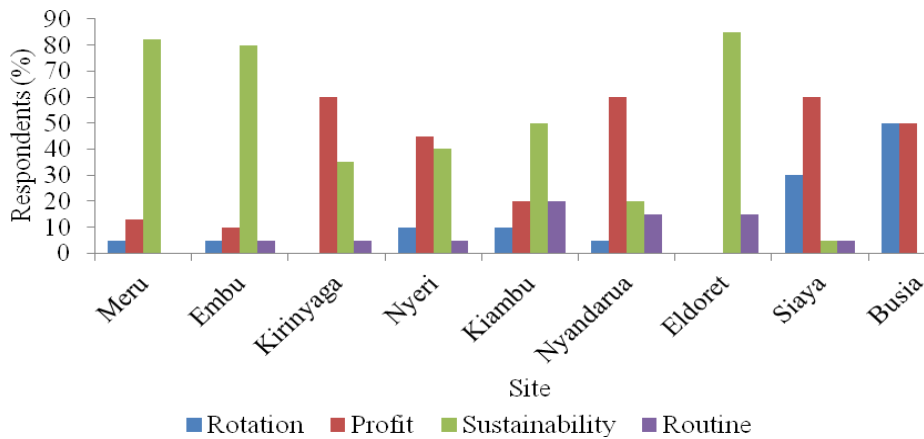
Most of the farmers in some of the research areas did not belong to any particular agricultural training group (Figure 2.1) except for Kirinyaga, Nyeri and Eldoret where 80%, 80% and 40%, respectively, of the farmers were members of the training groups. On average, less than 37% of the interviewed farmers were members of a training group. It was found out that most farmers were not interested in farmers' training groups because of unavailability of regular training programs.



**Figure 2.1: Percentage of farmers in each site who are members of some training groups**

### 2.3.2.3 Seasonal choice of type of crop to grow

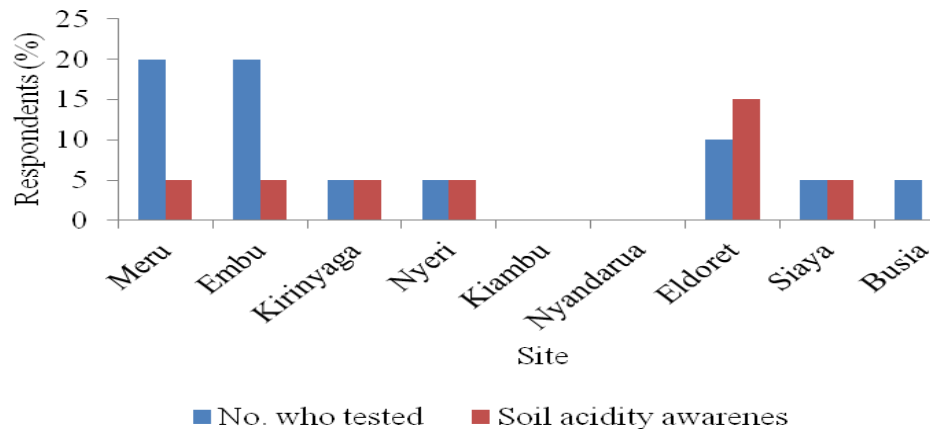
The criteria governing the choice of crops to be grown per season varied among sites and individuals (Figure 2.2). The majority of farmers in Meru, Embu and Eldoret chose crops depending on level of sustainability- whether the crops would be able to meet their food needs or not, while Kirinyaga, Nyeri, Nyandarua and Siaya farmers chose crops depending on their level of profitability.



**Figure 2.2: Criterion applied by farmers when choosing the type of crop to grow per season in the nine sites**

### 2.3.2.4 Soil acidity perceptions or awareness among farmers

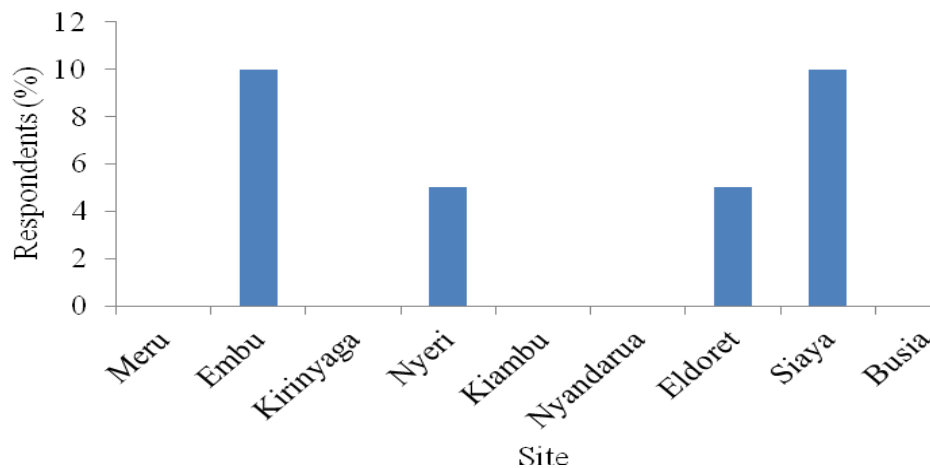
Most farmers were not aware of soil acidity problems (Figure 2.3). Kiambu, Nyandarua and Busia respondents were totally unaware of soil acidity problems while less than 15% were aware in the other areas. Only 20% of the farmers in Meru and Embu had carried out physical and chemical analyses for their soils that is evaluation of the fertility status of their soils at least once while the rest of the respondents had never analysed soils on their farms. On average, < 4% of all the interviewed farmers were aware of soil acidity while less than 8% had carried out nutrient analysis on their soils.



**Figure 2.3: Percentage of farmers having soil acidity knowledge and had tested their soils in the nine sites.**

### 2.3.2.5 Soil acidity management through liming

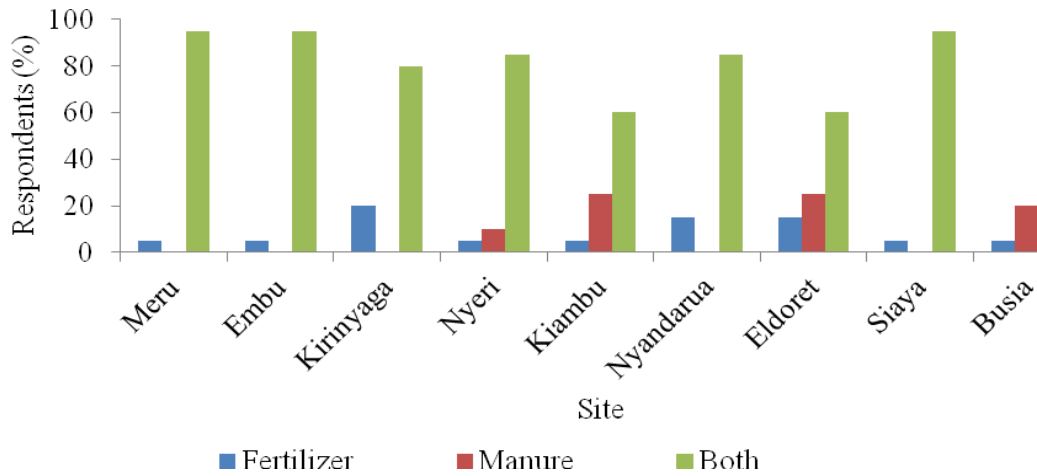
Farmers reported minimal use of lime in soils (Figure 2.4). Only 10% of the farmers from Embu and Siaya and 5% of farmers in Nyeri and Eldoret were using lime.



**Figure 2.4: Percentages of farmers applying lime on their farms at the nine sites**

### 2.3.2.6. Fertilizer and manure application

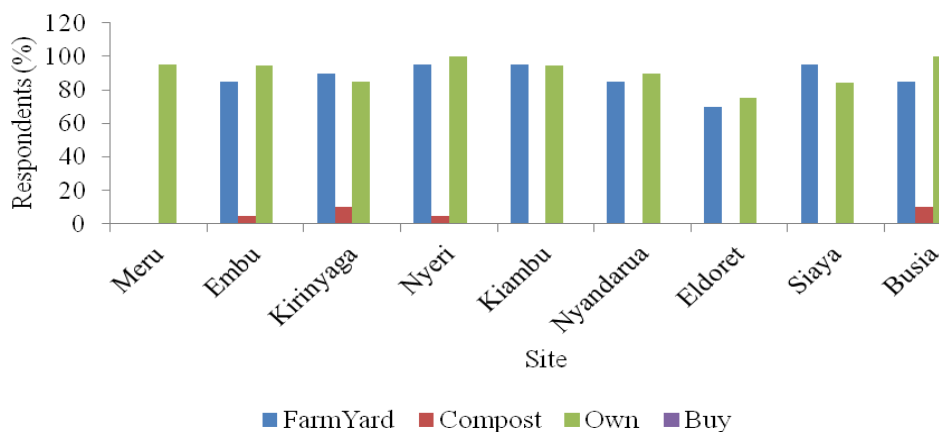
Use of fertilizers and manures varied from site to site (Figure 2.5). More than 75% of the respondents used both fertilizers and manures on their farms, except Kiambu and Eldoret where only 60% of respondents applied both.



**Figure 2.5: Percentages of farmers applying manures or fertilizers in their farms at the nine sites**

### 2.3.2.7 Manure types and sources

Farmers used only farmyard or compost manures (Figure 2.6). More than 75% of the manures were from their own homesteads with only few (< 1%) farmers sourcing the manures from relatives and friends and others purchasing it. The proportion of farmers using farmyard manure was > 70%, with < 10% using compost manure.



**Figure 2.6: Sources and types of manures applied by farmers at the nine sites.**

Farmers' choices of types of fertilizers and manures to apply was dictated by availability, advice from agricultural extension staff, what they are used to, and

advice from other farmers (Table 2.4). About 50% and 74% chose fertilizer, and manure, respectively, depending on local availability while 30% and 21% of the farmers chose fertilizer and manure type depending on what they were used to. Most farmers used fertilizers and manures mainly for soil fertility enhancement hence expecting crop yield increases. More than 50% of the farmers had benefited from fertilizer and manure use, with <50% of the farmers indicating that sometimes the costs of production were higher than the income. The fertilizers commonly used by farmers were DAP  $[(\text{NH}_4)_2\text{HPO}_4]$ , CAN  $[\text{Ca}(\text{NO}_3)_2 \cdot \text{NH}_4 \cdot \text{NO}_3]$ , and TSP  $[\text{Ca}(\text{H}_2\text{PO}_4)_2]$  while the common manure types were FYM and composts.

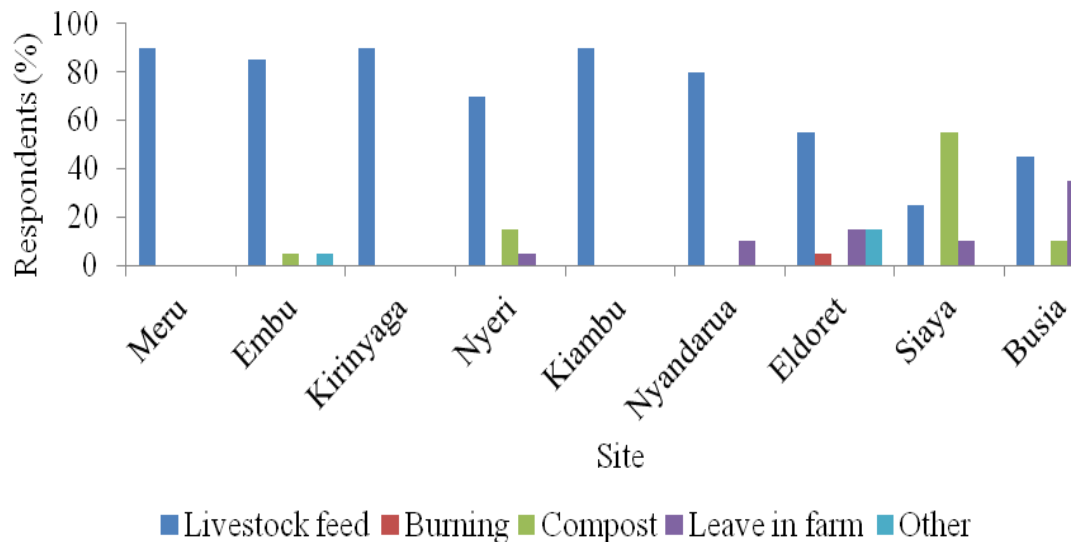
**Table 2.4: Factors determining fertilizer and manure choice in the Kenya Highlands.**

Question	Reasons	% Respondents	
		Fertilizer	Manure
Types choice	Availability	50	74
	Advice by extension staff	18	5
	Used to	30	21
	Others	2	0
Why apply	Fertility enhancement	52	5
	Increase yield	45	90
	Others	3	5
Availability of Benefit	Yes	60	50
	No	40	40
Acquisition of Profit	Yes	28	20
	No	20	27
	Sometimes	32	23
	Don't Know	20	30

### 2.3.2.8 Crop residues utilization by the farmers

Methods of crop residue disposal varied greatly (Figure 2.7) whereby 70% of the farmers interviewed claimed that they fed all the crop residues to their livestock, 9.4% utilized it for compost manure preparation, 0.5% burned the residues while

2.2% sold it to other progressive farmers. Only 8.3% of the farmers left residues on the farm for soil fertility improvement. For example, more than 85% of the farmers in Meru, Kirinyaga and Kiambu fed the crop residues to their livestock while 5% of the farmers in Eldoret disposed off their crop residues by burning. Busia had the highest number of farmers (35%) who left crop residues on the farm to be incorporated into the soil.



**Figure 2.7: Disposal of crop residues by farmers from the nine sites.**

### 2.3.3 Relationship between farmers' responses and soil chemical properties

A significant negative relationship was observed between farmers' age and fertilizer use levels (Table 2.5) but a positive relationship was observed between farmer education level, average maize yields and fertilizer use levels. Additionally, fertilizer use was also positively correlated with the frequency by which farmers participated in training programmes. Maize yields were positively correlated with soil pH, while organic carbon positively correlated with manure use. Additionally, soil fertility management practices such as fertilizer and manure use significantly affected the exchangeable bases in the soils.

**Table 2.5: Correlations between farmers soil management practices and soil chemical properties**

Pair	R <sup>2</sup>	P-value
Farmers age- Fertilizer application	-0.30**	0.002
Acreage- Average maize yield	0.29**	0.006
Education- Average maize yield	0.24*	0.025
Education- Fertilizer application	0.23*	0.024
Farmers training- Fertilizer application	0.40*	0.016
Maize yield- Fertilizer application	0.31**	0.005
Soil pH- Maize yield	0.34*	0.046
Organic carbon- Manure application	0.53**	0.007
Soil fertility management-Exchangeable bases	0.35**	0.005

\*Significant at  $P \leq 0.05$ ; \*\*Significant at  $P \leq 0.001$ .

## 2.4 DISCUSSION

### 2.4.1 Soil characterization

Following the categorization by Kanyanjua *et al.* (2002), the soils from the nine sites were extremely acidic ( $< \text{pH} 4.5$ ). Although there are no acceptable critical exchangeable  $\text{Al}^{3+}$  levels, Landon (1984) reported that exchangeable Al values  $> 2.0$   $\text{cmol Al kg}^{-1}$  are considered excessive for many crops. The percent Al saturations of the soils were also high (28.5-59.7%) for maize production. Aluminium saturation levels greater than 20% are unsuitable for most maize germplasms grown by farmers in Kenya (Ligeyo, 2007). Since exchangeable  $\text{Ca}^{2+} < 4.0$   $\text{cmol kg}^{-1}$  are considered low (Landon, 1991), then for Meru and Nyeri soils calcium levels were low but it was adequate for the other sites. Acid soils with high levels of Al, low contents of base cations and soil available P such as those reported in this study are characteristic of highly weathered soils, a common phenomenon in South Saharan Africa (Landon, 1991; Kanyanjua *et al.*, 2002; van Straaten, 2007). The high percentage of clays (56.3-58.3%) in the highlands west of the Rift Valley as compared to the eastern highlands could be attributed to the presence of kaolinitic clay minerals in the west as compared to the

east were gibbsite minerals are dominant (Sanchez, 1976; Jaetzold and Schmidt, 1983; Obura, 2008).

#### **2.4.2 Characteristics, perceptions and farmers' practices.**

Most farmers complained of lack of structures for establishment of concrete training platform as the reason they did not belong to any farmers' training group. According to Feder and Slade (2004), training of farmers is mostly through agricultural officials such as extension or field officers. The acquired knowledge by farmers enables them to learn, internalize, evaluate, try and adopt new technologies (Caswell *et al.*, 2001). However, Feder and Slade (2004) suggested that the extension officers must be knowledgeable and credible enough to win farmers trust. This is in agreement with farmers responses because they indicated that extension officers were knowledgeable but the problem was they were very few to meet farmers' demand for training and follow up.

The farmers (<10%) who had applied lime at least once complained that they were not aware of soil acidity problems, did not vividly know their importance and also that lime was not readily available in the local agricultural input shops. These findings are similar to those by Kisinyo *et al.* (2014a) who indicated that very few farmers in Kenya were aware of the soil acidity problem. They further stated that most farmers did not use lime either due to lack of knowledge about its importance or lack of liming materials in the market, or because the liming activity was labour intensive and expensive for smallholder farmers.

The preference of DAP as opposed to other phosphorus sources, despite its acidifying effect on the acid soils could be attributed to the cost of the N sources available in the market. Studies carried out by Kanyanjua and Ayaga (2006) to evaluate the cheapest source of N in the Kenyan market for farmers' use found that mono ammonium phosphate (MAP) and DAP were cheaper N sources compared to NPK fertilizers like 17:17:17, 20:20:0 and 23:23:0. The farmers claimed that they preferred FYM over other organic sources because it is readily available locally, is easy to handle and is cheaper than other manures. Similar studies by Opala *et al.* (2007; 2013) indicated that most smallholder farmers in Western Kenya preferred FYM as compared to other organic sources of plant nutrients whose costs could not be offset by the yields obtained.

Education level influences farmers' access to information as well as their ability to understand technical aspects of innovations which largely affects production decisions (Rahman, 2003). The positive correlation between educational level, maize yields and fertilizer application is in agreement with Zhou *et al.* (2010) who showed that educated farmers adopted recommended fertilizer rates with ease, leading to improved crop production and low environmental pollution. Olagunju and Salimonu *et al.* (2010) also established that education influenced the rate of adoption of developed technologies or innovations, hence positively influencing the resulting output.

The significant positive correlation between fertilizer use and participation in farmer trainings could be attributed to access of information and knowledge on handling of fertilizers. Baah *et al.* (2011) observed that farmers who were members of farmers'

associations had better access to fertilizer information that contributed to the adoption of appropriate fertilizer use practices. Similarly, Ajayi and Oloruntoba (2007) attributed non - adoption of some agricultural technologies by farmers to inadequate information and sketchy knowledge, lack of awareness of the technologies and lack of follow-up by extension staff, which are adequately catered for in training forums.

The significant negative correlation ( $r^2 = -0.30$ ) between farmers' age and fertilizer use might be attributed to fear of the unknown. The results of this study were in agreement with Teklewold *et al.* (2006), who observed that farmers who were above 39 years were most likely to have lower adoption rates of new technologies, because older people fear the risk of unexpected events whilst young farmers tend to be more flexible in their decisions to adopt new ideas and technologies more rapidly. Similarly, Ajayi and Oloruntoba (2007) and Zanu *et al.* (2012) reported that adoption of improved technologies and innovations were associated with age, education, farmsize, income, exposure, scientific orientation, knowledge level and training received.

## **2.5 CONCLUSIONS**

The results depicted that although soils from the nine counties within the Kenya highlands were acidic, with low plant available P and had high exchangeable aluminium levels; farmers' knowledge of soil acidity problems and management strategies is limited. Additionally, farmers' access to information on new technologies is constrained by failure to participate in farmers' trainings and literacy levels. Strategies should, therefore, be established which would encourage farmers' participation in agricultural training groups to improve their agricultural knowledge base. Such approach should be

the participatory rural appraisal (PRA), participatory learning and action research (PLAR) and participatory agro-ecosystem management (PAM). This will enhance levels of understanding and adoption of improved soil acidity and fertility management practices, hence improve crop yields and production across the Kenya highlands.

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## CHAPTER THREE

### 3.0 PHOSPHATE SORPTION BY ACID SOILS OF THE KENYA

#### HIGHLANDS

#### ABSTRACT

Low available phosphorus (P) is one of the major hindrances to crop production in the acid soils of the Kenya highlands. Although considerable work has been done to establish P application levels in the region, there is paucity of information on which to base P fertilizer recommendations due to potential crop production differences caused by different soil types and climate. Phosphorus adsorption capacity and its relationship with some soil properties were evaluated in acid soils from nine counties across the Kenya highlands. The counties were, Meru, Embu, Kirinyaga, Kiambu, Nyandarua, Siaya, Busia and Eldoret. Adsorption data was obtained by equilibrating 3 g of the nine soil samples with 30 ml of  $\text{KH}_2\text{PO}_4$  in 0.01 M  $\text{CaCl}_2$ , containing 0, 80, 100, 150, 180, 200, 250, 300  $\mu\text{g ml}^{-1}$  for 48 hours with shaking for 30 minutes at intervals of 8 hours. Data obtained was fitted in Langmuir and Freundlich adsorption models and the relationships between P adsorption and soil properties were determined by correlations. The result of this study showed that the soils were strongly to extremely acidic (pH 4.83 - 3.76), had high exchangeable  $\text{Al}^{3+}$  ( $> 2 \text{ cmol Al kg}^{-1}$ ), Al saturation of ( $> 20\% \text{ Al}$ ) and the maximal phosphorous adsorption varied from 1383.45-2258.19  $\text{mg kg}^{-1}$  soil. Standard phosphate requirement (SPR) of the soils also varied from 189.43-529.76  $\text{mg P kg}^{-1}$ . Comparing the two models, the Freundlich linear model showed a better fit to the tested soils compared to Langmuir model. The regression coefficients ( $R^2$ ) for the fitted Freundlich P adsorption isotherms were highly significant ranging from (0.882-0.990) for all tested soils.

Relationships between adsorption maximum and soil attributes revealed that adsorption maximum positively correlated with clay content, extractable P, exchangeable acidity and aluminium saturation and negatively correlated with organic matter and electrical conductivity. Due to differences in maximal P sorption capacities within the area, blanket P fertilizer recommendation might not be effective. There is, therefore, need for further research to determine optimal phosphorus requirements for soils in each research site.

**Keywords:** *Adsorption; acid soils; phosphorus; standard phosphate requirement, Kenya highlands*

### **3.1 INTRODUCTION**

Adsorption or sorption is the net accumulation of a chemical at the interface between the solid phase and aqueous solution phase, which determines availability of native soil nutrients and the rate of nutrients to be applied to soil as fertilizers. Phosphate adsorption is the process in which phosphate ions are held on active sites of soil particle surfaces (Khan *et al.*, 2010). The P adsorption by oxides of iron and aluminium and amorphous materials in soils affects the fate of applied P and availability of P to plants (Warren, 1994; Wang *et al.*, 2013). Many researchers have studied and proposed diverse techniques for evaluation of phosphorus status in a soil.

An adsorption equation is an important approach which has been used to estimate phosphorous concentration in aqueous phase of soil, energy of phosphorus adsorption and maximal value of its adsorption by soil. It also estimates buffer strength of a soil against phosphorus concentration variations in solution and

equilibrium state between phosphorus in aqueous and solid phases and their relationship (Olsen and Watanabe, 1957; Onweremadu, 2007). The equations can be described as the equilibrium relationship between amounts of adsorbed and dissolved phosphate at constant temperature in quantitative terms. They are explained by fitting of the isotherms to their mathematical descriptions using the Langmuir, Freundlich, Tempkin, Linear or Van Huay isotherm models, among other models (Khan *et al.*, 2010; Hoseini and Taleshmikael, 2013). However, the Freundlich model has been reported to give the best fit in many areas of the world (Niang *et al.*, 2002).

Although adsorption isotherm equations can be used to predict fertilizer requirements for crops (Gichangi *et al.*, 2008), the nutritional element in soil solution is closely linked to adsorption processes through the physico-chemical characteristics of the soil. This eventually governs the availability of nutrient ions to growing plants. Among the soil properties affecting P sorption capacity are texture, organic matter, soil pH, aluminium saturation, CEC and CaCO<sub>3</sub> content (Tisdale *et al.*, 1990; Brady and Weil, 2008). Knowledge of the relationship of these soil properties with adsorption capacity is, therefore, necessary in understanding P sorption behavior of varied soils. Research carried out on this has reported varied conclusions, with Agbenin and Tiessen (1994) reporting statistically significant relations between parameters of the Langmuir equation and soil properties such as clay percentage, organic carbon, Fe and Al contents while Anghiononi *et al.* (1996) recognized free iron as the only factor significantly correlating with maximal phosphorus adsorption in the Langmuir's model.

The Kenyan soils, similar to other agricultural soils of the tropics, are generally low in available P. Several authors have reported that the available P in Kenyan-acid soils is low, ranging between 2 to 5 mg P kg<sup>-1</sup> soil (Kanyajua *et al.*, 2002; Kisinyo *et al.*, 2013; Opala *et al.*, 2013). Many experimental results also indicate that these soils have high P-fixation capacity that makes about 80% of the inorganic added P to become unavailable for crop uptake (Hendrshot *et al.*, 1993; Okalebo *et al.*, 2002; Kisinyo *et al.*, 2013). However, limited work has been carried out to evaluate the relationship between the P sorption capacity and specific soil properties in the cited research areas. The objectives of this study were therefore: (i) to quantify and compare the applicability of Langmuir and Freundlich equations in describing the sorption of P in acid soils of the Kenya highlands and (ii) to evaluate the relationships between P sorption and properties of the acid soils across the Kenya highlands.

## **3.2 MATERIALS AND METHODS**

### **3.2.1 Location of the study sites**

Location of the study site is as described in section 2.2.1.

### **3.2.2 Soil sampling, preparation and characterization**

Soil sampling, preparation and characterization procedure adopted were as described in section 2.2.2

### **3.2.3 Phosphate sorption isotherms**

Three grammes air-dried 2 mm sieved composite soil sample portions were equilibrated in three replicates with 30 ml of KH<sub>2</sub>PO<sub>4</sub> in 0.01M CaCl<sub>2</sub> containing 0, 80, 100, 150, 180, 200, 250, 300µg P ml<sup>-1</sup> for 48 hours with shaking for 30 minutes

at intervals of 8 hours. Three drops of toluene were added to each of the soil-phosphate suspensions to inhibit microbial activity. Following equilibration, the soil suspensions were centrifuged at  $3000 \text{ rev min}^{-1}$  for 10 minutes and filtered through Whatman No. 5 filter papers to obtain clear filtrates. Phosphorus in the filtrates were then determined colorimetrically based on the Murphy and Riley (1962) method. The amounts of P sorbed were calculated as the differences between the amounts of P added and those remaining in the equilibrium solutions (Fox and Kamprath, 1970) and the P-adsorption isotherms plotted as adsorbed against equilibrium P concentrations. The P adsorption data for the soils used in this study were fitted into the linearized form of the Langmuir and Freundlich equations proposed by Holford *et al.* (1974), Le mare (1982) and Dubus and Becquer (2001). The linearized forms of the equations are:  $C/X = 1/ K_L b_L + C/b_L$  (Langmuir, 1918) and  $X = K_f C^{1/n}$  (Freundlich, 1926); where:

$C$  = Equilibrium concentration of phosphorus in solution ( $\text{mg P L}^{-1}$ )

$X$  = mg of P adsorbed ( $\text{mg P kg}^{-1}$ )

$b_L$  = Adsorption maximum for the Langmuir model ( $\text{mg P kg}^{-1}$ ) (inverse of the slope).

$K_L$  = Bonding energy constant of the Langmuir model ( $\text{L mg}^{-1} \text{P}$ ) (slope / intercept).

$n$  = Empirical constant related to bonding energy of soil for phosphate

$K_f$  = Proportionality constant for the Freundlich model ( $\text{mg kg}^{-1}$ ) (antilog of Y-intercept).

### 3.2.4 Statistical analysis

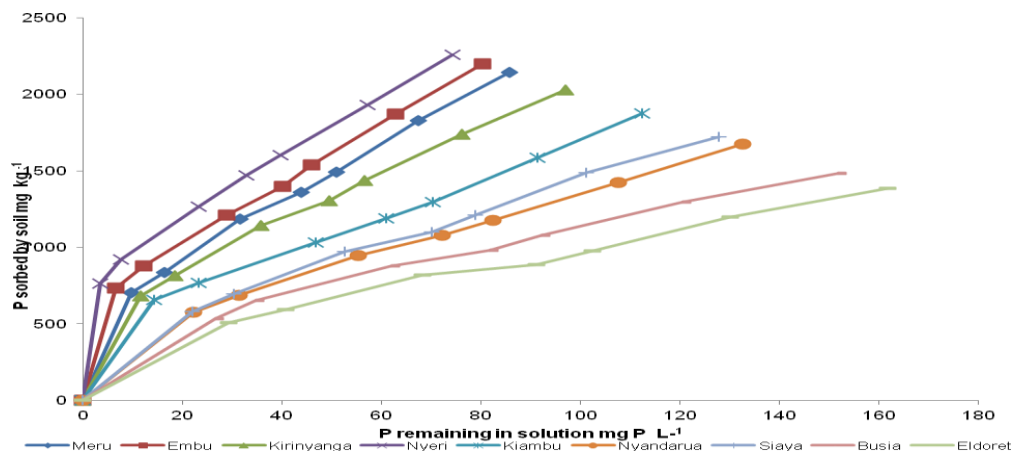
Relationships between P sorption parameters, and P sorbed at equilibrium with  $0.2 \text{ mg P L}^{-1}$  ( $P_{0.2}$ ), with selected soil chemical properties were determined by simple

regression and correlation and tested for significance at  $P \leq 0.05$  using the GenStat statistical software (Genstat, 2010).

### 3.3 RESULTS

#### 3.3.1 Phosphate adsorption by the soils

Comparing the highest amount of P adsorbed, it is evident that soils in each site had different capacities to adsorb P (Figure 3.1). The graphic representation of the adsorption data hence the adsorption isotherms indicate that the quantities of P adsorbed by the soils were in the order Nyeri > Embu > Meru > Kirinyanga > Kiambu > Siaya > Nyandarua > Busia > Eldoret.



**Figure 3.1: Phosphate adsorption isotherms of the soils from the nine sites**

The result of the study showed that Nyeri soils had the highest value of maximal P adsorbed while Eldoret soils had the lowest (Table 3.1). Nyeri soils also had the highest standard phosphate requirement (SPR) while Eldoret had the lowest. The coefficients of determination ( $R^2$ ) of the soils were significant for all the sites.

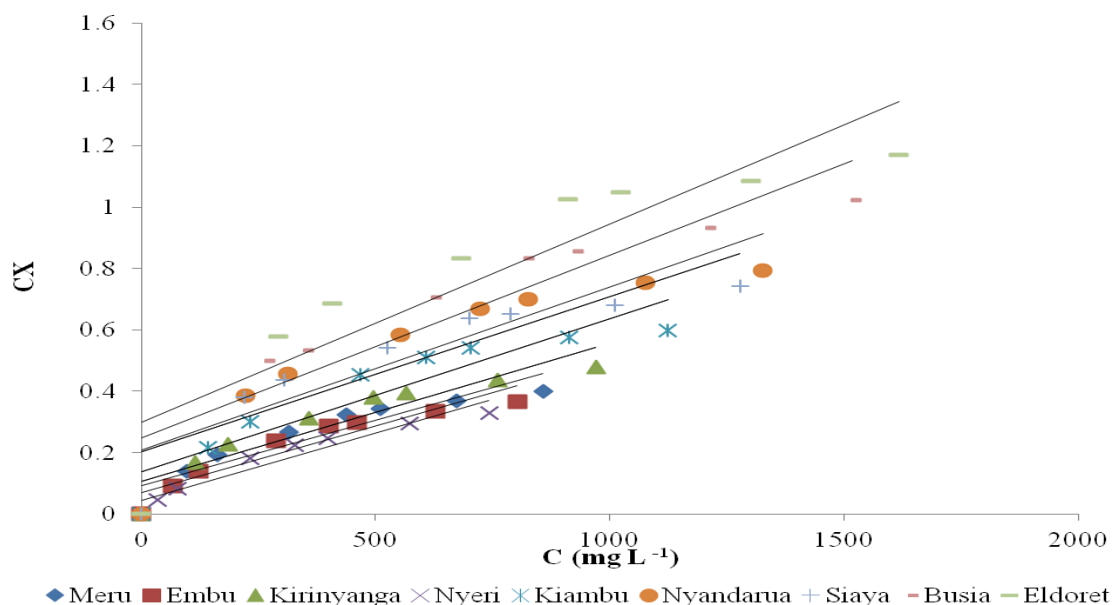
**Table 3.1: Maximal P adsorbed and standard phosphorus requirement (SPR) of the soils from the nine sites**

Site	*maximal P adsorbed (mg P kg soil <sup>-1</sup> )	SPR (mg P kg soil <sup>-1</sup> )	R <sup>2</sup>
Meru	2142.48	347.27	0.94
Embu	2197.59	415.64	0.92
Kirinyanga	2029.77	343.15	0.94
Nyeri	2258.19	529.76	0.89
Kiambu	1876.20	290.63	0.94
Nyandarua	1673.41	225.59	0.96
Siaya	1721.80	217.93	0.96
Busia	1483.02	226.73	0.94
Eldoret	1383.45	189.43	0.95

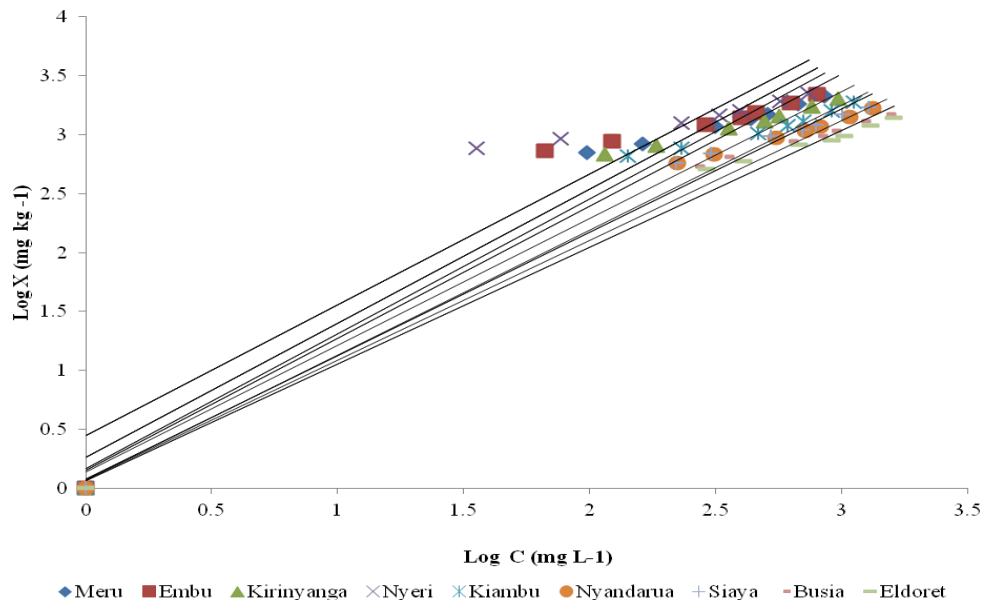
All R<sup>2</sup> values were significant at  $P \leq 0.05$  level, \* highest amount of P adsorbed at the highest level of P incubated.

### 3.3.2 Fitting the adsorption data to the Langmuir and Freundlich equation models

The Langmuir adsorption isotherms plotted by taking  $C/X$  against  $C$  are shown in Figure 3.2, while the linear form of the Freundlich equation plotted by taking  $\log C$  against  $\log X$  are given in Figure 3.3. The Freundlich equation showed a better linear fit to the data compared to the Langmuir equation in all sites except Nyeri.



**Figure 3.2: Langmuir adsorption isotherms for soils from the nine sites**



**Figure 3.3: Freundlich adsorption isotherms for soils from the nine sites**

Regression coefficients ( $R^2$ ) for the fitted Langmuir P adsorption isotherms were significant for soils from all sites (Table 3.2). The  $R^2$  values were highest in Nyeri and lowest in Siaya. Similarly, regression coefficients ( $R^2$ ) for the fitted Freundlich P adsorption isotherms were significant for all tested soils (0.882- 0.990).

**Table 3.2: Regression equations with  $R^2$  value for soils in the nine sites**

Site	Langmuir		Freundlich	
	$R^2$	Equation	$R^2$	Equation
Meru	0.864	$y=0.0004x+0.0914$	0.964	$y=1.1439x+0.1708$
Embu	0.892	$y=0.0004x+0.0693$	0.938	$y=1.1392x+0.2608$
Kirinyanga	0.872	$y=0.0004x+0.1061$	0.967	$y=1.1197x+0.1562$
Nyeri	0.928	$y=0.0004x+0.0459$	0.882	$y=1.1114x+0.4468$
Kiambu	0.851	$y=0.0005x+0.1388$	0.971	$y=1.10773x+0.1367$
Nyandarua	0.824	$y=0.0005x+0.2092$	0.987	$y=1.0467x+0.0787$
Siaya	0.805	$y=0.0005x+0.204$	0.988	$y=1.0587x+0.0735$
Busia	0.848	$y=0.0006x+0.2481$	0.988	$y=1.0159x+0.0723$
Eldoret	0.824	$y=0.0006x+0.3001$	0.990	$y=0.9926x+0.0621$

The slopes of the plots ( $1/ bL$ ) of the Langmuir equation were found to be less than 0.01 for all the soils (Table 3.3). The bonding energy was highest in Nyeri soils. It

was also observed that Busia and Eldoret soils had the lowest adsorption maxima in the Langmuir equation. In the Freundlich equation, the constant related to sorption capacity (Log a) was highest in Nyeri and lowest in Eldoret while the affinity constant was highest in Eldoret and lowest in Meru.

**Table 3.3: Parameters of the Langmuir and Freundlich adsorption equations**

Site	Langmuir		Freundlich	
	bL	Kl	n	log a
Meru	2500.00	0.004	0.874	0.171
Embu	2500.00	0.006	0.878	0.261
Kirinyanga	2500.00	0.004	0.893	0.156
Nyeri	2500.00	0.009	0.900	0.447
Kiambu	2000.00	0.004	0.903	0.137
Nyandarua	2000.00	0.002	0.955	0.079
Siaya	2000.00	0.002	0.945	0.074
Busia	1666.67	0.002	0.984	0.072
Eldoret	1666.67	0.002	1.007	0.062

bL- adsorption maxima ( $\text{mg kg}^{-1}$ ); kL- constant related to binding energy; n- The affinity; a- Constant related to sorption capacity.

### 3.3.3 Relationship between adsorption and soil properties

A significant correlation was observed between maximal adsorbed P, Langmuir and Freundlich constants, clay content and soil P (Bray 1) for all the added P concentrations and soils (Table 3.4). A positive correlation between the soil aluminium saturation, exchangeable aluminium and clay with P adsorption maxima was also observed. Organic matter, Ca and soil pH negatively correlated with the adsorption maxima while extractable P negatively correlated with exchangeable Al. On the other hand, Langmuir and Freundlich constants were positively correlated with the adsorption maxima and SPR.

**Table 3.4: Correlation between soil properties and the Langmuir and Freundlich adsorption parameters**

Pairs	Correlation coefficient ( $R^2$ )	P-value
bL vs n	-0.962	0.000
bL vs OC(%)	0.895	0.001
bL vs Maximal adsorbed P	0.974	0.000
bL vs SPR	0.873	0.002
kL vs log a	0.929	0.000
n vs Maximal adsorbed P	0.965	0.000
n vs SPR	0.828	0.006
log a vs Maximal adsorbed P	0.718	0.029
log a vs SPR	0.884	0.002
OC(%) vs Maximal adsorbed P	-0.822	0.007
OC(%) vs SPR	0.670	0.048
Phosphorus vs CEC	0.689	0.040
Calcium vs Aluminium saturation	-0.861	0.003
Exchangable Al. vs Phosphorus	-0.780	0.013
Maximal adsorbed P vs soil pH	-0.840	0.002
Maximal adsorbed P vs Clay	0.900	0.000
Maximal adsorbed P vs Calcium	-0.760	0.034
Maximal adsorbed P vs Al. sat.	0.860	0.010

bL- adsorption maxima ( $\text{mg kg}^{-1}$ ); kL- constant related to binding energy; n- The affinity; a- Constant related to sorption capacity; SPR- standard phosphate requirements; Correlation is significant at  $P = 0.05$  level (two tailed).

### 3.4 DISCUSSION

Accuracy of adsorption isotherms slightly declined in predicting phosphorous adsorption from Freundlich isotherm to Langmuir equations. Freundlich model showed a better fit to the data as compared to Langmuir model. The deviations from the expected linearity in Langmuir equations can be attributed to the equilibrium P concentrations used in the study. According to Olsen and Watanabe (1957), deviations from the expected linearity in Langmuir equations may occur due to high phosphate additions. Phosphorous sorption constants calculated through different adsorption isotherms also yielded varied results. The results are similar to work reported by Sanyal *et al.* (1993), Hoseini and Taleshmikael (2013) and Hadgu *et al.*

(2014). Similar results have also been reported by other researchers including Mehdi *et al.* (2008), Khan *et al.* (2010) and Espenjo and Cox (2008).

Soils from Meru, Embu, Kirinyaga, Kiambu and Nyeri had higher P sorption (290.63-529.76 mg kg<sup>-1</sup> soil) compared to soils from Siaya, Busia and Eldoret (189.43-226.73 mg kg<sup>-1</sup> soil). According to Buresh *et al.* (1997), P sorption levels of 0 -100, 100 - 400 and > 400 mg P kg<sup>-1</sup> are classified as low, moderate and high, respectively. Therefore, soils from all the sites had moderate P sorption levels apart from Embu and Nyeri which had a high P sorption levels. Earlier studies have also reported similar magnitudes of P sorption capacities (Kifuko *et al.*, 2007; Obura, 2008; Opala, 2009). The differences observed in P sorption capacities between soils from the various sites could be attributed to differences in the amounts and nature of the amorphous hydrous oxides of Al and clay minerals (Jaetzold and Schmidt, 1983; Obura, 2008). Acid soils from Embu, Meru, Kirinyaga, Kiambu and Nyandarua are highly weathered and consist predominantly of gibbsite minerals, with large surface area for P sorption as compared to kaolinite minerals in the acid soils of Siaya, Eldoret and Busia (Sanchez, 1976; Jaetzold and Schmidt, 1983; Tisdale *et al.*, 1990; Obura, 2008). This might have greatly influenced the P sorption reactions, hence the quantities of P adsorbed.

The significant correlation between maximal P adsorption and clay content, and the total amount of phosphorous adsorbed by the soil, could be attributed to presence of sorptive sites on the active soil constituents. This could be related to the relatively large number of positive charges that can react and strongly bind the negatively charged phosphate ions in the solution. Hoseini and Taleshmikael (2013) and Hadgu

*et al.* (2014) also observed that maximum adsorption value increased with increasing values of clay content and phosphorus in the soil. Negative correlation between adsorbed P with organic matter content and pH has also been reported by several researchers. Hoseini and Taleshmikael (2013); Munthambala *et al.* (2015) and Wolde *et al.* (2015) reported that presence of organic matter reduced P sorption capacities of soils due to occupation of adsorption sites by organic anions. The organic matter might also have reduced P - sorption capacity through direct competition for sorption sites between phosphate and organic ligands in the highly weathered soils (Burt *et al.*, 2002). The positive correlation of phosphate adsorption with aluminium saturation and exchangeable acidity is in agreement with findings by Tsado *et al.* (2012) and Hoseini and Taleshmikael (2013) where the phosphate ions react with  $Al^{3+}$  to form Al phosphates as precipitates.

Negative correlation between soil pH and maximum sorbed P in the current study supports the hypothesis that P sorption decreases with increasing pH. This is consistent with reports by Mnthambala *et al.* (2015) and Wolde *et al.* (2015). Haynes (1982) ascribed the sorption decrease to increased electrostatic repulsion caused by increased negative surface charge as pH increases. Hydroxyl ( $OH^{-1}$ ) concentrations 1,000 times higher have also been reported to compete with phosphate ions for specific sorption sites on mineral surfaces as pH increases (Smyth and Sanchez, 1980). The Al hydroxide polymers also neutralize sites where the more reactive Al surfaces once were present at high pH (Sanchez and Uehara, 1980). On the contrary Sims and Pierzynski (2005) indicated that the pH of both solid and liquid matrices of the soil can impact sorption of P by affecting protonation and deprotonation of functional groups and surface binding sites. These effects alter the electronegativity

of the surfaces of soil particles; a relationship commonly referred to as the adsorption envelope (Sims and Pierzynski, 2005). Soils dominated by kaolinite, goethite, and gibbsite, as those used in this study, are particularly susceptible to each of the above phosphate adsorption mechanisms (Jaetzold and Schmidt, 1983; Tisdale *et al.*, 1990). The high correlations between energies of bonding and P sorption such as seen in the present study have also been reported for Pakistan soils (Chaudhary *et al.*, 2003).

### **3.5 CONCLUSION**

The results of this study showed that the Freundlich adsorption model is more precise than the Langmuir model in predicting P adsorption in the Kenya highland acid soils. There were distinct differences in P adsorption and, therefore, SPR among soils from the study sites. The differences in the P adsorption maxima and SPR of the soils in the study sites indicate that application of blanket P fertilizer rates for all the study sites is not viable. The recommended P fertilizer of 26 kg P ha<sup>-1</sup> for maize production (Kenya Agricultural Research Institute, 1994) is, therefore, inadequate for optimal crop production at all the sites. This is because it can supply at most only 11.6 mg P kg<sup>-1</sup>, which is much below the soils SPR of between 189.43-529.76 mg P kg<sup>-1</sup>. Additionally, the study identified soil pH, organic matter, aluminium and bases like calcium as some of the factors that influence P availability in the soils. There is, therefore, a need for intensive studies to develop optimal management strategies of the soil constituents that increase organic matter, Ca and P availability in the study areas.

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## CHAPTER FOUR

### 4.0 INTERACTIVE EFFECTS OF LIME, ALUMINIUM AND PHOSPHORUS IN ACID SOILS OF THE KENYA HIGHLANDS

#### ABSTRACT

Liming and phosphorus (P) applications are recommended practices for improving crop production in acid soils of the tropics. Although considerable work has been done to establish liming rates for acid soils in many parts of the world, information on the role of the lime-Al-P interactions on P fertility management is minimal. A green house pot experiment was conducted at Waruhiu Farmers Training Centre, Githunguri to evaluate the interactive effect of lime, aluminium and phosphorus in acid soils of the Kenya highlands. Extremely acidic (pH 4.48) and strongly acidic (pH 4.59) soils were used for the study. Four lime (CaO) rates and phosphorus ( $(\text{H}_2\text{PO}_4)_2$ ) rates were used. The liming rates were: 0, 2.2, 5.2 and 7.4 tonnes  $\text{ha}^{-1}$  for extremely acidic soil and 0, 1.4, 3.2, and 4.5 tonnes  $\text{ha}^{-1}$  for the strongly acidic soil. Phosphorus applications rates were: 0, 0.15, 0.30 and 0.59 g P  $\text{kg}^{-1}$  soil for the extremely acidic soil and 0, 0.13, 0.26, and 0.51 g P  $\text{kg}^{-1}$  for strongly acidic soil. The experiments were a  $4^2$  factorial laid down in a Randomized Complete Block Design (RCBD) and replicated three times. Data collected included: plant height, number of leaves, P-uptake, dry matter yield, soil physicochemical properties and P adsorption capacities. The tested soils had high exchangeable Al ( $> 2 \text{ cmol Al kg}^{-1}$ ), Al saturation of ( $> 20\%$  Al) and low extractable P values ( $< 15 \text{ mg P kg}^{-1}$  soil). Lime-Al-P interaction significantly ( $P \leq 0.05$ ) increased P concentrations in maize tissues, maize height, drymatter yields, soil pH, extractable P, CEC, Ca, and, reduced exchangeable Al, exchangeable acidity, % Al saturation, P adsorption and standard phosphorus requirements (SPR). Use of 7.4 tonnes  $\text{ha}^{-1}$  in extremely acidic soils and

4.5 tonnes ha<sup>-1</sup> in strongly acidic soils significantly ( $P \leq 0.05$ ) reduced exchangeable Al and SPR by > 70% compared to lower lime rates. There was, however, no significant difference between combining 7.4 tonnes ha<sup>-1</sup> with either 0.59 g P kg<sup>-1</sup> or 0.3 g P kg<sup>-1</sup> in extremely acidic soils, and 4.5 tonnes ha<sup>-1</sup> with either 0.51 g P kg<sup>-1</sup> or 0.26 g P kg<sup>-1</sup> in strongly acidic soils indicating that the lower lime and P rates can be effectively used in the management of these acid soils. Analysis of the relationship between lime and P availability showed that liming significantly ( $P \leq 0.05$ ) positively correlated with soil pH, available P, exchangeable Ca, Langmuir maximum adsorption constant and the Langmuir constant related to binding energy. Lime also negatively correlated with SPR and exchangeable Al. It was, therefore, concluded that lime and P positively interact to reduce Al saturation and P adsorption rates in acid soils in the Kenya highlands. However, further research is required to evaluate the short and long term effects of the rates on crop yields, availability of other plant nutrients and the environment under field conditions.

*Key words: Lime, phosphorus, aluminium, standard phosphate requirement, acid soils*

#### **4.1 INTRODUCTION**

Inorganic phosphorus (P) in soil occurs mainly as H<sub>2</sub>PO<sub>4</sub><sup>-</sup> and HPO<sub>4</sub><sup>2-</sup> adsorbed onto the surfaces of oxides, hydroxides, organic matter or bound to cations like calcium (Olibone and Rosolem, 2010). The extent of this depends on soil acidity and clay mineralogy (Duputel *et al.*, (2013). Strong acidity is associated with aluminium (Al), hydrogen (H), iron (Fe) and manganese (Mn) toxicities to plant roots in the soil solution and corresponding deficiencies of the available P, molybdenum (Mo), calcium (Ca), magnesium (Mg) and potassium (K) (Jorge and Arrunda, 1997; Brady and Weil, 2008; Mohammadi, 2012; Nduwumuremyi, 2013). Although excess H<sup>+</sup>

ions are toxic and negatively affect root membrane permeability (Foy, 1984), the main constraint to crop production in highly acid soils is not high  $H^+$  ions but increased concentration of  $Fe^{3+}$  and  $Al^{3+}$  ions at  $pH < 5.5$  (Sale and Mokuwunye, 1993).

The process of release of Al ions from octahedral co-ordination in minerals through weathering processes (McLean, 1976) usually depends on  $H^+$  ion concentration. Upon release these Al ions combine with water to form  $Al(H_2O)_6^{3+}$  in solution and with an increase in soil pH, there is subsequent dissociation into various species of Al. The various forms range from simple monomeric species to polymeric species of varying molecular weight, either in combination with Fe or Si or both, depending on soil pH (Amarasiri and Olsen, 1973; Fageria and Baligar, 2008). At pH 4.5 - 6.5 aluminium-hydroxyls dominates, while in very acidic conditions of  $pH < 4.5$ ,  $Al^{3+}$  dominates (Carson and Dixon, 1979).

Soil acidity and P deficiency are not independent, and one of the primary reasons commonly proposed for liming acid soils is to increase availability of P to plants (Sanchez and Uechara, 1980). The mechanisms by which P availability increases are not clearly documented but are known to involve both the soil and plant components of the system. There are conflicting views as to the effects of liming on the P supplying power of highly weathered, acid soils. Liming has been reported to increase, decrease, or have no effect on the amount of P which can be extracted from the soils (Martini *et al.*, 1974; Janghorbani *et al.*, 1975; Ryan and Smillie, 1975; Kisinyo *et al.*, 2014b; Sarker *et al.*, 2014). Haynes (1982) attributed many of these apparent inconsistencies to differences in initial soil pH, soil mineralogy, the soil

extraction method used, the type of extracting reagents and the mechanisms involved.

Although liming of acid soils has been shown to have a variable effect on P sorption capacity, increased sorption on limed soils is attributed to formation of active x-ray amorphous Al hydroxyl polymers, which actively sorb more P than  $\text{Al}^{3+}$  (Robarge and Corey, 1979). The active Al hydroxyl polymers formed can also coat the surfaces of minerals, thereby affecting their surface charge characteristics (Sims and Ellis, 1983). Such change in surface charge would be expected to influence the P sorption characteristic of the soils. Liming has also been reported to increase plant growth up to pH 6 (Kamprath, 1971). This positive growth response to lime has been attributed to amelioration of Al-toxicity and / increased P availability (Sanchez and Uehara, 1980; Kisinyo *et al.*, 2014a).

However, high rates of lime, which increase the pH values above 6.5, have been reported to cause a depression in plant growth (Kamprath, 1971; Maier *et al.*, 2002). Kamprath (1971) attributed the decrease in yields to three possible reasons, namely, reduction of infiltration due to formation of smaller soil aggregates, micronutrient deficiencies at higher pH and induced P deficiency due to formation of insoluble calcium phosphate (Ca-P) compounds. However, Sumner (1979) attributed the yield decrease to Al reactions in the soil where the level of exchangeable Al at a given pH reflected the reactivity of the aluminium surfaces which, in turn, governed the solubility of P.

Kenyan soils, similar to other agricultural soils of the tropics, have low available P, high Al concentrations and high P-fixation capacities (Obura, 2008; Kisinyo *et al.*,

2012) This is attributed to extensive weathering and dominance of Al, Fe, and Mn oxyhydroxides and 1:1 layer silicates, and extensive leaching of the basic cations and high concentration of  $\text{Al}^{3+}$  and  $\text{Fe}^{3+}$  in the soil solution and on the cation retention sites and the soil colloids. Several workers have tested and documented the effect of liming on nutrient availability in acid soils of the western highlands of Kenya (Nekesa, 2007; Kisinyo *et al.*, 2012; 2014b). However, information on the interaction of lime, Al and P to ensure optimal availability of P as assessed by soil-testing procedures and plant uptake in the case of soils of the Kenya highlands is scanty. The objectives of this study were, therefore to: (i) evaluate the interactive effect of lime, Al and P on soil acidity and P uptake by maize plants and (ii) determine the interactive effect of lime, Al and P on selected chemical properties.

## **4.2 MATERIALS AND METHODS**

### **4.2.1 Experimental layout, design and crop husbandry**

A greenhouse pot experiment was carried out at Waruhiu Farmers' Training Centre, Githunguri, Kiambu County. Two composite soil samples representing extremely acid (pH 4.0-4.5) and strongly acidic (pH 5.0-5.5) soils, as described by Kanyanjua *et al.* (2002) were used. The experiments were a  $4^2$  factorial laid down in a Randomized Complete Block Design (RCBD) and replicated three times. The treatments were lime and phosphorus each applied at four levels. Liming rates were chosen to obtain 0, 30, 70 or 100% reduction in amounts of M KCl-extractable Al originally present in the soil while the phosphorus levels added were: 0, 0.5, 1 or 2 times the standard phosphorus requirement (SPR) of the tested soils (Table 4.1).

Burnt lime (CaO) containing about 21% calcium oxide was used in this study while triple superphosphate fertilizer [Ca (H<sub>2</sub>PO<sub>4</sub>)<sub>2</sub>] was the P- source.

**Table 4. 1: Actual amounts of phosphorus and lime added to the acid soils.**

Soil	Lime added (tonnes ha <sup>-1</sup> )				P added (g P kg <sup>-1</sup> soil)			
	0%	30%	70%	100%	0 SPR	0.5 SPR	1 SPR	2 SPR
Extremely Acidic	0	2.2	5.2	7.4	0	0.15	0.30	0.59
Strongly Acidic	0	1.4	3.2	4.5	0	0.13	0.26	0.51

SPR-Standard phosphate requirement

Five kilogramme composite soil sample portions for both extremely and strongly acid soils were weighed into ten litre plastic pots. The different lime levels were weighed and incorporated into the soil samples by thoroughly mixing and incubating at moist conditions for a period of 21 days. Water was added every 2 days to compensate for evaporative losses. After incubation, soils from each liming level were air-dried, sieved and returned to the plastic pots. The various P levels were then added and the soils re- incubated at the same conditions for 14 days after which they were air dried. Subsamples of the soils were then used for chemical analyses.

A plant growth study was conducted in a greenhouse. Lime-P treated soils (4 kg) were mixed with calcium ammonium nitrate (CAN) at the rate of 50 kg N ha<sup>-1</sup> then placed in plastic containers with the container lids placed underneath to obtain any leachate. Each treatment was replicated three times. The potted soils were moistened with water and three maize seeds planted in each pot. Data was collected from the 7<sup>th</sup> day after emergence to 35 days after emergence when the maize plants were harvested. Duma maize variety was used.

#### 4.2.2 Laboratory analysis

Soil physicochemical analysis and P adsorption were determined before and after application of treatments. Soil pH, exchangeable aluminum, CEC, exchangeable bases and particle size distribution were analyzed as described by Okalebo *et al.* (2002). Iron and aluminium contents were extracted using ammonium oxalate at pH 4.0 (McKeague and Day, 1966) and dithionate-citrate-bicarbonate (DCB) (Mehra and Jackson, 1960). Extractable P was determined as described by Mehlich *et al.* (1962) while phosphorus sorption capacities of the soils were evaluated as described by Fox and Kamprath (1970) and the P adsorbed data for the two soils fitted into the linearized form of the Langmuir equation. Phosphorus adsorption maxima were obtained by calculating the highest adsorbed P values from the adsorption isotherms. The 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, and is given as: Lime required (CaCO<sub>3</sub> equiv.) tones ha<sup>-1</sup> = 1.8[Al - RAS (Al + Ca + Mg) /100] where Al = cmol kg<sup>-1</sup> soil in the original exchange complex, RAS = Required percentage Al saturation, Ca = cmol kg<sup>-1</sup> soil in the original exchange complex, Mg = cmol kg<sup>-1</sup> soil in the original exchange complex. A RAS value of 20% was used. Soil characterization data in Table 4.2 below was used for lime requirement determinations.

#### 4.2.3 Maize crop growth data collection

Crop growth data collected included: plant height, number of leaves, and dry matter yield. Maize height and number of leaves were measured weekly from crop emergence until 35 days after emergence. Thirty five days after emergence, the maize plants were cut and the above ground parts, weighed, then oven dried at 70°C

to constant weights. Soil from each pot was also thoroughly mixed and subsamples taken to the soil science laboratory at the University of Nairobi for physico-chemical analysis.

#### **4.2.4 Statistical analysis**

Data obtained were subjected to Analysis of Variance (ANOVA) using the GenStat statistical package (GenStat, 2010) and treatment effects were tested for significance using the F-test at 5% level of significance. Means were ranked using Duncan's New Multiple Range Test (DNMRT). Dependency tests were also conducted to find out if there was a relationship between the various variables assessed.

### **4.3 RESULTS**

#### **4.3.1 Initial soil physical and chemical characteristics**

The tested soils were acidic with  $\text{pH} < 5.5$  (Table 4.2). Exchangeable Aluminium levels for both soils were  $> 2 \text{ cmol kg}^{-1}$  and % Aluminium saturation  $> 20\%$ . Both extractable P ( $< 15 \text{ mg kg}^{-1}$ ) and Ca ( $< 4.0 \text{ cmol kg}^{-1}$ ) were low while CEC was  $< 15 \text{ cmol kg}^{-1}$  soil and rated low. The tested soils had clay texture.

**Table 4.2: Physicochemical properties of the two soils prior to the pot experiment**

	Extremely acidic	Strongly acidic
pH (H <sub>2</sub> O)	4.48	4.59
Exch. Al (cmol kg <sup>-1</sup> )	3.85	3.90
N (%)	0.19	0.16
OC (%)	1.75	1.83
K (cmol kg <sup>-1</sup> )	0.15	0.20
Na (cmol kg <sup>-1</sup> )	0.58	0.95
Ca (cmol kg <sup>-1</sup> )	1.80	1.23
Mg (cmol kg <sup>-1</sup> )	0.75	3.50
P (mg kg <sup>-1</sup> )	9.25	10.50
CEC	10.82	11.68
Oxalate Al (cmol kg <sup>-1</sup> )	4.61	4.58
Dithionate Al (cmol kg <sup>-1</sup> )	3.85	3.48
Oxalate Fe (cmol kg <sup>-1</sup> )	6.75	6.85
Dithionate Fe (cmol kg <sup>-1</sup> )	3.85	3.82
Al Saturation (%)	55.82	49.66
PSD*		
% Clay	56.32	50.00
% Silt	21.00	17.00
% Sand	22.68	33.00
Textural class	Clay	Clay

\*Particle size distribution

### 4.3.2 The interactive effects of lime, Al and P on soils chemical properties.

Lime-Al-P interaction significantly ( $P \leq 0.05$ ) increased soil pH levels (Table 4.3).

The reduction of soil pH was in the order: 0 % reduction of Al<sup>3+</sup> < 30 % reduction of Al<sup>3+</sup> < 70 % reduction of Al<sup>3+</sup> ≤ 100 % reduction of Al<sup>3+</sup>. Phosphorus alone didnot, however significantly ( $P \leq 0.05$ ) raise the soil pH.

Extractable P levels were significantly ( $P \leq 0.05$ ) increased by lime-Al-P interactions in both extremely and strongly acidic soils (Table 4.4). The extractable P increased in the the order: 0 % reduction of Al<sup>3+</sup> < 30 % reduction of Al<sup>3+</sup> < 70 % reduction of Al<sup>3+</sup> ≤ 100 % reduction of Al<sup>3+</sup>. It was also observed that soil extractable P significantly ( $P \leq 0.05$ ) increased with increasing rates of applied P.

**Table 4.3: Effect of lime-Al-P interactions on the pH<sub>(water)</sub> of the acid soils.**

Lime to give:	Phosphorus levels applied (g P kg <sup>-1</sup> )							
	Extremely acidic soils				Strongly acidic soils			
	0	0.15	0.30	0.59	0	0.13	0.26	0.51
0% reduction in Al <sup>3+</sup>	3.96a	4.31a	4.17a	4.19a	3.91a	4.41a	4.07a	3.96a
30% reduction in Al <sup>3+</sup>	5.30b	5.37b	5.22b	5.15b	5.29b	5.24b	5.29b	5.30b
70% reduction in Al <sup>3+</sup>	6.24c	6.33c	6.27c	6.37c	5.62c	5.69c	5.53c	5.45b
100% reduction in Al <sup>3+</sup>	6.63d	6.40c	6.42c	6.39c	6.54c	6.51c	6.38d	6.27c
% CV	0.60	0.60	0.60	0.60	0.90	0.90	0.90	0.90

Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

**Table 4.4: Effect of lime-Al-P interactions on extractable phosphorus (mg kg<sup>-1</sup>) of the two acid soils.**

Lime to give:	Phosphorus levels applied (g P kg <sup>-1</sup> )							
	Extremely acidic soils				Strongly acidic soils			
	0	0.15	0.30	0.59	0	0.13	0.26	0.51
0% reduction in Al <sup>3+</sup>	6.80a	12.30a	18.00a	25.00a	6.60a	11.30a	11.30a	11.00a
30% reduction in Al <sup>3+</sup>	13.00a	16.20a	22.80b	26.50a	12.40b	16.30a	16.80a	23.40b
70% reduction in Al <sup>3+</sup>	28.20b	32.20b	36.30c	43.20b	41.00c	34.20b	30.60b	35.00c
100% reduction in Al <sup>3+</sup>	28.40b	31.20b	35.50c	43.90b	40.90c	30.00b	27.60b	39.70c
% CV	3.10	3.10	3.10	3.10	7.60	7.60	7.60	7.60

Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

Exchangable Ca levels were significantly ( $P \leq 0.05$ ) increased by lime-Al-P interactions (Table 4.5). The Ca levels were observed to increase with increased lime rates with lime rates resulting to 100% reduction of Al<sup>3+</sup> supporting the highest Ca levels in both extremely and strongly acidic soils.

**Table 4.5: Effect of lime-Al-P interactions on exchangeable calcium (cmol kg<sup>-1</sup>) of the two acid soils.**

Lime to give:	Phosphorus levels applied (g P kg <sup>-1</sup> )							
	Extremely acidic soils				Strongly acidic soils			
	0.00	0.15	0.30	0.59	0.00	0.13	0.26	0.51
0% reduction in Al <sup>3+</sup>	1.46a	1.54a	1.59a	1.57a	0.72a	1.63a	1.28a	1.07a
30% reduction in Al <sup>3+</sup>	2.31b	2.47b	2.48b	2.57b	2.90b	3.03b	2.83b	2.70b
70% reduction in Al <sup>3+</sup>	3.07b	2.92b	2.50b	2.81b	2.93b	3.30b	3.20b	3.10b
100% reduction in Al <sup>3+</sup>	4.33c	4.42c	3.03c	3.93c	4.57c	4.47c	4.73c	4.50c
% CV	2.50	2.50	2.50	2.50	4.60	4.60	4.60	4.60

Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

**Table 4.6: Effect of lime-Al-P interactions on CEC (cmol kg<sup>-1</sup> soil) of the two acid soils.**

Lime to give:	Phosphorus levels applied (g P kg <sup>-1</sup> )							
	Extremely acidic soils				Strongly acidic soils			
	0.00	0.15	0.30	0.59	0.00	0.13	0.26	0.51
0% reduction in Al <sup>3+</sup>	13.07a	15.07a	18.00a	12.17a	14.50a	12.20a	13.30a	14.70a
30% reduction in Al <sup>3+</sup>	14.53a	16.17a	21.53b	15.50b	15.70a	17.60a	17.10a	15.50a
70% reduction in Al <sup>3+</sup>	25.30b	25.33b	32.50c	25.58c	22.70b	26.80b	28.70b	27.70b
100% reduction in Al <sup>3+</sup>	26.97b	26.73b	33.67c	27.23d	23.10b	28.40b	30.00b	29.00b
% CV	0.70	0.70	0.70	0.70	5.50	5.50	5.50	5.50

Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

Exchangeable Al levels were observed to continuously decrease with increased lime levels (Table 4.7a). The significant ( $P \leq 0.05$ ) decrease of exchangeable Al followed the order: 0 % reduction of Al<sup>3+</sup> < 30 % reduction of Al<sup>3+</sup> < 70 % reduction of Al<sup>3+</sup> < 100 % reduction of Al<sup>3+</sup> in both extremely and strongly acidic soils. Phosphorus alone however did not significantly ( $P \leq 0.05$ ) influence Al levels in the soils.

**Table 4.7a: Effect of lime-Al-P interactions on exchangeable aluminium (cmol kg<sup>-1</sup>) on the two acid soils.**

Lime to give:	Phosphorus levels applied (g P kg <sup>-1</sup> )							
	Extremely acidic soils				Strongly acidic soils			
	0	0.15	0.30	0.59	0	0.13	0.26	0.51
0% reduction in Al <sup>3+</sup>	3.75a	3.53a	3.57a	3.48a	3.83a	3.69a	3.76a	3.97a
30% reduction in Al <sup>3+</sup>	2.91b	2.92b	2.85b	3.03b	2.80b	2.86b	2.74b	2.84b
70% reduction in Al <sup>3+</sup>	2.41c	2.22c	2.34c	2.29c	2.34c	2.05c	2.22c	2.27c
100% reduction in Al <sup>3+</sup>	1.82d	1.70d	1.88d	1.62d	1.81d	1.63d	1.72d	1.68d
% CV	1.60	1.60	1.60	1.60	0.80	0.80	0.80	0.80

Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

Percent Al saturation and exchangeable acidity levels were observed to continuously decrease with increased lime levels (Table 4.7 b&c). The significant ( $P \leq 0.05$ ) decrease of % Al saturation and exchangeable acidity followed the order: 0 % reduction of Al<sup>3+</sup> < 30 % reduction of Al<sup>3+</sup> < 70 % reduction of Al<sup>3+</sup> < 100 % reduction of Al<sup>3+</sup> in both extremely and strongly acidic soils. It was, however, observed that P application did not play a significant ( $P \leq 0.05$ ) role in % Al saturation and exchangeable acidity reduction in both soils.

**Table 4.7b: Effect of lime-Al-P interactions on aluminium saturation (%) of the two acid soils.**

Lime to give:	Phosphorus levels applied (g P kg <sup>-1</sup> )							
	Extremely acidic soils				Strongly acidic soils			
	0.00	0.15	0.3	0.59	0.00	0.13	0.26	0.51
0% reduction in Al <sup>3+</sup>	69.1a	62.0a	64.9a	60.8a	73.8a	69.4a	71.4a	69.1a
30% reduction in Al <sup>3+</sup>	45.9b	47.0b	48.3b	55.7a	45.3b	44.7b	46.4b	45.8b
70% reduction in Al <sup>3+</sup>	45.5b	39.1c	42.2c	44.7c	41.2c	37.5c	35.5c	39.2c
100% reduction in Al <sup>3+</sup>	31.7c	29.3d	40.5d	37.8d	29.0d	27.0d	26.7d	26.7d
% CV	7.9	7.9	7.9	7.9	3.2	3.2	3.2	3.2

Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

**Table 4.7c: Effect of lime-Al-P interactions on exchangeable acidity (cmols kg<sup>-1</sup> soil) on the two acid soils.**

Lime to give:	Phosphorus levels applied (g P kg <sup>-1</sup> )							
	Extremely acidic soils				Strongly acidic soils			
	0.00	0.15	0.3	0.59	0.00	0.13	0.26	0.51
0% reduction in Al <sup>3+</sup>	5.72a	5.40a	5.46a	5.33a	5.85a	5.64a	5.74a	6.05a
30% reduction in Al <sup>3+</sup>	4.47b	4.48b	4.38b	4.64b	4.31b	4.40b	4.21b	4.36b
70% reduction in Al <sup>3+</sup>	3.72c	3.44c	3.62c	3.54c	3.61c	3.18c	3.44c	3.51c
100% reduction in Al <sup>3+</sup>	2.83d	2.65d	2.93d	2.53d	2.82d	2.55d	2.69d	2.62d
% CV	1.50	1.50	1.50	1.50	0.80	0.80	0.80	0.80

Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

Lime-Al-P interactions significantly ( $P \leq 0.05$ ) reduced oxalate and dithionate extractable aluminium (Al<sub>o</sub> and Al<sub>d</sub> respectively) in the acid soils (Table 4.8 a&b). The Al<sub>o</sub> was reduced from  $\geq 6.0$  cmol kg<sup>-1</sup> to  $< 3$  cmol kg<sup>-1</sup> in both extremely and strongly acidic soils while Al<sub>d</sub> was reduced from  $> 5.0$  cmol kg<sup>-1</sup> to  $< 2.5$  cmol kg<sup>-1</sup> in both soils.

Lime-Al-P interactions significantly ( $P \leq 0.05$ ) reduced oxalate and dithionate extractable iron (Fe<sub>o</sub> and Fe<sub>d</sub> respectively) in the acid soils (Table 4.9 a&b). The Fe<sub>o</sub> levels were reduced from  $\geq 6.9$  cmol kg<sup>-1</sup> to  $\leq 5$  cmol kg<sup>-1</sup> while Al<sub>d</sub> levels were reduced from  $\geq 6.4$  cmol kg<sup>-1</sup> to  $\leq 5.5$  cmol kg<sup>-1</sup> in both extremely and strongly acidic soils.

**Table 4.8a: Effect of lime-Al-P interactions on oxalate aluminium (Al<sub>o</sub>) (cmol kg<sup>-1</sup>) on the two acid soils.**

Lime to give:	Phosphorus levels applied (g P kg <sup>-1</sup> )							
	Extremely acidic soils				Strongly acidic soils			
	0.00	0.15	0.3	0.59	0.00	0.13	0.26	0.51
0% reduction in Al <sup>3+</sup>	6.12a	6.05a	6.10a	5.99a	6.29a	6.22a	6.23a	6.40a
30% reduction in Al <sup>3+</sup>	4.95b	5.12b	5.09b	5.09b	4.94b	4.93b	4.86b	4.90b
70% reduction in Al <sup>3+</sup>	4.00c	3.79c	3.97c	3.87c	4.06c	4.05c	4.26c	4.26c
100% reduction in Al <sup>3+</sup>	2.77d	2.77d	2.87d	2.81d	2.99d	2.97d	2.99d	3.07d
% CV	0.70	0.70	0.70	0.70	0.60	0.60	0.60	0.60

Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

**Table 4.8b: Effect of lime-Al-P interactions on dithionate aluminium (Al<sub>d</sub>) (cmol kg<sup>-1</sup>) on the two acid soils.**

Lime to give:	Phosphorus levels applied (g P kg <sup>-1</sup> )							
	Extremely acidic soils				Strongly acidic soils			
	0.00	0.15	0.3	0.59	0.00	0.13	0.26	0.51
0% reduction in Al <sup>3+</sup>	5.44a	5.35a	5.29a	5.34a	5.39a	5.50a	5.52a	5.59a
30% reduction in Al <sup>3+</sup>	4.12b	4.28b	4.23b	4.36b	4.28b	4.13b	4.11b	4.19b
70% reduction in Al <sup>3+</sup>	3.11c	3.01c	3.08c	2.97c	3.82c	3.80c	3.70c	3.83c
100% reduction in Al <sup>3+</sup>	2.23d	2.24d	2.25d	2.25d	2.18d	2.13d	2.25d	2.32d
% CV	0.80	0.80	0.80	0.80	1.00	1.00	1.00	1.00

Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

**Table 4.9a: Effects of lime-Al-P interactions on oxalate iron (Fe<sub>o</sub>) and dithionate iron (Fe<sub>d</sub>) (cmol kg<sup>-1</sup>) in the two acid soils.**

Lime to give:	Phosphorus levels applied (g P kg <sup>-1</sup> )							
	Extremely acidic soils				Strongly acidic soils			
	0.00	0.15	0.3	0.59	0.00	0.13	0.26	0.51
0% reduction in Al <sup>3+</sup>	7.07a	6.88a	7.14a	6.93a	7.11a	6.89a	7.15a	7.20a
30% reduction in Al <sup>3+</sup>	6.68b	6.80a	6.76b	6.53b	6.50b	6.43b	7.01a	6.99a
70% reduction in Al <sup>3+</sup>	6.24c	5.96b	5.42c	6.09c	6.46b	6.03c	6.40b	6.39b
100% reduction in Al <sup>3+</sup>	5.86d	4.91c	4.98d	5.16d	5.77c	6.74d	5.01c	5.94c
% CV	0.90	0.90	0.90	0.90	3.10	3.10	3.10	3.10

Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

**Table 4.9b: Effects of lime-Al-P interactions on dithionate iron (Fe<sub>d</sub>) (cmol kg<sup>-1</sup>) in the two acid soils.**

Lime to give:	Phosphorus levels applied (g P kg <sup>-1</sup> )							
	Extremely acidic soils				Strongly acidic soils			
	0	0.15	0.3	0.59	0	0.13	0.26	0.51
0% reduction in Al <sup>3+</sup>	6.44a	6.72a	6.74a	6.64a	6.74a	6.51a	6.74a	6.93a
30% reduction in Al <sup>3+</sup>	6.36a	6.37a	6.40b	6.61b	6.16b	6.19b	6.34b	6.14b
70% reduction in Al <sup>3+</sup>	5.53c	5.99b	6.17c	6.03c	6.15b	6.03b	5.91c	6.05b
100% reduction in Al <sup>3+</sup>	5.04d	5.19c	5.90d	5.19d	5.47c	5.42c	5.49d	5.74c
% CV	0.60	0.60	0.60	0.60	1.40	1.40	1.40	1.40

Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

A significant ( $P \leq 0.05$ ) positive relationship was observed between soil pH, lime, exchangeable P and calcium (Table 4.10). Lime was also positively correlated with exchangeable P and Ca. On the contrary, soil pH, lime, exchangeable P,

exchangeable Ca exchangeable Al, Aluminium saturation, Al<sub>o</sub>, Al<sub>d</sub>, Fe<sub>o</sub> and Fe<sub>d</sub> were observed to have a significant ( $P \leq 0.05$ ) negative correlation.

**Table 4.10: Relationship between soil pH, P, exchangeable acidity, exchangeable aluminium and lime in the two acid soils.**

	pH	Lime	Exch. P	Exch.Ca	Exch. Al	Al <sub>o</sub>	Fe <sub>o</sub>	Al <sub>d</sub>	Fe <sub>d</sub>	Al. Sat.
pH	-	0.94	0.38	0.71	-0.93	-0.95	-0.54	-0.96	-0.46	-0.84
Lime	0.94	-	0.29	0.75	-0.95	-0.98	-0.47	-0.97	-0.39	-0.86
P	0.38	-	-	-	-0.33	-0.29	-0.30	-0.33	-0.30	-0.28
Ca	0.71	-	-	-	-	-0.75	-0.33	-0.74	-0.31	-0.93

All correlations had high significant relationship of  $P \leq 0.05$

### 4.3.3 The interactive effects of lime, Al and P on the growth of maize

The effect of lime-Al-P interaction on maize height varied with levels of P and lime used (Table 4.11). Lime rates resulting into 100% reduction in Al<sup>3+</sup> in the soils were observed to significantly ( $P \leq 0.05$ ) promote the highest maize plant heights in both extremely and strongly acidic soils.

**Table 4.11: Effect of lime-Al-P interactions on maize plant height (cm) in the two acid soils. (averaged over 5 sampling periods)**

Lime to give:	Phosphorus levels applied (g P kg <sup>-1</sup> )							
	Extremely acidic soils				Strongly acidic soils			
	0	0.15	0.3	0.59	0	0.13	0.26	0.51
0% reduction in Al <sup>3+</sup>	91.7a	108.0a	113.0a	116.0a	89.7a	102.0a	108.7a	103.8a
30% reduction in Al <sup>3+</sup>	97.8a	118.3a	123.5a	132.2b	97.0a	110.0b	114.6a	121.4b
70% reduction in Al <sup>3+</sup>	103.7a	138.3b	136.0b	132.2b	102.3a	118.0b	121.0b	122.0b
100% reduction in Al <sup>3+</sup>	115.6b	152.9c	207.2c	158.2c	112.9b	129.7c	131.3c	132.0c
% CV	3.2	3.2	3.2	3.2	2.0	2.0	2.0	2.0

Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

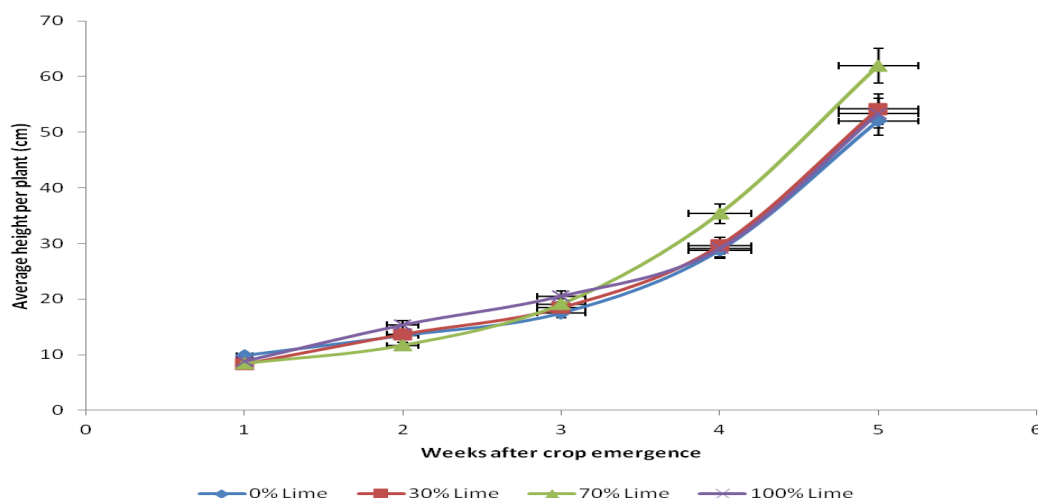
Phosphorus significantly ( $P \leq 0.05$ ) increased the number of leaves per maize plant in the acid soils (Table 4.12). Use of 0.3 g P kg<sup>-1</sup> gave the highest number of leaves for the extremely acidic soils while 0.26 g P kg<sup>-1</sup> gave the highest plant height for the strongly acidic soils.

**Table 4.12: Effect of lime-Al-P interactions on number of leaves per maize plant in the two acid soils (averaged over 5 sampling periods)**

Lime to give:	Phosphorus levels applied (g P kg <sup>-1</sup> )							
	Extremely acidic soils				Strongly acidic soils			
	0	0.15	0.3	0.59	0	0.13	0.26	0.51
0% reduction in Al <sup>3+</sup>	21.0a	26.7b	29.3c	26.3b	20.7a	21.3a	26.3b	23.7c
30% reduction in Al <sup>3+</sup>	22.0a	27.7b	30.3c	27.7b	21.3a	24.0b	27.0c	24.3b
70% reduction in Al <sup>3+</sup>	22.7a	27.7b	31.0c	27.7b	21.7a	24.0b	28.7c	24.3b
100% reduction in Al <sup>3+</sup>	23.0a	27.7b	31.0c	28.7b	22.7a	27.3a	31.7b	27.0b
% CV	3.7	3.7	3.7	3.7	4.7	4.7	4.7	4.7

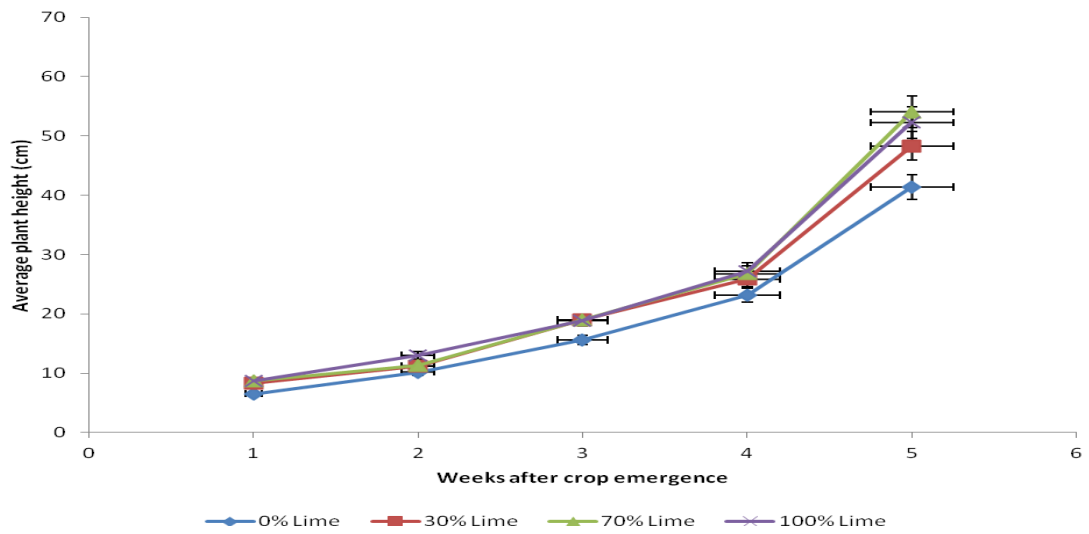
Values followed by the same letter(s) within a row are not significantly different at  $P \leq 0.05$ .

Average height of maize plants growing under different lime rates in the extremely acidic soils was not significantly different until the 4<sup>th</sup> week after germination (Figure 4.1). On the other side, the heights of the maize plants for the strongly acidic soils were significantly different from the 3<sup>rd</sup> week after emergence (Figure 4. 2).

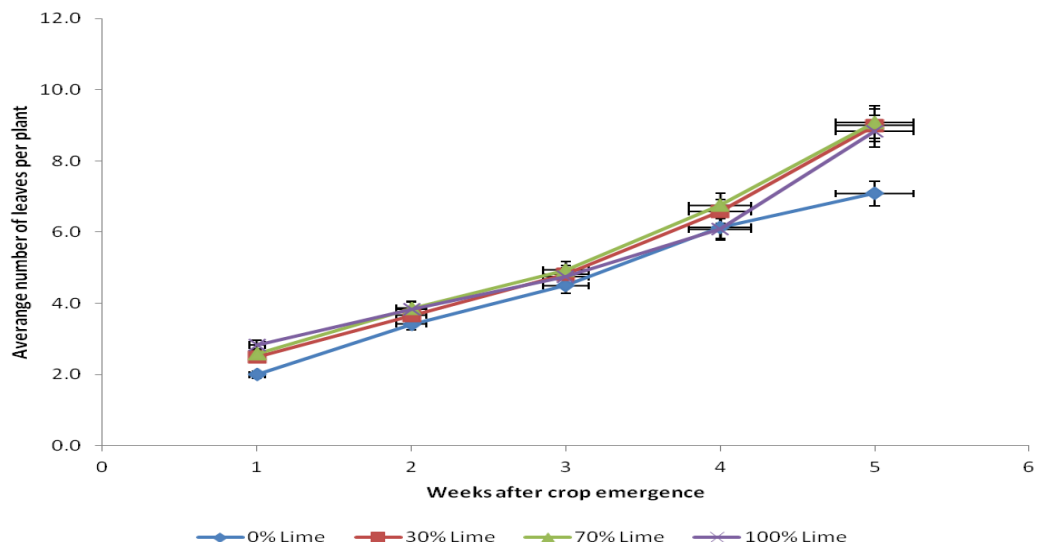


**Figure 4.1: Effects of liming on the heights of maize plants on the extremely acidic soils (LSD bars inserted)**

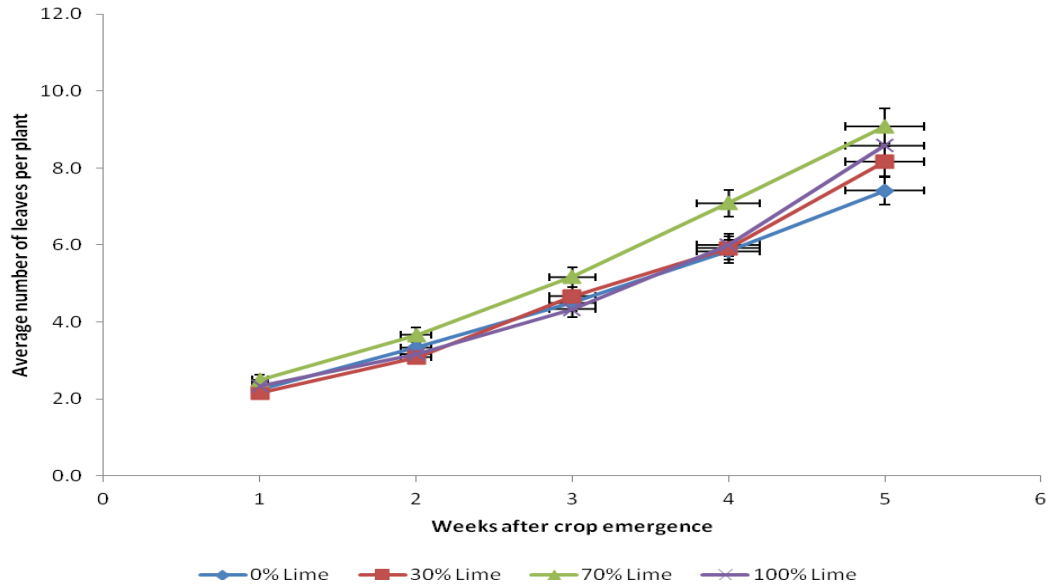
Average numbers of leaves from maize plants grown under different lime rates in extremely acidic soils were significantly different from the 4<sup>th</sup> week after emergence (Figure 4.3). On the contrary, numbers of leaves from plants grown in strongly acidic soils were significantly different from 2<sup>nd</sup> week after emergence (Figure 4.4).



**Figure 4.2: Effects of liming on the heights of maize plants on the strongly acidic soils (LSD bars inserted)**

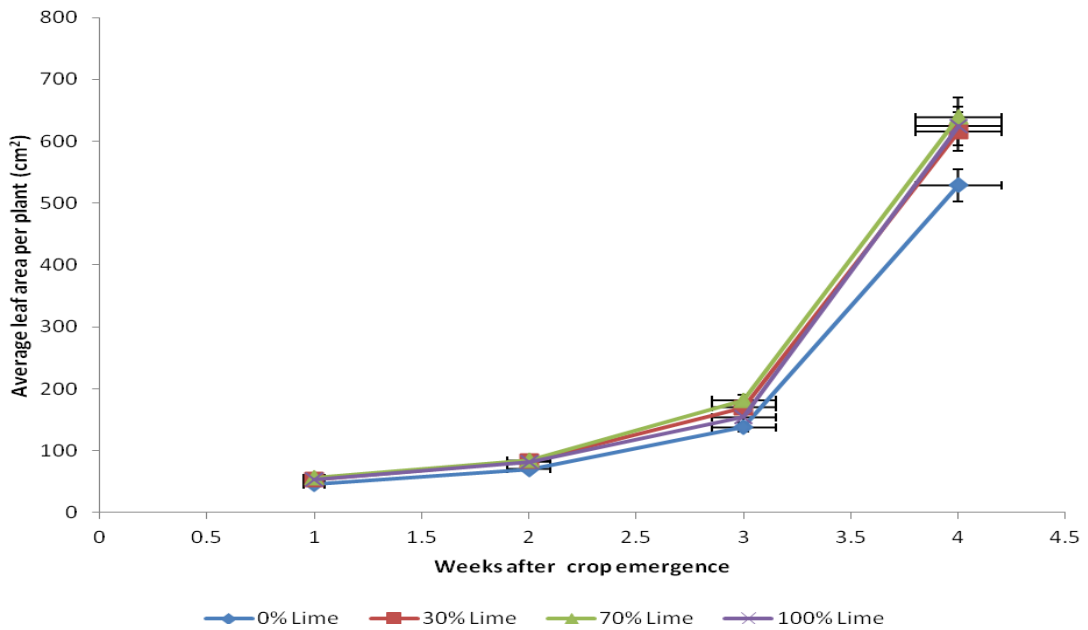


**Figure 4.3: Effects of liming on number of leaves from maize planted in extremely acidic soils (LSD bars inserted)**

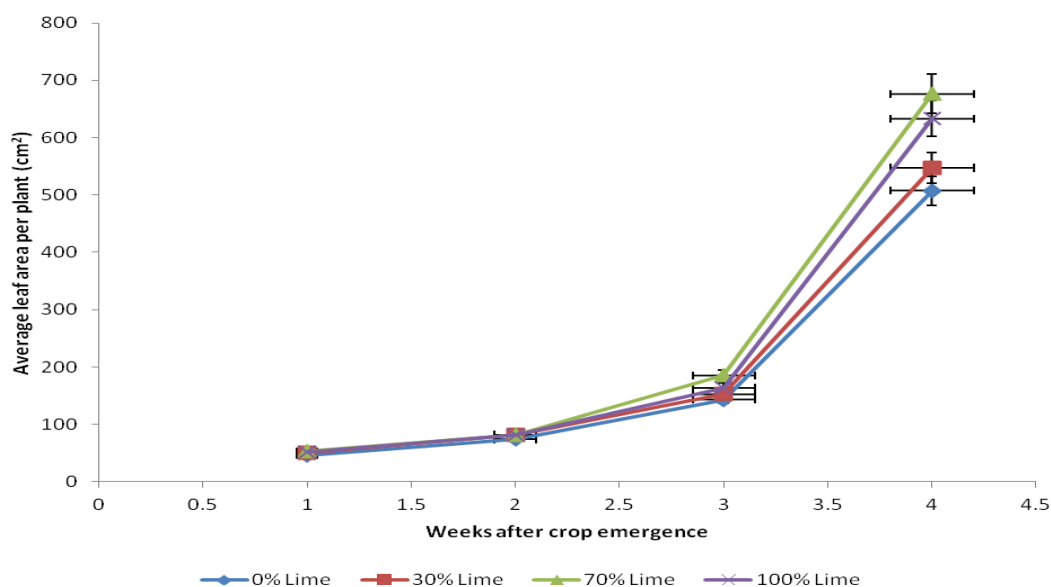


**Figure 4.4: Effects of liming on maize plant leaves in strongly acidic soils (LSD bars inserted)**

Maize leaf area index was significantly different from 3<sup>rd</sup> week after emergence under different lime rates in extremely acid soils (Figure 4.5). Similar trends were observed in strogly acid soils (Figure 4.6).



**Figure 4.5: Effects of liming on leaf area index of maize planted in extremely acidic soils (LSD bars inserted)**



**Figure 4.6: Effects of liming on leaf area index of maize planted in strongly acidic soils (LSD bars inserted)**

Phosphorus concentrations in plant tissues 35 days after emergence increased significantly with lime-Al-P interactions (Table 4.13). The P concentration increase was significantly dictated by reduction of Al concentrations in the soil in the order: 0 % reduction of  $Al^{3+}$  = 30 % reduction of  $Al^{3+}$  < 70 % reduction of  $Al^{3+}$  ≤ 100 % reduction of  $Al^{3+}$  in extremely acidic soils and, 0 % reduction of  $Al^{3+}$  = 30 % reduction of  $Al^{3+}$  < 70 % reduction of  $Al^{3+}$  = 100 % reduction of  $Al^{3+}$  in strongly acidic soils.

**Table 4.13: Effects of lime-Al-P interactions on P concentration (%) in maize tissues 35 days after emergence.**

Lime to give	Phosphorus levels applied (g P kg <sup>-1</sup> )							
	Extremely acidic soils				Strongly acidic soils			
	0.00	0.15	0.3	0.59	0.00	0.13	0.26	0.51
0% reduction in $Al^{3+}$	0.17a	0.26a	0.29a	0.31a	0.16a	0.23a	0.28a	0.30a
30% reduction in $Al^{3+}$	0.20b	0.27a	0.30a	0.31a	0.19a	0.23a	0.30a	0.32a
70% reduction in $Al^{3+}$	0.30c	0.35b	0.45b	0.47b	0.37b	0.40b	0.45b	0.49b
100% reduction in $Al^{3+}$	0.37d	0.43c	0.51c	0.53c	0.34b	0.41b	0.47b	0.49b
% CV	3.50	3.50	3.50	3.50	2.90	2.90	2.90	2.90

Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

Lime-Al-P interactions significantly increased maize drymatter yields (Table 4.14).

It was observed that liming to achieve 100% reduction in  $\text{Al}^{3+}$  significantly ( $P \leq 0.05$ ) produced the highest drymatter yields for the extremely acidic soils.

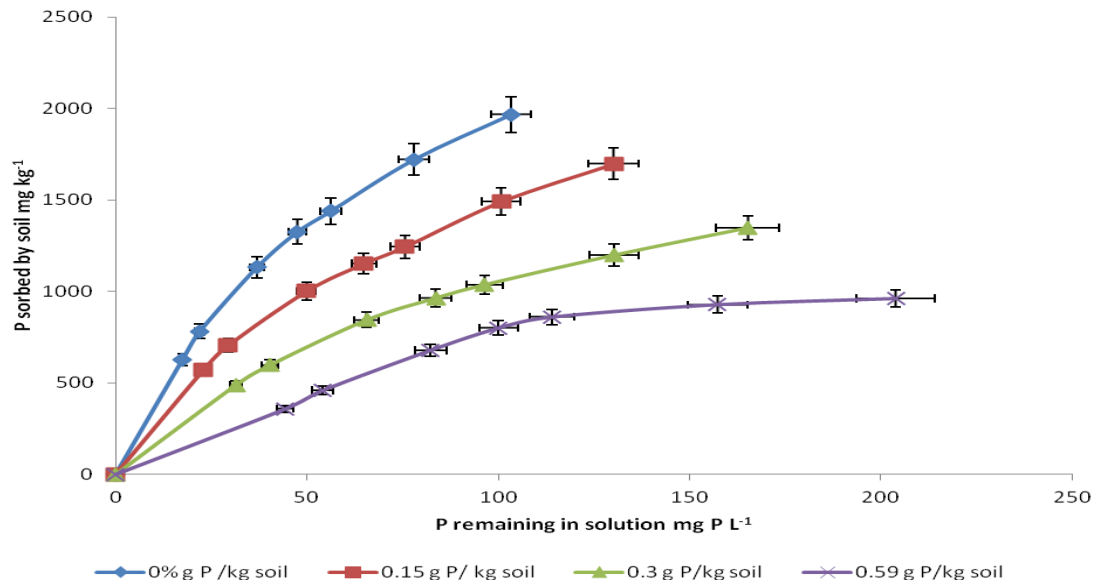
**Table 4.14: Effect of lime-Al-P interactions on maize dry matter (tonnes  $\text{ha}^{-1}$ ) 35 days after emergence**

Lime to give	Phosphorus levels applied (g P $\text{kg}^{-1}$ )							
	Extremely acidic soils				Strongly acidic soils			
	0	0.15	0.3	0.59	0	0.13	0.26	0.51
0% reduction in $\text{Al}^{3+}$	6.3a	29.7b	49.7c	39.4d	11.0a	23.0b	43.3c	32.2b
30% reduction in $\text{Al}^{3+}$	7.4a	31.2b	54.1c	49.8c	13.6a	29.1b	48.2c	40.5e
70% reduction in $\text{Al}^{3+}$	15.0b	32.6b	54.7c	54.4c	14.5a	33.4c	58.8d	42.3e
100% reduction in $\text{Al}^{3+}$	21.8c	39.1c	73.3d	59.0e	17.8a	41.1c	59.3d	44.1e
% CV	2.7	2.7	2.7	2.7	4.8	4.8	4.8	4.8

Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

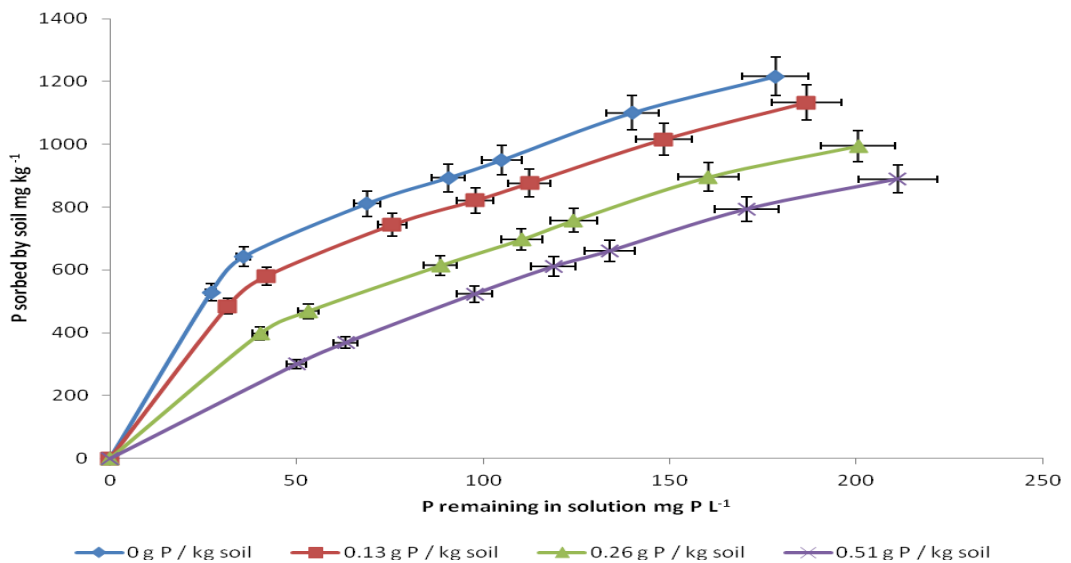
#### 4.3.4 The interactive effects of lime, Al and P on phosphorus adsorption by the two acid soils

The phosphate adsorption isotherms of soils in the nine study sites were determined by plotting the amounts of phosphate adsorbed (X) against the equilibrium concentrations of phosphate (C). Comparing the highest amount of P in extremely acidic soils; it is evident that soils treated with different levels of phosphorus had different capacities to adsorb P (Figure 4.7). The results of the study showed that maximal P adsorption decreased with increasing fertilizer P application. Soils supplied with 0 g P  $\text{kg}^{-1}$  had the highest values of maximum adsorption (1967 mg  $\text{kg}^{-1}$ ) while soils supplied with 0.59 g P  $\text{kg}^{-1}$  had the lowest maximal P adsorption (960 mg  $\text{kg}^{-1}$ ).



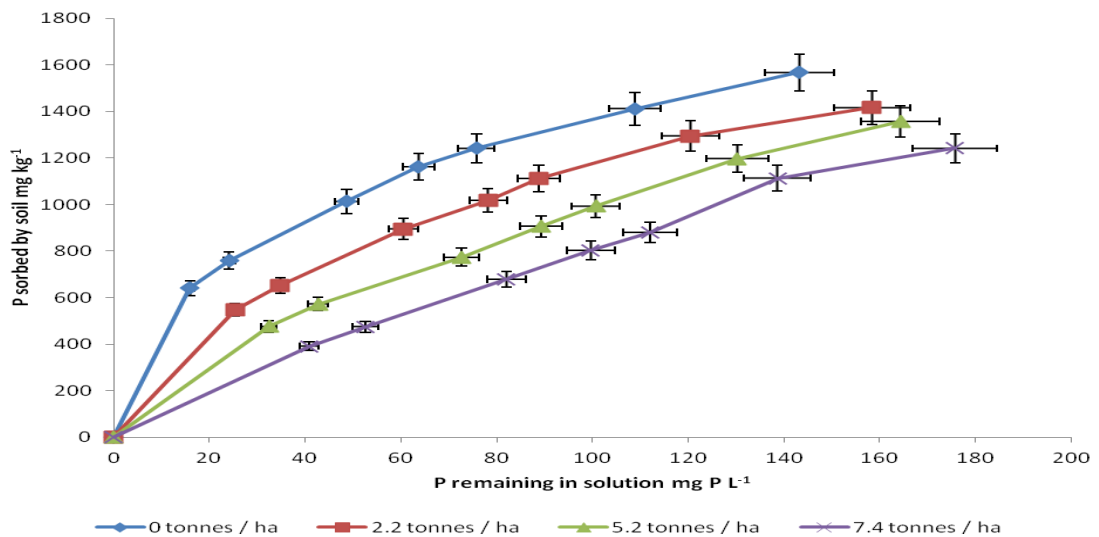
**Figure 4.7: Phosphate adsorption isotherm of extremely acidic soil treated with different phosphate fertilizer rates (Error bars inserted).**

Maximal P adsorption decreased with increasing fertilizer P application in strongly acidic soils (Figure 4.8). Soils supplied with 0 g P kg<sup>-1</sup> had the highest value of maximum adsorption (1216 mg kg<sup>-1</sup>) while soils supplied with 0.51 g P kg<sup>-1</sup> had the lowest maximal P adsorption (889 mg kg<sup>-1</sup>).

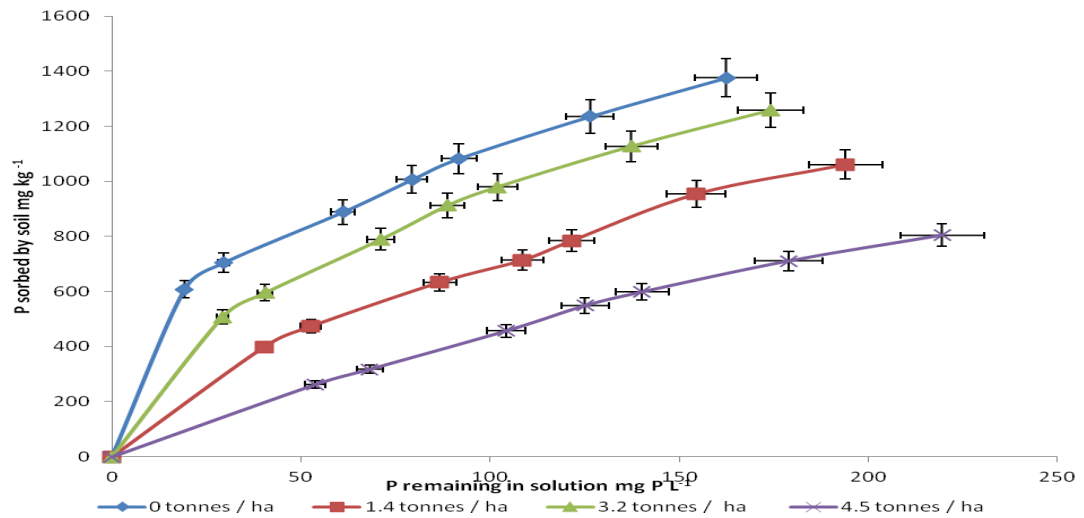


**Figure 4.8: Phosphate adsorption isotherm of the strongly acidic soil treated with different phosphate fertilizer rates (Error bars inserted).**

Lime application significantly influenced the capacity of soils to adsorb P (Figure 4.9). The results of the study showed that maximal P adsorption decreased with increasing liming rates. Soils which were not limed had the highest value of maximum adsorption ( $1\ 568\ \text{mg kg}^{-1}$ ) while soils supplied with  $7.4\ \text{tonnes ha}^{-1}$  lime had the lowest maximal P adsorption ( $1\ 242\ \text{mg kg}^{-1}$ ) in extremely acidic soils. Similarly, soils supplied with  $0\ \text{tonnes ha}^{-1}$  lime had the highest value of maximum adsorption ( $1\ 376\ \text{mg kg}^{-1}$ ) while soils supplied with  $7.4\ \text{tonnes ha}^{-1}$  lime had the lowest maximal P adsorption ( $804\ \text{mg kg}^{-1}$ ) in strongly acidic soils (Figure 4.10).



**Figure 4.9: Phosphate adsorption isotherm of extremely acidic soil treated with different rates of lime (Error bars inserted).**



**Figure 4.10: Phosphate adsorption isotherm of strongly acidic soil treated with different rates of lime (Error bars inserted).**

Phosphorus application significantly ( $P \leq 0.05$ ) reduced the standard phosphorus requirement (SPR) of extremely acid soils (Table 4.15). The rate  $0.59 \text{ g P kg}^{-1}$  reduced SPR by more than 40% as compared to  $0 \text{ g P kg}^{-1}$  while  $7.4 \text{ tonnes ha}^{-1}$  of lime significantly reduced SPR of the soils by >81% as compared to  $0 \text{ tons ha}^{-1}$ .

**Table 4.15: Effect of lime-Al-P interaction on standard phosphorus requirement (SPR) in extremely acidic soils of the Kenya Highlands**

Phosphorus ( $\text{g kg}^{-1}$ )	SPR	R <sup>2</sup>	Lime ( $\text{tonnes ha}^{-1}$ )	SPR	R <sup>2</sup>
0.00	308.71	0.93	0.00	409.63	0.84
0.15	256.41	0.94	2.20	279.25	0.90
0.30	220.87	0.92	5.20	162.13	0.96
0.59	184.08	0.85	7.40	75.34	0.98

Lime-Al-P interaction significantly ( $P \leq 0.05$ ) reduced SPR in strongly acidic soils (Table 4.16). The rate  $0.51 \text{ g P kg}^{-1}$  significantly reduced SPR by 73% while  $4.5 \text{ tonnes ha}^{-1}$  reduced SPR by 84% compared to the control.

Phosphorus significantly ( $P \leq 0.05$ ) reduced the standard phosphorus requirement (SPR) of strongly acid soils (Table 4.16). The rate  $0.51 \text{ g P kg}^{-1}$  led to > 73% reduction of SPR as compared to  $0 \text{ g P kg}^{-1}$  while  $4.5 \text{ tonnes ha}^{-1}$  of lime led to >84% reduction of SPR in the soils compared to  $0 \text{ tons ha}^{-1}$ .

**Table 4.16: Effect of lime-Al-P interaction on standard phosphorus requirement (SPR) in strongly acidic soils of the Kenya Highlands**

Phosphorus (g kg <sup>-1</sup> )	SPR	R <sup>2</sup>	Lime (tonnes ha <sup>-1</sup> )	SPR	R <sup>2</sup>
0.00	293.06	0.86	0.00	352.84	0.85
0.13	243.02	0.88	1.40	241.83	0.90
0.26	153.33	0.94	3.20	135.53	0.96
0.51	77.83	0.97	4.50	54.85	0.98

Significant ( $P \leq 0.05$ ) negative relationships were observed between standard phosphorus requirement (SPR) of tested acid soils, lime application, the Langmuir adsorption constants (bL) and the Langmuir constant related to binding energy (kL) (Table 4.17). Significant relationships were also observed between lime, bL and kL.

**Table 4.17: Relationship between standard phosphate requirement, lime application and Langmuir equation constants of the acid soils of the Kenya Highlands**

Pair	R	P- Value
SPR and lime application	-0.90	0.00
SPR and bL	-0.57	0.00
SPR and kL	-0.68	0.00
Lime and bL	0.54	0.00
Lime and kL	0.68	0.00

SPR-Standard lime requirement; bL- Langmuir equation adsorption maxima (mg P kg<sup>-1</sup>); kL- Langmuir equation constant related to binding energy; Significant at  $P < .001$  level.

## 4.4 DISCUSSION

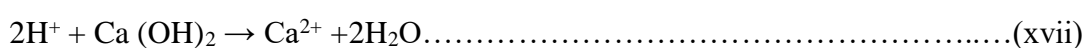
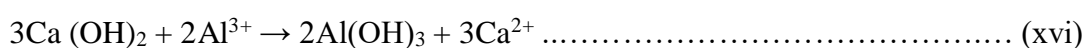
### 4.4.1 Soil chemical and physical characteristic of the soils

As per the rating suggested by Landon (1991), the soils had low levels of CEC (<15 cmol kg<sup>-1</sup>), Ca (< 4.0 cmol kg<sup>-1</sup>) and P (< 10 bicarbonate extractable P) and high levels of exchangeable aluminium (> 2.0 cmolkg<sup>-1</sup>) and Al saturation (> 20%) implying that they were of low fertility status. The high levels of Al and Al saturation are considered to be toxic to maize plants (Landon, 1991; Okalebo *et al.*, 2002). According to Kanyajua *et al.* (2002), the soils were strongly to extremely

acidic with pH of 4.48-4.58. Such acid soils with high  $\text{Al}^{3+}$  ions, low bases and CEC are characteristic of highly weathered soils, which have lost most of the basic cations through the process of leaching (Landon, 1991). As a result, their high levels of Fe and Al sesquioxides may lead to high P fixation, resulting in low available P (Landon, 1991; Buresh *et al.*, 1997; Sanchez *et al.*, 1997; Van Straaten, 2002). Additionally, the acidity could be attributed to the mineralogy of the parent materials (Van Straaten, 2002) because most of these soils are developed from non calcareous parent materials such as syenites, phololites, trachytes and nepholites which are acidic in nature (Sombroek *et al.*, 1982).

#### 4.4.2 The interactive effects of lime, Al and P on soil chemical properties

The significant increase of soil pH and available P with liming in the present study could be attributed to the presence of  $\text{Ca}^{2+}$  ions contained in the lime. The  $\text{Ca}^{2+}$  ions displaces  $\text{H}^+$  and  $\text{Al}^{3+}$  ions from the soil adsorption sites (Equation xvi & xvii) which are subsequently neutralized resulting in increased soil pH (Kamprath, 1984).



Therefore, the increase in soil available P can be attributed to reduction of P fixation by Al oxides due to their displacement by  $\text{Ca}^{2+}$  ions (Kamprath, 1984; Van Straaten, 2002). On the other hand, P added resulted in increased soil P and decreased soil pH in some treatments. The decreased soil pH could have been caused by release of  $\text{H}^+$  ions during P dissolution (Tisdale *et al.*, 1990). Similar findings on reduction of nutrient toxicities and corresponding increase in nutrient availabilities as a result of lime and P application have also been reported (Opala *et al.*, 2007; Kisinyo, 2011; Sarker *et al.*, 2014).

The significant reduction of exchangeable Al, aluminium saturation, exchangeable acidity, oxalate Al and dithionate Al upon liming could be attributed to reaction of the calcium oxide with carbon dioxide and water in the soil to yield Ca bicarbonate ( $\text{CaHCO}_3$ ). The resulting Ca bicarbonate reacts with exchangeable and residual soil acidity, hence replacing  $\text{H}^+$  and  $\text{Al}^{3+}$  on the colloidal complex (Brady and Weil, 2008; Lauchli and Bielecki, 2012) that is subsequently neutralized.

The negative correlation between extractable P and oxalate Fe and Al ( $\text{Fe}_o$  and  $\text{Al}_o$  respectively) could be attributed to the fact that Fe and Al oxyhydroxides act as sinks for soluble phosphates (Rayment and Lyons, 2011). According to Gasparatos *et al.* (2006) and Vaananen *et al.* (2008), iron enriched concretions are major sinks of P, which control P dynamics in agricultural soils by maintaining high sorption capacity. The positive correlation between maximum P sorbed with  $\text{Fe}_o$  and  $\text{Al}_o$  can be attributed to the ability of the oxalate extractable method to extract poorly crystalline oxyhydroxides of Fe and Al, which are directly associated with P sorption and not extracting the crystalline forms (Rayment and Lyons, 2011). Similar findings were reported by Janardhanan and Daroub (2010).

#### **4.4.3 The interactive effects of lime, Al and P on growth of maize**

The significant ( $P \leq 0.05$ ) positive relationship between P concentrations in plant tissues, biomass accumulation, and lime-Al-P interactions can be attributed to reduced acidity and consequent amelioration of Al toxicity in the acid soils. The Al toxicity is characterized by inhibition of uptake, translocation and utilization of phosphate by plants (Haynes, 1982). Once P is taken up by plants, it plays a great role in energy transfer processes including, photosynthesis which leads to biomass accumulation (Brady and Weil, 2008; Xie *et al.*, 2015). Such high positive relation

between shoot P and biomass have been reported among *sesbania* seedlings in Kenyan acid soils (Gudu *et al.*, 2009). Increase in crop yields, due to lime-P interaction has been reported by Fageria *et al.* (1995) and attributed the positive response to increased P uptake by plants.

#### **4.4.4 The interactive effects of lime, Al and P on soil phosphorus adsorption**

The continuous reduction of P adsorption levels and hence the SPR by the lime-Al-P interactions could be attributed to the combined effect of physical and chemical amelioration effects of lime on soil acidity and increased P concentration on the sorption sites, hence, reducing the number of active sorptive sites (Haynes, 1982, Indiat *et al.*, 1995; Zhang *et al.*, 2008). Physical amelioration might have occurred through dispersion and flocculation of colloid particles (Bolan *et al.*, 2003). Chemical amelioration of the acidity may have occurred through increased soil pH levels, which makes the surfaces of Al-hydroxy compounds increasingly negative. This increases electrostatic repulsion and decreases electrostatic potential, hence reduced P sorption and increased  $\text{HPO}_4^{2-}$  in soil solution (Haynes, 1982; Bolan *et al.*, 2003; Van Straaten, 2007). Soil pH changes are also associated with stimulation of mineralization of soil organic phosphorus (Haynes, 1982; The *et al.*, 2006).

#### **4.5 CONCLUSIONS**

Lime-Al-P interactions significantly increased soil pH, extractable P, exchangeable bases, P- uptake, and reduced P adsorption, SPR, Fe and Al levels. High rates of lime which resulted into 100% reduction of  $\text{Al}^{3+}$  were more effective as compared to lower rates in both extremely and strongly acidic soils. However, the effectiveness of combined application of 7.4 tonnes  $\text{ha}^{-1}$  lime + 0.59 g P  $\text{kg}^{-1}$  for extremely acidic soils and 4.5 tonnes  $\text{ha}^{-1}$  + 0.51 g P  $\text{kg}^{-1}$  for strongly acidic soils did not differ

significantly with combined application of 7.4 tonnes ha<sup>-1</sup> + 0.3 g P kg<sup>-1</sup>, and 4.5 tonnes ha<sup>-1</sup> + 0.26 g P kg soil<sup>-1</sup> respectively. This implies that either of the combined rates can effectively improve crop production in acid soils with similar properties. However, further research is required to evaluate the short and long term effects of the rates hence their interactions on crop yields, other plant nutrients and the environment under field conditions.

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## CHAPTER FIVE

### 5.0 INTERACTIVE EFFECT OF TILLAGE, PHOSPHORUS AND LIME IN ACID SOILS OF KIAMBU COUNTY, KENYA.

#### ABSTRACT

Soil acidity and phosphorus (P) deficiency are some of the major causes of low maize yields in Kenya. Sustainable food production therefore requires development of efficient fertilizer management strategies in these acid soils. Field experiments were carried out during the 2014 long rains and 2014/15 short rains at Waruhiu Farmers Training Centre, Githunguri, Kiambu County, to evaluate the effects of tillage-P-lime interactions in acid soils of Kiambu County. Tillage practices included: ploughing, strip tillage and use of the hand hoe while fertilizer and lime treatments included: DAP + lime (DAPL), TSP + lime (LP), TSP (P) alone and lime alone as burnt lime containing 21% of calcium oxide. The rates of P and lime were 52kg P ha<sup>-1</sup> and 3.2 tones ha<sup>-1</sup> respectively. The soil at the study site was strongly acidic (pH 4.7 - 4.8), had high exchangeable Al<sup>3+</sup> (> 2 cmol Al kg<sup>-1</sup>) and Al saturation (> 20% Al), which most maize germplasms grown in Kenya are sensitive to. The CEC (< 15 cmol kg<sup>-1</sup>) and available P (< 30 mg kg<sup>-1</sup> Mehlich double acid) rated as low. Tillage-P-lime interaction significantly ( $P \leq 0.05$ ) decreased soil acidity. Plough-P-lime interactions significantly ( $P \leq 0.05$ ) led to > 90% increase of soil pH, extractable P, Ca and CEC, and reduced Al concentrations as compared to the control. Similarly, plough-DAPL interactions significantly ( $P \leq 0.05$ ) increased CEC and available P for more than 90% compared to the control. The interaction did not, however, significantly affect exchangeable Mg levels. It can, therefore, be

concluded that integrating ploughing with either DAPL or LP can be effective in the management of soil acidity in the Kenya highlands. Further research is, however, advocated to ascertain the long term effects of the interaction on soil clay mineralogy and overall soil fertility.

**Key words:** *Acid soils, phosphorus, lime, tillage, maize*

## 5.1 INTRODUCTION

Acid soils occupy 13% of the Kenyan land area (Kanyajua *et al.*, 2002) and most of them are found in the highland east and west of the Rift Valley (Obura, 2008). The soil acidity may be attributed to the clay mineralogy, leaching of bases due to high rainfall, presence of Al, Fe and Si-oxides and oxyhydroxides, and continuous use of acid forming fertilizers (Sombroek *et al.*, 1982; Obura, 2008). Most of the acid soils in Kenya were developed from non-calcareous parent materials such as syenites, phololites, trachytes, olivines, older basic tuffs and nepholites which are acidic in nature (Sombroek *et al.*, 1982). The predominant clay minerals in the highlands of Kenya are kaolinite, gibbsite, goethite, Al and Fe oxides (Obura, 2008; Otinga, 2012), which are the products of extensive weathering of the parent materials.

According to Kisinyo *et al.* (2013), soils of the highlands east of the Rift Valley are strongly acidic ( $\text{pH} < 5$ ), have high exchangeable  $\text{Al}^{3+}$ , and high % Al saturations attributed to extensive weathering and leaching of the bases. The exchangeable  $\text{Al}^{3+}$  is usually  $> 2.0 \text{ cmol kg}^{-1}$  and Al saturation  $> 20 \%$ . This high level of exchangeable  $\text{Al}^{3+}$  is considered by Landon (1991) to be too high for many crops, and such Al saturation level cannot be tolerated by many maize germplasms grown in Kenya (Ligeyo, 2007). The P sorption capacities of the soils have been reported to be high

(343 to 402 mg kg<sup>-1</sup> soil) (Kisinyo *et al.*, 2013). This leads to low recovery of applied P, hence low availability of soil P (< 5 mg P kg<sup>-1</sup>) in most soils and hence low recovery of applied P.

The form in which the applied P accumulates in soils after regular fertilization depends on the amounts applied, amounts exported, soil type and soil management practices (Tiecher *et al.*, 2012). Practices like liming and tillage have been documented to play a significant role in soil P management. According to Robson and Taylor (1987), tillage practices alter nutrients via 3 processes: (i) mixing nutrients through the soil and altering their availability to crops (ii) changing the soil physical environment and (iii) modifying the soil biological activities. For example, long term zero tillage produced significantly higher concentrations of P in the surface soil (0-0.05 m), whereas P levels were decreased at the 0.05-0.15 m depth as compared to chisel ploughing (Andraski *et al.*, 2003). The accumulation of P in the surface soil under zero-tillage was attributed to the lack of physical disturbance that mixes fertilizer P thoroughly within the plough layer (Selles *et al.*, 1997) and the P immobility in soils. According to Redel *et al.* (2007) and Zamuner *et al.* (2008), the accumulated P gradually saturates the high P affinity in the acid soils' surface layer, decreasing the binding energy of P hence increasing its availability (Rheinheimer and Anghinon, 2001; Rheinheimer *et al.*, 2003).

Wortmann *et al.* (2003) observed that lime mobility in soils is about 1.27cm per year on fine textured soils, hence taking several years to reach considerable depths. This makes it difficult to ameliorate subsurface acidity through surface liming alone and makes a combination of deep tillage and incorporation of lime an important method for ameliorating subsurface soil acidity. Deep tillage has also been observed by

Bollard and Brennan (2006) to aid in mixing previously applied P fertilizer, hence improving the effectiveness of P fertilizer for subsequent crops.

Soil acidity management practices such as use of organic materials as an alternative to liming, liming and breeding for acid tolerant maize germplasms (Opala *et al.*, 2010a, 2010b and 2014; Kisinyo, 2011; Ouma *et al.*, 2013; Kisinyo *et al.*, 2014) have been widely evaluated in Western Kenya. However, despite the significant effects of tillage on soil physical, chemical and biological properties, the role of tillage methods in soil acidity management have received limited attention in Kenya. The study, therefore, aimed at evaluating (i) the effects of tillage methods on soil chemical properties and (ii) the interaction effects of tillage, lime and phosphorus applications in the management of soil acidity in the Kenya highlands.

## **5.2 MATERIALS AND METHODS**

### **5.2.1 Experimental design, layout and crop husbandry**

A field experiment was conducted at Waruhiu Agricultural Training Centre (ATC), Githunguri, Kiambu County, to evaluate the effects of integrating tillage practices, lime and P applications in soil acidity management. Treatments were laid out in a Randomized Complete Block Design with a split plot arrangement and replicated three times. The main plots consisted of tillage practices while subplots were fertilizer P and lime treatments. Tillage practices evaluated were: ploughing (15 cm), hand-hand hoe tillage (5-10 cm) and double-digging strip tillage (30 cm deep) using modified hand hoe 15 cm wide. Fertilizer and lime treatments were DAP + lime (DAPL), TSP + lime (LP), TSP alone (P) and lime alone (L). Controls consisted of plots without fertilizer and lime treatments. Plots of 3 m x 4.5 m were planted with certified maize seed, Nduma variety, at the spacing of 75 cm between rows and 30

cm within rows. The distance between blocks was 2 m while 1 m wide spaces separated the subplots. Each subplot consisted of six rows of maize plants with 11 plants in each row. The two outer rows acted as guard rows, while sampling was done in the four inner rows.

Lime at the rate of 3.2 tones  $\text{ha}^{-1}$  was applied three weeks before planting during land preparation and thoroughly mixed with soils in the lime treatment plots. The rate of 3.2 tones  $\text{ha}^{-1}$  lime was derived from the greenhouse findings in Chapter Four. Other fertilizer treatments were applied during planting, and a blanket amount of calcium ammonium nitrate (CAN) 100 kg N  $\text{ha}^{-1}$  was applied to all treatments except those with DAP application. Weeding was done using hand hoe but strip tillage plots were weeded by clearing using a panga. Top dressing was carried out when the crop was knee high using CAN at a rate of 100 kg N  $\text{ha}^{-1}$ . Triple superphosphate (TSP) fertilizer was used as P source. All P applications were done at a rate of 52 kg P  $\text{ha}^{-1}$ . Data collected included, soil pH, extractable P, CEC, Ca, Mg and exchangeable Al.

### **5.2.2 Soil Characterization**

Soil physicochemical properties and lime requirement of the soils in the research plots were evaluated before planting and after harvesting. Subsoil samples were taken with a soil auger from the topsoil (0-30 cm) based on procedures described by Carter and Gregorich (2007). The composite samples were then packed in polythene bags, properly labeled and taken to the laboratory for both physio-chemical analyses. Laboratory analyses were carried out as described in 4.2.2 and soil characterization data in Table 5.1 were used for lime requirement determinations.

### **5.2.3 Data analysis**

For each variable determined, data were subjected to Analysis of Variance (ANOVA) using the PROC ANOVA procedure of GenStat (Lawes Agricultural Trust Rothamsted Experimental station 2011, version 14.2) (Genstat, 2010). Means were ranked using the Duncan's New Multiple Range Test.

## **5.3 RESULTS**

### **5.3.1 Initial soil chemical and physical characteristics**

Some of the chemical and physical properties of the soil used in the study are presented in Table 5.1. The soil was strongly acidic, with low pH values (4.5-5.0). The exchangeable aluminium and % aluminium saturation were high ( $> 2 \text{ cmol kg}^{-1}$  soil and  $> 20\%$  Al, respectively). The standard phosphate requirements (SPR) of the soils were also high ( $> 150 \text{ mg kg}^{-1}$  soil) while the available P and CEC were low ( $< 30 \text{ mg kg}^{-1}$  Mehlich P and  $< 15 \text{ cmol kg}^{-1}$  soil, respectively).

### **5.3.2 Effects of tillage-P-lime interactions on chemical properties of acid soils**

Tillage-P-lime interaction significantly ( $P \leq 0.05$ ) increased the pH values of the acid soils (Table 5.2). Plough-LP interaction was observed to significantly ( $P \leq 0.05$ ) increase soil pH increase during both the long and short rains compared to other treatments. The mean soil pH increase due to plough-LP interaction was  $> 38\%$  compared to the control.

**Table 5.1: Some baseline physical and chemical properties of the soil at the study site**

	Long rains	Short rains
pH (1:2.5 soil:water suspensions)	4.7	4.8
Exch. Al (cmol kg <sup>-1</sup> )	2.5	2.6
Total N (%)	0.3	0.3
OC (%)	2.5	2.4
Extractable P (mg kg <sup>-1</sup> )	20.0	11.0
Exchangable K (cmol kg <sup>-1</sup> )	0.8	0.8
Exchangable Ca (cmol kg <sup>-1</sup> )	3.5	2.1
Exchangable mg (cmol kg <sup>-1</sup> )	3.2	3.2
Exchangable Na (cmol kg <sup>-1</sup> )	0.2	0.2
CEC	11.9	12.4
AL Saturation (%)	35.1	37.7
SPR mg kg <sup>-1</sup> soil	257.0	260.0
PSD*		
% Clay	9	12
% Silt	31	31
% Sand	60	57
Textural Class	Sandy loam	Sandy loam

\*Particle size distribution; SPR \*\* Standard phosphate requirement defined as the amount of P required to raise equilibrium solution P level to 0.2 mg P L<sup>-1</sup>.

**Table 5.2: Effect of tillage-P-lime interaction on pH of acid soils of Kiambu**

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	4.55a	3.83a	4.76a	4.70a	4.30a	5.64a
DAPL	5.39b	4.29b	5.96b	5.19b	4.64b	6.77b
L	5.87c	4.83c	6.36b	5.42c	5.23c	7.25c
LP	5.73c	4.74c	6.74c	5.34bc	4.91c	7.81d
P	4.87a	4.49b	5.29d	4.96d	4.59b	6.28e
% CV	4.60	4.60	4.60	1.00	1.00	1.00

April- August 2014 long rains and October 2014-February 2015 short rains. DAPL - DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

Extractable P was significantly ( $P \leq 0.05$ ) increased by tillage-P-lime interactions (Table 5.3). Plough-DAPL interaction was observed to have the highest extractable P levels during the long rains while the P levels from plough-DAPL and plough-LP interactions were not significantly different during the short rains.

**Table 5.3: Effect of tillage-P-lime interaction on extractable P (mg kg<sup>-1</sup>) in acid soils of Kiambu**

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	12.80a	12.70a	10.40a	15.00a	9.30a	18.80a
DAPL	46.60b	28.40b	55.60b	44.70b	29.20b	72.80b
L	18.30a	9.30a	17.50a	19.10a	11.40a	22.80a
LP	43.40b	38.10c	37.40c	41.70b	36.00b	74.20b
P	27.00ac	28.40b	28.60ac	27.00c	16.60a	30.80c
% CV	3.90	3.90	3.90	2.90	2.90	2.90

April- August 2014 long rains and October 2014-February 2015 short rains. DAPL - DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

Cation exchange capacity (CEC) was significantly increased by tillage-P-lime interactions (Table 5.4). Although the plough-LP and plough-DAPL interactions gave the highest CEC values compared to the other treatments during both the long and short rains, CEC values from both plough-DAPL and plough-LP were not significantly ( $P \leq 0.05$ ) different. The CEC of control-handhoe and control-strip tillage interactions during the long rains were observed to be lower than the initial soil CEC of 11.9 cmols kg<sup>-1</sup> as presented in Table 5.1.

**Table 5.4: Effect of tillage-P-lime interaction on cation exchange capacity (CEC) (cmol kg<sup>-1</sup>) in acid soils of Kiambu**

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	8.04a	9.75a	16.96a	12.11a	12.59a	12.58a
DAPL	16.57b	12.79c	33.31b	13.58a	15.53b	35.42b
L	12.53c	12.50c	25.97c	10.54a	10.36a	17.42a
LP	15.37b	17.80b	35.85b	15.38ab	15.41b	39.02b
P	13.97c	17.13b	29.77d	11.98a	13.18ab	20.99a
% CV	4.60	4.60	4.60	8.90	8.90	8.90

April- August 2014 long rains and October 2014-February 2015 short rains. DAPL - DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

Exchangeable Ca values varied among treatments and seasons (Table 5.5). During the long rains, strip tillage-LP interaction significantly ( $P \leq 0.05$ ) gave the highest exchangeable Ca levels while plough-LP interaction gave the highest Ca levels during the short rains.

Magnesium levels varied greatly among treatments and seasons (Table 5.6). Plough-LP interaction significantly ( $P \leq 0.05$ ) promoted the highest magnesium levels during both long and short rains.

Exchangeable Al in the soils continuously decreased with tillage-P-lime interactions (Table 5.7). Plough-LP interaction significant ( $P \leq 0.05$ ) reduced exchangeable aluminium resulting to the lowest Al levels during both the long and short rains.

**Table 5.5: Effect of tillage-P-lime interaction on exchangeable Ca ( $\text{cmol kg}^{-1}$ ) in acid soils of Kiambu**

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	2.86a	2.91a	2.34a	2.00a	2.07a	2.67a
DAPL	4.45b	4.69b	4.19b	3.65b	3.22a	4.64b
L	4.15b	4.47b	3.53b	3.35ab	2.93a	3.55a
LP	5.04c	5.36c	4.86c	4.32c	4.11c	5.47c
P	5.12c	4.86b	3.84b	4.24c	3.49c	4.20b
% CV	1.30	1.30	1.30	2.70	2.70	2.70

April- August 2014 long rains and October 2014-February 2015 short rains. DAPL - DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

**Table 5.6: Effect of tillage-P-lime interaction on exchangeable magnesium (cmol kg<sup>-1</sup>) in acid soils of Kiambu**

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	0.45a	0.58a	0.57a	0.46a	0.49a	0.45a
DAPL	0.74b	0.87b	0.83b	0.74b	0.81b	0.91b
L	0.76b	0.87b	0.86b	0.76b	0.89b	0.85b
LP	0.91c	0.86b	1.04c	0.98c	0.91b	1.17c
P	0.83bc	0.90b	0.70d	0.83b	0.90b	0.77bd
% CV	7.60	7.60	7.60	7.00	7.00	7.00

April- August 2014 long rains and October 2014-February 2015 short rains. DAPL - DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

**Table 5.7: Effect of tillage-P-lime interaction on exchangeable Al (cmol kg<sup>-1</sup>) in acid soil of Kiambu**

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	2.98a	3.32a	2.08a	3.32a	2.14a	2.04a
DAPL	1.68b	2.44b	1.33b	1.56b	1.71b	1.45b
L	1.46b	1.69bc	1.29b	1.34bc	0.98c	0.86c
LP	0.46c	1.01d	0.39c	0.97c	0.57d	0.30d
P	1.37d	2.02b	1.18a	2.64d	1.96a	1.98a
% CV	3.90	3.90	3.90	3.80	3.80	3.80

April- August 2014 long rains and October 2014-February 2015 short rains. DAPL - DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$

## 5.4 DISCUSSION

The high levels of exchangeable Al ( $> 2.0$  cmol Al kg<sup>-1</sup>) and Al saturation ( $> 20\%$ ) observed in the present studies are classified by Ligeyo (2007) as unsuitable for most maize germplasms grown by farmers in Kenya. Based on the rating set by Landon (1991) and Mehlich (1962), the available phosphorus in the plough layer of the soils was low and inadequate for supporting optimum crop yields. Additionally, the soil CEC values ( $< 15$  cmol kg<sup>-1</sup>) and exchangeable Ca<sup>2+</sup> ( $< 4.0$  cmol kg<sup>-1</sup>) were limiting (Landon, 1991), implying that the ability of the soil to avail most plant nutrients from the exchange complex for plant uptake was low.

The significant increase of soil pH, CEC and Ca upon ploughing, liming and application of P fertilizers could be attributed to the thorough mixing of soils with lime and P fertilizers through the ploughing process. This might have resulted in the manipulation of the physical, chemical and biological processes in the soils (Quan *et al.*, 2005) leading to displacement of  $\text{Al}^{3+}$ ,  $\text{H}^+$ , and  $\text{Fe}^{3+}$  ions by  $\text{Ca}^{2+}$  ions from the lime (CaO) and TSP fertilizer. When liming material (CaO) is added to the acid soils, it reacts with carbon dioxide and water to yield Ca bicarbonate which reacts with the exchangeable and residual acidity with consequent replacement of the  $\text{H}^+$  and  $\text{Al}^{3+}$  on the colloidal complex by  $\text{Ca}^{2+}$  (Brady and Weil, 2008). The adsorption of the calcium ions lowers the percentage acid saturation of the colloidal complex and the pH of the soil solution increases hence increased adsorption of bases on the exchange complex (Nelson and Su, 2010; Martins *et al.*, 2014). Similar results have been reported by Kamprath (1984); The *et al.* (2006); Fageria *et al.* (2007); Auxtero *et al.* (2012).

The lower pH values in soils treated with DAPL as compared to LP could be attributed to the  $\text{H}^+$  produced during biological oxidation of ammonium (nitrification) into nitrates for plant uptake. Similar observations and trends were reported by Manoharan *et al.* (1995) and Mwangi *et al.* (2002). Mwangi *et al.* (2002) observed that the topsoil pH of soils supplied with 23:23:0/CAN or DAP / CAN gradually decreased over the years while the pH of soils where TSP/CAN were applied remained constant. Similarly, Manoharan *et al.* (1995), working on pastures in New Zealand, observed that soil acidification was more pronounced in DAP treated plots, and this led to significantly low soil pH, exchangeable Ca, and Ca saturation, and increased soluble Al and exchangeable acidity.

Increased soil extractable P on Plough-DAPL and Plough-LP interactions as compared to other interactions can be attributed to stimulation of soil organic P mineralization by tillage and lime (Haynes, 1982). Ploughing the soils might have disrupted soil aggregates resulting in concomitant organic matter oxidation; increased aeration and porosity hence increased the microbial activities and net mineralization of P from soil organic P (Buresh *et al.*, 1997; The *et al.*, 2006; Selles *et al.*, 1997). Comparing effects of P alone and lime alone, the significant increase of soil available P after application of P alone as compared to lime alone could be attributed to the provision of starter P to the soils which have very low soil solution P. Antoniadis *et al.* (2015) reported similar findings in a greenhouse experiment and concluded that P alone was more beneficial than lime alone when soils had low initial P levels while lime alone was beneficial when the soils had moderate initial P levels.

The significant increase of soil pH, extractable P, Ca, CEC, and reduction of exchangeable Al by plough tillage compared to other tillage methods can be attributed to enhanced rate of soil reactions due to improved soil porosity resulting from deep turning and mixing of the soil, lime and P fertilizer (Bollard and Brennan, 2006). Similar findings have been reported by Guan *et al.* (2014) and Zhang *et al.* (2013).

## **5.5 CONCLUSIONS**

Tillage-P-lime interactions significantly increased soil pH, extractable P, exchangeable Ca, CEC, and reduced exchangeable Al. Plough-LP interactions were observed to significantly increase soil pH, P, CEC, Ca and Mg, and reduced

exchangeable Al while plough-DAPL interactions were observed to significantly increase extractable P, and CEC. Strip-LP interaction on the other hand, increased exchangeable Ca in the soils. It can, therefore, be concluded that integrating ploughing with either LP or DAPL can be effective in the management of soil acidity in Kiambu County. Further studies are, however, required to ascertain the long term effects of tillage-P-lime interactions in the management of soil acidity in acid soils of Kiambu as part of the Kenya highlands.

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## CHAPTER SIX

### 6.0 THE INTERACTIVE EFFECTS OF TILLAGE, PHOSPHORUS AND LIME ON GROWTH AND PHOSPHORUS UPTAKE BY MAIZE

#### ABSTRACT

Low soil fertility is a major constraint to maize production in the Kenya highlands. Careful soil management is therefore key to sustainable maize production. Field experiments were carried out during the 2014 long rains and 2014/15 short rains at Waruhiu farmers training centre, Githunguri-Kiambu County. The objective was to evaluate the effect of integrating tillage, P and lime on P uptake and maize yields. Tillage practices included; ploughing, strip tillage and use of hand hoe while fertilizer and lime treatments included, DAPL, LP, P alone and lime alone. Burnt lime containing 21% of calcium oxide was used. Maize growth was monitored by measuring plant height and recording number of leaves while nutrient uptake and yield was evaluated by plant tissues analysis at 30 days after emergence and full tasseling, and drymatter and grain yield. Integrating plough, DAPL and LP significantly increased maize height, P- uptake, dry matter yield and grain yield. There was no significance difference between grain yield from DAPL and LP. Plough increased grain yield by > 50% compared to strip and hand hoe. It can therefore be concluded that integration of tillage, lime and either DAPL or LP is effective in improving grain yield in acid soils. Further research is however needed to quantify the long term effects of the integration on maize production in acid soils.

**Key words:** Adsorption, acid soils, phosphorus, lime, tillage, P-uptake.

## 6.1 INTRODUCTION

Declining soil fertility due to soil degradation through intensive cultivation and nutrient removal via crop harvests is a major problem faced by smallholder farmers in the Kenya highlands (Sanchez and Jama, 2002). Use of commercial fertilizers to address the declining soil fertility remains minimal due to farmer's low income which limits their fertilizer purchasing power (Makokha *et al.*, 2001). Several researchers have recommended integrated soil fertility management (ISFM) options for increasing soil fertility and agronomic efficiency of applied inputs (Sanginga and Woomer, 2009; Vanlauwe *et al.*, 2010). The ISFM practices comprise the use of two or more resources in an integrated and compatible manner to maximize their use efficiency and crop productivity. The viable combinations involve inorganic and organic inputs, utilization of improved germplasm, cultural and mechanical soil fertility management practices (Sanginga and Woomer, 2009; Vanlauwe *et al.*, 2010; Fairhurst, 2012).

The predominant soils in the highlands east of the rift valley are "humic nitisols" that have moderate to high acidity with inherently high P fixing ability (Kanyanjua *et al.*, 2002). The acidity prevalence is associated with nitrogen (N) and phosphorus (P) deficiencies in the soils, and aluminium (Al) toxicity, low extractable bases (Ca, Mg, K and Na) and reduced microbial activities resulting in low crop yields (Crawford *et al.*, 2008). Use of lime raises soil pH by displacement of H<sup>+</sup> ions from soil adsorption site and reduces the hydrolysis of Al<sup>3+</sup> (Onwonga *et al.*, 2010). Lime also supplies significant amounts of Ca and Mg, depending on the type used. Indirect effects of lime include increased availability of P, Mo, and B, and more favorable conditions for microbial-mediated reactions such as nitrogen fixation and nitrification and in some cases improved soil structure (Crawford *et al.*, 2008). Despite its role in soil

acidity amelioration, lime is rarely used by most farmers in the Kenya highlands because of its relatively high cost and high recommended application rates (Kisinyo *et al.*, 2014). Alternative application strategies or complementary strategies which can enhance soil acidity amelioration hence increased crop yields are, therefore, needed.

Tillage practices affect soil properties, crop growth and nutrient uptake under various agro-ecological conditions (Spedding *et al.*, 2004). Among the crop production factors, tillage contributes up to 20% (Khurshid *et al.*, 2006) and affects the sustainable use of soil resources through its influence on soil properties and uptake of nutrients (Iqbal *et al.*, 2005; Lal and Stewards, 2013). The uptake of water and nutrients is largely dependent on the root systems of crops (Spedding *et al.*, 2004). Cultivation affects the rooting conditions of the crops grown hence affecting crop growth and nutrient uptake (Lipiec and Stepniewski, 1995). Tillage methods differ in their role of promotion of favourable environment for nutrient uptake. Conventional tillage practices change soil structure by modifying soil bulk density and soil moisture content, but repeated disturbance leads to finer and loose soil structure (Iqbal *et al.*, 2005; Rashidi and Kashavarzpour, 2007), leading to enhanced soil degradation and poor crop productivity. On the other hand, conservation and no-tillage or strip tillage methods leave the soil intact and improve soil quality indicators with time, hence improved crop yields (Iqbal *et al.*, 2005; Plaza *et al.*, 2013). Limited research has, however, been carried out on the effects of tillage practices in acid soils of the Kenya highlands.

Adoption of ISFM practice has been reported to be a viable solution to restore and maintain soil fertility. Therefore, this study aimed at (i) evaluating the effects of

types of tillage on maize growth and yields and (ii) determining the effects of tillage-P-lime interaction on maize growth, P uptake and yields in acid soils of the Kenya highlands.

## **6.2 MATERIALS AND METHODS**

### **6.2.1 Experimental design, layout and crop husbandry**

Experimental layout, design and crop husbandry were as described in chapter 5, section 5.2.1.

### **6.2.2 Effect of tillage-P-lime interaction on maize growth**

Plant growth was evaluated by measuring plant height, Internode interval, number of leaves, percent silking and % tasseling. Plant heights and Internode intervals were determined by measuring the heights of five maize plants in each plot. Measurements were done weekly from the 2<sup>nd</sup> to the 10<sup>th</sup> week after crop emergence. Number of leaves per plant was also evaluated on the same plants. Percent tasseling and silking was evaluated by counting the number of maize plants in the middle four rows which had tasseled and silked and expressed as a percent of total plant population.

### **6.2.3 Effect of tillage-P-lime interactions on P-uptake and maize yields**

Phosphorus uptake was evaluated by determining the concentrations of P in the plant tissues. Whole plant samples were harvested 30 days after crop emergence, and the blade opposite and below the cob at tasseling stage following the sampling procedures described by Reuter and Robinson (1997). Phosphorus concentration in plant tissues was then analysed at the University of Nairobi Soil Science Laboratory as described by Okalebo *et al.* (2002).

Maize yields were evaluated by determining dry matter and grain yields per plot per treatment at harvesting. The dry matter and grain yields were then expressed as tonnes ha<sup>-1</sup>.

#### 6.2.4 Data analysis

Statistical analysis of data was carried out as in chapter 5, section 5.2.3.

### 6.3 RESULTS

#### 6.3.1 Effects of tillage-P-lime interaction on maize growth

Maize height was increased by tillage-P-lime integrations (Table 6.1). Average maize height varied from treatment to treatment, with plough-DAPL and plough-LP interaction significantly providing the tallest plants.

**Table 6.1: Effect of tillage-P-lime interactions on height (cm) of maize grown in acid soils of Kiambu.**

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	50.45a	61.64a	81.57a	36.05a	41.90a	48.77a
DAPL	93.38b	93.78b	114.43b	66.79b	62.52b	83.13b
L	58.19c	68.98c	85.63a	43.36c	42.23a	57.19c
LP	89.13b	95.02b	108.07b	62.98b	62.56b	79.28b
P	67.46e	86.79d	99.41c	56.20d	51.10c	63.01c
% CV	6.20	6.20	6.20	7.60	7.60	7.60

Number of leaves averaged over 9 sampling periods in the April- August 2014 long rains and October 2014-February 2015 short rains. DAPL-DAP+lime, L-lime alone, LP-lime + TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

Leaf development was significantly increased by tillage-P-lime interactions (Table 6.2). Plough-DAPL and plough-LP interaction promoted the greatest leaf development compared to other treatments. There was however no significant difference between LP and DAPL.

**Table 6.2: Effect of tillage-P-lime interactions on number of maize leaves in acid soils of Kiambu.**

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	7.53a	6.93a	8.17a	6.90a	7.09a	7.47a
DAPL	9.90b	9.19b	9.52b	8.58b	8.36b	8.94b
L	8.14a	7.89c	8.83c	7.14a	7.15a	7.66a
LP	9.88b	9.02b	9.54b	8.48b	8.34b	8.63b
P	8.58a	8.74e	8.85c	8.23b	7.73c	7.76a
% CV	0.80	0.80	0.80	3.60	3.60	3.60

April- August 2014 long rains and October 2014-February 2015 short rains. DAPL - DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

Internode interval varied significantly from treatment to treatment (Table 6.3). Hand hoe-DAPL and hand hoe-PL interaction promoted the highest internode interval as compared to the other treatments. Internode intervals of both DAPL and PL were, however, not significantly ( $P \leq 0.05$ ) different during both the long and short rains.

**Table 6.3: Effect of tillage-P-lime interactions on internode interval of maize plants grown in acid soils of Kiambu.**

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	8.37a	8.91a	9.61a	9.74a	7.14a	9.36a
DAPL	14.50b	13.83b	12.47b	14.77b	13.09b	12.91b
L	10.65c	11.49c	11.02c	12.02c	9.68c	10.32c
LP	14.48b	12.45b	13.59b	14.47b	12.95b	13.11b
P	10.58c	11.76c	11.16c	12.58c	9.94c	10.63c
% CV	4.50	4.50	4.50	3.10	3.10	3.10

April- August 2014 long rains and October 2014-February 2015 short rains. DAPL - DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

Silking was significantly increased by lime-P-interaction (Table 6.4). Plough-DAPL and plough-LP interactions promoted the highest % silking during both long and short rains. The effect of DAPL and LP on silking was however not significantly different.

**Table 6.4: Effects of tillage-P-lime interactions on percent silking of maize planted in acid soils of Kiambu.**

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	66.92a	71.18a	64.18a	8.30a	13.00a	12.00a
DAPL	82.67b	84.33b	85.33b	32.90b	47.20b	51.40b
L	77.67c	79.00c	78.00c	13.00a	25.50a	16.70a
LP	79.33b	85.33b	86.33b	40.70b	45.40b	50.50b
P	78.33b	83.00b	77.00c	20.40a	34.70ab	16.70a
% CV	2.00	2.00	2.00	7.60	7.60	7.60

April- August 2014 long rains and October 2014-February 2015 short rains. DAPL - DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

Lime-P-tillage interactions significantly influenced % tasseling of maize (Table 6.5). Although % tasseling did not differ significantly among treatments during the long rains, plough-DAPL and plough-LP interaction promoted the highest % tasseling during the short rains. The effect of tillage on % tasseling was insignificant.

**Table 6.5: Effects of tillage-P-lime interactions on percent (%) tasseling of maize grown in acid soils of Kiambu.**

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	74.97a	69.47a	69.93a	30.60a	32.40a	33.80a
DAPL	75.00a	76.00b	80.33b	49.50b	56.00b	83.10b
L	75.00a	75.33b	77.33ab	35.20a	39.80a	52.30c
LP	76.00a	79.00b	81.33b	47.70b	54.60b	84.30b
P	75.00a	77.33b	74.00c	43.50b	45.40b	44.00c
% CV	0.80	0.80	0.80	6.60	6.60	6.60

April- August 2014 long rains and October 2014-February 2015 short rains. DAPL - DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

### 6.3.2 Effects of tillage-P-lime interaction on maize plant P-uptake.

It was observed that tillage-P-lime interaction significantly influenced phosphorus content in plant tissues (Table 6.6). Although tillage-P-lime interaction did not

significantly ( $P \leq 0.05$ ) influence P-uptake in maize during the long rains, ploughing-DAPL and ploughing-LP interactions significantly ( $P \leq 0.05$ ) increased P concentrations in the plant tissues during the short rains.

Phosphorus concentrations in maize plant tissues at tasseling stage varied from one tillage-P-lime interaction to another (Table 6.7). Although tillage-P-lime interaction did not significantly ( $P \leq 0.05$ ) influence P-uptake in maize during the long rains, plough-DAPL and plough-LP interactions significantly ( $P \leq 0.05$ ) increased P concentrations in the plant tissues during the short rains.

**Table 6.6: Effects of tillage-P-lime interactions on P- uptake ( $\text{mg kg}^{-1}$ ) by maize grown in acid soils of Kiambu 30 days after emergence.**

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	0.21a	0.19a	0.19a	0.26a	0.21a	0.32a
DAPL	0.40b	0.40b	0.49b	0.41b	0.44b	0.59b
L	0.29c	0.27c	0.28c	0.29a	0.27a	0.33a
LP	0.37b	0.45b	0.45b	0.38b	0.45b	0.51b
P	0.34b	0.42b	0.37d	0.34b	0.43b	0.44c
% CV	6.40	6.40	6.40	5.70	5.70	5.70

April- August 2014 long rains and October 2014-February 2015 short rains. DAPL - DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

**Table 6.7: Effects of tillage-P-lime interactions on P-uptake at tasseling stage of maize grown in acid soils of Kiambu.**

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	0.12a	0.12a	0.12a	0.13a	0.15a	0.18a
DAPL	0.25b	0.24b	0.30b	0.26b	0.26bc	0.38b
L	0.16ac	0.18a	0.17a	0.15a	0.18a	0.20a
LP	0.28b	0.27b	0.30b	0.27b	0.29b	0.32b
P	0.20c	0.24b	0.25c	0.20c	0.24c	0.27c
% CV	3.80	3.80	3.80	3.40	3.40	3.40

April- August 2014 long rains and October 2014-February 2015 short rains. DAPL - DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

### 6.3.3 Effects of tillage-P-lime interaction on maize yields.

Tillage-P-lime interactions significantly increased maize drymatter yield (Table 6.8). Although tillage-P-lime interaction effects on drymatter yield were insignificant ( $P \leq 0.05$ ) during the long rains, plough-DAPL and plough-LP interactions significantly ( $P \leq 0.05$ ) increased dry matter yield during the short rains.

**Table 6.8: Effects of tillage-P-lime interactions on dry matter yields (tonnes ha<sup>-1</sup>) of maize grown in acid soils of Kiambu.**

Fertilizer / Tillage	Long rains			Short rains		
	Hand hoe	Strip	Plough	Hand hoe	Strip	Plough
Control	6.36a	10.81a	11.51a	7.68a	6.96a	12.63a
DAPL	16.06b	22.96b	30.97b	19.09b	14.37bc	37.48b
L	10.17c	15.40c	15.86a	9.29a	9.88ac	10.94a
LP	14.35b	22.85b	34.01b	17.37b	19.53b	38.42b
P	13.70b	22.45b	23.41c	7.47a	13.92c	14.87a
% CV	4.10	4.10	4.10	3.50	3.50	3.50

April- August 2014 long rains and October 2014-February 2015 short rains. DAPL - DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

Grain yield was significantly ( $P \leq 0.01$ ) increased by tillage-P-lime interactions (Table 6.9). The yield increase was in the order control < P < L < LP=DAPL in all fertilizer treatments. Ploughing-DAPL and ploughing- LP interaction was observed to have the greatest maize grain yield compared to other interactions. However maize yields from ploughing-DAPL and ploughing-LP interactions were not significantly differently.

**Table 6.9: Effects of tillage-P-lime interactions on grain yield (tonnes ha<sup>-1</sup>) of maize grown in acid soils of Kiambu.**

Fertilizer / Tillage	Hand hoe	Strip	Plough
Control	2.75a	2.76a	3.34a
DAPL	5.93b	6.66b	8.56b
L	4.30c	3.74c	4.59c
LP	6.01b	6.86b	8.59b
P	5.13d	5.82d	5.49d
% CV	3.50	3.50	3.50

April- August 2014 long rains and October 2014-February 2015 short rains. DAPL - DAP+lime, L-lime alone, LP-lime+TSP, P-TSP alone. Values followed by the same letter(s) on the same column are not significantly different at  $P \leq 0.05$ .

#### 6.4 DISCUSSION

The phosphorus concentrations (%) in plant tissues 30 days after emergence varied from 0.2% - 0.4%. According to Okalebo *et al.* (2002), P concentrations between 0.4% - 0.8% are adequate for maize plant growth. Tillage-DAPL and tillage-LP interaction, therefore, resulted in increased P availability and uptake by plants. Similarly, since percent concentrations of P in the blades opposite and below the cob at full tassel are critical at 0.25% (Okalebo *et al.*, 2002), DAPL and LP resulted in adequate uptake and maintenance of P in plant tissues at tasseling stage. The increased P concentrations in plant samples can be attributed either to combined effects of tillage-P-lime interaction or individual effect of either tillage, lime or P. Liming can influence P uptake by its effect of raising soil pH and Ca levels, which further decreases adsorption and precipitation reactions and increased P desorption in the soil (Barrow, 1984), leading to increased P in the soil solution. Addition of P, on the other hand, increases concentration of P in the soil solution of acid soils (Bukvic *et al.*, 2003) by saturating the high P affinity sites in the soil and decreasing the binding effect of P hence increasing the availability of P for plant uptake (Rheinheimer and Anghinon, 2001, Rheinheimer *et al.*, 2003).

Ploughing significantly increased P concentrations in maize plant tissues compared to strip and hand hoeing. Similar results have been reported by Vogeler *et al.* (2009), Agbede (2010) and Guan *et al.* (2014). When working on maize crop for two years, Guan *et al.* (2014) found that the delivery rate of P in cell sap was significantly higher under ploughing than the no till at different plant developmental stages. He then attributed the increased P concentration in cell sap to root biomass in ploughed plots compared to no till. The P concentration in cell sap can also be attributed to improved soil moisture retention hence increased plant available water due to deep ploughing. Similar results of increased soil moisture retention and plant available P have been reported in Bangladesh soils by Alam *et al.* (2014).

The significantly taller plants after plough-LP and plough-DAPL interactions compared to hand hoe-LP / DAPL or strip-LP / DAPL interactions can be attributed to improved availability and uptake of nutrients by the plants. The nutrient availability might have resulted from improved physical, chemical and biological reactions in the soils due to thorough mixing of lime and P fertilizers with the acid soils attributable to the ploughing process (Selles *et al.*, 1997; Bolland and Brennan, 2006; Zhang *et al.*, 2013). The results contradicts findings by Braga *et al.* (2015) who evaluated the effects of tillage methods and lime on corn growth and reported that no tillage promoted maximum corn height as compared to conventional tillage. He also reported lime to have increased plant height in the conventional tillage system compared to no till.

The increase in maize yields resulting from tillage-P-lime interactions can be attributed to the existing positive synergies between tillage, lime and mineral P

fertilizer, leading to favourable soil environment (soil moisture, temperature, microbial activities) for crop growth. Similar results have been reported by Guan *et al.* (2014) and Zhang *et al.* (2013). According to Fageria (2004) and Doussan *et al.* (2006), tillage practices markedly influence root attributes which ultimately impact on the crops' potential capacity for nutrient absorption and water uptake, hence affecting crop growth and yields. Guan *et al.* (2014), therefore, attributed the increased maize yield on ploughing to increased root biomass, hence improved water and nutrient uptake compared to no tilled plots. On the other hand, Zhang *et al.* (2013) worked on the effects of tillage and fertilization mode on corn and reported highest yields on tillage combined with organic and inorganic fertilizers than either fertilizer or tillage alone. Similar findings of increased nutrient uptake and yields on integrating conventional tillage with fertilizers as compared to tillage alone or fertilizer application alone have been reported by Agbede (2010) and Dudenhoefter *et al.* (2012).

The yields obtained from DAPL and LP treatments were not significantly different. This indicates that DAPL and LP has equal ability in promoting maize growth and yields in acid soils. These findings contrast those by Gokmen and Sencar (1999) and Dudenhoefter *et al.* (2012) that different sources of P affect yield differently in cereals. Nekesa *et al.* (2011) also reported increased yields from DAPL as compared to LP in a maize-soybeans intercrop in Uasin Gishu district, Kenya.

## **6.5 CONCLUSIONS**

Tillage-P-lime interactions significantly ( $P \leq 0.05$ ) increased maize growth, P uptake and maize yields. Addition of plough-DAPL or LP interactions were observed to

significantly promote, maize growth and yield compared to use of P alone or other tillage- P-lime interactions. It can, therefore, be concluded that plough-DAPL or plough-LP interactions were found to be effective in enhancing maize growth and yields in acid soils of Kiambu as part of the Kenya highlands. Due to the fact that the conclusions were made from a short term research, the study, therefore, serves as an initial step in the development of integrated approaches to the control and reduction of soil degradation. Further research is, therefore, required to discern the longterm effects and financial implications of tillage-P- lime interactions on maize production in these acid soils.

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## CHAPTER SEVEN

### 7.0 GENERAL CONCLUSIONS AND RECCOMENDATIONS

The results of the survey depicted that, although, soils from all the study sites within the Kenya highlands were acidic, with low plant available P and high exchangeable aluminium levels, farmers' knowledge of soil acidity and management strategies was limited. Additionally, farmers' access to information and new technologies were constrained by failure to participate in farmers trainings. The study also identified a positive relationship between farmers' trainings, age, and education level, adoption of new technologies and use of the technologies. Strategies should, therefore, be established which would encourage farmers participation in farmers training groups for agricultural knowledge base enhancement. Soil fertility and productivity research should, therefore, adopt the participatory rural appraisal (PRA), participatory learning and action research (PLAR) and participatory agro-ecosystem manangement (PAM) approaches.

Although Freundlich adsorption model was found to be the most precise in predicting P adsorption in all soils in the sites, phosphate adsorption maxima and SPR varied from site to site. The SPR was also more than the 11.6 mg P kg<sup>-1</sup> recommended by Kenya Agricultural Research Institute, for P fertilizer application in Kenya. Additionally, the study identified soil pH, organic matter, aluminium and bases like calcium, as some of the factors that influence P availability in the soils at the sites. There is, therefore, need for more intensive studies to understand the role and interactions of soil properties on P availability in the study areas. New phosphate fertilizer recommendations are also crucial for optimal crop production in the research sites.

Lime-Al-P interactions significantly increased soil pH, extractable P, exchangeable bases, P- uptake, and reduced P adsorption, SPR, Fe and Al levels. High rates of lime resulting to 100% reduction of  $Al^{3+}$  saturation were more effective as compared to lower rates. It was, however, observed that combined use of 7.4 tonnes  $ha^{-1}$  lime + 0.59 g P  $kg^{-1}$  for extremely acidic soils and 4.5 tonnes  $ha^{-1}$  + 0.51 g P  $kg^{-1}$  for strongly acidic soils did not differ significantly ( $P \leq 0.05$ ) with combined application of 7.4 tonnes  $ha^{-1}$  + 0.3 g P  $kg^{-1}$ , and 4.5 tonnes  $ha^{-1}$  + 0.26 g P  $kg\ soil^{-1}$  respectively. This implies that either of the combined rates can be, effectively applied to improve crop production in acid soils with similar properties. However, further research is required to evaluate the short and long term effects of the rates on crop yields, availability of other plant nutrients and the environment under field conditions.

Field experiment results indicated that tillage-P- lime interactions significantly ( $P \leq 0.05$ ) increased soil pH, extractable P, CEC, Ca, maize growth, P-uptake and yields. Plough-LP interactions significantly increased soil pH, extractable P, CEC and Ca and reduced exchangeable Al levels in the acid soils. On the other hand, plough-DAPL interactions significantly increased soil CEC and extractable P compared to the control. Similarly, Plough-DAPL and plough-LP interactions significantly ( $P \leq 0.05$ ) increased maize plant height, P uptake, drymatter yields and grain yields. It can, therefore, be concluded that integrating ploughing with either DAPL or LP is effective in promoting maize growth and yields in acid soils of Kiambu. However, these conclusions are made from short term experiments. Further research is, therefore, needed to ascertain the long term effects of the tillage-P-lime interactions on soil acidity and maize yields in the Kenya highlands.

## 8.0 APPENDICES

### Appendix 2.1: Interview Questionnaire

Interviewer's name:

Household Code:

#### Section one: Basic information

- Name of the farmer:
- Sex:
- Location:
- Age:
- Number of children:
- Farm size (acres):
- Educational level a)none b)primary c)secondary d)Tertiary
- Land tenure:
- Are you a member of a training group (s) related to agriculture? a)Yes b) No
- If Yes, How many trainings do have per year?
- Where do you source information on new technologies?
- Have you ever carried out a simple experiment/ comparison on your fields between two farm management activities? a)Yes b) No
- If Yes, What kind of comparison? And what did you learn?

#### Section Two: Types of Crops Grown in the Area and Their Productivity

- Which crops do you grow in your farm (list in order of importance)?
- Which is the most profitable crop in terms of yield and financial returns?
- How much maize yield did you get from one acre/hectare last season? (Kg)
- On average how much maize yields have you been getting for the last 4 seasons (kg/hectare)?
- If THERE IS ANY CHANGE, do you have any explanation as to why the yields have been fluctuating? (yes) (No)
- If YES, What is the probable reason?
  - a) What is the most crop growth limiting factor in your farm?
  - b) How do you solve the problem?

#### Section Three: Knowledge of Soil Characteristics

- (a) Do you know the type of soil in your farm? (a) Yes (b) No (c) somehow
- (b).Your soil is what type?
- (c). Have you ever tested/analysed your soils? (a) Yes (b) No
- If yes, where, when and what was the results?
  - (a) Are you aware of the term soil acidity? (a) Yes (b) No (c) somehow
  - (b) What is soil acidity?
- Are your soils acidic? (a) Yes (b) No ; How did you know?

#### Section Four: Soil Acidity Management

##### If the soil are acidic:

- How do you manage the soil acidity problem?
- Do you apply lime?
- Which type of lime do you apply? and why?
- How much lime do you apply per hectare?
- Where did you get the information about lime application?
- What is the importance of lime application?

- Do you apply mineral fertilizers or manure or both?
- If you apply fertilizer, which type of fertilizer (s)?
- Why do you apply this particular fertilizer (s) and not any other types of fertilizer(s)?
- How much fertilizer do you apply on maize (kg/ha)? And how many times per season?
- If you apply manure/ compost which type of manure?
- Why do you apply this type (s) of manure/compost and not any other type?
- Where do you source your manure? (a) Own source (b) Buying
- Why do you apply the manure in your farm?
- Do you apply manure to all types of crops in your farm? a)Yes b) No
- If No, which crops and why?
- Apart from addition of nutrients do you know any other importance of manure application in your farm?
- How do you dispose extra slurry from your farm? a) Biogas production b) Selling c) Others
- Which other management practices do you carry out in maize?
- Do you usually get any benefit from soil management? Does the cost of management and production break even with the output cost?

**If the soils are not acidic:**

- How do you manage soil fertility problem?
- Do you apply lime?
- Which type of lime do you apply? and why?
- How much lime do you apply per hectare?
- Where did you get the information of lime application?
- What is the importance of lime application?
- Do you apply fertilizers or manure or both?
- If you apply fertilizer, which type of fertilizer (s)?
- Why do you apply this particular fertilizer (s) and not any other types of fertilizer(s)?
- If you apply manure which type of manure?
- Why do you apply this type (s) of manure and not any other type?
- Where do you source your manure? (a) Own source (b) Buying
- Why do you apply the manure in your farm?
- Apart from addition of nutrients do you know any other importance of manure application in your farm?
- Which other management practices do you carry out in maize?
- Do you usually get any benefit from soil management?
- Does the cost of management and production break even with the output cost? Do you get any profit and how much?

**Have you received any fertilizer subsidy?**

- If yes, when? how much? and which type of fertilizers?
- Did you observe any difference in yields after application? If not, why?
- What is your view of subsidy programs?

**Appendix 4.1: Analysis of variance of plant height for the green house pot experiment.**

Source of variation	Degrees of freedom	Sum of squares	Mean squares	Variance Ratio	Pr.>F
Block stratum	2	559.5	279.8	1.4	
Lime	3	9391.5	3130.5	15.4	<.001
Phosphorus	3	18719.1	6239.7	30.7	<.001
Lime.Phosphorus	9	5882.2	653.6	3.2	0.008
Residual	30	6092.8	203.1		
Total	47	40645.1			

**Appendix 4.2: Analysis of variance of number of leaves in green house pot experiment.**

Source of variation	Degrees of freedom	Sum of squares	Mean squares	Variance Ratio	Pr.>F
Block stratum	2	27.08	13.54	3.15	
Block.Units stratum					
Lime	3	46.45	15.48	3.6	0.017
Phosphorus	3	665.37	221.79	51.58	<.001
Lime.Phosphorus	9	33.68	3.74	0.87	0.555
Residual	78	335.42	4.30		
Total	95	1107.99			

**Appendix 4.3: Analysis of variance of dry matter in green house experiment.**

Source of variation	Degrees of freedom	Sum of squares	Mean squares	Variance Ratio	Pr.>F
Block stratum	2	229.39	114.69	2.15	
Block.Units stratum					
Lime	3	654.13	218.04	4.09	0.015
Phosphorus	3	13454.38	4484.79	84.11	<.001
Lime.Phosphorus	9	1487.87	165.32	3.1	0.009
Residual	30	1599.58	53.32		
Total	47	17425.35			

**Appendix 5.1: Analysis of variance of soil pH for the soils sampled during long rains**

Source of variation	Degrees of freedom	Sum of Squares	Mean squares	Variance Ratio	Pr.>F
Block stratum	2	1.71	0.85	2.29	
Block.Tillage stratum					
Tillage	2	15.54	7.77	20.85	0.008
Residual	4	1.49	0.37	1.86	
Block.Tillage.Fertilizer stratum					
Fertilizer	4	11.04	2.76	13.77	<.001
Tillage.Fertilizer	8	2.10	0.26	1.31	0.287
Residual	24	4.81	0.20		
Total	44	36.68			

**Appendix 5.2: Analysis of variance of soil pH for the soils sampled during short rains**

Source of variation	Degrees of freedom	Sum of squares	Mean squares	Variance Ratio	Pr.>F
Block stratum	2	0.08	0.04	0.58	
Block.Tillage stratum					
Tillage	2	34.49	17.24	235.3	<.001
Residual	4	0.29	0.07	1.54	
Block.Tillage.Fertilizer stratum					
Fertilizer	4	7.97	1.99	41.86	<.001
Tillage.Fertilizer	8	2.89	0.36	7.59	<.001
Residual	24	1.14	0.05		
Total	44	46.87			

**Appendix 5.3: Analysis of variance of soil available P for the soils sampled during short rains**

Source of variation	Degrees of freedom	Sum of Squares	Mean squares	Variance ratio	Pr.>F
Block stratum	2	24.05	12.03	0.04	
Block.Tillage stratum					
Tillage	2	4167.73	2083.87	7.25	0.047
Residual	4	1150.44	287.61	4.93	
Block.Tillage.Fertilizer stratum					
Fertilizer	4	10757.55	2689.39	46.1	<.001
Tillage.Fertilizer	8	1975.68	246.96	4.23	0.003
Residual	24	1400.17	58.34		
Total	44	19475.63			

**Appendix 5.4: Analysis of variance of soil CEC for the soils sampled during long rains**

Source of variation	Degrees of freedom	Sum of Squares	Mean squares	Variance ratio	Pr.>F
Block stratum	2	21.63	10.82	1.64	
Block.Tillage stratum					
Tillage	2	2200.11	1100.06	166.56	<.001
Residual	4	26.42	6.61	1.11	
Block.Tillage.Fertilizer stratum					
Fertilizer	4	723.55	180.89	30.42	<.001
Tillage.Fertilizer	8	211.58	26.45	4.45	0.002
Residual	24	142.72	5.95		
Total	44	3326.01			

**Appendix 5.5: Analysis of variance of soil CEC for the soils sampled during short rains**

Source of variation	Degrees of freedom	Sum of squares	Mean squares	Variance Ratio	Pr.>F
Block stratum	2	71.24	35.62	3.17	
Block.Tillage stratum					
Tillage	2	2079.59	1039.79	92.66	<.001
Residual	4	44.89	11.22	0.58	
Block.Tillage.Fertilizer stratum					
Fertilizer	4	563.67	140.92	7.32	<.001
Tillage.Fertilizer	8	610.54	76.32	3.97	0.004
Residual	24	461.93	19.25		
Total	44	3831.86			

**Appendix 5.6: Analysis of variance of the soil exchangeable Al for the soils sampled during long rains**

Source of variation	Degrees of freedom	Sum of Squares	Mean squares	Variance ratio	Pr.>F
Block stratum	2	0.83	0.42	0.57	
Block.Tillage stratum					
Tillage	2	12.67	6.34	8.62	0.035
Residual	4	2.94	0.73	1.57	
Block.Tillage.Fertilizer stratum					
Fertilizer	4	15.83	3.96	8.48	<.001
Tillage.Fertilizer	8	4.40	0.55	1.18	0.351
Residual	24	11.20	0.47		
Total	44	47.88			

**Appendix 5.7: Analysis of variance of the soil exchangeable Al for the soils sampled during short rains**

Source of variation	Degrees of freedom	Sum of Squares	Mean squares	Variance ratio	Pr.>F
Block stratum	2	0.42	0.21	0.4	
Block.Tillage stratum					
Tillage	2	13.9	6.97	13.27	0.017
Residual	4	2.10	0.52	3.16	
Block.Tillage.Fertilizer stratum					
Fertilizer	4	14.79	3.70	22.22	<.001
Tillage.Fertilizer	8	3.64	0.46	2.74	0.027
Residual	24	3.99	0.16		
Total	44	38.89			

**Appendix 5.8: Analysis of variance of dry matter yields during short rains**

Source of variation	Degrees of freedom	Sum of Squares	Mean squares	Variance ratio	Pr.>F
Block stratum	2	1045.43	522.72	7.33	
Block.Tillage stratum					
Tillage	2	1336.63	668.31	9.37	0.031
Residual	4	285.36	71.34	2.2	
Block.Tillage.Fertilizer stratum					
Fertilizer	4	1690.34	422.58	13.04	<.001
Tillage.Fertilizer	8	1086.16	135.77	4.19	0.003
Residual	24	777.95	32.41		
Total	44	6221.86			

**Appendix 6.1: Analysis of variance of average maize grain yields.**

Source of variation	Degrees of freedom	Sum of Squares	Mean squares	Variance ratio	Pr.>F
Block stratum	2	1.05	0.53	0.88	
Block.Tillage stratum					
Tillage	2	13.43	6.72	11.22	0.02
Residual	4	2.40	0.60	1.83	
Block.Tillage.Fertilizer stratum					
Fertilizer	4	119.10	29.78	91.2	<.001
Tillage.Fertilizer	8	10.60	1.33	4.06	0.004
Residual	24	7.84	0.33		
Total	44	154.42			

**Appendix 6.2: Average monthly rainfall (mm) at Waruhui farmers Training Centre, Githunguri**

Year	Month	No. of rainfall days	Rainfall (mm)
2014	January	1	1.5
2014	February	9	5.4
2014	March	8	4.5
2014	April	10	6.0
2014	May	13	2.4
2014	June	7	5.7
2014	July	6	0.7
2014	August	8	1.4
2014	September	5	2.7
2014	October	8	3.0
2014	November	17	5.1
2014	December	5	2.3
2015	January	1	0.8
2015	February	1	1.1

Source: Kenya Agrometeorological Department, Githunguri