EFFECTIVENESS OF LIMING MATERIALS AND PHOSPHORUS FERTILIZER APPLICATION ON MAIZE PRODUCTION IN ACID SOILS OF SIAYA AND KAKAMEGA COUNTIES.

BY

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DECLARATION

Declaration by the student

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DEDICATION

To my late mother Mary Achieng Omenyo. You were and will always be an inspiration to me. To my family for your relentless support throughout my studies and to my supervisors for seeing the potential in me. May the Lord bless you abundantly.

ABSTRACT

Soil acidity is a major contributor to soil infertility in western Kenya. Smallholder farmers in this region have persistently realized low yields (< 1 t ha^{-1} $season^{-1}$ maize) in comparison to potential estimates of 6 – 8 t $ha^{-1}$$season^{-1}$. Liming, as an intervention to ameliorate soil acidity, is hardly practiced in the region where acid soils occupy about 0.9 million hectares of farm land. An on-farm research was conducted during the 2010 long and short rains and 2011 long rains at selected sites in Kakamega (Chimoroni and Tumbeni) and Siaya (Got Nanga and Sihay) Counties, to evaluate direct and residual effects of various lime sources on soil pH, phosphorus availability and maize yields. Two separate experiments were carried out. In one, two agricultural lime materials from two sources; Koru, (20.8 % CaO) and Athi River (45 % CaO), were used to evaluate maize yield response, soil pH and P availability to a combination of lime and P fertilizer. The experiment was laid out in a split plot design with 3 replicates. The second experiment tested the effectiveness of four liming and P fertilizer sources (Koru and Athi River lime, Minjingu phosphate rock - MPR (38 % CaO, 29 % P_2O_5) and Mavuno fertilizer (26 % P_2O_5, 10 % N, 10 % CaO, 4 % MgO, 4 % S_2O) on soil pH, P availability in soil and maize yields. Triple superphosphate (46 % P_2O_5), supplied P to the two agricultural limes without P. The experiment too was laid in a split plot design. A blanket application of 75 kg N $ha^{-1}$was applied to all plots with exception of the absolute control. Comparison between treatment means was achieved by using single degree of freedom contrasts. Results for 2010 LR indicated significant ($p<0.05$) responses of maize yield to the soil amendment materials applied. Koru lime applied at 3 t ha^{-1} gave the highest yield of 4.96 t ha^{-1} (Got Nanga site) and 3 t ha^{-1} Koru lime + TSP gave a yield of 3.85 t ha^{-1}in Chimoroni site for the first experiment. For the second experiment, Mavuno fertilizer (0.48 t ha^{-1}) had the highest yield of 6.72, 5.70 and 4.72 t ha^{-1} at Sihay, Got Nanga and Tumbeni sites, respectively. There was a positive and significant correlation between yield and extractable soil P in all the sites at the third sampling. During 2010 SR, maize yields were very low, due to the poor and inadequate rainfall experienced during that season. In the final season (2011 LR), the soil amendment materials still showed residual effects, though there was a reduction in maize grain yield, soil pH and extractable soil P values in almost all the sites. Mavuno fertilizer (0.24 t ha^{-1}) gave the highest external P use efficiency of 182.9 kg grain kg^{-1} of applied P at Sihay. In conclusion, lime application increases yield above the control, though, the yield is insignificant except at Got Nanga where 3 t ha^{-1} lime significantly increased maize yield. Lime in combination with P is the best practice for optimum yield. Additionally, fertilizer blends (Mavuno) can both lime the soil and provide essential nutrients as was observed in this experiment. Lime requirements and nutritional levels of these soils should be determined and farmers advised accordingly for better maize production in this region. A green house study for the second experiment was conducted to isolate effects of materials used in the field after it was realized that Mavuno performed better. Soil was collected from Sihay and Tumbeni. All treatments without K, Mg, S, and Zn received these nutrients in forms of solutions except K and S. The treatments were arranged in a complete randomize design. Dry matter yield of the control treatment differed significantly ($p < 0.05$) from treatments. However, treatments did not differ significantly from each other in Sihay and Tumbeni soils. Thus, Mavuno fertilizer performed better in the field due to both macro and micronutrients it contains.

TABLE OF CONTENTS

DECLARATION i
DEDICATION ii
ABSTRACT iii
TABLE OF CONTENTS iv
LIST OF FIGURES xi
LIST OF PLATES xiii
LIST OF APPENDICES xiv
ACRONYMS AND ABBREVIATIONS xv
ACKNOWLEDGEMENT xvi

CHAPTER ONE 1
INTRODUCTION 1
1.1 Background 1
1.2 Statement of the problem 2
1.3 Justification 3
1.4 Objectives 4
1.4.1 Overall objective 4
1.4.2 Specific objectives 5
1.5 Main Hypothesis 5
1.5.1 Specific Hypotheses 5

CHAPTER TWO 6
LITERATURE REVIEW 6
2.1 Soil acidity 6
2.2 Soil acidity and plant growth 7
2.2.1 Aluminium solubility 7
2.2.2 Toxicity of Aluminium and Manganese to plants 8
2.2.3. Deficiencies of P, Ca, Mg and K in acid soils (acid soil infertility 9
2.2.4 Phosphorus availability in soils and its functions in plants 9
2.3 Crop tolerance to soil acidity 10
2.4 Management of soil acidity 11
2.4.1 Agricultural liming materials 12
2.4.1.1 Lime placement and its residual effect 12
2.4.2 Phosphate rocks 14
2.4.2.1 Solubility of phosphate rocks 14
2.4.2.2 Residual effect of PR 16
2.5 Maize (*Zea mays L.*) 16
2.6 Economic analysis 17

CHAPTER THREE 19
MATERIALS AND METHODS 19
3.1 Site description 19
3.1.1 Siaya County 19
3.1.2 Kakamega County 19
3.2. Site characterization 20
3.3 Description of materials used 21

3.3.1 Athi River lime ... 21
3.3.2 Koru (Homa) lime ... 22
3.3.3 Mavuno fertilizer ... 22
3.3.4 Minjingu Phosphate Rock (MPR) ... 23
3.3.5 Triple Superphosphate ... 24
3.3.6 Calcium Ammonium Nitrate ... 25
3.4 Soil sampling and preparation ... 25
3.5 Field experiments ... 25
3.5.1 Experimental treatments and design ... 25
3.5.2 Statistical model for field experiments ... 26
3.6 management of the field experiments ... 27
3.6.1 Application of treatments ... 27
3.6.2 Planting of maize ... 28
Plate 3: Planting of maize at the start of 2010 LR. (Source: Omenyo, 2013) ... 28
3.6.3 Harvesting of maize ... 29
3.7 The greenhouse experiment ... 29
3.7.1 Statistical model for the greenhouse experiment ... 30
3.8 Laboratory analysis ... 31
3.8.1. Soil particle size analysis by the hydrometer method ... 31
3.8.2. Soil pH ... 31
3.8.3 Extractable soil phosphorus: the Olsen method ... 31
3.8.4 Total nitrogen and phosphorus in soils and plants ... 32
3.8.5 Exchangeable cations in soils ... 32
3.8.6 Determination of EDTA-soluble copper, iron, manganese and zinc in soil ... 33
3.8.7 Organic carbon content of soils ... 33
3.9 Statistical Analysis ... 33
3.10 Nutrient use efficiency ... 34
3.10.1 Agronomic (external) nutrient use efficiency ... 34
3.10.2 Internal (physiological) nutrient use efficiency ... 34
3.10.3 Partial factor productivity (PFP) ... 35
3.11 Economic analysis ... 35

CHAPTER FOUR ... 37
RESULTS ... 37
4.1: Field experiments ... 37
4.1.1: Physical and chemical characteristics of the soils at the study sites prior to treatment applications ... 37
4.1.2. Soil profile characterization of the study sites ... 38
4.1.3. Direct and residual effect of lime and P fertilizer application on soil pH (0 – 15 cm depth) ... 40
4.1.4. Site differences in terms of soil pH (0 – 15 cm) changes over time as influenced by lime applications ... 43
4.1.7. Correlation between maize grain yield, available soil P and soil pH as affected by the combination of lime and P fertilizer application ... 51
4.1.8. Uptake of N and P in maize grain as influenced by P and Lime application ... 53
4.1.9. Nutrient Use Efficiency in the maize grain as affected by lime and P application. ... 56
4.1.10 Economic analysis ... 61

4.2.1 Direct and residual effect of different lime and P sources on soil pH (0 – 15 cm) ... 63
4.2.3 Maize grain yield as affected by different lime and P sources in all sites during three cropping seasons ... 68
4.2.4 Uptake of N and P by maize grain as influenced by different sources of lime and phosphorus ... 71
4.2.5 Nutrient use efficiency by the maize grain as affected by different sources of lime and P ... 74
4.2.6 Economic analysis of different lime and P sources on maize grain yield ... 79
4.3 The Greenhouse Pot Experiment (Tumbeni and Sihay soils) ... 81
4.3.1: Soil pH ... 81
4.3.2: Available soil P ... 82
4.3.3: Dry matter yield of maize tops ... 84
4.3.4. Uptake of N and P as influenced by treatments ... 86

CHAPTER FIVE ... 90
DISCUSSION ... 90
5.1. Field experiments ... 90
5.1.1. Physical and chemical characteristics of the soils at the study sites ... 90
5.1.2. Soil profile characterization of the study sites ... 91
5.1.3. Direct and residual effect of lime and P fertilizer application on soil pH ... 91
5.1.4. Site differences in terms of pH change over time as influenced by lime and P application ... 93
5.1.5. Direct and residual effect of lime and P application on available soil P ... 93
5.1.6. Maize grain yield as affected by combination of lime and P application in all the sites during the three cropping seasons ... 94
5.1.7. Correlations between maize grain yield, available soil P and soil pH ... 95
5.1.8. Uptake of N and P in Maize crop as influenced by P and Lime application .. 96
5.1.9 Agronomic and physiological nitrogen and phosphorus use efficiencies ... 97
5.1.10 Partial factor of productivity ... 97
5.1.11 Economic analysis ... 97
5.2.1. Direct and residual effect of different lime and P sources on soil pH ... 98
5.2.2. Direct and residual effect of different lime and P sources on available soil P 98
5.2.3 Maize grain yield as affected by different lime and P sources in all the sites during the three cropping seasons ... 99
5.2.4 Uptake of N and P in maize crop as influenced by different lime and P sources 100
5.2.5 Agronomic and physiological N and P use efficiencies ... 101
5.2.6 Partial factor of productivity and economic analysis ... 101
5.3. The Greenhouse pot Experiment ... 102
5.3.1. Soil pH ... 102
5.3.2. Available soil P ... 102
5.3.3. Maize biomass dry matter yield ... 102
5.3.4. Uptake of N and P as influenced by treatments ... 103

CHAPTER SIX ... 104
CONCLUSIONS AND RECOMMENDATIONS ... 104
6.1. CONCLUSIONS ... 104
6.2. RECOMMENDATIONS ... 105
REFERENCES ... 107

APPENDICES 123
Appendix I: ANOVA for soil pH 123
Appendix II: ANOVA for available soil P 128
Appendix III: ANOVA for Maize yield 129
Appendix IV: Rainfall distribution (mm) during 2010 and 2011LR 134
Appendix V: Plot layout 135
Appendix VI: ANOVA skeletons 136
ANOVA skeleton for the greenhouse experiment 136

LIST OF TABLES

Table 1: Chemical composition of Calmax 21

Table 2: Chemical composition of Koru lime 22

Table 3a: Field treatment combination for experiment 1 27

Table 3b: Field treatment combination for experiment 2 27

Table 3c: Values used to calculate costs and benefits analysis (Kshs.) during 2010 LR to 2011 LR in all the sites... 36

Table 4a: Initial surface (0 – 15 cm) soil properties at the study sites 38

Table 4b: Exchangeable cations down the profile as observed at Chimoroni site (Ferralo - humic acrisol) 39

Table 4c: Exchangeable cations down the profile as observed at Tumbeni site (Ferralo - humic acrisol) 39

Table 4d: Exchangeable cations down the profile as observed at Sihay site (Orthic acrisol) 40

Table 4e: Exchangeable cations down the profile as observed at Got Nanga site (Orthic acrisol).. 40

Table 5a: Mean changes in soil pH (0 – 15 cm) as influenced by treatment application over time in Siaya county.. 44

Table 5b: Mean changes in soil pH as influenced by lime application over time in Kakamega North county 44

Table 6a: Maize grain yield (t/ha) as affected by lime and P application during three cropping seasons at Got Nanga site 49

Table 6b: Maize grain yield (t/ha) as affected by lime and P application during three cropping season at Sihay site.. 49

Table 6c: Maize grain yield (t/ha) as affected by lime and P application during three cropping seasons at Chimoroni Site... 50

Table 6d: Maize grain yield (t/ha) as affected by lime and P application during three cropping seasons at Tumbeni site 50

was significantly ($p < 0.05$) correlated to soil Ph 51

Table 7a: Nitrogen and phosphorus uptake in the maize grain as influenced by lime and P application at Got Nanga site during 2010 LR 54

Table 7b: Nitrogen and phosphorus uptake in the maize grain as influenced by lime and P application at Sihay site during 2010 LR 54

Table 7c: Nitrogen and phosphorus uptake in the maize grain as influenced by lime and P application at Chimoroni site during 2010 LR 55

Table 7d: Nitrogen and phosphorus uptake in the maize grain as influenced by lime and P application at Tumbeni site during 2010 LR. 55

Table 8a: Mean agronomic nitrogen use efficiency (kg grain kg N-1) and agronomic phosphorus use efficiency (kg grain kg P-1) for three cropping seasons at Got Nanga and Sihay 56

Table 8b: Mean agronomic nitrogen use efficiency (kg grain kg N^{-1}) and agronomic phosphorus use efficiency (kg grain kg P^{-1}) for three cropping season at Chimoroni and Tumbeni 57

Table 9a: Mean partial factor of productivity (kg/ha) for three cropping seasons at Got Nanga and Sihay 60

Table 9b: Mean partial factor of productivity (kg/ha) for three cropping seasons at Chimoroni and Tumbeni 60

Table 10a: Gross field benefits, total costs that vary, net field benefit and marginal rate of returns analysis of treatments during 2010 LR,SR and 2011 LR at Got Nanga and Sihay sites 62

Table 10b: Gross field benefits, total costs that vary, net field benefit and marginal rate of returns analysis of treatments during 2010 LR, SR and 2011 LR at Chimoroni and Tumbeni sites 62

Table 11a: Maize grain yield (t/ha) as affected by different sources of lime and P during three cropping season at Sihay site 69

Table 11b: Maize grain yield (t/ha) as affected by different sources of lime and P during three cropping season at Got Nanga site 70

Table 11c: Maize grain yield (t/ha) as affected by different sources of lime and P during three cropping season at Chimoroni site 70

Table 11d: Maize grain yield (t/ha) as affected by different sources of lime and P during three cropping season at Tumbeni site 71

Table 12a: Uptake of N and P as influenced by treatments at Sihay site during 2010 LR 72

Table 12b: Uptake of N and P as influenced by treatments at Got Nanga site during 2010 LR 73

Table 12c: Uptake of N and P as influenced by treatments at Chimoroni site during 2010 LR 73

Table 12d: Uptake of N and P as influenced by treatments at Tumbeni site during 2010 LR 74

Table 13a: Mean ANUE (kg grain kg N $^{-1}$) and APUE (kg grain kg P^{-1}) as affected by treatments at Got Nanga and Sihay sites 75

Table 13b: Mean ANUE (kg grain kg N^{-1}) and APUE (kg grain kg P^{-1}) as affected by treatments at Chimoroni and Tumbeni sites 75

Table 14a: Mean PFP (kg/ha) as affected by treatments at Got Nanga and Sihay sites ... 78

Table14b: Mean PFP (kg/ha) as affected by treatments at Got Nanga and Sihay sites 79

Table 15a: Gross field benefits, total costs that vary, net field benefit and marginal rates of returns analysis of treatments during 2010 LR, SR and 2011 LR at Got Nanga and Sihay sites 80

Table 15b: Gross field benefits, total costs that vary, net field benefit and marginal rates of returns analysis of treatments during 2010 LR, SR and 2011 LR at Chimoroni and Tumbeni sites.. 80

LIST OF FIGURES

Figure 1: Lime reaction in acid soil to form weak acids (water) 12

Figure 2a: Effect of lime and P application on soil pH (0 – 15 cm) during 2010 LR, SR and 2011 LR at Got Nanga site. 41

Figure 2b: Effect of lime and P application on soil pH (0 – 15 cm) during 2010 LR, SR and 2011 LR at Sihay site. 42

Figure 2c: Effect of lime and P application on soil pH (0 – 15 cm) during 2010 LR, SR and 2011 LR at Chimoroni site 42

Figure 2d: Effect of lime and P on soil pH (0 – 15 cm) during 2010 LR, SR and 2011 LR at Tumbeni site 43

Figure 3a: Effect of lime and P application on available soil P (0 – 15 cm) during 2010 LR, SR and 2011 LR at Got Nanga site. 46

Figure 3b: Effect of lime and P application on available soil P (0 – 15 cm) during 2010 LR, SR and 2011 LR at Sihay site 46

Figure 3c: Effect of lime and P application on available soil P (0 – 15 cm) during 2010 LR, SR and 2011 LR at Chimoroni site 47

Figure 3d: Effect of lime and P application on available soil P (0 – 15 cm) during 2010 LR, SR and 2011 LR at Tumbeni site. 47

Figure 4a: Correlation between maize grain yield and available soils P 80 DAP at Sihay (a), Got Nanga (b), Chimoroni (c) and Tumbeni (d) sites respectively 52

Figure 4b: correlation between available soil P and soil pH 80 DAP at Sihay (a) and Got Nanga (b) .... **Error! Bookmark not defined.**

Figure 5b: Mean physiological P use efficiency by the grain for three cropping seasons. 58

Figure 6b: Effect of different sources of lime and P on soil pH (0 – 15 cm) for three cropping seasons at Sihay site. 64

Figure 6c: Effect of different sources of lime and P on soil pH (0 – 15 cm) for three cropping seasons at Chimoroni site. 65

Figure 6d: Effect of different sources of lime and P on soil pH (0 – 15 cm) for three cropping seasons at Tumbeni site ... 65

Figure 7a: Effect of different sources of lime and P on available soil P (0 – 15 cm) for three cropping seasons at Got Nanga site ... 66

Figure 7b: Effect of different sources of lime and P on available soil P (0 – 15 cm) for three cropping seasons at Sihay site. ... 67

Figure 7c: Effect of different sources of lime and P on available soil P (0 – 15 cm) for three cropping seasons at Chimoroni site. ... 67

Figure 7d: Effect of different sources of lime and P on available soil P (0 – 15 cm) for three cropping seasons at Tumbeni site. ... 68

Figure 8a: Effects of different sources of lime and phosphorus fertilizer on a three season mean physiological N use efficiency by the grain at the study sites. ... 77

Figure 8b: Effects of different sources of lime and phosphorus fertilizer on a three season mean physiological P use efficiency by the grain at the study sites ... 77

Table 14a: Mean PFP (kg/ha) as affected by treatments at Got Nanga and Sihay sites ... 78

Figure 9a: Soil pH as affected by treatments at harvesting pot trials in Sihay soils ... 81

Figure 9b: Soil pH as affected by treatments at harvesting pot trials in Tumbeni soils ... 82

Figure 10b: Available soil P as influenced by treatments at harvesting pot trials in Tumbeni soil ... 84

Figure 11a: Dry matter yield of maize as influenced by different lime and P sources in Sihay soils ... 85

Figure 11b: Dry matter yield of maize as influenced by treatment application in Tumbeni soils.

Fig 12c: P uptake as influenced by treatments in Tumbeni soil ... 88

LIST OF PLATES

Plate 1: Soil profile pit used to describe the soils at Got Nanga 20

Plate 2: Soil profile pit used to describe the soils at Chimoroni 21

Plate 3: Planting of maize at the start of 2010 LR 28

Plate 4: Green house pot experiment showing treatments in ascending order of P rates. Control (extreme left) to lower rate of 26 kg P/ha to higher rate of 52 kg P 89

Plate 5: Greenhouse pot experiment showing difference in growth of maize plants. L – Kakamega and R- Siaya counties 89

LIST OF APPENDICES

Appendix 1: ANOVA for soil pH 123

Appendix 2: ANOVA for available soil P 128

Appendix 3: ANOVA for Maize yield 129

Appendix 4: Rainfall distribution (mm) during 2010 and 2011LR 134

Appendix 5: Plot layout 135

Appendix 6: ANOVA skeletons 136

ACRONYMS AND ABBREVIATIONS

AGNUE	–	Agronomic nitrogen use efficiency
AGPUE	–	Agronomic phosphorus use efficiency
AGRA	–	Alliance for a Green Revolution in Africa
ANOVA	–	Analysis of variance
CEC	–	Cation Exchange Capacity
DAP	–	Days after planting
FURP	–	Fertilizer Use Recommendation Project
GAO	–	Government Accountability Office of U.S.A
GFB	–	Gross field benefit
ICRAF	–	International Center for Research in Agroforestry
LR	–	Long Rains
MPR	–	Minjingu Phosphate Rock
MRR	–	Marginal rate of return
NFB	–	Net field benefit
NUE	–	Nutrient Use Efficiency
PFP	–	Partial factor of production
PNUE	–	Physiological nitrogen use efficiency
PPUE	–	Physiological phosphorus use efficiency
PR	–	Phosphate Rock
SED	–	Standard Error of Difference
SR	–	Short Rains
SSA	–	sub Saharan Africa
TCV	–	Total costs that vary
TSP	–	Triple Superphosphate

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CHAPTER ONE

INTRODUCTION

1.1 Background

In Sub-Saharan Africa (SSA), land degradation i.e. the loss of production capacity of land in terms of loss of soil fertility, soil bio-diversity and degradation of natural resources (FAO, 2002), is the most serious threat to food production, food security and natural resource conservation (Bationo *et al.*, 2006). Land degradation, is caused by soil water erosion, wind erosion, loss of nutrients, physical deterioration and salinization (Bationo *et al.*, 2006). In addition, the population growth, at 2.4%, the highest in the world, is worsening food security and soil nutrient depletion on the continent. As discussed by Bationo *et al.*, (2006), currently, only 16% of Africa's soil is estimated to be of high quality, 13% of medium quality, 16% of low potential, whereas 55% is unsuitable for cultivated agriculture but supports nomadic grazing. About 30% of the population (about 250 million) depends on the low potential land resources. Western Kenya is one of the densely populated regions in the world, with about 700 humans per km^2 and farm sizes averaging 0.5 ha (Sanchez *et al.*, 1997) of which about one – third is planted to maize (staple food in the region). Over 95% of the total farming community in this region is smallholder who often harvest maize yields below 1 t ha^{-1} $season^{-1}$ (Nekesa *et al.*, 1999; Sanchez *et al.*, 1997). The low maize crop production in this region, particularly in areas under rainfed agriculture, is mainly attributed to the low soil fertility that continues to decline and low use of either inorganic or organic fertilizers. In most smallholder farms in western Kenya, loss of soil fertility through soil erosion is more severe than loss through leaching. It has been projected that about 0.9 million hectares of land in this region has acidic soils with soil pH < 5.5, with consequent P deficiencies (Woomer *et al.*, 1997, Kanyanjua *et al.*, 2002).

Large yield increases can however, be attained when inorganic fertilizers are used as demonstrated in field experiments. Maize yield increases due to NPK fertilizer application can be as high as 150%, but when soil is amended with lime and manure, yield responses of 184% are obtained (Bationo *et al.,* 2006). Despite these increases in yield, fertilizer use in this region is very low, caused by a complex, challenging set of issues, ranging from inappropriate national policies, to weak rural input supply chains, to lack of trained retailers, to farmer lack of money to buy fertilizers and farmer ignorance on how to use fertilizer effectively among others (Eilitta, 2006).

In April 2008, the President of the World Bank called for a *New Deal for a Global Food Policy* that would involve a combination of long-term efforts to boost agricultural productivity in developing countries and short-term emergency aid to address immediate food crises (GAO, 2008). The objective of the Alliance for Green Revolution in Africa (AGRA), initiated and launched in 2008 by Kofi Annan (former UN secretary General), is to revive soil fertility on the continent. It is set to assist millions of smallholder farmers and their families against poverty and hunger, while safeguarding the environment and biodiversity (www.agra.org). If Africa is to achieve a green revolution that will help the continent in its quest for dignity and peace, then there is need to replenish the depleted soil fertility through creating awareness of the problem and its solutions, i. e. educating smallholder farmers on use of organic and inorganic nutrient sources and their combinations together with appropriate management practices to curb soil infertility, hence increase agricultural productivity.

1.2 Statement of the problem

Soil fertility depletion and acidity in smallholder farms are a fundamental biophysical root cause of the declining per capita food production, and has largely contributed to poverty and food insecurity in SSA, Kenya included (Sanchez *et al.*, 1997). Aluminium toxicity, phosphorus (P) and nitrogen (N) deficiencies reduce maize grain yields by about 26, 16 and 30 %, respectively (Kanyanjua *et al.*, 2002). In western Kenya, smallholder farmers have dismally low yields of crops (< 1 t ha^{-1} $season^{-1}$ of maize) in comparison to the potential estimates of 6 – 8 t $ha^{-1}season^{-1}$ (Nekesa *et al.*, 1999; Sanchez *et al.*, 1997; Okalebo *et al.*, 2006). This has resulted in persistent food insecurity and poverty, particularly among smallholder farmers in the region.

1.3 Justification

Liming practice has been adopted to effectively neutralize soil acidity. Data obtained from liming experiments in other parts of Africa have however, shown that addition of agricultural lime alone is insufficient to rehabilitate depleted soils (Rutunga *et al.*, 1998). As a result the combination of agricultural lime, organic and inorganic fertilizer materials has been observed to be the most effective technique of addressing the problem of soil acidity and enhancing soil fertility (Rutunga *et al.*, 1998).

Despite the fact that P deficiency is acute on these soils, farmers use no or very little P fertilizers because of high costs and problems with accessibility. However, there has been sufficient evidence that use of inorganic fertilizers along with high - yielding cereal varieties, dramatically increase food production (Okalebo *et al.*, 2003) and can be highly profitable despite, the high costs (Bationo *et al.*, 2006). Additions of nutrients such as Zn, B, S and Mg can also dramatically improve fertilizer – use efficiency and crop profitability when targeted to deficient soils, something that has not been addressed in most countries of SSA, Kenya included (Sanginga and Woomer, 2009). Due to the secondary and micronutrient contents of “Mavuno” fertilizer blend, it may outperform existing fertilizers, particularly where K and S become limiting and acidification of soils is increasing (Poulton *et al*., 2006). The use of reactive locally available phosphate rocks could however, be an alternative to imported P fertilizers. Moreover, past studies have shown that a one-time large application of PR has positive residual effects on crop yields during several consecutive cropping seasons, which justifies the use of PR to improve the soil's P and pH status (Buresh *et al*., 1997).

No country in modern history has made great strides in agricultural production without first correcting soil reaction problems, acidity or alkalinity followed by increasing the use of fertilizer which provides the key nutrients needed by the crop. This study therefore, sought to address the use of agricultural lime to correct soil acidity, Minjingu phosphate rock (MPR) and Mavuno (blended) fertilizer at lowest effective rates which the majority of smallholder farmers may afford to ameliorate soil acidity, replenish soil P and improve crop production in smallholder farms of western Kenya.

1.4 Objectives

1.4.1 Overall objective

To evaluate direct and residual effects of agricultural lime from Koru and Athi River Mining Companies, MPR and Mavuno fertilizers on selected soil properties and maize yields in western Kenya

1.4.2 Specific objectives

1. To assess the fertility status of soils at the experimental sites in Kakamega and Siaya counties
2. To determine soil pH, P availability and maize yield response to lime and its combination with P applications in the target counties.
3. To determine the effects of different sources of lime and P (Mavuno and MPR) on soil pH, available P and maize yield in Kakamega and Siaya counties.
4. To determine the economics of using MPR, Mavuno fertilizer and agricultural lime (Koru and Athi River) including TSP on maize production in the two counties.

1.5 Main Hypothesis

Use of agricultural lime from Koru and Athi River sources, MPR and Mavuno fertilizer will ameliorate soil acidity and replenish soil P hence, increase yields of maize in acid soils of western Kenya.

1.5.1 Specific Hypotheses

1. Agricultural lime from Koru and Athi River, MPR and Mavuno fertilizer will ameliorate soil acidity in the region
2. Maize yields will increase significantly as a result of application of lime from Koru and Athi River, MPR and Mavuno fertilizer.
3. The economical practical system for the farmers will be one that incorporates lowest rates of the liming and P fertilizer materials to give optimum economic returns in terms of maize yield.

CHAPTER TWO

LITERATURE REVIEW

2.1 Soil acidity

Approximately 40 % of the world's total land area consists of acidic soils, out of which the tropics and subtropics account for 60 % (Buresh *et al,*. 2006; Crozier and Hardy, 2003). Soils that developed from granite material are likely to be more acidic than soils developed from calcareous shale or limestone. According to Crozier and Hardy (2003), root growth and plant development may be severely restricted if acidic cations, especially aluminium, occupy a large percentage of the negatively charged cation exchange capacity (CEC). This negative charge is due to the chemical makeup of the soil clay and organic matter and means that it can attract positively charged ions. The exchangeable aluminium is in equilibrium with dissolved aluminium in the soil solution and reacts with water to form hydrogen ions in the solution:

$$Al^{3+} + H_2O \leftrightarrow Al\,(OH)^{2+} + \mathbf{H^+}$$

The larger the percentage of exchange sites occupied by aluminium, the greater the amount of hydrogen formed, thus the lower the pH and the higher the acidity of the soil (Crozier & Hardy, 2003). Over time, soils become more acid due to the leaching of calcium and magnesium mainly. The loss of these basic cations is permanent if they are leached out of root zone or removed through crop harvests. However, the loss is temporary if they are taken up by the plants and returned to the soil in litter or on death of the plants (Wild, 1988). Acidification also occurs when hydrogen is added to soils by decomposition of plant residues and organic matter and during the nitrification of ammonium added to soils as fertilizers (Kennedy, 1992; Crozier and Hardy, 2003):

$$NH_4^+ + 1\tfrac{1}{2}\,O_2 \rightarrow NO_3^- + \mathbf{4H^+}$$

$$NH_3 \text{ (Anhydrous ammonia) } + 2O_2 \rightarrow NO_3^- + \mathbf{H^+} + H_2O$$

The H^+ added to soils reacts with the clay minerals (aluminium silicates) and releases Al^{3+}, which goes on to soil solution acidity as noted above (Crozier & Hardy, 2003). Soil pH also influences the concentration of many dissolved ions in the soil solution, including aluminium, which decreases in concentrations as soil pH increases.

2.2 Soil acidity and plant growth

2.2.1 Aluminium solubility

Aluminium exists in soils in many mineral forms including hydrous oxides, aluminosilicates, sulphates and phosphates. Acid soils have high Al saturation, i.e. an appreciable portion of the cation exchange capacity is satisfied by Al ions. While these Al ions are referred to as exchangeable Al, they are a mixture of monomeric Al ions [Al^{3+}, $Al(OH)^{2+}$, $Al(OH)_2^+$] with an average charge per Al between 2 and 3, decreasing as pH increases (Wild, 1988). Aluminium is tightly held to exchange sites and, as a result, concentrations in soil solution are characteristically low, often ranging between 10 and 250μM Al (Adams& Moore, 1983; Curtin & Smillie, 1983; Kamprath, 1978). When an acid soil is limed, exchangeable and soluble Al precipitate as hydroxyl-Al species, this is because the solubility of Al is highly pH-dependent. The positively charged monomeric Al $(OH)^{2+}$ and Al $(OH)_2^+$ species can polymerize to form both large and small positively-charged polynuclear complexes which become sorbed to clay mineral and organic matter surfaces (Rengasamy & Oades, 1978; Stole *et al.,* 1976). Thus, liming an acid soil to about pH 5.5 results in concentrations of soluble and exchangeable Al being lowered to negligible levels and Al toxicity no longer limits crop growth.

2.2.2 Toxicity of Aluminium and Manganese to plants

Aluminum toxicity is considered the most important growth-limiting factor for plants in acid soils (Foy, 1988; Carver and Ownby, 1995; Jayasundara *et al.*, 1998). The most prominent symptom is inhibition of root growth and affected roots are usually stubby with reduced growth of the main axis and inhibited lateral root formation (Foy, 1988). The impedance of both cell elongation and cell division results in inhibition of root growth (Kochian, 1995). Since root growth is restricted, the ability of the plant to explore the soil volume for nutrients and water is much reduced. Hence, nutrient and/or water stresses are common in plants suffering from Al toxicity (Haynes and Mokolobate, 2001). Aluminium toxicity also interferes directly with active ion uptake processes functioning across the root-cell plasma membrane (Kochian, 1995; Wright, 1989). The mechanism of the Al - P interaction is thought to be an adsorption – precipitation reaction between Al and P at the root surface or in the root free space, i.e. cell walls (McCormick & Borden, 1974; Naidoo *et al.*, 1978). The P may be adsorbed by hydroxy-Al already precipitated in the root free space or the P may be precipitated as insoluble aluminium phosphates; both occurrences are likely (Haynes and Mokolobate, 2001). The practical result is that P deficiency symptoms are common in plants suffering from Al toxicity (Foy, 1988; Haynes, 1984). Thus, amelioration of Al toxicity by liming characteristically results in greatly increased P uptake by plants even though the availability of soil P may be unchanged or even decreased (Haynes, 1982). Although not as widespread as aluminium toxicity, Mn toxicity is a serious problem for plants in certain acid soils with a high content of Mn- containing minerals (Brady and Weil, 2004). Unlike Al, it is an essential plant nutrient but is toxic when taken up in excessive quantities. Mn toxicity is common at pH (H_2O) levels as high as 5.6 (Brady and Weil, 2004).

2.2.3. Deficiencies of P, Ca, Mg and K in acid soils (acid soil infertility

Soils become acidic when a considerable portion of the cation exchange capacity is filled with H^+ and $A1^{3+}$, instead of the basic cations, Ca^{2+}, Mg^{2+}, K^+, and Na^+ (Adams, 1984). H^+ and Al^{3+} replace the basic cations from the exchange complex and they can be leached deep into the soil profile or groundwater (Adams, 1984). This results into deficiencies of basic cations in the upper horizon.

2.2.4 Phosphorus availability in soils and its functions in plants

Soil P is present in the soil as mineral or inorganic P (P_i) and organic P (P_o) forms, usually in amounts ranging from 0.1 % to 0.4 %. According to Okalebo (1987), values of upto 0.7 % total P have been found in some arable soils in East Africa. In plant nutrition, extractable P i.e. the portion of P in soil that can be taken up by plants, is more important than the total P. The quantity of P in solution in most soils is always small, about 0.1- 0.5 mg kg^{-1} (Okalebo, 2009). However, Beckwith (1965) concluded from P sorption studies that successful growth of plants in soils would require a P concentration of approximately 0.2 mg kg^{-1}. P plays a series of functions in the plant and is one of the essential nutrients required for plant growth and development. It has functions of a structural nature in macromolecules such as nucleic acids and of energy transfer in metabolic pathways of biosynthesis and degradation (Brady and Weil, 2004). P stimulates the development of roots which proliferate extensively in areas with higher P concentration. It is also needed in the final growth stages of a plant for seed filling and fruit formation.

Phosphorus is fairly mobile in plants and will move from older to younger plant tissues (Russell, 1973; Van Straaten, 2007). The concentration of P in soil solution is usually very small and must be replenished if the supply to plants is to be adequate (Wild, 1988; Okalebo, 2009). In many tropical regions, Kenya included, low P reserves in soils have resulted from long periods of intensive leaching, soil erosion and weathering and the low P status of the parent rocks, such as granite, rhyollite (acidic) (Okalebo, 2009). In addition, human – induced P depletion, known to contribute to declining food security, is through continuous removal of nutrients from crop harvests and residues (Sanchez *et al.,* 1997). At low pH, large quantities of Al and Fe hydroxides, which have the ability to adsorb P onto their surfaces, are present in soils. Thus much of the added P is fixed and is not readily available for crop use. However, as the pH increases, the activity of the reactants is decreased with P solubility being maximum at pH range of 5.5 – 6.5. Above pH 7.0, the ions of Ca and Mg, as well as the carbonates of these metals in the soil, tend to precipitate the added P and its availability decreases (Tisdale and Werner, 1961).

2.3 Crop tolerance to soil acidity

From past research, it is clear that there are two distinct classes of Al tolerance mechanisms: those that operate to exclude Al from the root apex and those that allow the plant to tolerate Al accumulation in the root and shoot symplasm (Taylor, 1988; Carver and Ownby, 1995; Kochian, 1995). It has been demonstrated that 50-70% of total Al might be present in the symplasm (Lazof *et al.,* 1994) and that Al can be present in the symplasm after only 30 minutes' exposure to a solution containing Al (Lazof *et al.,* 1994). The understanding of the mechanisms and genetics of Al tolerance has advanced considerably and traditional screening and breeding programmes have resulted in considerable success over the years (Vitorello *et al.,* 2005). Results from studies provide very strong evidence that Al- tolerant genotypes of wheat, maize, soybean and common bean, among others, exclude Al from roots by excretion of organic acids e.g. oxalate, malic and citric that chelate Al (Ma, 2000; Ma *et al.,* 2001; Ryan *et al.,* 2001; Kochian *et al.,* 2002). In cowpea, root cap mucilage was shown to bind Al and removal of mucilage increased the sensitivity of roots to Al (Horst *et al.*, 1982), while in maize, the mucilage from the roots has been shown to bind Al (Li *et al.*, 2000) but did not protect roots from Al toxicity.

2.4 Management of soil acidity

Several methods have been used to manage soil acidity. These include use of soil amendments that counteract the effects of soil acidity or using crops that are tolerant to high levels of exchangeable Al (Biswas and Mukherjee, 1994). Young (1989) also reported the use of mulch from agroforestry tree species, burning of sites to produce ash and use of animal wastes such as poultry manure. However, in most cases these materials are too bulky, and variable in quality (Probert *et al.,* 1992; Woomer *et al.*, 1999) and are always not available in adequate amounts desired. Agricultural lime, PRs and fertilizers that contain Ca and Mg have a liming potential which has not been fully tapped, therefore need exists to demonstrate the usefulness of these materials to farmers (Sanginga and Woomer, 2009; Okalebo, 2009). Maize breeding programs have also developed germplasm tolerant to Al toxicity and low P (Parentoni *et al*., 2006: Donswell *et al.,* 1996). These genotypes have high P use efficiency even from sparingly soluble P forms. A lot of effort has been made towards breeding for tolerance to Al toxicity in Kenya. However, there are no commercial maize germplasm available to farmers that are tolerant to high Al toxicity (Ligeyo *et al.*, 2006). Therefore, the need exists to use other soil acidity management options to increase maize yields in western Kenya.

2.4.1 Agricultural liming materials

To decrease soil acidity (raise pH), the soil is usually amended with alkaline materials that provide conjugated bases of weak acids. Examples of such conjugated bases include carbonate (CO_3^-), hydroxide and silicates (SiO_3^{2-}), (Brady and Weil, 2004). These conjugated bases are anions that are capable of consuming (reacting with) H^+ ions to form weak acids (such as water) figure 1.

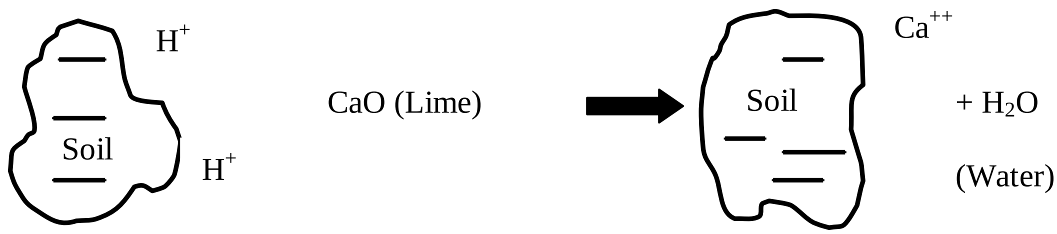

Figure 1: Lime reaction in acid soil to form weak acids (water)

These bases are most commonly supplied in their calcium or magnesium forms and are referred to as agricultural limes. Some liming materials contain carbonates, oxides or hydroxides of alkaline earth metals (e.g. Ca or Mg oxides), which form hydroxide ions in water (Brady and Weil, 2004). The purpose of liming is to change the chemical make-up of a substantial part of the root zone. Therefore, lime must be added in large enough quantities to chemically react with a large volume of soil (Brady and Weil, 2004).

2.4.1.1 Lime placement and its residual effect

Because of its gradual reaction effects, lime should be broadcast several days or weeks before planting the crop. Liming will be most beneficial to acid sensitive plants if as much as possible of the root environment is altered (Brady and Weil, 2004). It is economically and physically feasible to incorporate lime into only the upper 15 to 20 cm of soil (Sanchez, 1976; Brady and Weil, 2004). This is because the Ca^{2+} ions provided by lime replace acid cations on the exchange complex and do not move readily down the profile. Thus, the effect of lime is mainly limited to the soil layer into which the material is incorporated.

Liming, although a relatively costly remedial treatment initially, is the most effective solution for the problem of soil acidity (Ukrainetz 1984; Mahli *et al*. 1995). An important consideration in the economics of liming is the length of time the effect will last. The residual liming effect is dependent on the soil's buffer capacity (organic matter and texture) and management practices, especially application of ammonium based nitrogen (N) fertilizers and the extent of removal of cations (mainly calcium) from the soil by leaching and cropping (Robertson 1982; Beckie and Ukrainetz, 1995). However, subsoil acidity limits crop yields even when the plough layer is adequately limed (Haynes, 1984) and deep placement of lime below the normal plough layer is both costly and undesirable. Therefore, amelioration of subsoil acidity will depend on leaching of surface-applied amendments. Cifu *et al.,* (2004) reported that the decline in subsoil acidity occurred 4 years after liming, and thereafter the effect was strengthened with time. In an experiment carried out in Mata, Rwanda, effects of 2 t ha^{-1} lime remained significant up to 3 – 4 cropping seasons (Rutunga and Neel, 2006). Nekesa (2007) also reported that lime increased pH > 5.5 and maintained the soil pH to almost stable values for two cropping seasons with positive effect that was manifested in good crop yields. In a study by Kisinyo (2011), it was reported that it was necessary to reapply 2 t/ha lime after a period of about 2 years, because at this time the pH levels had dropped below the critical level of 5.5.

2.4.2 Phosphate rocks

The phosphate rocks (PRs) occurring in East and Southern Africa can simultaneously be used as liming materials as well as sources of P (Van Kauwenburgh, 1991; Nekesa, 2007). PR minerals occur in three groups: the Fe and Al phosphates which include wavellite, variscite and strengite; the calcium – iron – aluminium phosphate and the apatites. Le Mare (1991) reported that most apatites are complex molecules that contain varying amounts of sodium and magnesium instead of calcium; carbonate, instead of phosphate and hydroxyl, instead of fluoride in the crystal structure. The substitution of phosphate by carbonate is most important because the effect of apatite in crops is greater as the ratio of carbonate to phosphate increases within certain limits. The substitution of the fluoride by hydroxy ions also increases the effect of apatite on crop yield (Van Kauwenburgh, 1991). Other silicates found in sedimentary PRs can include feldspars and micas (biotite and muscovite). Clay minerals found in sedimentary PRs include illite, kaolinite, smectites and palygorskite/sepiolite. The success in the use of PR for direct application in SSA is limited and experiences with less reactive PR have discouraged many farmers (Sanginga and Woomer, 2009). However, readily dissolving PRs may be applied to soils after crushing and grinding as this result into positive crop response (Szilas *et al.,* 2006; Nekesa, 2007).

2.4.2.1 Solubility of phosphate rocks

The soil properties that favour the dissolution of PR are, soil acidity ($pH < 5.5$), low solution concentration of Ca ions, low P levels and high organic-matter content among others (Bolan *et al.,* 1990; Smalberger *et al.,* 2006; Van Straaten, 2002). This may be illustrated by the dissolution equilibrium of a fluorapatite:

$$Ca_{10}(PO_4)_6F_2 + 12H_2O \leftrightarrow 10Ca^{2+} + 6H_2PO_4^- + 2F^- + 12OH^-$$

(Phosphate rock) (Water) (Dissociation products)

Source: Szilas *et al.* (2006)

According to this equation, the equilibrium shifts to the right i.e. the apatite dissolves with increased H^+ ions (decreased pH) and decreased Ca and phosphate concentrations. Calcium in solution is in equilibrium with exchangeable Ca i.e. dissolved Ca decreases when exchangeable Ca decreases (Borggaard and Elberling, 2004). For continual dissolution of PR, it is important that the Ca ion be removed or that its concentration in soil solution be maintained at a lower level than that in the film surrounding the dissolving PR particle. It is possible to achieve these outcomes if there are adequate soil cation exchange sites available to adsorb the Ca ions released from the PR, or if Ca is leached away from the site of PR dissolution. Perrott (2003) reported that high exchangeable magnesium (Mg) in soils may also enhance PR dissolution. Soil organic matter also increases PR dissolution (Szilas *et al.*, 2006). This seems to arise from: (i) the high cation exchange capacity of organic matter; (ii) the formation of Ca-organic-matter complexes; and (iii) organic acids dissolving PR and blocking soil P sorption sites (Chien *et al.*, 1990). Higher moisture content enhances apatite dissolution because of increased leaching or translocation of reaction products, which in turn causes Ca and P concentrations to decline. Similarly, phosphate adsorption decreases dissolved phosphate and shifts the equation to the right (Szilas *et al.*, 2006). The removal of Ca^{2+} gives the PR a liming potential and also provides Ca^{2+} to the plants (Sikora and Giordano, 1993).

2.4.2.2 Residual effect of PR

Khasawneh and Doll (1978) reported that soils which have been fertilized with PR fertilizer may contain residual fertilizer for years after application, because only a portion (between about 5-40%) dissolves quickly in weeks and the remainder dissolves slowly in years (Symth and Sanchez, 1982; Hughes and Gilkes, 1986). Research results also show that one time large application of PR has positive residual effects on crop yields during several consecutive cropping seasons, which justifies the use of PR to improve the soil's P status and reduce acidity (Buresh *et al.,* 1997; Ndung'u *et al.,* 2006). Noordin (2002) reported effects of up to 10 cropping seasons from MPR whereas Ndung'u *et al.,* (2006) reported residual effects of upto three years from modest rate of 60 kg P ha^{-1} as MPR applied to ferralsols in western Kenya. Subsequently, Nekesa (2007) reported that MPR increased soil pH to values greater than 5.5 and maintained the pH for two consecutive cropping seasons.

2.5 Maize (*Zea mays L.*)

Maize originated from the tropics of Central America. It was domesticated from the wild Teosinte, Zea mexicana (Guantai *et al.,* 2007). Early explorers spread it to other countries in the 16th and 17th centuries. Maize belongs to the family *Graminaceae* and the tribe *Maydeae*, which has two main genera *Zea* and *Tripsacum*. Maize is the third most important cereal crop in the world, in terms of area cultivated, after wheat and rice. It is the highest yielding cereal with a world average of 4.3 t ha^{-1} (World Grain, 2000). It is also produced as fodder, and the grain is ground and mixed with minerals and other materials to make livestock and poultry feed concentrate. In Kenya, it is the staple food for most communities. It provides calories to over 85% of the Kenyan population (Guantai *et al.,* 2007). It does well at altitude range of 100 to 2,900 metres above sea level and generally performs best under optimal soil pH of 5.5 – 6.0 and optimal conditions of temperature, and rainfall (Guantai *et al.*, 2007).

In Kenya, maize production increased marginally from 26.2 million bags in 2008 by 3.2 % to record a total of 27.1 million bags in 2009. However, yields per ha remained low at about 14.4 bags per ha. The projected consumption level that year was 36.0 million bags thus necessitating imports to cover the deficit (Ministry of Agriculture , Kenya, 2010). Over 95% of the total farming community in western Kenya is smallholder who often harvest maize yields below 1 t ha^{-1} $season^{-1}$ (Nekesa et al., 1999; Sanchez et al., 1997), a factor that is attributed to N and P deficiencies and soil acidity. This production is enough to feed smallholder farmers for a period of four months in a year and often the farmers purchase more from the market during the remaining months or endure hunger periods (Sanchez *et al.*, 1997).

2.6 Economic analysis

When an agricultural technology/ project is introduced, economic analysis is undertaken to compare costs with benefits and to establish which among the technology has a satisfactory return. Costs of agricultural projects include labour, land, emergency allowances and physical goods such as fertilizers, pesticides, quality seeds etc. Emergency allowances are included in budgeting to accommodate adjustments due to price changes or any other cost that was unanticipated. Increased physical production is the most frequent benefit of agricultural projects (CIMMYT, 1988). The values of cost and benefits are usually identified based on the market prices of inputs and outputs by going out into the market and determining the actual prices. When costs and benefits have been identified, priced and valued, then analysts can determine which among the many projects to accept or reject. According to Gittinger (1995), the use of discounting approach is the most appropriate to evaluate projects that last several years and have different future costs and benefits. The three discounting methods recommended for evaluation of farm projects include; gross field benefit (GFB), net field benefits (NFB) and marginal rate of returns (MRR). MRR was used in this study.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Site description

Field studies were conducted in two counties in western Kenya, viz, Siaya and Kakamega

3.1.1 Siaya County

The experiment was conducted at Mr. Isaac Ochieng (Sihay, 00.22762°N 034.26279°E) and Mr. Jacob Owoko's (Got Nanga, 00.22422°N 034.24244°E) farms. The altitude varies from 1,140 m to 1,400 m above sea level. Siaya district receives a bimodal rainfall pattern with long rains starting mid-March to June with the peak in April and May. The short rains start in September to November with a peak in October. The average annual rainfall ranges from 800 – 2,000 mm, while the annual mean maximum temperature ranges between 27° and 30°C and the annual minimum temperature varies between 15° and 17°C (Jaetzold *et al.*, 2006; Government of Kenya, 1997). The soils of this district are well drained, deep and friable, but some places are shallow lying over petroferric layer (Murram). The predominant soils are Orthic acrisols

3.1.2 Kakamega County

The experiment was carried out on Mr. Phanuel Atsangu (Chimoroni, Latitude 00° 26' and 00° 52' N and longitude 34° 52' and 15°E) and Peter Burudi's (Tumbeni) farms in Kabras Division. Kabras Division in western Kenya is located between longitudes 34° 52' and 15°E and latitudes 00° 26' and 00° 52' N. It rises between altitudes of 1300 to 1900 m above sea level. The area receives bimodal rainfall of about 2000 mm per annum and a mean minimum and maximum temperature of 8° and 25°C respectively (Jaetzold *et al.*, 2006; Republic of

Kenya, 1997). The area has an average population density of 700 person's km^{-2}. The soils are highly weathered clay loams classified as Ferralo-humic acrisols.

3.2. Site characterization

Profile pits of 1 m x 1 m x 1 m were dug out (see plate 1 and 2) in the study sites and described. Soil samples from each horizon were taken and analyzed for Ca, Mg, K and exchangeable acidity according to methods in Okalebo *et al.*, (2002). This was to show the distribution of these cations down the profile as a result of weathering process over millennia.

Plate 1: Soil profile pit used to describe the soils at Got Nanga. (Source: Omenyo, 2013)

Plate 2: Soil profile pit used to describe the soils at Chimoroni. (Source: Omenyo, 2013)

3.3 Description of materials used

3.3.1 Athi River lime

It is popularly referred to as Calmax. It is dull white to cream fine grade calcium, with low magnesium content mined by Athi River Limited, Nairobi from calcitic limestone (Table 1).

Table 1: Chemical composition of Calmax

Compound	**% in Calmax**
$CaCO_3$	93.5
CaO	45
MgO	2.4
Al_2O_3	0.44
K_2O	0.01
Na_2O	0.09

Source: Athi River Company Limited, 2010

3.3.2 Koru (Homa) lime

Koru lime, also known as Super calcium fertilizer, is a mixture of calcium hydroxide, calcium oxide and calcium carbonate, a by – product of the hydration plant at Homa Mining Company in Koru, Kenya (Table 2).

Table 2: Chemical composition of Koru lime

Compound	% in Koru lime
$CaCO_3$	78.58
CaO (burnt lime)	20.8
Fe_2O_3	0.29
Al_2O_3	1.2
MgO	1.06
SiO_2	0.42

(Source: Homa Lime Mining Company, 2010)

3.3.3 Mavuno fertilizer

Mavuno fertilizer is manufactured by Athi River Mining Company Limited at its factory based at Athi River, Kenya in the outskirts of Nairobi since 2003. It is a blended fertilizer containing 10 essential plant nutrients. The fertilizer comes in two forms of “planting” and “top dressing”.

The Essential Nutrients contained in MAVUNO planting are:

- Nitrogen (N) - 10%
- Phosphorous (P_2O_5) - 26%
- Potassium (K_2O) - 10%
- Sulphur (SO_4) - 4%
- Calcium (CaO) - 10%
- Magnesium (MgO) - 4%

Plus appropriate additions of other Trace Elements like:

- Zinc
- Copper
- Molybdenum
- Boron

Mavuno top dressing fertilizer on the other hand is composed of nitrogen (26 % N), calcium and sulphur.

3.3.4 Minjingu Phosphate Rock (MPR)

The Minjingu phosphate rock deposit is located in the eastern Rift Valley in the northeastern Tanzania near Lake Manyara around the foot-slopes of a small inselberg that served as a resting/nesting place for large bird colony sometimes during Pleistocene (Szilas, 2002). The deposit consists of locally so-called hard and soft MPR. The two MPRs are formed similarly but due to its lower position in landscape, soft MPR was submerged in saline L. Manyara water for longer periods than hard MPR, while the hard MPR must have been exposed to alteration by weathering (Msolla *et al.,* 2005, Szilas, 2002). The hard MPR occurs in layers of somewhat silica-cemented phosphates (apatite) mixed with clays. The soft MPR is present as white, porous phosphate (apatite) beds interlayered with sandy, clayey, and marly sediments. MPRs differ in physical properties. The soft MPR has a fine texture and friable consistence, while the hard MPR is massive and occurs as sandy conglomeratic and silicified rock (Szilas, 2002). Current and previous production, has concentrated on the soft ore. The ore is processed by dry beneficiation, which involves drying, fine grinding, screening and size classification (ICRAF, 1999; Szilas et al., 2006). The final product contains 13.3% P, 38.0% CaO, 3.5% F and 3.2% Si (Szilas, 2002). According to Szilas et al., (2006), a positive crop response to directly applied MPR is expected on soils with acidic pH, low exchangeable Ca, little available P and high phosphate adsorption capacity in humid areas.

3.3.5 Triple Superphosphate

Triple superphosphate (TSP) became extensively used in the 20th century as one of the first high analysis P fertilizers. Theoretically, it is known as calcium dihydrogen phosphate and as monocalcium phosphate, [$Ca(H_2PO_4).2H_2O$] (www.ipni.net/specifics). It is an exceptional P source, but its use has deteriorated as other P fertilizers have become more popular. Granular TSP is commonly produced by reacting finely ground phosphate rock with liquid phosphoric acid in a cone-type mixer. The resulting slurry is sprayed as a coating onto small particles to build granules of the desired size. The product is allowed to cure for several weeks as the chemical reactions are slowly completed (www.ipni.net/specifics). The chemistry and process of the reaction will vary somewhat depending on the properties of the phosphate rock

Chemical properties

Chemical formula: $Ca(H_2PO_4).2H_2O$

Fertilizer analysis: 46 % P_2O_5 (0-46-0), 15% Ca

Water-soluble P: Generally > 90 %

Solution pH 1 to 3

Source: www.ipni.net/specifics

3.3.6 Calcium Ammonium Nitrate

Calcium ammonium nitrate (CAN) 27 % N, is a highly efficient nitrogen fertilizer with calcium. It contains nitrogen in both the ammoniacal (NH^{+}) and nitric (NO^{3+}) forms to provide plant nutrition during the plant growing period (www.uralchem.com).

3.4 Soil sampling and preparation

For each of the experimental sites, surface soil (from 0-15 cm) was collected from 15 random sampling points, air dried for a period of about one week and passed through a 2 mm sieve, to determine soil pH, particle size, soil available P (Olsen P), exchangeable bases (Ca^{2+}, K^{+}, Mg^{2+} and Na^{+}) and exchangeable acidity (H^{+} and Al^{3+}). The soils were further ground and passed through a 0.02 mm (60 mesh) sieve to determine organic carbon (C %) and total (N %) contents. These parameters were also used for initial characterization of the study sites. After treatment application, soil samples were collected again as described above at different time intervals (days after planting – DAP) during the growing period, so as to monitor changes in pH and available P which were determined in the lab according to the methods described by Okalebo *et al.,* (2002).

3.5 Field experiments

Two parallel field experiments were carried out to determine effective and affordable rate of lime and P fertilizer for the majority of smallholder farmers in western Kenya.

3.5.1 Experimental treatments and design

Experiment 1: The treatments were applied in a split plot design as per Appendix 5 layout on page 134 (i.e. two factors, P and lime, P at two levels of 0 and 26 kg P ha^{-1} (FURP, 1994) while lime was added at five levels, L1 (0), L2 (KL1), L3 (KL2), L4 (AL1), L5 (AL2). This experiment determined soil pH, P availability and maize yield response to a combination of lime and P application.

Experiment 2: Split plot layout as per experimental layout given in Appendix 5 on page 134 (P at 26 and 52 kg P ha $^{-1}$ while lime was at 4 levels L1 (KL), L2 (AL), L3 (MPR), L4 (MVN) with three replicates. The second experiment assessed the effects of different lime and P sources on soil pH, available P and maize yield. The main plot treatment was phosphorus, while the split plot treatments were the different liming materials. Practically, farmers apply these materials the way they are formulated, so the study assessed them the way they are. The two experiments were sited on the same farm and were carried out concurrently.

3.5.2 Statistical model for field experiments

$Xijk = \mu+\alpha i + \beta j + £ij +\lambda k + \gamma ik + £ijk$

Where;

μ = Overall mean

αi = Main treatment effect

βj = Block/ replication effect

£ij = Experimental error 1

λk = Sub – plot effect

γik = Interaction between main and sub – plot treatment effects

£ijk = Experimental error 2

NB: The statistical model was applicable for both experiment 1 and 2

Table 3a: Field treatment combination for experiment 1

Description				Description			
No.	Lime	**0 kg P/ha (P0)**	**Code**	**No.**	Lime	**26 kg P/ha (P1)**	**Code**
1	L0	Control. No inputs	**L0P0**	**6**	L0	26 kg P ha^{-1} as TSP (128 .5 kg TSP ha^{-1})	**L0P1**
2	KL1	312 kg CaO ha^{-1} (1.5 t ha^{-1} Koru lime)	**KL1P0**	**7**	KL1	26 kg P ha^{-1} as TSP + 312 kg CaO ha^{-1} Koru lime	**KL1P1**
3	AL1	312 kg CaO ha^{-1} (0.7 t ha^{-1} Athi River lime)	**AL1P0**	**8**	AL1	312 kg CaO ha^{-1} Athi River lime + 26 kg P ha^{-1} as TSP	**AL1P1**
4	KL2	624 kg CaO ha^{-1} (3.0 t ha^{-1} Koru lime)	**KL2P0**	**9**	KL2	26 kg P ha^{-1} as TSP + 624 kg CaO ha^{-1} as Koru lime	**KL2P1**
5	AL2	624 kg CaO ha^{-1} (1.4 t ha^{-1} Athi River lime)	**AL2P0**	**10**	AL2	624 kg CaO ha^{-1} Athi River lime + 26 kg P ha^{-1} as TSP	**AL2P1**

Table 3b: Field treatment combination for experiment 2

3.6 management of the field experiments

No.	Lime	**26 kg P/ha (P1)**	**Code**	**No.**	Lime	**52 kg P/ha (P2)**	**Code**
1	MVN	76 kg CaO ha^{-1} (0.24 t/ha Mavuno + 0.17 t/ha AL)	**MVN1**	**5**	MVN	152 kg ha^{-1}CaO (0.48 t ha-1Mavuno + 0.34 t ha-1 Athi lime)	**MVN2**
2	MPR	76kg CaO ha^{-1} (0.2 t/ha MPR)	**MPR1**	**6**	MPR	152 kg ha^{-1} CaO (0. 4 t ha-1 MPR)	**MPR2**
3	KL	76 kg CaO ha^{-1} Koru lime (0.4 t/ha lime)	**KL3P1**	**7**	KL	152 kg CaO ha^{-1} Koru lime (0.8 t ha-1 lime)	**KL4P2**
4	AL	76 kg CaO ha^{-1} Athi lime (0.2 t/ha lime)	**AL3P1**	**8**	KL2	152 kg CaO ha^{-1} Athi lime (0.4 t ha-1 lime)	**AL4P2**

3.6.1

Application of treatments

The treatments were applied simultaneously in plots measuring 4.5m x 4.8m in all the sites. To do away with the possible deficiency of the commonly limiting nitrogen, all experimental units received a blanket application of 75 kg N ha^{-1} (FURP, 1994) except for the absolute controls. The plots received nitrogen as CAN in two applications: 35 kg N ha^{-1} at planting and 40 kg N ha^{-1} as topdressing at mid vegetative stage. Agricultural lime, Minjingu

Phosphate Rock, Triple Super Phosphate and Mavuno fertilizers were broadcast evenly and incorporated using a hoe within 15 cm soil depth (plough layer).

3.6.2 Planting of maize

Hybrid 513 from Kenya Seed Company, which is recommended for medium altitude areas of Kenya (Guantai *et al.,* 2007), was planted in all the sites. Two seeds of maize were planted per hole and later thinned to one at two weeks after emergence. The crops were sprayed to control pests during growth. They were also weeded two times and harvested at physiological maturity for all the seasons in the sites. The yields of the crops were reported on dry weight basis.

Plate 3: Planting of maize at the start of 2010 LR. (Source: Omenyo, 2013)

3.6.3 Harvesting of maize

At physiological maturity (black layer seed formation), maize was harvested to obtain both cobs and biomass. Harvesting was done within centre rows of each plot in which two outer rows were discarded for every plot including one plant from the end of each row. In the harvested area (17.01 m^2), total cobs and stover samples fresh weights were measured and 10 ears or cobs of fresh maize were taken and recorded. The maize or sample cobs were sun-dried and later were hand shelled to obtain grain and stover weights which were recorded for computation of dry weights. The stover within the harvested area (17.01 m^2) was cut at ground level and its fresh weight taken. Sub – samples (about 4 stalks $plot^{-1}$) from the stover were randomly taken and cut into small pieces (2 – 3 cm) and mixed thoroughly after which fresh weight samples of about 200 g $plot^{-1}$ were obtained. All the maize cobs and stover samples were air- dried and their dry weights recorded which were used to compute yield per plot. The samples were ground and passed through a 0.02 mm sieve for plant tissue analysis to determine N, and P contents, and their uptake and use efficiencies.

3.7 The greenhouse experiment

A greenhouse study was conducted in an attempt to see the effects of liming and P fertilizer used in the field experiment at Sihay and Tumbeni without nitrogen as compared to Mavuno fertilizer that has the entire three – N, P and lime. This was carried out after it was realized that Mavuno performed better in the field at Sihay and Tumbeni. The greenhouse treatments laid in a completely randomized design using soils from the two sites were:

1. Control
2. 0.24 t ha^{-1} Mavuno fertilizer + 0.17 t ha^{-1} Athi River lime; 76 kg CaO ha^{-1} + 26 kg P ha^{-1}
3. 0.2 t ha^{-1} MPR; 76 kg CaO ha^{-1} + 26 kg P ha^{-1}

4. 76 kg CaO ha^{-1} Koru lime + 26 kg P ha^{-1} TSP
5. 76 kg CaO ha^{-1} Athi lime + 26 kg P ha^{-1} TSP
6. 152 kg CaO ha^{-1} Koru lime + 52 kg P ha^{-1} TSP
7. 152 kg CaO ha^{-1} Athi lime + 52 kg P ha^{-1} TSP
8. 0.40 t ha^{-1} MPR; 152 kg CaO ha^{-1} + 52 kg P ha^{-1}
9. 0.44 t ha^{-1} Mavuno fertilizer + 0.34 t ha^{-1} Athi lime; 152 kg CaO ha^{-1} + 52 kg P ha^{-1}

3.7.1 Statistical model for the greenhouse experiment

$Xi = \mu + \alpha i + £i$

Where;

μ = Overall mean

αi = Treatment effect

£i = Experimental error

Soils were collected randomly from various spots at the sites of the experiments (outside field experiments) both in Siaya and Kakamega North counties. The soils were air –dried, sieved through 5 mm mesh and weighed into all the pots at the quantity of 4 kg soil pot^{-1}. All the treatments without potassium (K), magnesium (Mg), sulphur (S) and zinc (Zn) received these nutrients in form of solutions except for K and S. Magnesium and zinc sulphate salts were dissolved and thoroughly mixed in a known quantity of water. Each pot then received equal amount of the salt solution depending on the rate received by Mavuno treatments. Three maize seeds were planted which were later thinned to one seedling. Soil/ pot water was maintained (distilled water) at field capacity for all treatments by regular watering and weeds were removed by hand. Plants were harvested at 6 weeks by cutting the maize tops at soil level. The harvested plants were oven dried at 70°C to a constant weight for 48 hours.

The dried samples were weighed and later ground and sieved through 0.02 mm mesh for total N and P contents. Soils were also sampled from each pot and analyzed for pH, Olsen P and Total N as described in Okalebo *et al.*, (2002).

3.8 Laboratory analysis

3.8.1. Soil particle size analysis by the hydrometer method

The particle size analysis of a soil estimates the percentage sand, silt and clay contents of the soil and is often reported as percentage by weight of oven-dry and organic matter-free soil. The analyses are usually performed on air-dry soil. Based on the proportions of different particle sizes, a soil textural category may be assigned to the sample. The first stage in particle size analysis was the dispersion of the soil into the individual particles. These are the sand (2.00 - 0.05 mm), silt (0.05 - 0.002 mm) and clay (< 0.002 mm) fractions. Individual soil particles are often bound into aggregates hence the requirement for dispersion. The hydrometer method of silt and clay measurement relies in the effects of particle size on the differential settling velocities within a water column.

3.8.2. Soil pH

Measurement of pH is expressed as the inverse log of the hydrogen ion concentration. The pH of the soil solution controls the form and solubility of many plant nutrients. Soil pH was measured on 2.5:1 soil water suspension on a glass electrode.

3.8.3 Extractable soil phosphorus: the Olsen method

The principle behind this method is that soil was extracted with 0.5 M solution of sodium bicarbonate. In calcareous, alkaline or neutral soils containing calcium phosphate, this extractant decreases the concentration of Ca in solution by precipitating Ca as $CaCO_3$. The result is an increase of the P concentration in the solution. In acid soils containing Al and Fe phosphate, the P concentration in the solution increases as the pH rises. Precipitation reactions in acid and calcareous soils are reduced to a minimum because the concentrations of Al, Ca and Fe remain at a low level in this extractant.

3.8.4 Total nitrogen and phosphorus in soils and plants

The content of total nitrogen and phosphorus was measured in a digest obtained by treating soil and plant sample with hydrogen peroxide + sulphuric acid + selenium and salicylic acid + Lithium sulphate. The principle took into account the possible loss of nitrates by coupling them with salicylic acid in an acid media to form 3-nitrosalicylic and or 4-nitrosalicylic. The compounds were reduced to their corresponding amino acid forms by the soil organic matter. The analysis of total nutrients required complete oxidation of organic matter. The hydrogen peroxide oxidized the organic matter while the selenium compound acted as catalyst for the process and the H_2SO_4 completed the digestion at elevated temperatures resulting from use of lithium sulphate.

3.8.5 Exchangeable cations in soils

Soil sample was extracted with an excess of 1 M NH_4OAc at pH 7 (ammonium acetate) solution such that the maximum exchange occurred between the NH_4 and the cations originally occupying exchange sites on the soil surface. The amounts of exchangeable sodium, potassium, calcium and magnesium in the extract were determined by flame photometry (Na and K) and by atomic absorption spectrophotometry (Ca and Mg). Lanthanum was added as a releasing agent to prevent formation of refactory compounds, which may interfere with the determinations (e.g. phosphate).

3.8.6 Determination of EDTA-soluble copper, iron, manganese and zinc in soil

Because of the low concentration in soils and plant requirement for micronutrients, it is necessary to accurately determine their levels in soils. Chelating agents such ethylenediaminetetraacetic acid (EDTA) was used in this determination (Vitro, 1955). A suspension of 1% EDTA and soil forms metal-chelate ionic complexes. These complexes, when subjected to an air–acetylene flame in the atomic absorption spectrophotometer are atomised and absorb radiation at element-specific wavelengths. This phenomenon formed the bases for the analysis of these trace elements.

3.8.7 Organic carbon content of soils

Organic carbon was determined by the sulphuric acid and aqueous potassium dichromate ($K_2Cr_2O_7$) mixture. After complete oxidation from the heat of solution and external heating (Nelson and Sommers, 1975), the unused or residual $K_2Cr_2O_7$ (in oxidation) was titrated against ferrous ammonium sulphate. The used $K_2Cr_2O_7$, the difference between added and residual $K_2Cr_2O_7$, gives a measure of organic C content of soil. The chemical reaction in the method is;

$$\mathbf{2Cr_2O_7^{2-} + 3C + 16\ H^+ \rightarrow 4Cr^{3+}\ 3CO_2 + 8\ H_2O}$$

3.9 Statistical Analysis

Crop yield, soil and plant data obtained were subjected to analysis of variance (ANOVA) with the Mixed Procedures using SAS. Means were separated by way of contrast. Correlations were done.

3.10 Nutrient use efficiency

According to Hussein (2009), a number of indices are usually used in agronomic research to evaluate the efficiency of the applied P and N fertilizers. This is principally to find out crop response to inputs. Nutrient use efficiency (NUE) is a function of the crop genotype, soil factors, types, method and time of application of the nutrient and environmental differences. In addition, the recovery fraction of added nutrient fertilizer depends on its losses, movement of the nutrient to plant roots including the rooting patterns from genotypes (Obura *et al*., 2003). NUE of a given fertilizer or organic source is useful in predicting crop response due to application of inputs. A number of approaches used to define NUE for nutrients such as P and N by crops (Van Cleemput *et al* 2008) are discussed below.

3.10.1 Agronomic (external) nutrient use efficiency

Agronomic efficiency (AE) is the amount of harvestable product e.g. kg of grain per kg of applied nutrient. It is expressed by the following equation:

$$AE = \frac{Y_f - Y_o}{Q_f}$$

Where AE is the agronomic efficiency, Y_f is crop yield (kg ha^{-1}) at a certain level of nutrient applied, Y_o is the yield of control treatment (no nutrient/ fertilizer) and Q_f is the rate of fertilizer applied (Van Cleempot et al., 2008).

3.10.2 Internal (physiological) nutrient use efficiency

It is a measure of the incremental yield above the control per unit nutrient absorbed by the plant. It is expressed by the equation:

$$= (Y_f - Y_o) / (U_f - U_o)$$

Where, Y_f is crop yield (kg ha^{-1}) at a certain level of nutrient applied, Y_o is the yield of control treatment, U_f is total nutrient uptake at a certain level of fertilization and U_o is total nutrient uptake by control. A large percentage recovery of added nutrient implies an efficient use of the nutrient by the plant.

3.10.3 Partial factor productivity (PFP)

It reflects crop yield per unit of nutrient applied. It measures the productivity of a cropping system in comparison to its nutrient input. It is determined by the following equation

$(Y_o/Q_f) + AE$

Where, Y_o is crop yield (kg/ha) in control treatment and Q_f is the rate of fertilizer nutrient applied.

3.11 Economic analysis

Partial budgeting (includes costs that vary from the control) was used to compare cost and benefits of treatments. The price of lime, TSP, CAN, MPR, Mavuno fertilizers, sacks or bags for storing maize, transport, harvesting, shelling of maize cobs, applying inputs and maize grain were determined through market surveys of each of the study sites. Yield data were adjusted downward by 10% since research has found out that farmers using the same technologies would obtain 10% yield even lower than those obtained by researcher (Kisinyo,2011). The discounted rate capital was determined at the rate of 10 % per season and was applied to cash costs only. The steps in partial budgeting used for calculating the net financial benefits, marginal rates of returns and gross field benefits are described below

Table 3c: Values used to calculate costs and benefits analysis (Kshs.) during 2010 LR to 2011 LR in all the sites

Amount of TSP at 26 P/kg/ha	130 kg /ha
Amount of TSP at 52 P/kg/ha	260 kg/ha
Amount of CAN at 75 N/kg/ha	288.46 kg/ha
Amount of Mavuno at 26 P/kg/ha	236 kg/ha
Amount of Mavuno at 52 P/kg/ha	472 kg/ha
Amount of MPR at 26 P/kg/ha	200 kg/ha
Amount of MPR at 52 P/kg/ha	400 kg/ha
Price of TSP/kg	77
Price of CAN/kg	50
Price of MPR/kg	50
Price of Mavuno/kg	68
Cost of transporting 50 kg fertilizer to homestead	70
Cost of 50 kg lime at factory gate	220
Cost of transporting 50 kg bag of Koru lime from factory to homesteac	80
Cost of 50 kg AL fertilizer	250
Cost of transporting 50 kg bag of Athi lime from factory to homestead	300
Unit cost of 90 kg grain storage bag	35
Labour costs	
Baseline cost of lime application per hactare	4707
Baseline application of TSP/CAN/MPR/Mavuno fertilizer/ha	576
Cost of harvesting 90 kg bag of maize	30
Cost of shelling 90 kg dry maize grain	40
Price of dry maize grain per kg	28
Opportunity cost of Capital (%)	10%

CHAPTER FOUR

RESULTS

4.1: Field experiments

4.1.1: Physical and chemical characteristics of the soils at the study sites prior to treatment applications

Soil properties at the experimental sites are presented in Table 4a. All the experimental sites had acidic soils with pH below 5.5 in Kakamega County. The soil at Tumbeni was extremely acidic, had low available soil P, moderate carbon contents and low exchangeable bases (Landon, 1984). The same applied to the soil at Chimoroni that was strongly acidic, with low available soil P, moderate carbon, high N contents and low exchangeable bases. In Siaya, sites had acidic soils. The Sihay site had strongly acidic soil, low available soil P, low exchangeable bases, moderate N and low carbon contents. At Got Nanga, the soil was moderately acidic. In all the soils across the two counties, micronutrient levels were low except for iron. The soils at Tumbeni, Sihay and Got Nanga were sandy clay loam, while that at Chimoroni was sandy loam classified as Ferralo humic acrisols

Table 4a: Initial surface (0 – 15 cm) soil properties at the study sites

	Siaya County		Kakamega North County	
Soil parameter	**Got Nanga**	**Sihay**	**Chimoroni**	**Tumbeni**
pH (1:2.5 soil: water)	5.49	4.92	4.63	4.36
Olsen P (mg kg-1)	9.6	2.4	3.5	3.0
% N	0.13	0.14	0.28	0.22
% C	1.5	1.3	2.3	2.5
C: N ratio	11:01	9:01	8:01	11:01
Exchangeable acidity (cmol /kg)	0.4	0.5	0.8	1.0
Exchangeable bases (cmol /kg)				
Ca	3.84	6.16	3.52	4.2
K	0.43	1.52	1.72	2.35
Mg	0.75	0.99	0.67	0.53
Micronutrients (cmol/kg)				
Zn	0.21	0.23	0.20	0.22
Fe	2.24	2.33	2.79	2.66
Cu	0.063	0.092	0.137	0.097
% Texture				
Sand	59	55	80	75
Clay	23	22	13	9
Silt	18	23	7	16
Textural class	Sandy clay loam	Sandy clay loam	Sandy loam	Sandy clay loam
FAO Soil Classification	Orthic Acrisol	Orthic Acrisol	Ferralo-humic Acrisol	Ferralo-humic Acrisol

4.1.2. Soil profile characterization of the study sites

Exchangeable cation analysis of each horizon showed these soils to have low exchangeable cations in the upper horizon, but the concentration increased down the profile as shown in the Tables 4b-e. In Chimoroni, however, the trend was different. There was a higher concentration of exchangeable cations in upper horizons than lower ones. Siaya soils are shallower compared to Kakamega soils. This is because at a depth of about 1 m, the C horizon is reached whereas in Kakamega, B horizon continues beyond 1 m depth. For exchangeable acidity, the opposite was observed. There was a decrease of Al^{3+} + H^{+} ions concentration down the profile.

Table 4b: Exchangeable cations down the profile as observed at Chimoroni site (Ferralo - humic acrisol)

Horizons	Calcium (cmol kg^{-1})	Magnesium (cmol kg^{-1})	Potassium (cmol kg^{-1})	Exchangeable acidity (cmol kg^{-1})
0-8 cm (A_p)	10.06	0.35	0.95	0.7
8 – 33 cm (A)	1.57	0.07	0.11	0.5
33 – 78 cm (AB)	3.13	0.22	0.16	0.6
78 – 99 cm (B)	0.67	0.32	0.05	0.4

Table 4c: Exchangeable cations down the profile as observed at Tumbeni site (Ferralo - humic acrisol)

Horizons	Calcium (cmol kg^{-1})	Magnesium (cmol kg^{-1})	Potassium (cmol kg^{-1})	Exchangeable acidity (cmol kg^{-1})
0 - 19 cm (A_p)	2.46	0.16	0.85	1.2
19 -49 cm (A)	3.35	0.02	0.31	0.9
49 - 59 cm (AB)	0.58	0.04	0.01	0.8
59 - 99 cm (B)	0.13	0.09	0.39	0.8

Table 4d: Exchangeable cations down the profile as observed at Sihay site (Orthic acrisol)

Horizons	Calcium (cmol kg^{-1})	Magnesium (cmol kg^{-1})	Potassium (cmol kg^{-1})	Exchangeable acidity (cmol kg^{-1})
0-25 cm (A_p)	14.65	0.55	0.81	0.5
25-66 cm (AB)	10.51	0.61	0.83	0.4
66-79 cm (B_1)	19.79	0.91	1.25	0.4
79+ cm (B_2)	19.45	1.64	2.85	0.3

Table 4e: Exchangeable cations down the profile as observed at Got Nanga site (Orthic acrisol)

Horizons	Calcium (cmol kg^{-1})	Magnesium (cmol kg^{-1})	Potassium (cmol kg^{-1})	Exchangeable acidity (cmol kg^{-1})
0-13 cm (A_p)	15.88	0.61	1.02	0.4
13-39 cm (AB)	52.44	0.56	2.36	0.3
39-78 cm (B)	40.47	1.5	2.26	0.3
78+ cm (C)	29.52	0.85	0.97	0.3

Results from experiment 1:

4.1.3. Direct and residual effect of lime and P fertilizer application on soil pH (0 – 15 cm depth)

The effects of lime on soil pH for three cropping seasons are shown in Figures 2a - 2d and Appendix 1. Soil pH increased with increasing rate of lime application. At Sihay, where 1.5 and 3 t ha^{-1} lime were applied, the highest peaks of pH 5.7 and 6.22 were reached in about

80 and 120 days, respectively. However, the pH dropped below the critical level of 5.5 in about 198 and 365 days where 1.5 and 3 t ha^{-1} lime was applied respectively. At Got Nanga, the highest peaks of pH 6.42 and 6.47 were reached in about 38 days where 1.5 and 3 t ha^{-1} lime was applied. The pH dropped below 5.5 in about 120 days where 1.5 t ha^{-1} lime was applied. However, 3 t ha^{-1} lime applications maintained soil pH above 5.5 for 3 cropping seasons (492 days). At this site, application of P fertilizer (TSP) increased soil pH above 5.5 and maintained this for three cropping seasons.

At Chimoroni, the highest peaks of 5.12 and 5.51 were reached in 147 days where 1.5 and 3 t ha^{-1} lime were applied respectively. At Tumbeni, where 1.5 and 3 t ha^{-1} lime were applied, the highest peaks of 4.96 and 5.25 were reached in about 147 and 80 days respectively. Application of lime at 1.5 or 3 t ha^{-1} did not increase soil pH above the critical levels of 5.5 at which Al toxicity becomes a problem, in these two sites of Kakamega County.

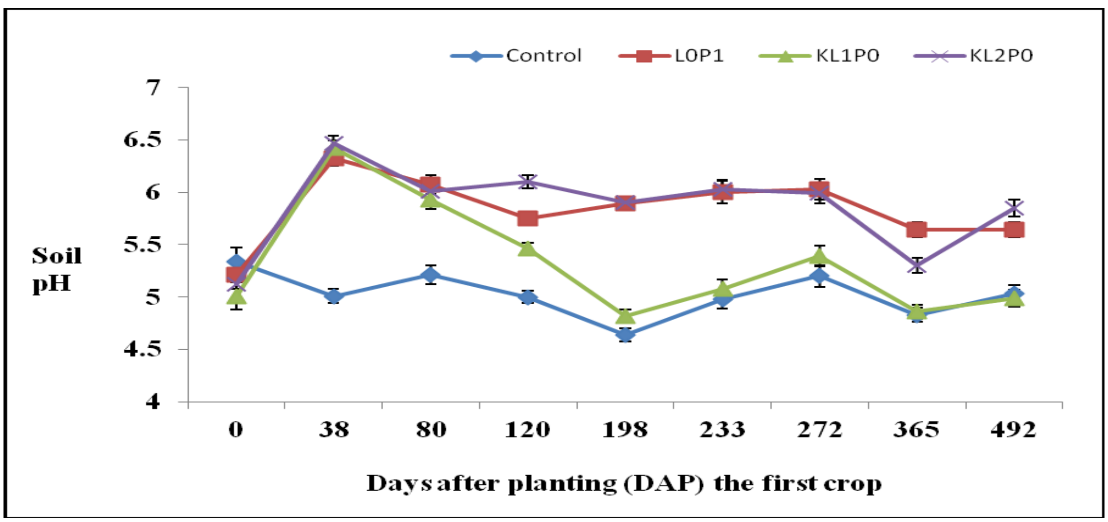

Figure 2a: Effect of lime and P application on soil pH (0 – 15 cm) during 2010 LR, SR and 2011 LR at Got Nanga site. *Where L0P1 = 26 kg P ha^{-1}, KL1P0= 1.5 t ha^{-1} lime as Koru, KL2P0 = 3 t ha^{-1} as Koru.*

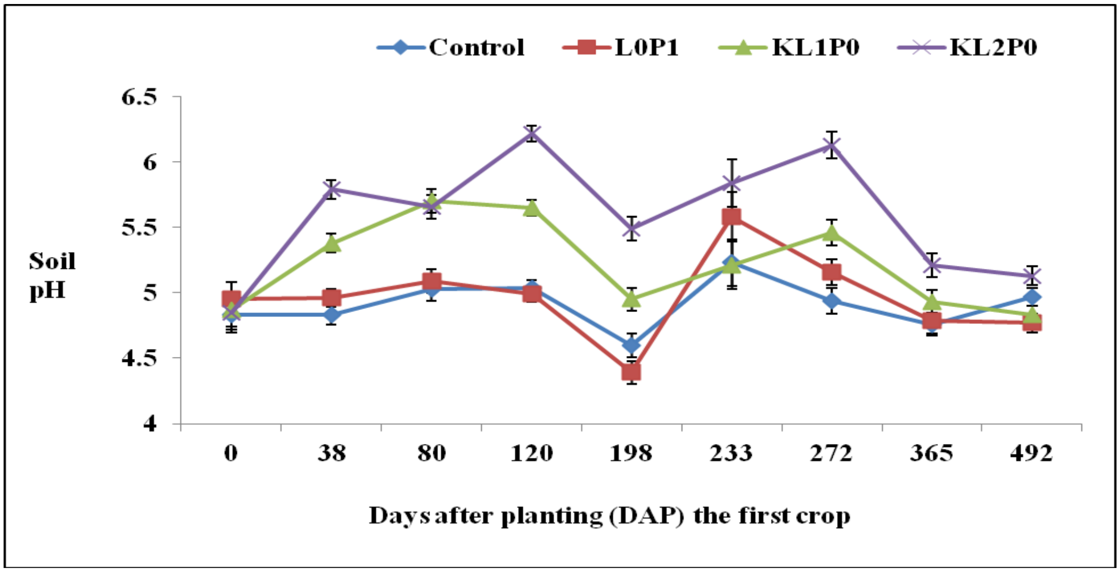

Figure 2b: Effect of lime and P application on soil pH (0 – 15 cm) during 2010 LR, SR and 2011 LR at Sihay site. *Where L0P1 = 26 kg P ha*$^{-1}$*, KL1P0= 1.5 t ha*$^{-1}$ *lime as Koru, KL2P0 = 3 t ha*$^{-1}$ *as Koru.*

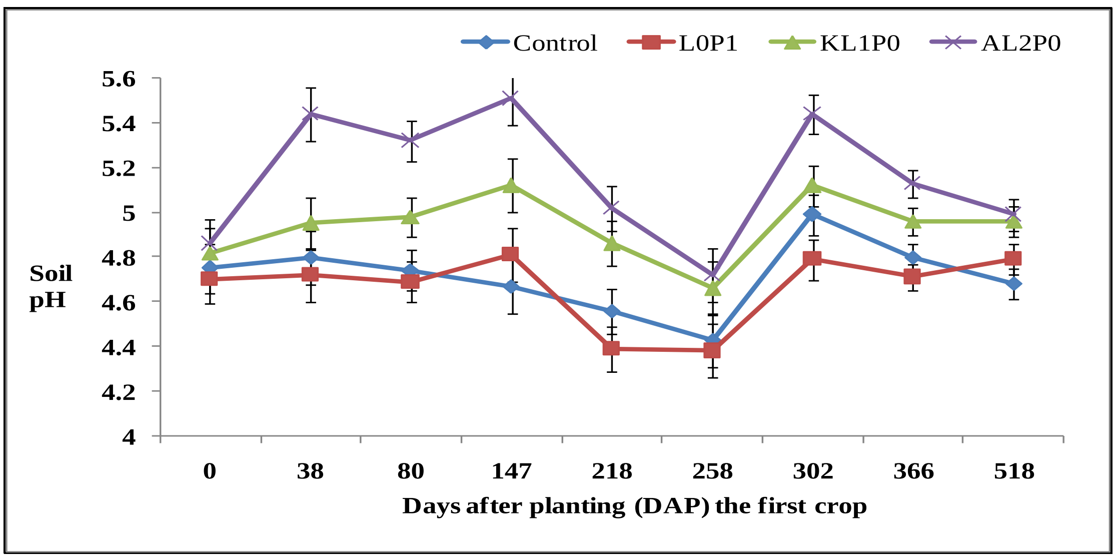

Figure 2c: Effect of lime and P application on soil pH (0 – 15 cm) during 2010 LR, SR and 2011 LR at Chimoroni site. *Where L0P1 = 26 kg P ha*$^{-1}$*, KL1P0= 1.5 t ha*$^{-1}$ *lime as Koru, AL2P0 = 1.4 t ha*$^{-1}$ *as Athi lime.*

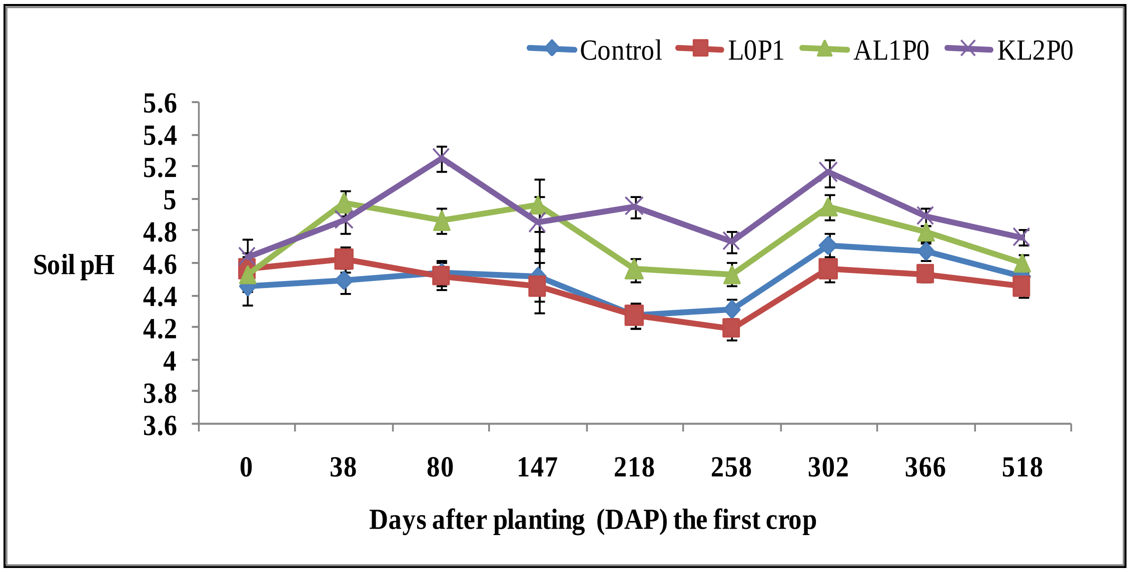

Figure 2d: Effect of lime and P on soil pH (0 – 15 cm) during 2010 LR, SR and 2011 LR at Tumbeni site. ***Where L0P1 = 26 kg P ha^{-1}, AL1P0= 0.7 t ha^{-1} lime as Athi, KL2P0 = 3 t ha^{-1} as Koru lime***

4.1.4. Site differences in terms of soil pH (0 – 15 cm) changes over time as influenced by lime applications

The Sihay site had higher soil pH values during the 2010 LR as influenced by lime application compared to Got Nanga (Fig. 2a). But this changed in the succeeding seasons as shown in Table 5a. Application of lime at 3 (Koru lime) and 1.4 (Athi lime) t ha^{-1} maintained the soil pH above 5.5 at Got Nanga during the three cropping seasons. At Sihay site, soil pH was above 5.5 for two cropping seasons. In Kakamega County, lime did increase soil pH above control during the three cropping seasons though the pH was < 5.5. Average soil pH at Chimoroni was generally higher than that of Tumbeni as shown in Table 5b.

Table 5a: Mean changes in soil pH (0 – 15 cm) as influenced by treatment application over time in Siaya county

SIAYA COUNTY													
		GOT NANGA						SIHAY					
		CONTROL	KL1	KL2	AL1	AL2	MEAN	CONTROL	KL1	KL2	AL1	AL2	MEAN
P0	2010 LR	5.00	5.46	6.10	5.35	5.91	**5.71**	5.04	5.65	6.22	5.43	6.01	**5.83**
	2010 SR	5.20	5.39	5.99	5.42	6.17	**5.74**	4.94	5.46	6.13	5.26	5.92	**5.69**
	2011 LR	5.03	4.99	5.85	5.01	5.77	**5.41**	4.97	4.83	5.13	4.86	5.00	**4.96**
	MEAN	**5.08**	**5.28**	**5.98**	**5.26**	**5.95**		**4.98**	**5.31**	**5.83**	**5.18**	**5.64**	

Table 5b: Mean changes in soil pH as influenced by lime application over time in Kakamega North county

Where KL1 and KL2, = 1.5 and 3 t ha^{-1} Koru lime. AL1 and AL2 = 0.7 and 1.4 t ha^{-1} Athi

KAKAMEGA NORTH COUNTY													
		CHIMORONI						TUMBENI					
		CONTROL	KL1	KL2	AL1	AL2	MEAN	CONTROL	KL1	KL2	AL1	AL2	MEAN
P0	2010 LR	4.67	5.12	5.48	5.07	5.51	**5.3**	4.52	4.62	4.85	4.96	4.67	**4.78**
	2010 SR	4.99	5.16	5.48	5.04	5.44	**5.28**	4.71	4.75	5.16	4.95	5.02	**4.97**
	2011 LR	4.68	4.96	5.07	4.83	4.99	**4.96**	4.51	4.67	4.76	4.60	4.58	**4.65**
	MEAN	**4.78**	**5.08**	**5.34**	**4.98**	**5.31**		**4.58**	**4.68**	**4.92**	**4.84**	**4.76**	

lime. P0 = 0 kg P/ha

4.1.5. Direct and residual effect of lime and P fertilizer application on available soil phosphorus

Analysis of the available soil P data during the 2010 LRs showed significant ($p < 0.01$) increase over time through application of both lime and P fertilizer at Sihay and Got Nanga sites in Siaya County. In Kakamega, application of lime significantly ($p < 0.05$) increased P availability at Chimoroni, while P application was significant ($p < 0.01$) in increasing available P at Tumbeni. However, at harvesting, treatments did not show any significant differences in all the sites. Available soil P increased from 0.9 mg kg^{-1} initially to 12.8 mg kg^{-1} at 80 DAP where Athi lime plus TSP (1.4 t ha^{-1} lime + 26 kg P ha^{-1}) were applied, whereas the control had a value of 1.1 mg kg^{-1} P at the same sampling time at Sihay as shown in Figures 3a – 3d. Application of Koru lime plus TSP (1.5 t ha^{-1} + 26 kg P ha^{-1}) increased extractable soil P from 0.6 mg kg^{-1} initially to 10.2 mg kg^{-1} 38 DAP. At Got Nanga, Koru lime (3 t ha^{-1} lime) increased extractable soil P from 7.3 to 14.7 mg kg^{-1} at 120 DAP. At this time, the control treatment had a value of 4.8 mg kg^{-1} P. At Chimoroni, extractable soil P increased from 4.9 to 8.1 mg kg^{-1} 120 DAP where Koru lime + TSP (3 t ha^{-1} lime + 26 kg P ha^{-1}) was applied. During 2010 SR, there was a significant ($p < 0.05$) P X lime interaction at Got Nanga site. However, lime and P application did not significantly affect available soil P at Sihay during this season.

Since, the experiment was to monitor residual effects of both lime and P, there was a reduction in the available soil P values during this season (2010 SR) in all sites. This season also experienced inadequate rainfall as shown in Appendix 4. Available soil P values fell from 11 to 3.5 mg kg^{-1} where Athi lime + TSP (1.4 t ha^{-1} lime + 26 kg P ha^{-1}) were applied. Same observation applied to Koru lime application (3 t ha^{-1} lime) that decreased from 5.7 to 4 mg kg^{-1} as opposed to the previous cropping season, where 3 t ha^{-1} Koru lime application had significantly increased extractable soil P at Got Nanga. Chimoroni farm also had reduced available soil P values during this season. For instance, 3 t ha^{-1} Koru lime application decreased from 9.5 to 3.2 mg kg^{-1} available P.

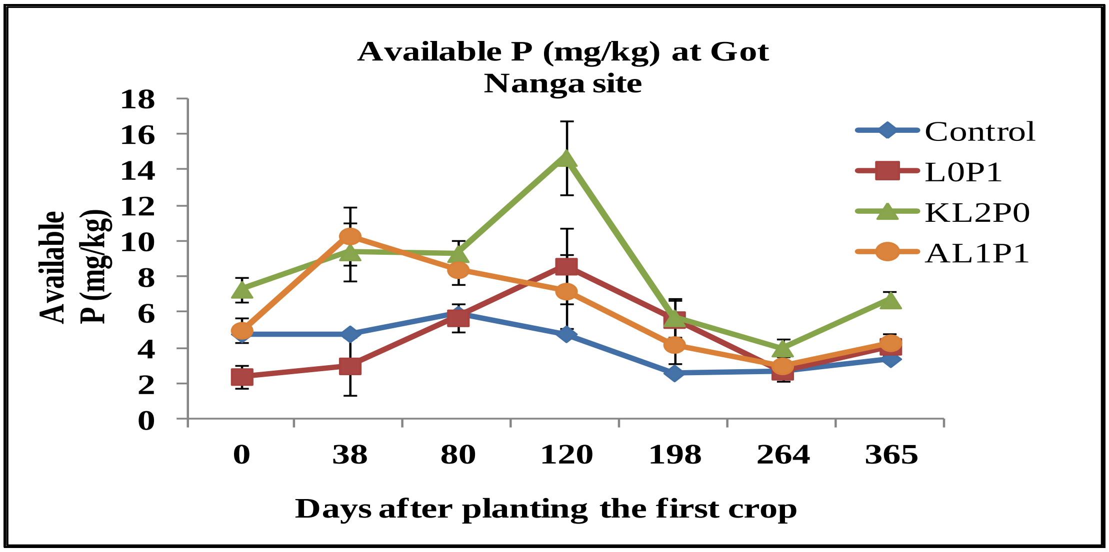

Figure 3a: Effect of lime and P application on available soil P (0 – 15 cm) during 2010 LR, SR and 2011 LR at Got Nanga site. *Where L0P1 = 26 kg P ha^{-1}, KL2P0= 3 t ha^{-1} lime as Koru , AL1P1 = 0.7t ha^{-1} Athi lime + 26 kg P ha^{-1}*

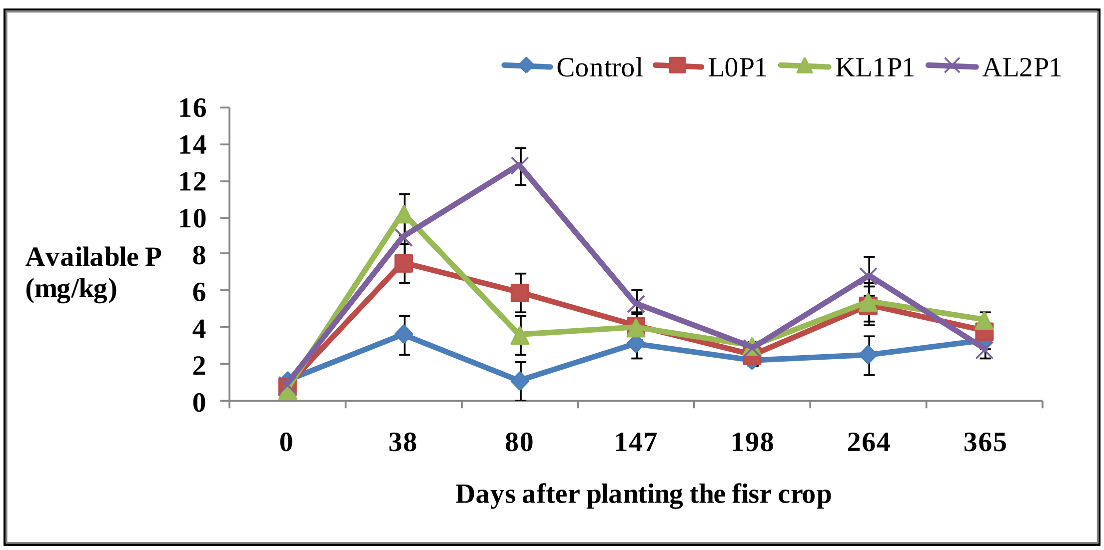

Figure 3b: Effect of lime and P application on available soil P (0 – 15 cm) during 2010 LR, SR and 2011 LR at Sihay site. *Where L0P1 = 26 kg P ha^{-1}, KL1P1= 1.5 t ha^{-1} lime as Koru + 26 kg P ha^{-1}, AL2P1 = 1.4 t ha^{-1} Athi lime + 26 kg P ha^{-1}*

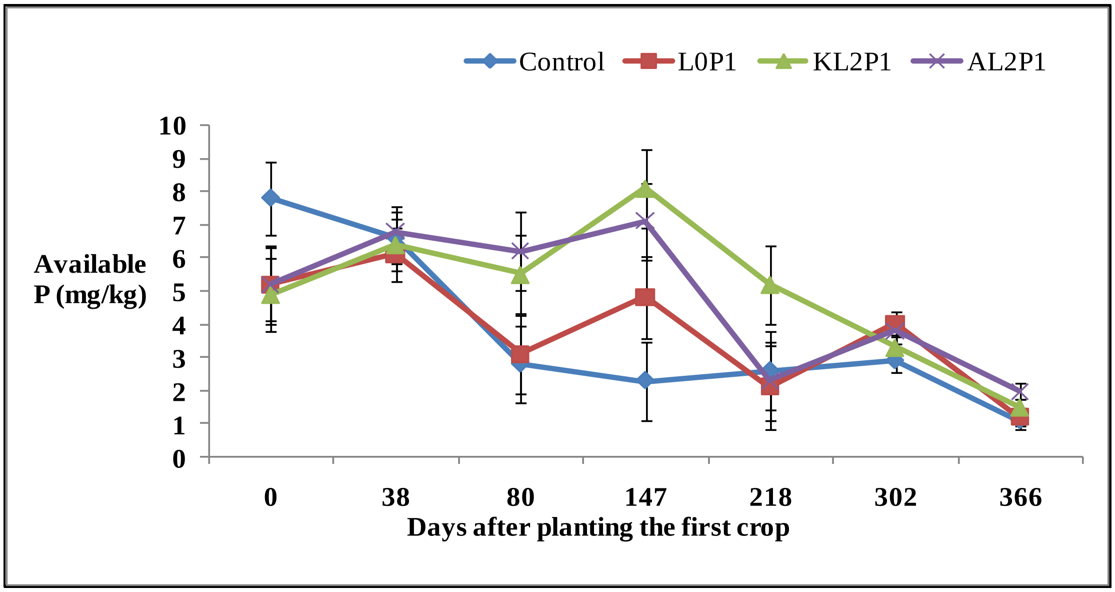

Figure 3c: Effect of lime and P application on available soil P (0 – 15 cm) during 2010 LR, SR and 2011 LR at Chimoroni site.

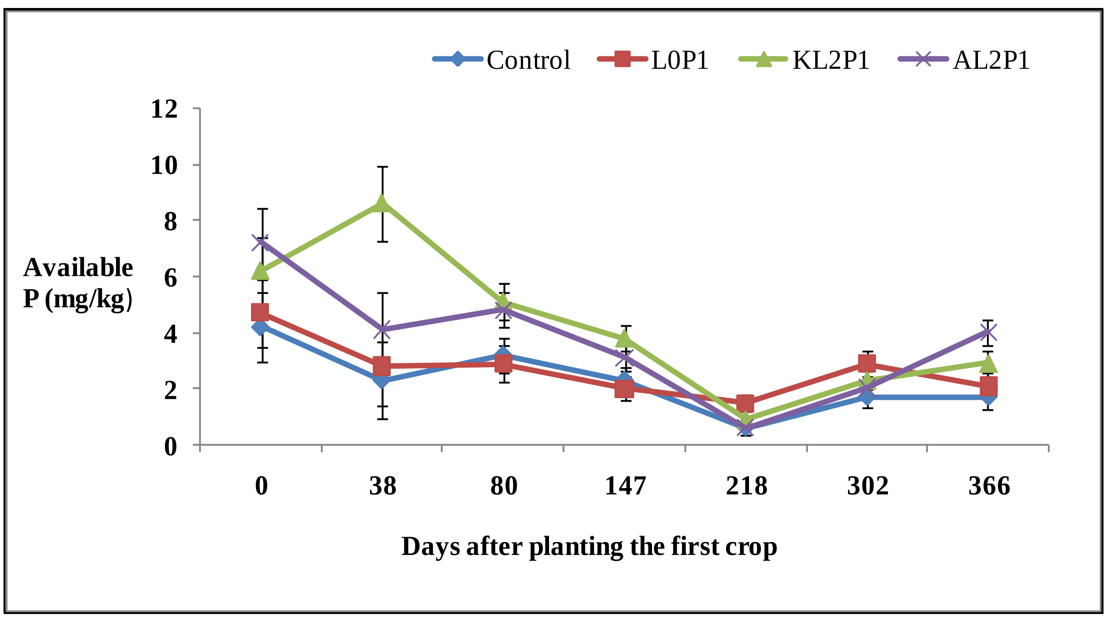

Figure 3d: Effect of lime and P application on available soil P (0 – 15 cm) during 2010 LR, SR and 2011 LR at Tumbeni site. *Where L0P1 = 26 kg P ha^{-1}, KL2P1= 3 t ha^{-1} lime as Koru + 26 kg P ha^{-1}, AL2P1 = 1.4 t ha^{-1} Athi lime + 26 kg P ha^{-1}*

4.1.6. Maize grain yield as affected by combination of lime and P during three cropping seasons.

Mean maize grain yields from all the treatments were generally higher in Siaya, giving 3.24, 1.81 and 2.65 t ha^{-1} compared to the yields of 2.77, 0.98 and 1.62 t ha^{-1} obtained in Kakamega North in the respective 3 cropping seasons (2010 LR, 2010 SR and 2011 LR). The treatment means for the 4 sites are presented in tables 6a – 6d. During 2010 LR, P x lime interaction significantly ($p<0.05$) increased maize grain yield at Got Nanga, while there was a significant P effect on grain yield at Sihay in Siaya district. In Kakamega North district, neither P nor lime significantly increased maize yield above the control during this season. Maize grain yield ranged from 1.04 t ha^{-1} in the control to 4.60 t ha^{-1} (0.7 t ha^{-1} Athi lime + 26 kg P ha^{-1}) treatment at Sihay site and 1.1 t ha^{-1} (1.5 t ha^{-1} Koru lime) to 3.81 t ha^{-1} (0.7 t ha^{-1} Athi lime + 26 kg P ha^{-1}) at Tumbeni. In the short rains of that year, maize grain yields were very low ranging from 0.60 t ha^{-1}(26 kg P ha^{-1}) treatment to 1.67 t ha^{-1}(3 t ha^{-1} Koru lime) treatment at Chimoroni and 1.15 t ha^{-1} (1.4 t ha^{-1}Athi lime) to 2.68 t ha^{-1} (1.5 t ha^{-1} Koru lime + 26 kg P ha^{-1}) treatment at Got Nanga site. This was mainly due to the inadequate and poorly distributed rainfall that was experienced during that season as shown in Appendix 4. In the last season of the experiment (2011 LR), there was a significant ($p<0.05$) lime x P interaction at Tumbeni while only P was significant at Sihay. Maize yield varied from 0.92 t ha^{-1} (control) to 2.6 t ha^{-1} (3 t ha^{-1} Koru lime + 26 kg P ha^{-1}) at Sihay and 1.65 t ha-[1] (control) to 5.01 t ha^{-1} (3 t ha^{-1} Koru lime + 26 kg P ha^{-1}) at Got Nanga. In Kakamega North, yield ranged from 0.41 t ha^{-1} (1.5 t ha^{-1} Koru lime) to 1.85 t ha^{-1} (3 t ha^{-1} Koru lime + 26 kg P ha^{-1}) at Tumbeni and 1.4 t ha^{-1} (26 kg P ha^{-1}) to 3.16 t ha^{-1} (1.5 t ha^{-1} Koru lime + 26 kg P ha^{-1}). A combination of both lime, and P generally gave higher yields as compared to either P or lime alone, except for Koru lime (3 t ha^{-1}) that gave a yield of 4.69 t ha^{-1} at Got Nanga during 2010 LR.

Table 6a: Maize grain yield (t/ha) as affected by lime and P application during three cropping seasons at Got Nanga site

GOT NANGA SITE										
	2010 LR			2010 SR			2011 LR			
	P0	P1	**Mean**	P0	P1	**Mean**	P0	P1	**Mean**	**Overall Lime Mean**
L0	3.08	2.06	**2.57**	1.16	2.15	**1.66**	1.65	3.57	**2.61**	**2.27**
KL1	3.20	4.68	**3.94**	1.18	2.68	**1.93**	2.03	4.45	**3.24**	**3.04**
KL2	4.96	4.34	**4.65**	2.51	2.52	**2.52**	4.48	5.01	**4.75**	**3.97**
AL1	3.31	4.71	**4.01**	1.36	2.68	**2.02**	2.92	3.93	**3.43**	**3.15**
AL2	3.61	4.02	**3.82**	1.15	2.22	**1.69**	3.97	4.24	**4.11**	**3.20**
Mean	**3.63**	**3.96**		**1.47**	**2.45**		**3.01**	**4.24**		
SED (P)		*0.32*			*0.19*			*0.67*		
SED (L)		*0.32*			*0.19*			*0.61*		

Table 6b: Maize grain yield (t/ha) as affected by lime and P application during three cropping season at Sihay site

SIHAY SITE										
	2010 LR			2010 SR			2011 LR			
	P0	P1	**Mean**	P0	P1	**Mean**	P0	P1	**Mean**	**Overall Lime Mean**
L0	1.04	3.47	**2.26**	0.63	2.05	**1.34**	0.92	2.15	**1.54**	**1.71**
KL1	2.01	3.59	**2.80**	1.24	2.64	**1.94**	1.66	2.23	**1.95**	**2.23**
KL2	1.26	3.97	**2.62**	1.15	2.66	**1.91**	1.12	2.69	**1.91**	**2.14**
AL1	0.76	4.60	**2.68**	0.44	2.39	**1.42**	0.52	2.15	**1.34**	**1.81**
AL2	1.61	4.55	**3.08**	0.95	2.33	**1.64**	1.16	2.10	**1.63**	**2.12**
Mean	**1.34**	**4.04**		**0.88**	**2.41**		**1.08**	**2.26**		
SED (P)		*0.27*			*0.32*			*0.31*		
SED (L)		*0.27*			*0.32*			*0.31*		
SED (L x P)		*ns*			*0.32*			*ns*		

Where ns= not significant, L0 = No lime, KL1 and KL2 = 1.5 and 3 t ha^{-1} Koru lime. AL1 and AL2 = 0.7 and 1.4 t ha^{-1} Athi lime. P0 and P1 = 0 and 26 kg P ha^{-1}

Table 6c: Maize grain yield (t/ha) as affected by lime and P application during three cropping seasons at Chimoroni Site

CHIMORONI SITE										
	2010 LR			2010 SR			2011 LR			
	P0	P1	**Mean**	P0	P1	**Mean**	P0	P1	**Mean**	**Overall Lime Mean**
L0	2.92	2.39	**2.66**	0.99	0.60	**0.80**	2.00	1.40	**1.70**	**1.71**
KL1	3.03	3.78	**3.41**	0.88	1.02	**0.95**	2.36	3.16	**2.76**	**2.37**
KL2	3.56	3.85	**3.71**	1.40	1.67	**1.54**	2.75	3.10	**2.93**	**2.72**
AL1	3.44	3.53	**3.49**	0.91	1.39	**1.15**	2.27	2.80	**2.54**	**2.39**
AL2	2.94	3.75	**3.35**	1.11	1.59	**1.35**	2.12	2.90	**2.51**	**2.40**
Mean	**3.18**	**3.46**		**1.06**	**1.25**		**2.30**	**2.67**		
SED (P)		*0.27*			*0.26*			*0.29*		
SED (L)		*0.27*			*0.25*			*0.29*		

Table 6d: Maize grain yield (t/ha) as affected by lime and P application during three cropping seasons at Tumbeni site

TUMBENI SITE										
	2010 LR			2010 SR			2011 LR			
	P0	P1	**Mean**	P0	P1	**Mean**	P0	P1	**Mean**	**Overall Lime Mean**
L0	1.20	1.94	**1.57**	0.48	0.41	**0.45**	0.92	0.97	**0.95**	**0.99**
KL1	1.10	3.73	**2.42**	0.41	0.91	**0.66**	0.41	1.56	**0.99**	**1.35**
KL2	1.89	2.77	**2.33**	1.03	0.73	**0.88**	1.6	1.85	**1.73**	**1.65**
AL1	1.22	3.81	**2.52**	1.08	1.30	**1.19**	1.21	1.79	**1.50**	**1.74**
AL2	1.30	3.22	**2.26**	0.78	0.90	**0.84**	1.33	1.72	**1.53**	**1.54**
Mean	**1.34**	**3.09**		**0.76**	**0.85**		**1.09**	**1.58**		
SED (P)		*0.41*			*0.20*			*0.29*		
SED (L)		*0.37*			*0.19*			*0.29*		
SED (L x P)		*ns*			*0.21*			*ns*		

Where ns = not significant, L0= No lime, KL1 and KL2 = 1.5 and 3 t ha^{-1} Koru lime. AL1 and AL2 = 0.7 and 1.4 t ha^{-1} Athi lime. P0 and P1 = 0 and 26 kg P ha^{-1}.

4.1.7. Correlation between maize grain yield, available soil P and soil pH as affected by the combination of lime and P fertilizer application

The Pearson Correlation equation was used to determine the relationship between soil pH, extractable soil P and maize grain yield at third (80 DAP) and fourth (harvesting) sampling (120 /147 DAP) in all the sites. Maize grain yield correlated significantly ($p < 0.01$) with soil pH and available soil P at Got Nanga. Available soil P and soil pH also showed significant ($p < 0.01$) and positive correlations 80 DAP. At Sihay maize yield was significantly ($p < 0.001$) and positively correlated to available soil P. Again, P was significantly ($p < 0.05$) correlated to soil pH at this site. However, there was a weak and non significant correlation between maize grain yield and soil pH at this site. In Kakamega North, maize grain yield significantly ($p < 0.01$) correlated with available soil P both at Chimoroni and Tumbeni as shown Figures 4a and 4b. At harvesting, yield was positively and significantly ($p < 0.05$) correlated to available P at Sihay, Tumbeni and Chimoroni, while at Got Nanga yield was significantly ($p < 0.05$) correlated to soil pH.

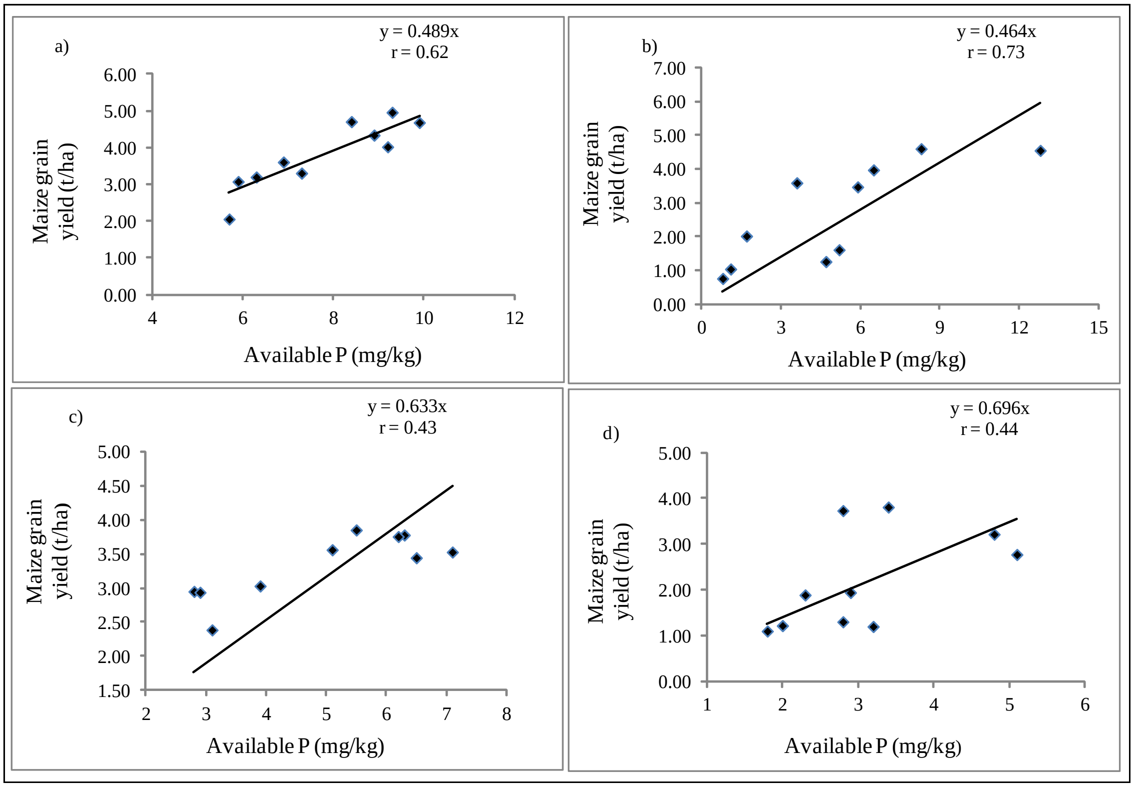

Figure 4a: Correlation between maize grain yield and available soils P 80 DAP at Sihay (a), Got Nanga (b), Chimoroni (c) and Tumbeni (d) sites respectively

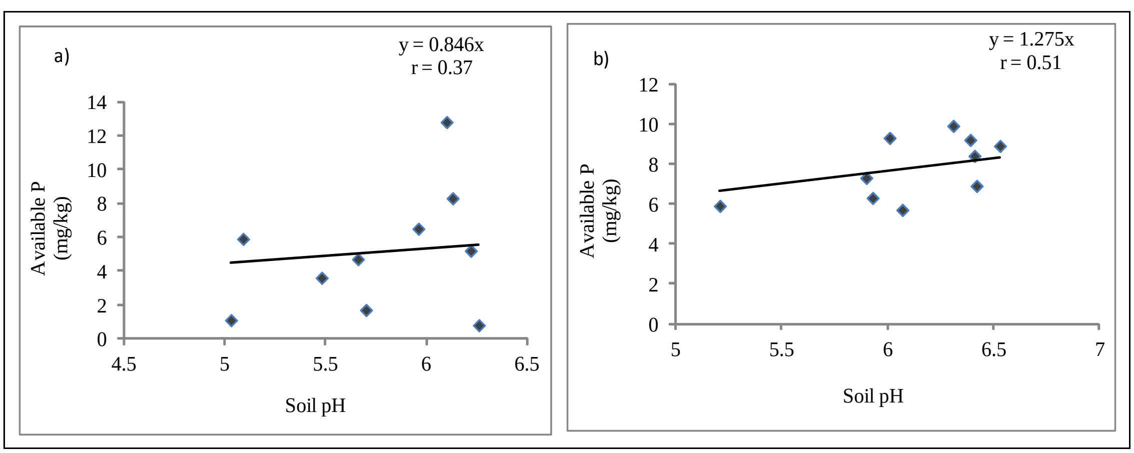

Figure 4b: Correlation between available soil P and soil pH 80 DAP at Sihay (a) and Got Nanga (b)

4.1.8. Uptake of N and P in maize grain as influenced by P and Lime application

Application of P significantly ($p < 0.001$) gave higher N uptake values compared to control at Sihay during 2010 LR, 2010 SR and 2011 LR. At Got Nanga, lime x P interaction significantly increased N uptake ($p < 0.01$) during 2010 LR, whereas P was significant during 2010 SR and 2011 LR. Lime with P significantly ($p < 0.05$) increased N uptake as compared to the control at Tumbeni during 2010 LR. At Chimoroni, lime application significantly ($p < 0.05$) gave higher N uptake values compared to those of the controls during 2010 and 2011 LRs. When all treatment means were computed, Sihay had high N uptake (63.8 kg N ha^{-1}) as compared to 55 kg N ha^{-1} at Got Nanga during 2010 LR. In Kakamega North county, Chimoroni had the highest N uptake of 51.9 kg N ha^{-1} at the same time of sampling. Mean N and P uptake for three cropping seasons are given on Tables 7a – 7d.

For phosphorus uptake, generally, application of P significantly ($p < 0.001$) influenced P uptake in the grain at Sihay and Tumbeni farms. When treatment means were contrasted, it showed that control significantly ($p < 0.05$) differed from 0.7 t ha^{-1} Athi lime + 26 kg P ha^{-1}, 1.4 t ha^{-1} Athi lime + 26 kg P ha^{-1} the same to 0.7 t ha^{-1} Athi lime and 0.7 t ha^{-1} Athi lime + 26 kg p ha^{-1} at Tumbeni during 2010 LR. For Chimoroni site, analysis for 2010 LR showed no significance. Orthogonal contrast tests also showed that control differed significantly ($p < 0.01$) from 0.7 and 1.4 t ha^{-1} AL + 26 kg P ha^{-1} and 1.5 and 3 t ha^{-1} KL + 26 kg P ha^{-1} at Sihay. At Got Nanga, application of lime was significant ($p< 0.001$). During 2010 SR and 2011 LR, treatments did not significantly influence P uptake at Tumbeni. However, at Sihay, P application was significant ($p < 0.01$). At Chimoroni lime significantly ($p < 0.05$) increased P uptake, while both lime and P application was significant ($p < 0.05$) in influencing P uptake at Got Nanga. Computation of treatment means indicated that Got

Nanga had the highest P uptake of 8.7, 3.9 and 6.9 kg P ha^{-1} during 2010 LR, SR and 2011 LR respectively.

Table 7a: Nitrogen and phosphorus uptake in the maize grain as influenced by lime and P application at Got Nanga site during 2010 LR

GOT NANGA SITE						
	N Uptake			P Uptake		
	P0	P1	**MEAN**	P0	P1	**MEAN**
L0	40.4	26.3	**33.4**	5.5	4.5	**5.0**
KL1	34.6	59.1	**46.9**	6.4	10.8	**8.6**
AL1	42.2	62.9	**52.6**	7.9	11.3	**9.6**
KL2	64.3	59.7	**62.0**	11.9	10.4	**11.2**
AL2	45.8	51.2	**48.5**	8.7	9.3	**9.0**
MEAN	**45.5**	**51.8**		**8.1**	**9.3**	

Table 7b: Nitrogen and phosphorus uptake in the maize grain as influenced by lime and P application at Sihay site during 2010 LR

SIHAY SITE						
	N Uptake			P Uptake		
	P0	P1	**MEAN**	P0	P1	**MEAN**
L0	11.8	45.5	**28.7**	1.9	7.3	**4.6**
KL1	27.6	46.9	**37.3**	3.8	6.8	**5.3**
AL1	10.5	60.2	**35.4**	1.4	9.7	**5.6**
KL2	18.0	53.6	**35.8**	2.4	8.3	**5.4**
AL2	22.6	62.9	**42.8**	3.1	9.1	**6.1**
MEAN	**18.1**	**53.8**		**2.5**	**8.2**	

Where L0= No lime, KL1 and KL2 = 1.5 and 3 t ha^{-1} Koru lime. AL1 and AL2 = 0.7 and 1.4 t ha^{-1} Athi lime. P1 = 26 kg P ha^{-1}.

Table 7c: Nitrogen and phosphorus uptake in the maize grain as influenced by lime and P application at Chimoroni site during 2010 LR

CHIMORONI SITE						
	N Uptake			P Uptake		
	P0	P1	**MEAN**	P0	P1	**MEAN**
L0	24.4	13.8	**19.1**	6.2	4.5	**5.4**
KL1	20.3	23.3	**21.8**	6.1	7.2	**6.7**
AL1	20.3	29.6	**25**	6.5	6.7	**6.6**
KL2	32.8	36.9	**34.9**	7.1	6.9	**7.0**
AL2	25.6	35.5	**30.6**	5.6	6.8	**6.2**
MEAN	**24.7**	**27.8**		**2.3**	**5.3**	

Table 7d: Nitrogen and phosphorus uptake in the maize grain as influenced by lime and P application at Tumbeni site during 2010 LR.

TUMBENI SITE						
	N Uptake			P Uptake		
	P0	P1	**MEAN**	P0	P1	**MEAN**
L0	17.0	29.5	**23.3**	2.8	2.9	**2.9**
KL1	13.0	47.2	**30.1**	1.8	6.3	**4.1**
AL1	14.9	45.9	**30.4**	1.7	6.1	**3.9**
KL2	21.1	33.5	**27.3**	3.2	5.0	**4.1**
AL2	15.5	36.7	**26.1**	2.1	6.4	**4.3**
MEAN	**16.3**	**38.6**		**2.3**	**5.3**	

Where L0= No lime, KL1 and KL2 = 1.5 and 3 t ha^{-1} Koru lime. AL1 and AL2 = 0.7 and 1.4 t ha^{-1} Athi lime. P1 =26 kg P ha^{-1}.

4.1.9. Nutrient Use Efficiency in the maize grain as affected by lime and P application.

4.1.9.1. Agronomic nitrogen and phosphorus use efficiencies (AE)

Mean agronomic nitrogen and phosphorus use efficiencies (ANUE and APUE) for all the sites is given in Tables 8a and 8b. Koru lime (3 t ha^{-1}) application gave the highest mean ANUE and APUE in three sites. At Tumbeni, 1.5 t ha^{-1} Koru lime application had the highest APUE of 46.2 kg grain/ kg P applied. ANUE increased with P application in all the sites. APUE increased with increased lime rates at Sihay, Got Nanga and Chimoroni sites.

Table 8a: Mean agronomic nitrogen use efficiency (kg grain kg N-1) and agronomic phosphorus use efficiency (kg grain kg P-1) for three cropping seasons at Got Nanga and Sihay

GOT NANGA					**SIHAY**			
	ANUE			APUE	ANUE		**MEAN**	APUE
	P0	P1	**MEAN**	P1	P0	P1		P1
L0	0.0	25.2	**25.2**	24.2	0.0	8.4	**8.4**	73.9
KL1	6.9	79.0	**42.9**	75.9	2.3	26.3	**14.3**	94.3
KL2	80.8	79.7	**80.3**	76.6	26.9	26.6	**26.8**	106.6
AL1	22.7	72.4	**47.5**	69.6	7.6	24.1	**16.2**	97.4
AL2	37.8	61.2	**49.5**	58.9	12.6	20.4	**16.5**	100.0
MEAN	**29.6**	**63.5**		**61.1**	**9.9**	**21.2**		**94.5**

Where L0= No lime, KL1 and KL2 = 1.5 and 3 t ha^{-1} Koru lime. AL1 and AL2 = 0.7 and 1.4 t ha^{-1} Athi lime. P0 and P1 = 0 and 26 kg P ha^{-1}.

Table 8b: Mean agronomic nitrogen use efficiency (kg grain kg N^{-1}) and agronomic phosphorus use efficiency (kg grain kg P^{-1}) for three cropping season at Chimoroni and Tumbeni

CHIMORONI					TUMBENI			
	ANUE			APUE	ANUE		**MEAN**	APUE
	P0	P1	**MEAN**	P1	P0	P1		P1
L0	0.0	-6.9	**-6.9**	0.0	0.0	3.2	**3.2**	9.2
KL1	1.5	9.0	**5.2**	25.9	-3.0	16.0	**6.5**	46.2
KL2	7.9	11.9	**9.9**	34.4	8.5	12.2	**10.4**	35.3
AL1	3.0	7.9	**5.5**	22.8	4.1	19.1	**11.6**	55.1
AL2	1.0	10.3	**5.6**	29.6	3.6	14.4	**9.0**	41.5
MEAN	**2.7**	**6.4**		22.5	**2.6**	**13.0**		37.5

Where L0= No lime, KL1 and KL2 = 1.5 and 3 t ha^{-1} Koru lime. AL1 and AL2 = 0.7 and 1.4 t ha^{-1} Athi lime. P0 and P1 = 0 and 26 kg P ha^{-1}.

4.1.9.2. Internal (physiological) nitrogen and phosphorus use efficiencies

Figures 5a and 5b show three seasons mean effects of lime and P fertilizer on physiological N and P use efficiency (PNUE and PPUE) by maize grain. Application of P fertilizer increased grain PNUE and PPUE in all sites. There was no significant difference between different lime rates in grain PPUE at all sites.

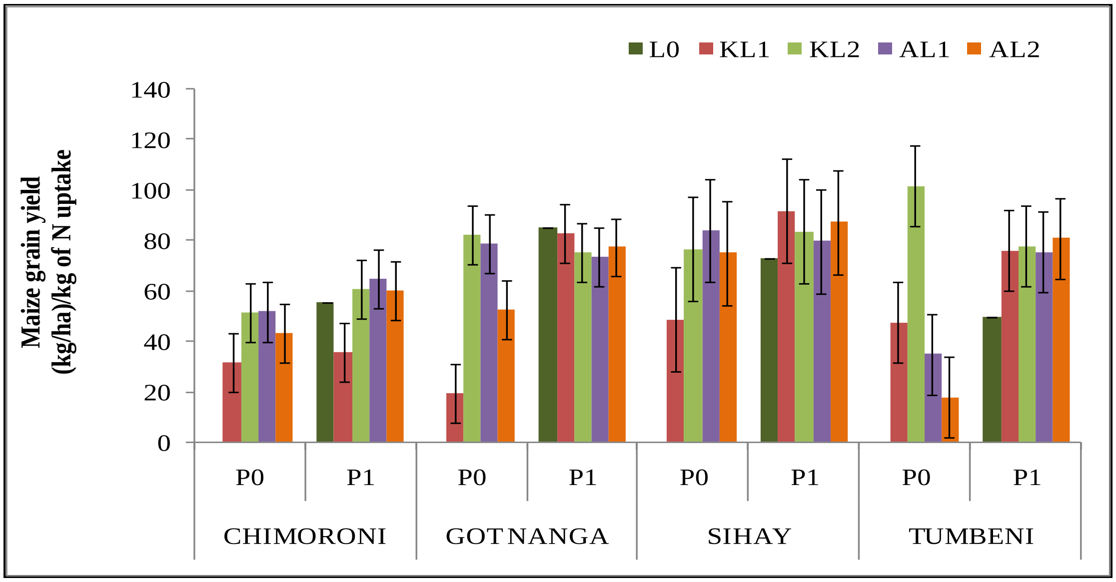

Figure 5a: Mean physiological N use efficiency by the grain for three cropping seasons.

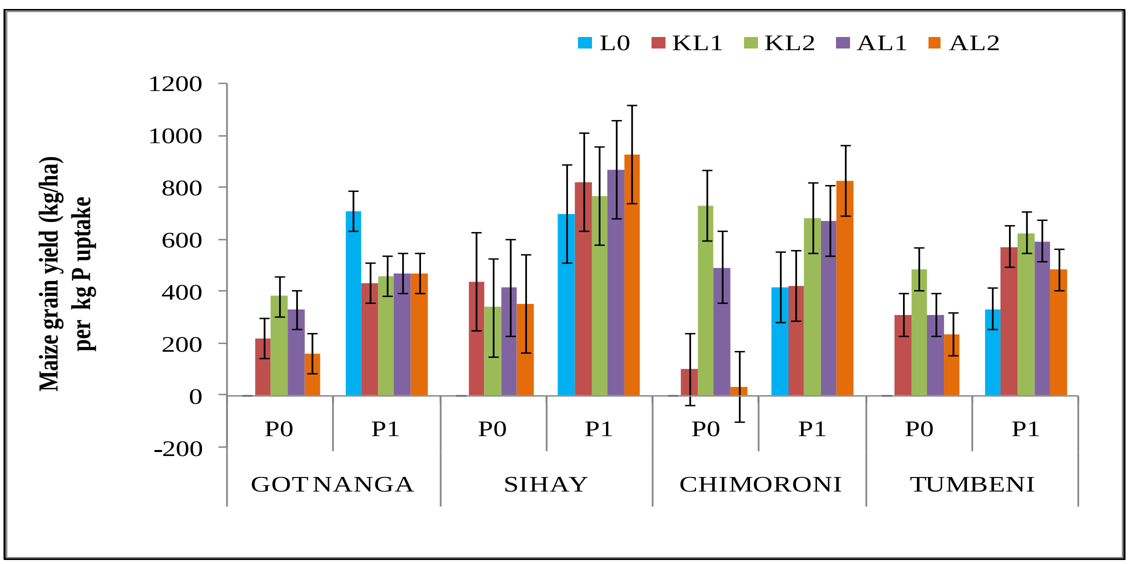

Figure 5b: Mean physiological P use efficiency by the grain for three cropping seasons.

Where L0= no lime, KL1 and KL2 = 1.5 and 3 t/ha Koru lime, AL1 and AL2 = 0.7 and 1.4 t/ha Athi lime, P0 and P1 = 0 and 26 kg P/ha respectively.

4.1.9.3 Partial factor of productivity (PFP)

Mean effects of lime and P fertilizer on partial factor of productivity (PFP) are presented on Tables 9a and 9b. Application of P fertilizer gave higher PFP (nitrogen) at all sites except at Tumbeni. Partial factor of productivity (nitrogen) increased with increasing lime rates at all sites. Koru lime application at 3 t ha^{-1} gave the highest PFP (nitrogen and phosphorus) at Got Nanga, Sihay and Chimoroni.

Table 9a: Mean partial factor of productivity (kg/ha) for three cropping seasons at Got Nanga and Sihay

GOT NANGA					SIHAY			
	PFP (N)			PFP (P)	PFP (N)		**MEAN**	PFP (P)
	P0	P1	**MEAN**	P1	P0	P1		P1
L0	26.1	51.3	**38.7**	99.6	14.7	39.9	**27.3**	66.9
KL1	33.0	105.1	**69.1**	151.3	21.6	93.6	**57.6**	118.6
KL2	107.0	105.8	**106.4**	152.0	95.5	94.4	**94.9**	119.3
AL1	48.8	98.5	**73.6**	145.0	37.3	87.0	**62.2**	112.3
AL2	64.0	87.4	**75.7**	134.3	52.5	75.9	**64.2**	101.6
MEAN	**55.8**	**89.6**		**136.4**	**44.3**	**78.2**		**103.7**

Where L0= No lime, KL1 and KL2 = 1.5 and 3 t ha^{-1} Koru lime. AL1 and AL2 = 0.7 and 1.4 t ha^{-1} Athi lime. P0 and P1 = 0 and 26 kg P ha^{-1}.

Table 9b: Mean partial factor of productivity (kg/ha) for three cropping seasons at Chimoroni and Tumbeni

CHIMORONI					TUMBENI			
	PFP (N)			PFP (P)	AE N		**MEAN**	AE (P)
	P0	P1	**MEAN**	P1	P0	P1		P1
L0	26.4	19.5	**23.0**	76.2	11.6	14.8	**13.2**	42.7
KL1	27.9	35.4	**31.6**	102.1	8.6	27.6	**18.1**	79.7
KL2	34.3	38.3	**36.3**	110.6	20.1	23.8	**22.0**	68.8
AL1	29.4	34.3	**31.9**	99.0	15.7	30.7	**23.2**	88.6
AL2	27.4	36.7	**32.0**	105.8	15.2	26.0	**20.6**	75.0
MEAN	**29.1**	**32.8**		**98.7**	**14.2**	**13.0**		**70.9**

Where L0= No lime, KL1 and KL2 = 1.5 and 3 t ha^{-1} Koru lime. AL1 and AL2 = 0.7 and 1.4 t ha^{-1} Athi lime. P0 and P1 = 0 and 26 kg P ha^{-1}.

4.1.10 Economic analysis

Tables 10a and 10b presents the gross margin analysis of farm operations using the partial budgeting techniques. Certain treatments produced high gross field benefits (GFB) and /or net field benefits (NFB), however, they were not economically viable for implementation because the marginal rate of return (MRR) ensued was below 50 %, the rate considered appropriate and suitable for investment. Also, some treatments produced lower NFBs than the previous ones with lower total costs that vary (TCVs) were not considered for investment and were thus, eliminated for further analysis. They are called dominated and were marked with letter “D”. At Got Nanga, majority of treatments realized economically viable returns that are worth adoption by farmers. For the three cropping seasons, 0.7 and 1.4 t ha^{-1} Athi lime, 3 t ha-1 Koru lime, 1.5 t ha^{-1} Koru lime + 26 kg P ha^{-1} and 0.7 t ha^{-1} Athi lime + 26 kg P ha^{-1} were viable. However, at Sihay quite a number of treatments did not realize economically viable returns due to high cost of production. 1.5 t ha^{-1} Koru lime, 26 kg P ha^{-1} and 0.7 t ha^{-1} Athi lime + 26 kg P ha^{-1} with NFB of 95722, 162280 and 181904, respectively were viable.

In Kakamega County, the same predicament as in Sihay above was realized. At Chimoroni, 1.5 t ha^{-1} + 26 kg P ha^{-1} and 0.7 t ha^{-1} + 26 kg P ha^{-1} with NFB of 158843 and 144911 respectively were viable. At Tumbeni, 3 t ha^{-1} Koru lime, 0.7 t ha^{-1} Athi lime, 1.5 and 3 t ha^{-1} Koru lime + 26 kg P ha^{-1} with NFB of 76665, 65871, 113752 and 84209 respectively were viable.

Table 10a: Gross field benefits, total costs that vary, net field benefit and marginal rate of returns analysis of treatments during 2010 LR,SR and 2011 LR at Got Nanga and Sihay sites

CUMMULATIVE (Seasons 2010 LR - 2011 LR)									
GOT NANGA					SIHAY				
Treatment	GFB (Ksh)	TCV (Ksh)	NFB (Ksh)	MRR (%)	Treatment	GFB (Ksh)	TCV (Ksh)	NFB (Ksh)	MRR (%)
Control	144956	13422	130192		Control	65268	6043	58621	
KL1P0	158676	28699	127107	D	**KL1P0**	**123732**	**25464**	**95722**	**174**
KL2P0	**279552**	**49191**	**225441**	**849**	KL2P0	88956	31544	54258	D
AL1P0	**184688**	**29508**	**152229**	**411**	AL1P0	43176	16405	25131	D
AL2P0	**221228**	**40591**	**176578**	**200**	AL2P0	93660	28779	62003	D
L0P1	159068	24949	131625	11	**L0P1**	**193200**	**28109**	**162280**	**228**
KL1P1	**269500**	**49181**	**215401**	**309**	KL1P1	213108	43959	164753	D
KL2P1	272076	58719	207485	D	KL2P1	234780	55266	173988	D
AL1P1	**257180**	**46440**	**206096**	**459**	**AL1P1**	**230244**	**43946**	**181904**	**113**
AL2P1	242032	52737	184021	D	AL2P1	226296	51280	169888	D

Where L0= No lime, KL1and KL2 = 1.5, and 3 t ha^{-1} Koru lime. AL1 and AL2 = 0.7 and 1.4 t ha^{-1} Athi lime. P0 and P1 = 0 and 26 kg P ha^{-1} respectively.

Table 10b: Gross field benefits, total costs that vary, net field benefit and marginal rate of returns analysis of treatments during 2010 LR, SR and 2011 LR at Chimoroni and Tumbeni sites

CAUMMULATIVE (Seasons 2010 LR - 2011 LR)									
CHIMORONI					TUMBENI				
Treatment	GFB (Ksh)	TCV (Ksh)	NFB (Ksh)	MRR (%)	Treatment	GFB (Ksh)	TCV (Ksh)	NFB (Ksh)	MRR (%)
Control	149520	13844	134291		Control	65520	6067	58847	
KL1P0	161280	28940	129446	D	KL1P0	48468	18495	28124	D
KL2P0	188916	40799	144037	D	**KL2P0**	**113904**	**33854**	**76665**	**74**
AL1P0	172900	28416	141642	46	**AL1P0**	**88536**	**20605**	**65871**	**68**
AL2P0	152096	34190	114487	D	AL2P0	86100	28079	55213	D
L0P1	115472	20912	92469	D	L0P1	83664	17967	63901	39
KL1P1	**206528**	**43350**	**158843**	**394**	**KL1P1**	**156324**	**38701**	**113752**	**695**
KL2P1	207480	52738	149468	D	**KL2P1**	**134820**	**46010**	**84209**	**692**
AL1P1	**189056**	**40132**	**144911**	**50**	AL1P1	173796	38719	131205	D
AL2P1	199192	48771	145544	D	AL2P1	147084	43946	98744	D

Where L0= No lime, KL1and KL2 = 1.5, and 3 t ha^{-1} Koru lime. AL1 and AL2 = 0.7 and 1.4 t ha^{-1} Athi lime. P0 and P1 = 0 and 26 kg P ha^{-1} respectively.

Results from experiment 2:

4.2.1 Direct and residual effect of different lime and P sources on soil pH (0 – 15 cm)

Data on initial soil properties before amendment are applicable to both experiment 1 and 2 since these trials were close to each other in the fields. Generally, the liming component (CaO) in the different lime and P sources significantly ($p<0.01$) increased soil pH at Sihay and Tumbeni, but at Got Nanga, the different rates of P significantly increased pH ($p < 0.05$) during 2010 LR. There was a significant ($p < 0.05$) P x lime interaction at Chimoroni. Soil pH averaged 5.44, 5.17, 4.79 and 4.46 at Got Nanga, Sihay, Chimoroni and Tumbeni sites, respectively 120 DAP. At harvesting, there was no significant difference between the individual treatments at Sihay, Chimoroni and Tumbeni sites. Soil pH ranged from 5.01 (0.4 t ha^{-1} KL + 26 kg P ha-^{1}) to 5.35 (0.8 t ha^{-1} KL + 52 kg P ha-1) at Sihay and 5.18 (0. 4 t ha^{-1} MPR) to 5.69 (0.2 t ha^{-1} MPR) at Got Nanga 120 DAP. In Kakamega, pH varied from 4.49 (0.4 t ha^{-1} MPR) to 5.07 (0.4 t ha^{-1} AL + 52 kg P ha^{-1}) at Chimoroni, while at Tumbeni, it ranged from 4.41 (0.2 t ha^{-1} AL + 26 kg P ha^{-1}) to 4.51 (0.8 t ha^{-1} + 52 kg P ha^{-1}) at the same time of sampling. At the end of 2010 SR, soil pH at Got Nanga were stable with 0.2 t ha^{-1} MPR (MPR1) having the highest pH of 5.78, whereas at Sihay, 0.8 t ha^{-1} KL + 52 kg P ha^{-1} (KL4P2) had the highest pH of 5.36. In Kakamega County, the pH was very low during this time. During the last season of the experiment (2011 LR), soil pH as influenced by different lime and P sources was < 5.5 in all the sites as shown in figures 6a – 6d.

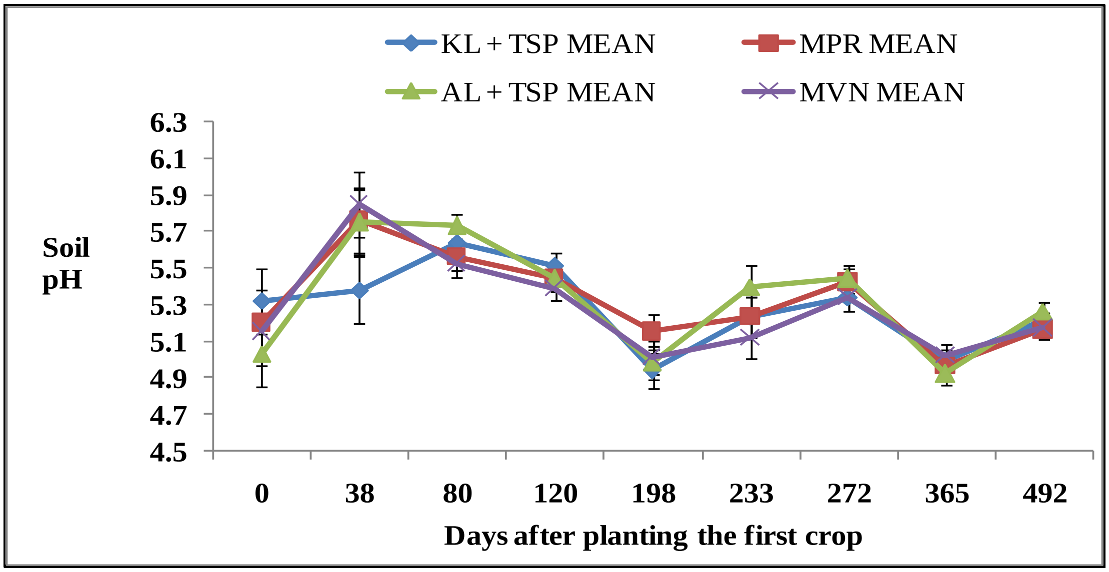

Figure 6a: Effect of different sources of lime and P on soil pH (0 – 15 cm) for three cropping seasons at Got Nanga site. *Where KL = Koru lime, AL = Athi lime, MPR = Minjingu phosphate rock, MVN = Mavuno fertilizer and TSP = triple superphosphate*

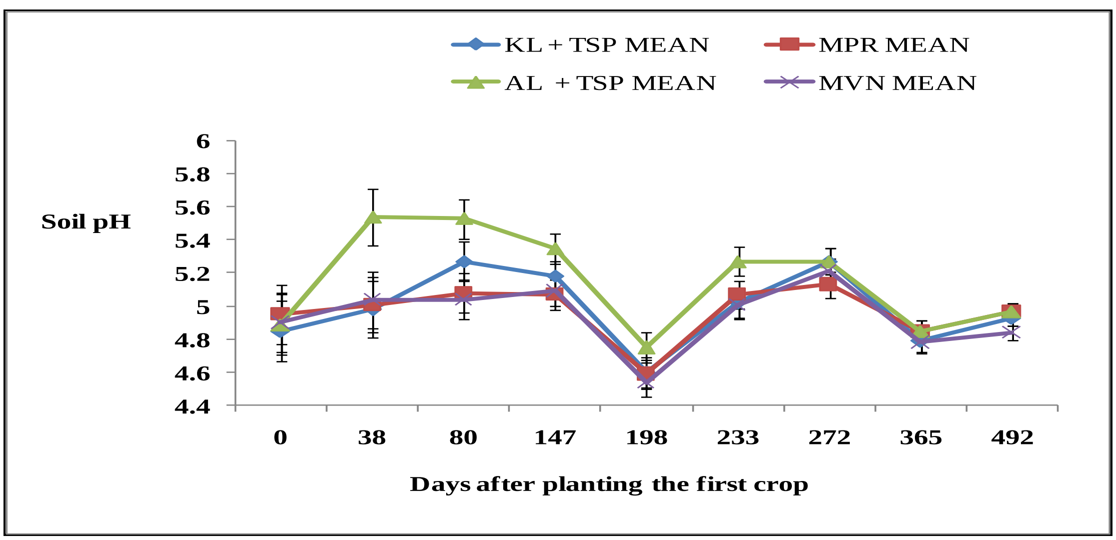

Figure 6b: Effect of different sources of lime and P on soil pH (0 – 15 cm) for three cropping seasons at Sihay site.

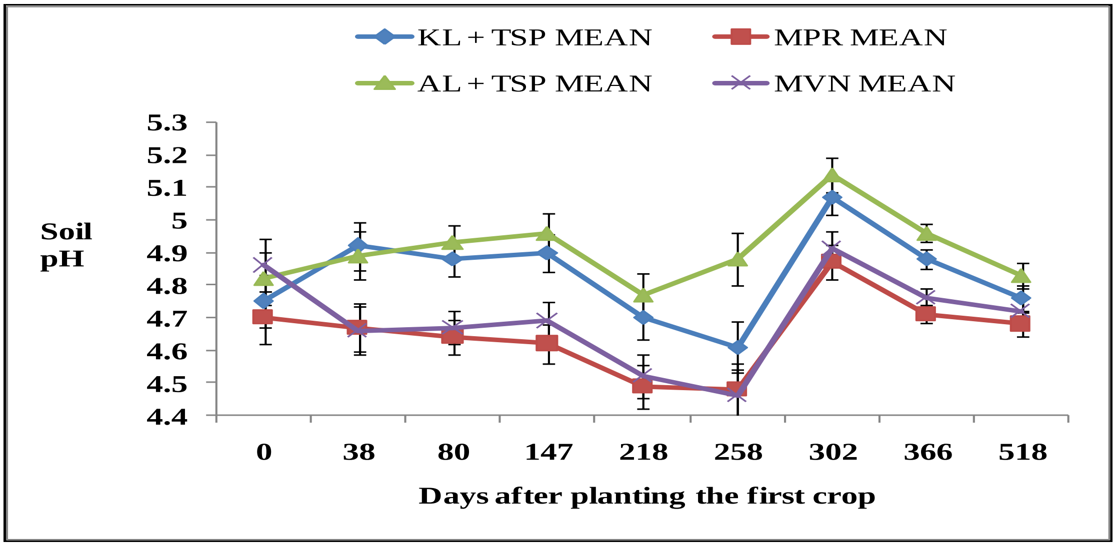

Figure 6c: Effect of different sources of lime and P on soil pH (0 – 15 cm) for three cropping seasons at Chimoroni site. Where KL = Koru lime, AL = Athi lime, MPR = Minjingu phosphate rock, MVN = Mavuno fertilizer and TSP = triple superphosphate

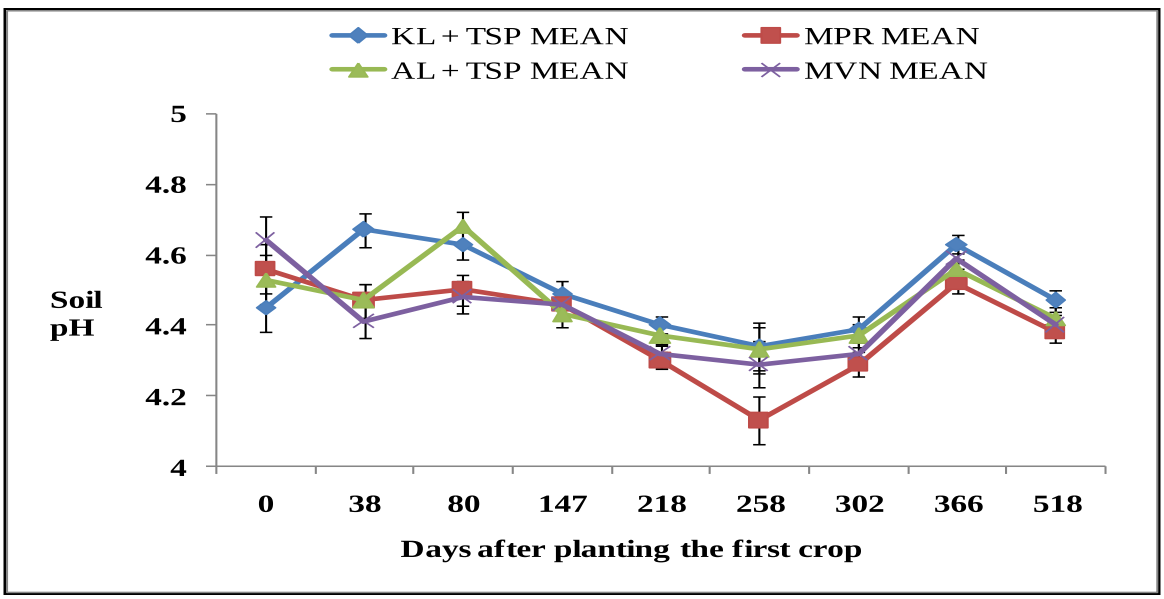

Figure 6d: Effect of different sources of lime and P on soil pH (0 – 15 cm) for three cropping seasons at Tumbeni site. *Where KL = Koru lime, AL = Athi lime, MPR = Minjingu phosphate rock, MVN = Mavuno fertilizer and TSP = triple superphosphate*

4.2.2 Direct and residual effect of different sources of lime and P on available soil P

Figures 7a – 7d show that available soil P averaged 11, 7, 8 and 4 mg kg^{-1} at Got Nanga, Sihay, Chimoroni and Tumbeni, respectively 120 DAP. Generally, there was no significant difference between different sources of lime and P in Kakamega during 2010 LR. Available P values ranged from 5.3 mg kg^{-1} (0.2 t ha^{-1} MPR) to 12.5 mg kg^{-1} (0.2 t ha^{-1} AL + 26 kg P ha^{-1}) at Chimoroni. In Siaya, both P and lime significantly increased available soil P. Contrasts tests between treatment means showed significant ($p < 0.05$) differences 80 DAP at Got Nanga. In Sihay, lime significantly ($p < 0.05$) increased available soil P at harvesting. Individual treatment means showed significant ($p < 0.01$) differences as shown in Figures 7a and 7b. Available P varied from 4.5 mg kg^{-1}(0.2 t ha^{-1} MPR) to 14 mg kg^{-1} (KL + TSP) at Sihay during 2010 LR. At Got Nanga, it ranged from 6.6 mg kg^{-1}(MPR) to 22.1 mg kg^{-1}(MVN) 80 DAP. Generally, there was a decrease in available soil P values as influenced by different sources of lime and P in the following cropping seasons.

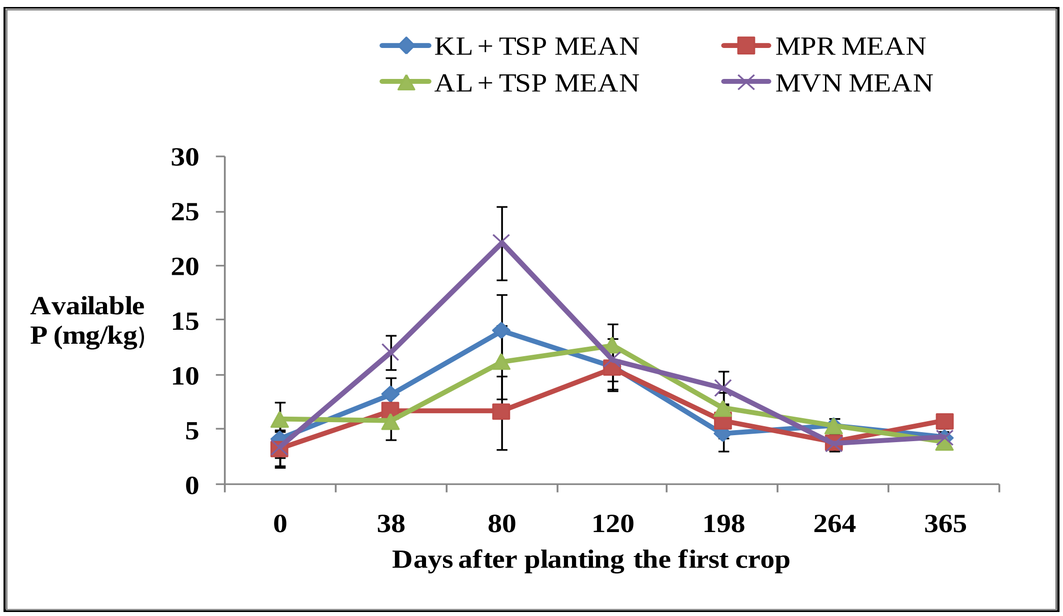

Figure 7a: Effect of different sources of lime and P on available soil P (0 – 15 cm) for three cropping seasons at Got Nanga site. *Where KL = Koru lime, AL = Athi lime, MPR = Minjingu phosphate rock, MVN = Mavuno fertilizer and TSP = triple superphosphate*

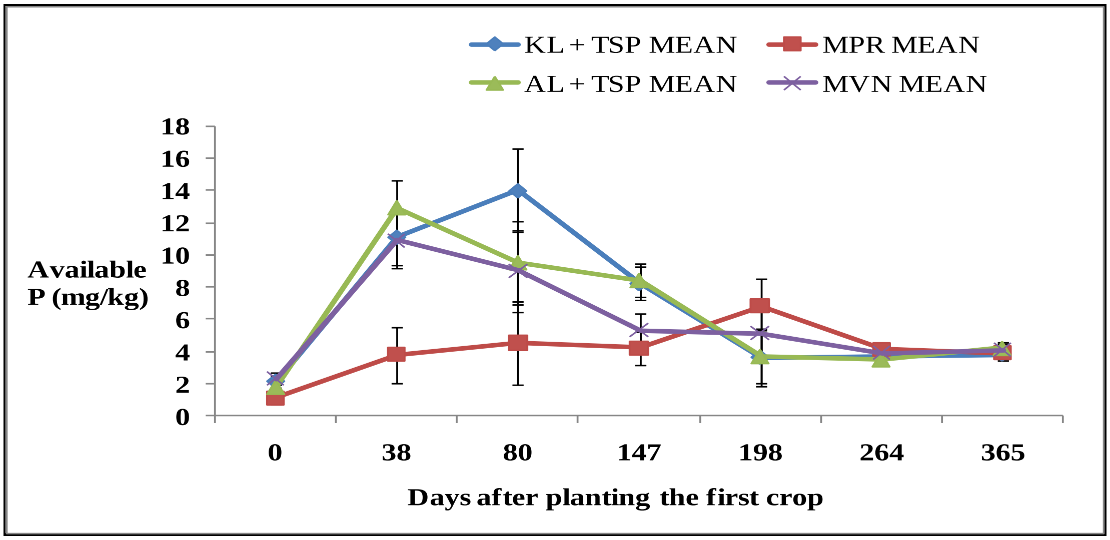

Figure 7b: Effect of different sources of lime and P on available soil P (0 – 15 cm) for three cropping seasons at Sihay site.

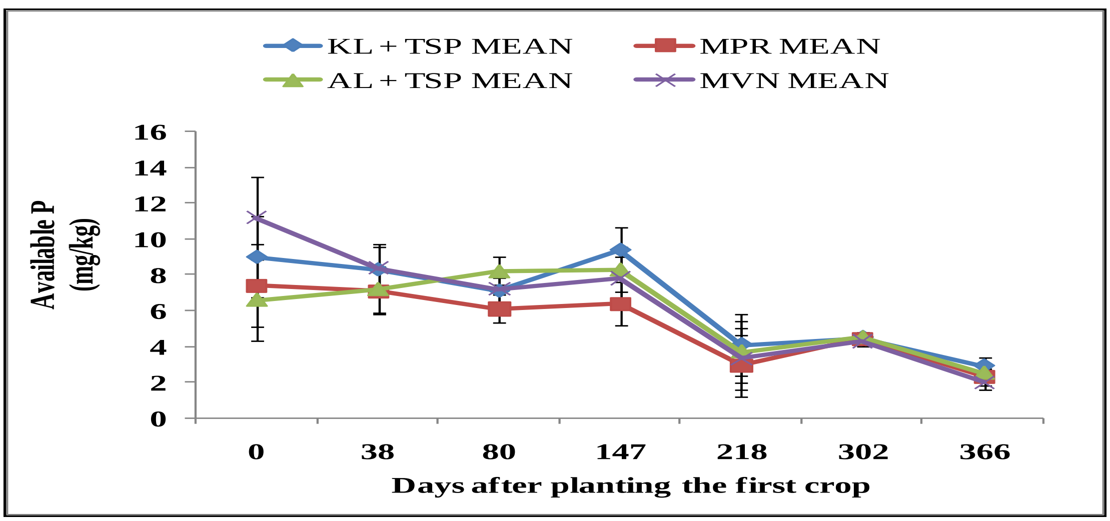

Figure 7c: Effect of different sources of lime and P on available soil P (0 – 15 cm) for three cropping seasons at Chimoroni site. *Where KL = Koru lime, AL = Athi lime, MPR = Minjingu phosphate rock, MVN = Mavuno fertilizer and TSP = triple superphosphate*

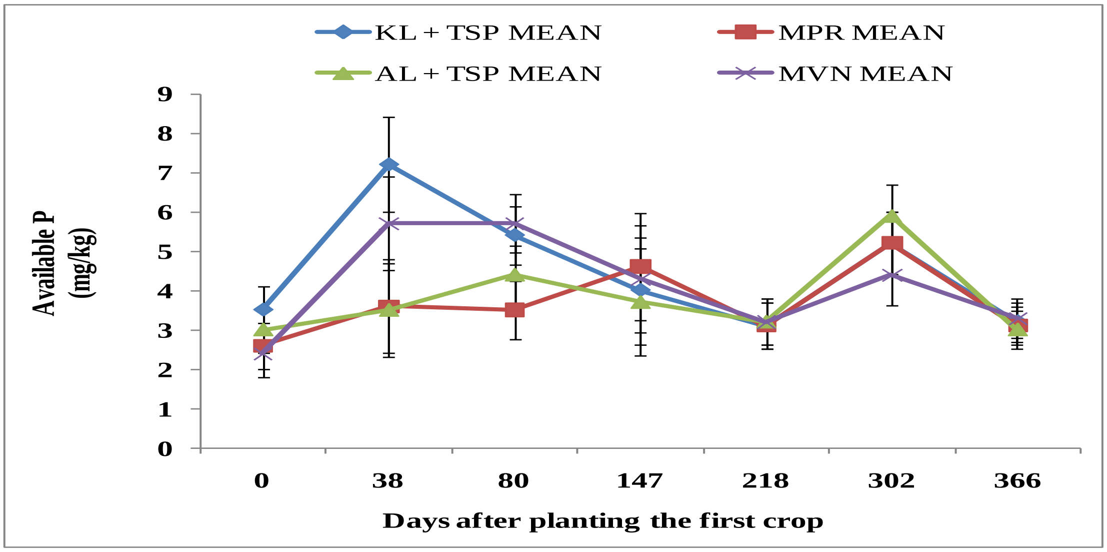

Figure 7d: Effect of different sources of lime and P on available soil P (0 – 15 cm) for three cropping seasons at Tumbeni site. *Where KL = Koru lime, AL = Athi lime, MPR = Minjingu phosphate rock, MVN = Mavuno fertilizer and TSP = triple superphosphate*

4.2.3 Maize grain yield as affected by different lime and P sources in all sites during three cropping seasons

Maize grain yields as influenced by different lime and P sources are presented in Tables 11a – 11d. Generally, different sources of lime and P gave higher yields above the control in all sites during 2010 LR and 2011 LR. Mean maize grain yields for all treatments were again higher in Siaya (4.71, 2.33 and 3.15 t ha^{-1}) compared to yields of 3.45, 1.21 and 2.52 obtained in Kakamega North during 2010 LR, 2010 SR and 2011 LR, respectively. There was a significant ($p<0.05$) lime x P interaction in the different fertilizer sources used in all the three seasons at Got Nanga, whereas only lime gave a significant effect ($p< 0.05$) at Sihay during the 2010 LR. Contrast test showed significant differences between treatments as shown in the ANOVA tables in Appendix 3. Phosphorus application at 26 and 52 kg P ha^{-1} did not differ significantly from each other in all the sites during this season. In Kakamega

North district, the soil amendment materials did not give any significant difference in grain yield during the 2010 LR. However, contrast test showed significant ($p < 0.05$) differences between treatments. Mavuno fertilizer gave higher yields compared to the other fertilizer sources at Got Nanga, Sihay and Tumbeni. Maize grain yield ranged from 2.58 t ha^{-1} (0.4 t ha^{-1} MPR) to 5.70 t ha^{-1} (0.48 t ha^{-1} MVN) at Got Nanga whereas at Sihay it ranged from 3.82 t ha^{-1} (0.2 t ha^{-1} MPR) to 6.72 t ha^{-1} (0.48 t ha^{-1} MVN) during the 2010 LR. Although grain yields were very low in all the sites in 2010 SR, there was a significant lime x P interaction at Chimoroni. In the final season (2011 LR), maize yields ranged from 2.35 t ha^{-1} (0.24 t ha^{-1} MVN) to 4.17 t ha $^{-1}$ (0.4 t ha^{-} MPR) at Sihay and from 2.24 t ha $^{-1}$ (0.24 t ha^{-1} MVN) to 4.6 t ha $^{-1}$ (0.48 t ha^{-1} MVN) at Got Nanga. All treatments did not show any significant difference during the other seasons at Chimoroni and none at all at Tumbeni in all the cropping seasons. Maize yield ranged from 1.53 t ha^{-1} where MPR was applied (26 kg P ha^{-1}) to 4.72 t ha^{-1} where Mavuno fertilizer (52 kg P ha^{-1}) was applied at Tumbeni during 2011 LR. At the same time in Chimoroni, maize yield ranged from 3.21 t ha $^{-1}$ (0.4 t ha^{-1} AL + 52 kg P ha^{-1}) to 4.69 t ha^{-1} (0.8 t ha^{-1} KL + 52 kg P ha^{-1}).

Table 11a: Maize grain yield (t/ha) as affected by different sources of lime and P during three cropping season at Sihay site

SIHAY SITE										
	2010 LR			2010 SR			2011 LR			
	P1	P2	**Mean**	P1	P2	**Mean**	P1	P2	**Mean**	**Overall Lime Mean**
KL	4.54	5.75	**5.15**	2.08	3.47	**2.78**	2.39	3.00	**2.70**	**3.54**
AL	4.80	4.84	**4.82**	3.09	3.50	**3.30**	3.86	3.30	**3.58**	**3.90**
MPR	3.82	5.26	**4.54**	2.21	2.81	**2.51**	3.35	4.17	**3.76**	**3.60**
MVN	5.80	6.72	**6.26**	3.69	3.07	**3.38**	2.35	2.78	**2.57**	**4.07**
Mean	**4.06**	**5.64**		**2.77**	**3.21**		**2.99**	**3.31**		
SED (P)		*0.36*			*0.25*			*0.45*		
SED (L)		*0.36*			*0.25*			*0.45*		
SED (L x P)		*ns*			*ns*			*ns*		

Table 11b: Maize grain yield (t/ha) as affected by different sources of lime and P during three cropping season at Got Nanga site

GOT NANGA SITE										
	2010 LR			2010 SR			2011 LR			
	P1	P2	**Mean**	P1	P2	**Mean**	P1	P2	Mean	**Overall Lime Mean**
KL	4.38	4.62	**4.50**	1.84	1.28	**1.56**	3.26	3.33	3.30	**3.12**
AL	3.61	4.33	**3.97**	1.54	1.40	**1.47**	2.75	2.99	2.87	**2.77**
MPR	3.97	2.58	**3.28**	2.07	1.2	**1.64**	3.15	2.85	3.00	**2.64**
MVN	4.56	5.70	**5.13**	1.27	2.67	**1.97**	2.24	4.60	3.42	**3.51**
Mean	**4.13**	**4.32**		**1.68**	**1.64**		**2.85**	**3.44**		
SED (P)		*0.41*			*0.29*			*0.38*		
SED (L)		*0.27*			*0.25*			*0.26*		
SED (L x P)		*0.41*			*0.29*			*0.38*		

Where ns = not significant, KLP1 = 0.4 t /ha Koru lime + 26 kg P/ha KLP2= 0.8 t/ ha Koru lime + 52 kg P/ha. ALP1 = 0.2 t /ha Athi lime + 26 kg P/ha and ALP2 = 0.4 t /ha Athi lime + 52 kg P/ha. MPRP1 = 0.2 t/ha and MPRP2 = 0.4 t/ha Minjingu phosphate rock respectively. MVNP1 = 0.24 and MVNP2= 0.48 t/ ha Mavuno fertilizer. P1 and P2 = 26 and 52 kg P/ha respectively.

Table 11c: Maize grain yield (t/ha) as affected by different sources of lime and P during three cropping season at Chimoroni site

CHIMORONI SITE										
	2010 LR			2010 SR			2011 LR			
	P1	P2	**Mean**	P1	P2	**Mean**	P1	P2	**Mean**	**Overall Lime Mean**
KL	4.24	4.69	**4.47**	1.04	1.98	**1.51**	3.71	4.76	**4.24**	**3.40**
AL	3.21	4.67	**3.94**	0.85	2.16	**1.51**	2.69	4.04	**3.37**	**2.92**
MPR	3.52	3.52	**3.52**	0.71	1.67	**1.19**	2.79	4.14	**3.47**	**2.73**
MVN	3.84	4.22	**4.03**	1.23	0.67	**0.95**	3.21	3.41	**3.31**	**2.79**
Mean	**3.70**	**4.28**		**0.96**	**1.62**		**3.10**	**4.09**		
SED (P)		*0.35*			*0.13*			*0.38*		
SED (L)		*0.34*			*0.13*			*0.37*		
SED (L x P)		*ns*			*0.13*			*ns*		

Table 11d: Maize grain yield (t/ha) as affected by different sources of lime and P during three cropping season at Tumbeni site

TUMBENI SITE										
	2010 LR			2010 SR			2011 LR			
	P1	P2	**Mean**	P1	P2	**Mean**	P1	P2	Mean	**Overall Lime Mean**
KL	2.43	2.86	**2.65**	0.20	1.28	**0.74**	1.74	2.10	1.92	**1.77**
AL	2.28	3.86	**3.07**	0.79	1.26	**1.03**	1.07	1.66	1.37	**1.82**
MPR	1.53	3.05	**2.29**	0.96	1.09	**1.03**	0.86	1.33	1.10	**1.47**
MVN	2.42	4.72	**3.57**	0.83	1.62	**1.23**	0.96	1.80	1.38	**2.06**
Mean	**2.17**	**3.62**		**0.7**	**1.31**		**1.16**	**1.72**		
SED (P)		*0.40*			*0.25*			*0.32*		
SED (L)		*0.33*			*0.16*			*0.20*		
SED (L x P)		*0.40*			*0.25*			*0.32*		

Where ns = not significant, KLP1 = 0.4 t /ha Koru lime + 26 kg P/ha KLP2= 0.8 t/ ha Koru lime + 52 kg P/ha. ALP1 = 0.2 t /ha Athi lime + 26 kg P/ha and ALP2 = 0.4 t /ha Athi lime + 52 kg P/ha. MPRP1 = 0.2 t/ha and MPRP2 = 0.4 t/ha Minjingu phosphate rock respectively. MVNP1 = 0.24 and MVNP2= 0.48 t/ ha Mavuno fertilizer. P1 and P2 = 26 and 52 kg P/ha respectively.

4.2.4 Uptake of N and P by maize grain as influenced by different sources of lime and phosphorus

Generally, P in the different fertilizer sources significantly ($p < 0.05$) increased N uptake at Tumbeni, while P and lime significantly ($p < 0.01$) increased N uptake at Sihay. There was no significant difference at Chimoroni, however lime gave a significant ($p < 0.05$) increase at Got Nanga during 2010 LR. Contrast tests showed significant ($p < 0.05$) differences when treatment means were compared against each other at Tumbeni, Sihay and Got Nanga during 2010 LR. During 2010 SR, P x lime interaction gave a significant ($p < 0.05$) N uptake at Chimoroni and Got Nanga. There was no significance in N uptake at Tumbeni and Sihay during this season. N uptake increased with increasing rate of P. Mavuno fertilizer had the highest N uptake of 76.5, 64.4 and 42 kg N ha^{-1} at Sihay, Got Nanga and Tumbeni farms respectively during 2010 LR. At Chimoroni, Koru lime + TSP had the highest uptake of 61.5 kg N ha^{-1} at the same sampling date as shown in tables 12a -12d.

P in the different fertilizer sources significantly ($p < 0.01$) influenced P uptake in the maize grain at Sihay and Tumbeni. At Got Nanga, lime gave a significant ($p < 0.05$) P uptake, whereas at Chimoroni, the treatments did not give any significance during 2010 LR. Mavuno treatment (0.48 t ha^{-1}) gave the highest P uptake of 13.4 and 10.8 kg P ha^{-1} at Sihay and Got Nanga respectively. At Chimoroni, 0.8 t/ha KL + 52 kg P/ha and 0.4 t/ha AL + 52 kg P/ha gave the highest uptake of 9.8 kg P ha^{-1}, while at Tumbeni, 0.48 t/ha Mavuno and 0.4 t /ha AL + 52 kg P/ha gave an uptake of 8.5 kg P ha^{-1}.

Table 12a: Uptake of N and P as influenced by treatments at Sihay site during 2010 LR

SIHAY SITE						
	N Uptake			**P Uptake**		
	P1	P2	**MEAN**	P1	P2	**MEAN**
KL	49.0	57.3	**53.2**	9.5	10.9	**10.2**
AL	47.7	43.0	**45.3**	9.1	8.7	**8.9**
MVN	55.0	74.4	**64.7**	7.3	10.5	**8.9**
MPR	34.4	55.1	**44.8**	11.0	13.4	**12.2**
MEAN	**46.5**	**57.5**		**9.3**	**10.9**	

Table 12b: Uptake of N and P as influenced by treatments at Got Nanga site during 2010 LR

GOT NANGA SITE						
	N Uptake			**P Uptake**		
	P1	P2	**MEAN**	P1	P2	**MEAN**
KL	16.8	22.1	**19.5**	8.8	9.7	**9.3**
AL	8.6	15.1	**11.9**	7.9	8.7	**8.3**
MVN	20.4	27.6	**24.0**	8.7	5.4	**7.1**
MPR	13.4	-7.2	**3.1**	9.6	10.8	**10.2**
MEAN	**14.8**	**14.4**		**8.8**	**8.7**	

Where = KLP1 = 0.4 t /ha Koru lime + 26 kg P/ha KLP2= 0.8 t/ ha Koru lime + 52 kg P/ha. ALP1 = 0.2 t /ha Athi lime + 26 kg P/ha and ALP2 = 0.4 t /ha Athi lime + 52 kg P/ha. MPRP1 = 0.2 t/ha and MPRP2 = 0.4 t/ha Minjingu phosphate rock respectively. MVNP1 = 0.24 and MVNP2= 0.48 t/ ha Mavuno fertilizer. P1 and P2 = 26 and 52 kg P/ha respectively

Table 12c: Uptake of N and P as influenced by treatments at Chimoroni site during 2010 LR

CHIMORONI SITE						
	N Uptake			**P Uptake**		
	P1	P2	**MEAN**	P1	P2	**MEAN**
KL	21.4	24.5	**23.0**	9.3	9.8	**9.6**
AL	2.1	21.1	**11.6**	6.4	9.8	**8.1**
MVN	8.3	17.4	**12.9**	7.0	7.4	**7.2**
MPR	4.6	7.8	**6.2**	7.3	8.9	**8.1**
MEAN	**9.1**	**17.7**		**7.5**	**9.0**	

.

Table 12d: Uptake of N and P as influenced by treatments at Tumbeni site during 2010 LR

TUMBENI SITE						
	N Uptake			**P Uptake**		
	P1	P2	**MEAN**	P1	P2	**MEAN**
KL	25.3	35.2	**30.3**	4.1	5.4	**4.8**
AL	28.9	53.1	**41.0**	4.3	8.5	**6.4**
MVN	29.6	54.3	**42.0**	3.2	6.7	**5.0**
MPR	20.6	41.4	**31.0**	4.8	8.5	**6.7**
MEAN	**26.1**	**46.0**		**4.1**	**7.3**	

Where = KLP1 = 0.4 t /ha Koru lime + 26 kg P/ha KLP2= 0.8 t/ ha Koru lime + 52 kg P/ha. ALP1 = 0.2 t /ha Athi lime + 26 kg P/ha and ALP2 = 0.4 t /ha Athi lime + 52 kg P/ha. MPRP1 = 0.2 t/ha and MPRP2 = 0.4 t/ha Minjingu phosphate rock respectively. MVNP1 = 0.24 and MVNP2= 0.48 t/ ha Mavuno fertilizer. P1 and P2 = 26 and 52 kg P/ha respectively.

4.2.5 Nutrient use efficiency by the maize grain as affected by different sources of lime and P

4.2.5.1 Agronomic nitrogen and phosphorus use efficiencies

Application of phosphorus at 52 kg P ha^{-1} generally gave higher agronomic nitrogen use efficiency (ANUE) in all sites. Mavuno fertilizer at 52 kg P ha^{-1} had the highest agronomic nitrogen use efficiency of 31.5, 41.1 and 24.6 kg grain/kg N applied at Got Nanga, Sihay and Tumbeni sites, respectively. At Chimoroni, Koru lime + TSP (52 kg P ha^{-1}) had the highest ANUE of 24.4 kg grain/kg N applied as shown in table 13a – 13b. Mean agronomic phosphorus use efficiency (APUE) decreased with increased phosphorus application in Siaya while the opposite was true in Kakamega North. Koru lime (0.4 t ha^{-1} + 26 kg P ha^{-1}) gave highest APUE of 46.1 and 39.2 kg grain/kg P applied at Got Nanga and Chimoroni respectively. Mavuno fertilizer (26 and 52 kg P ha^{-1}) had the highest APUE of 109.1 and 35.5 kg grain/kg P applied at Sihay and Tumbeni respectively.

Table 13a: Mean ANUE (kg grain kg N^{-1}) and APUE (kg grain kg P^{-1}) as affected by treatments at Got Nanga and Sihay sites

	GOT NANGA						SIHAY					
	ANUE			APUE			ANUE			APUE		
	P1	P2	**MEAN**	P1	P2	**MEAN**	P1	P2	**MEAN**	P1	P2	**MEAN**
KL	16.0	14.8	**15.4**	46.1	21.4	**33.7**	25.3	39.6	**32.4**	72.9	57.1	**65.0**
AL	9.0	12.6	**10.8**	25.9	18.2	**22.0**	37.5	37.0	**37.2**	108.0	53.3	**80.7**
MVN	9.7	31.5	**20.6**	27.9	45.4	**36.7**	37.8	41.1	**39.5**	109.1	59.3	**84.2**
MPR	14.7	3.3	**9.0**	42.3	4.8	**23.5**	26.9	39.6	**33.3**	77.6	57.2	**67.4**
MEAN	**12.3**	**15.6**		**35.5**	**22.4**		**31.9**	**39.3**		**91.9**	**56.7**	

Table 13b: Mean ANUE (kg grain kg N^{-1}) and APUE (kg grain kg P^{-1}) as affected by treatments at Chimoroni and Tumbeni sites

	CHIMORONI						TUMBENI					
	ANUE			APUE			ANUE			APUE		
	P1	P2	**MEAN**	P1	P2	**MEAN**	P1	P2	**MEAN**	P1	P2	**MEAN**
KL	13.6	24.4	**19.0**	39.2	35.2	**37.2**	12.3	16.1	**14.2**	35.4	23.2	**29.3**
AL	3.6	21.9	**12.8**	10.4	31.6	**21.0**	6.9	18.6	**12.7**	19.8	26.8	**23.3**
MVN	10.4	10.5	**10.5**	30.0	15.1	**22.6**	7.2	24.6	**15.9**	20.7	35.5	**28.1**
MPR	4.8	15.0	**9.9**	13.8	21.7	**17.8**	3.3	12.8	**8.1**	9.7	18.4	**14.0**
MEAN	**8.1**	**18.0**		**23.4**	**25.9**		**7.4**	**18.0**		**21.4**	**26.0**	

Where, KLP1 and KLP2 = 0.4 and 0.8 t ha^{-1} Koru lime + 26 and 52 kg P ha^{-1} respectively. ALP1 and ALP2 = 0.2 and 0.4 t ha^{-1} Athi lime + 26 and 52 kg P ha^{-1} respectively. MVNP1 and MVNP2 = 0.24 t/ha (76 kg CaO/ha + 26 kg P/ha) and 0.48 t ha^{-1} (152 kg CaO/ha + 52 kg P ha^{-1}) as Mavuno fertilizer. MPRP1 and MPRP2 = 0.2 t/ha (76 kg CaO/ha + 26 kg P/ha) and 0.4 t ha^{-1} (152 kg CaO/ha + 52 kg P ha^{-1}) as Minjingu phosphate rock. P1 and P2 = 26 and 52 kg P ha^{-1} respectively.

4.2.5.2 Internal (physiological) nitrogen and phosphorus use efficiencies

Figures 8a and 8b show three season mean effect of different sources of lime and P fertilizer on physiological N and P use efficiencies (PNUE and PPUE) in the maize grain. There was a significant ($p < 0.05$) difference between grain PNUE due to treatments at Got Nanga, Chimoroni and Tumbeni. The grain PPUE decreased with increase in phosphorus rate at Got Nanga, Chimoroni and Tumbeni. The Mean PPUEs were 549.1 to 545.1, 457.9 to 434.5 and 596.9 to 435.1 grain yield increase (kg/ha) per kg P fertilizer uptake due to 26 and 52 kg P/ha addition at Tumbeni, Chimoroni and Got Nanga sites, respectively. At Sihay, PPUEs were 497.0 and 521.9 grain yield increase (kg/ha) per kg P uptake due to 26 and 52 kg P/ha respectively.

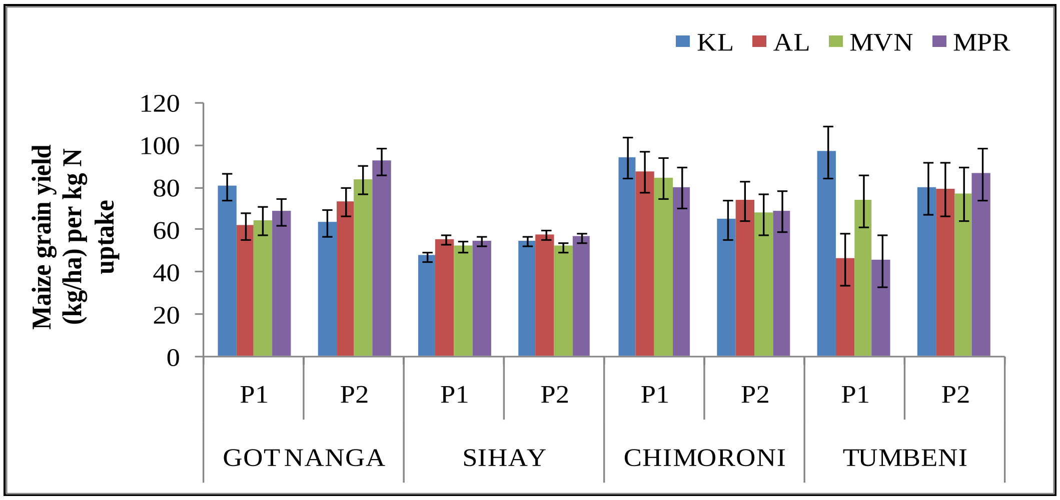

Figure 8a: Effects of different sources of lime and phosphorus fertilizer on a three season mean physiological N use efficiency by the grain at the study sites.

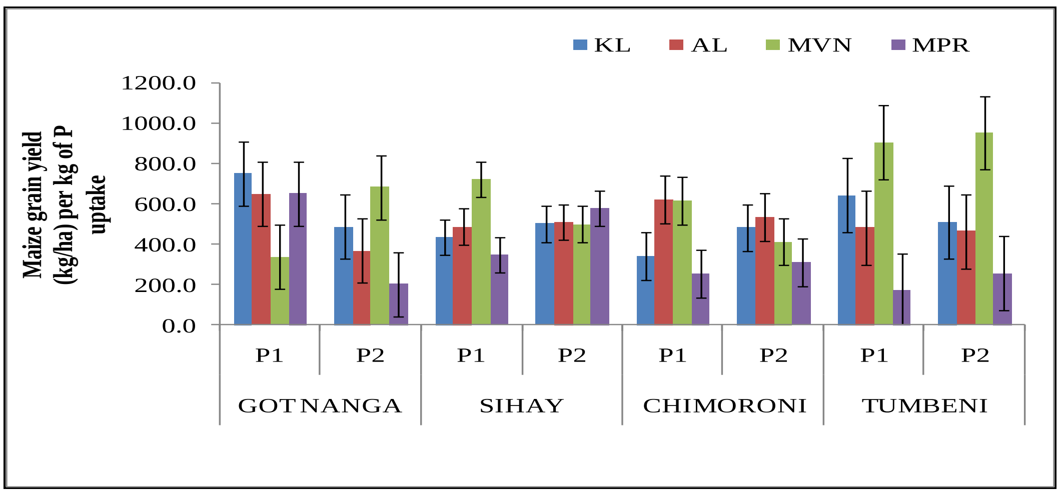

Figure 8b: Effects of different sources of lime and phosphorus fertilizer on a three season mean physiological P use efficiency by the grain at the study sites. *Where, KLP1 and KLP2 = 0.4 and 0.8 t ha^{-1} Koru lime + 26 and 52 kg P ha^{-1} respectively. ALP1 and ALP2 = 0.2 and 0.4 t ha^{-1} Athi lime + 26 and 52 kg P ha^{-1} respectively. MVNP1 and MVNP2 = 0.24 t/ha (76 kg CaO/ha + 26 kg P/ha) and 0.48 t ha^{-1} (152 kg CaO/ha + 52 kg P ha^{-1}) as Mavuno fertilizer. MPRP1 and MPRP2 = 0.2 t/ha (76 kg CaO/ha + 26 kg P/ha) and 0.4 t ha^{-1} (152 kg CaO/ha + 52 kg P ha^{-1}) as Minjingu phosphate rock. P1 and P2 = 26 and 52 kg P ha^{-1} respectively.*

4.2.5.3. Partial factor of productivity

Partial factor of productivity (PFP) due to nitrogen increased with increasing rates of P. However, the PFP due to phosphorus decreased with increasing phosphorus rates. Mavuno fertilizer gave the highest PFP (nitrogen) at Got Nanga, Sihay and Tumbeni as shown in tables 14a – 14b. At Chimoroni, Koru lime + TSP had the highest PFP (nitrogen). In Siaya, Mavuno fertilizer had the highest PFP (phosphorus) of 93.2 and 116.0 at Got Nanga and Sihay. In Kakamega North, Koru lime + TSP application gave the highest PFP (phosphorus) at Chimoroni and Tumbeni

Table 14a: Mean PFP (kg/ha) as affected by treatments at Got Nanga and Sihay sites

	GOT NANGA						SIHAY					
	PFP (N)			PFP (P)			PFP (N)			PFP (P)		
	P1	P2	**MEAN**	P1	P2	**MEAN**	P1	P2	**MEAN**	P1	P2	**MEAN**
KL	42.1	41.0	**41.5**	121.5	59.1	**90.3**	40.0	54.3	**47.1**	115.3	78.2	**96.8**
AL	35.1	38.7	**36.9**	101.2	55.9	**78.6**	52.1	51.6	**51.9**	150.3	74.5	**112.4**
MVN	35.8	57.6	**46.7**	103.3	83.1	**93.2**	52.5	55.8	**54.1**	151.5	80.5	**116.0**
MPR	40.8	29.4	**35.1**	117.6	42.5	**80.1**	41.6	54.3	**47.9**	120.0	78.3	**99.1**
MEAN	**38.5**	**41.7**		**110.9**	**60.1**		**46.5**	**54.0**		**134.4**	**73.6**	

Where, KLP1 and KLP2 = 0.4 and 0.8 t ha^{-1} Koru lime + 26 and 52 kg P ha^{-1} respectively. ALP1 and ALP2 = 0.2 and 0.4 t ha^{-1} Athi lime + 26 and 52 kg P ha^{-1} respectively. MVNP1 and MVNP2 = 0.24 t/ha (76 kg CaO/ha + 26 kg P/ha) and 0.48 t ha^{-1} (152 kg CaO/ha + 52 kg P ha^{-1}) as Mavuno fertilizer. MPRP1 and MPRP2 = 0.2 t/ha (76 kg CaO/ha + 26 kg P/ha) and 0.4 t ha^{-1} (152 kg CaO/ha + 52 kg P ha^{-1}) as Minjingu phosphate rock. P1 and P2 = 26 and 52 kg P ha^{-1} respectively

Table14b: Mean PFP (kg/ha) as affected by treatments at Got Nanga and Sihay sites

	CHIMORONI						TUMBENI					
	PFP (N)			PFP (N)			PFP (N)			PFP (P)		
	P1	P2	**MEAN**	P1	P2	**MEAN**	P1	P2	**MEAN**	P1	P2	**MEAN**
KL	40.0	50.8	**45.4**	115.3	73.2	**94.3**	24.3	28.1	**26.2**	70.0	40.5	**55.3**
AL	30.0	48.3	**39.2**	86.5	69.7	**78.1**	18.9	30.6	**24.7**	54.4	44.1	**49.3**
MVN	36.8	36.9	**36.9**	106.2	53.2	**79.7**	19.2	36.6	**27.9**	55.3	52.8	**54.1**
MPR	31.2	41.4	**36.3**	90.0	59.8	**74.9**	15.3	24.8	**20.1**	44.3	35.7	**40.0**
MEAN	**34.5**	**44.4**		**99.5**	**64.0**		**19.4**	**30.0**		**56.0**	**43.3**	

Where, KLP1 and KLP2 = 0.4 and 0.8 t ha^{-1} Koru lime + 26 and 52 kg P ha^{-1} respectively. ALP1 and ALP2 = 0.2 and 0.4 t ha^{-1} Athi lime + 26 and 52 kg P ha^{-1} respectively. MVNP1 and MVNP2 = 0.24 t/ha (76 kg CaO/ha + 26 kg P/ha) and 0.48 t ha^{-1} (152 kg CaO/ha + 52 kg P ha^{-1}) as Mavuno fertilizer. MPRP1 and MPRP2 = 0.2 t/ha (76 kg CaO/ha + 26 kg P/ha) and 0.4 t ha^{-1} (152 kg CaO/ha + 52 kg P ha^{-1}) as Minjingu phosphate rock. P1 and P2 = 26 and 52 kg P ha^{-1} respectively

4.2.6 Economic analysis of different lime and P sources on maize grain yield

At Got Nanga, majority of treatments did not realize economically viable returns. 0.4 t/ha Koru lime + 26 kg P/ha (KL3), MPR1 (26 kg P/ha) and MVN2 (52 kg P/ha) with NFB of Ksh. 187004, 179159, and 239317, respectively were viable. At Sihay, 0.2 t/ha Athi lime + 26 kg P/ha, MVN1 (26 kg P/ha) Mavuno fertilizer, MPR1 (26 kg P/ha) and MPR2 (52 kg P/ha) with NFB of Ksh, 247027, 249156, 200284 and 253782, respectively were viable. In Kakamega North too, Majority of treatments realized economically viable returns as shown in Tables 15a and 15b.

Table 15a: Gross field benefits, total costs that vary, net field benefit and marginal rates of returns analysis of treatments during 2010 LR, SR and 2011 LR at Got Nanga and Sihay sites

CUMMULATIVE (Season 2010 LR - 2011 LR)									
GOT NANGA					SIHAY				
Treatment	GFB (Ksh)	TCV (Ksh)	NFB (Ksh)	MRR (%)	Treatment	GFB (Ksh)	TCV (Ksh)	NFB (Ksh)	MRR (%)
Control	144956	13422	130192		Control	65268	6043	58621	
KL3	**229432**	**38571**	**187004**	**89**	KL3	227052	38350	184867	D
AL3	190708	34785	152444	D	**AL3**	**296016**	**44536**	**247027**	**360**
MVN1	209664	36387	119215	D	**MVN1**	**298200**	**44585**	**249156**	**393**
MPR1	**212772**	**30557**	**179159**	**260**	**MPR1**	**236292**	**32735**	**200284**	**482**
KL4	239036	52080	181748	D	KL4	308112	58476	243789	D
AL4	220948	50005	165942	D	AL4	293328	56707	230950	D
MVN2	**307328**	**61828**	**239317**	**935**	MVN2	316848	62710	247867	D
MPR2	158620	35823	119215	D	**MPR2**	**308448**	**49696**	**253782**	**82**

Table 15b: Gross field benefits, total costs that vary, net field benefit and marginal rates of returns analysis of treatments during 2010 LR, SR and 2011 LR at Chimoroni and Tumbeni sites

CUMMULATIVE (Season 2010 LR - 2011 LR)									
CHIMORONI					TUMBENI				
Treatment	GFB (Ksh)	TCV (Ksh)	NFB (Ksh)	MRR (%)	Treatment	GFB (Ksh)	TCV (Ksh)	NFB (Ksh)	MRR (%)
Control	149520	13844	134291		Control	65520	6067	58847	
KL3	**226716**	**38319**	**184565**	**710**	**KL3**	**135156**	**29841**	**105315**	**854**
AL3	170100	32877	133935	D	**AL3**	**104496**	**26803**	**77692**	**146**
MVN1	**208740**	**36302**	**168808**	**219**	**MVN1**	**106260**	**26813**	**79447**	**170**
MPR1	**176904**	**27236**	**146944**	**86**	**MPR1**	**84504**	**18680**	**65824**	**58**
KL4	**287952**	**56609**	**225682**	**650**	KL4	156660	44453	112207	47
AL4	**274008**	**54918**	**213598**	**195**	**AL4**	**170856**	**45367**	**125489**	**145**
MVN2	209160	52739	151147	D	**MVN2**	**205044**	**52358**	**152686**	**389**
MPR2	**234948**	**42890**	**187769**	**64**	MPR2	137928	33907	104021	D

Where KL3 and KL4 = 0.4 and 0.8 t ha^{-1} Koru lime. AL3, and AL4 = 0.2 and 0.4 t ha^{-1} Athi lime. P1 and P2 = 26 and 52 kg P ha^{-1} respectively. MPR1 and MPR2 = 0.2 and 0.4 t ha^{-1} Minjingu phosphate rock, MVN1 and MVN2 = 0.24 and 0.48 t ha^{-1} Mavuno fertilizer.

4.3 The Greenhouse Pot Experiment (Tumbeni and Sihay soils)

This experiment was conducted after the field experiments when it was realized that Mavuno fertilizer gave the highest maize yields than the other treatments. Therefore, it was carried out to isolate the effects liming and P fertilizer materials used in the field experiment at these two sites only and also to correct possible micronutrient deficiencies from other P sources, but with those nutrients contained in Mavuno. This study was carried out in two soils due to logistics.

4.3.1: Soil pH

Lime and P combined effect significantly ($p < 0.01$) increased pH above the control in Sihay as shown in Figure 9a. Analysis showed no significance in Tumbeni soils however, specific analysis indicated significant differences between treatment means as shown in Figure 9b.

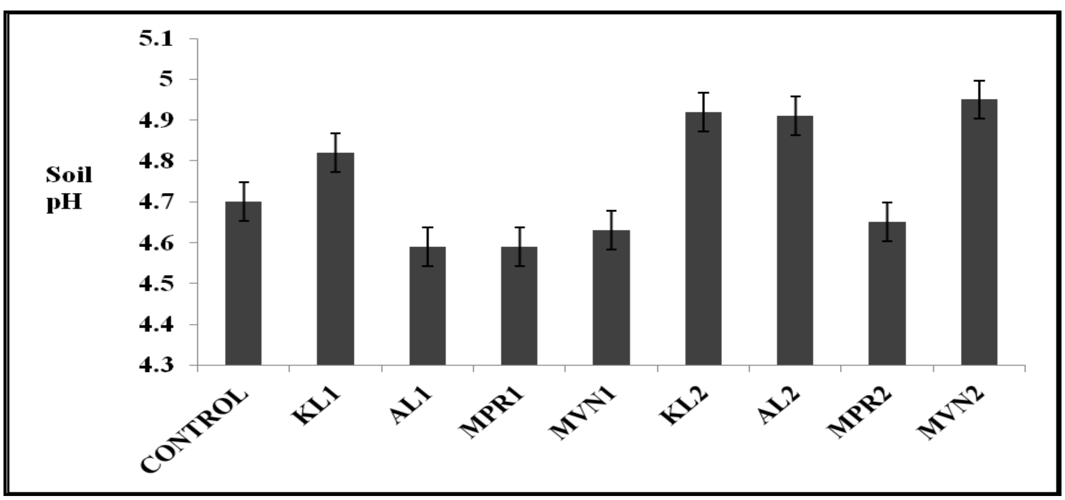

Figure 9a: Soil pH as affected by treatments at harvesting pot trials in Sihay soils

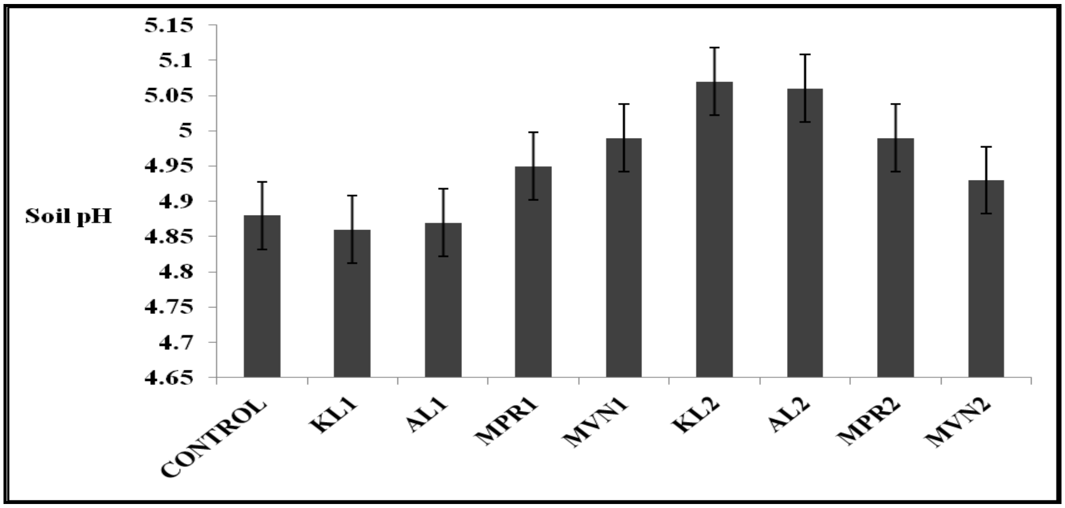

Figure 9b: Soil pH as affected by treatments at harvesting pot trials in Tumbeni soils

Where KL1 and KL2 = 0.4 t/ha koru lime + 26 kg P/ha and 0.8 t/ha koru lime + 52 kg P/ha. AL1 and AL2 = 0.2 and 0.4 t/ha Athi lime + 26 and 52 kg P/ha respectively. MPR1 and MPR2 = 0.2 (26 kg P/ha) and 0.4 t/ha (52 kg P/ha) Minjingu phosphate rock. MVN1 and MVN2= 0.24 (26 kg P/ha) and 0.48 t/ha (52 kg P/ha) Mavuno fertilizer. The error bars show significant difference between treatment means in terms of pH change.

4.3.2: Available soil P

In both soils, P in the different fertilizer sources significantly ($p < 0.01$) influenced P availability at harvesting. Lime however, had no significant effect on P availability. Extractable P ranged from 4.7 mg kg^{-1}(MPR1) to 8.9 mg kg^{-1}(AL2) in Tumbeni soils and 1.7 mg kg^{-1}(control) to 7.7 mg kg^{-1}(MVN2) in Sihay soils as shown in Figure 10a and 10b.

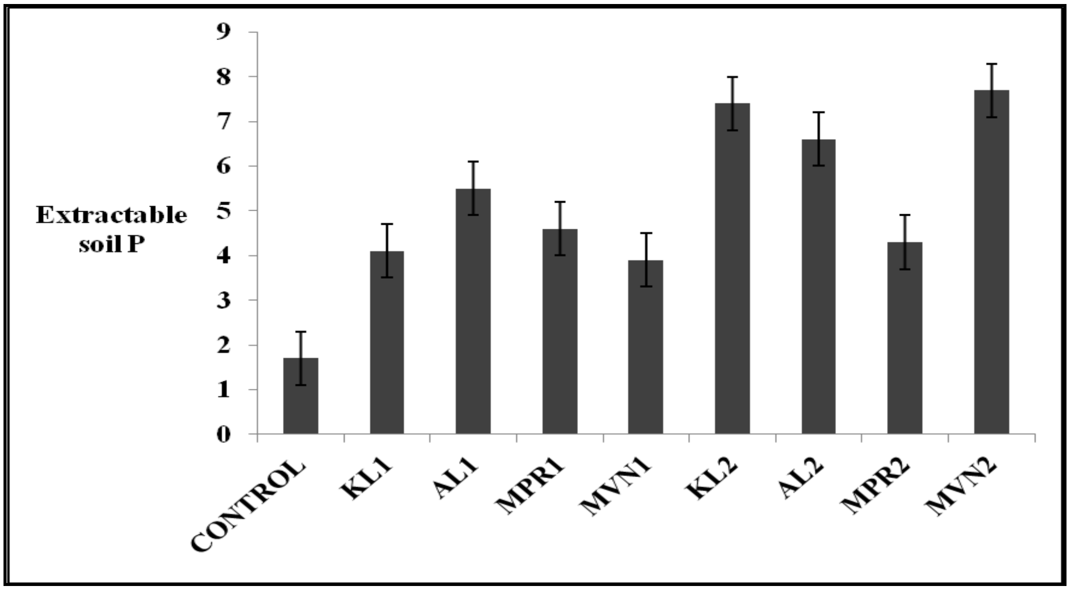

Figure 10a: Available soil P as influenced by treatments at harvesting pot trials in Sihay soil. *Where KL1 and KL2 = 0.4 t/ha koru lime + 26 kg P/ha and 0.8 t/ha koru lime + 52 kg P/ha. AL1 and AL2 = 0.2 and 0.4 t/ha Athi lime + 26 and 52 kg P/ha respectively. MPR1 and MPR2 = 0.2 (26 kg P/ha) and 0.4 t/ha (52 kg P/ha) Minjingu phosphate rock. MVN1 and MVN2= 0.24 t/ha (26 kg P/ha) and 0.48 t/ha (52 kg P/ha) Mavuno fertilizer. The error bars show significant difference between treatment means in terms of P availability*

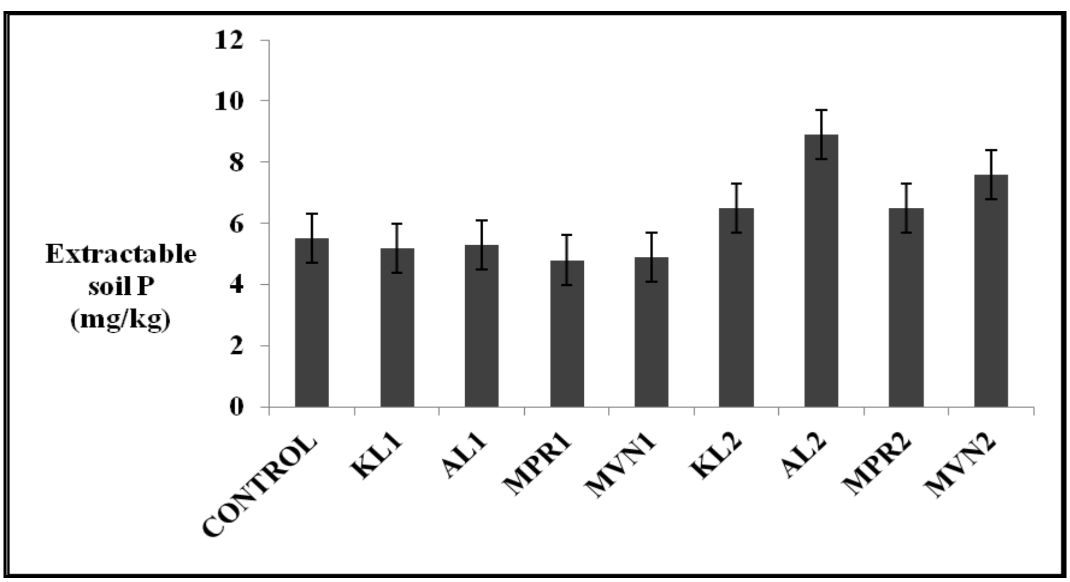

Figure 10b: Available soil P as influenced by treatments at harvesting pot trials in Tumbeni soil. *Where KL1 and KL2 = 0.4 t/ha koru lime + 26 kg P/ha and 0.8 t/ha koru lime + 52 kg P/ha. AL1 and AL2 = 0.2 and 0.4 t/ha Athi lime + 26 and 52 kg P/ha respectively. MPR1 and MPR2 = 0.2 (26 kg P/ha) and 0.4 t/ha (52 kg P/ha) Minjingu phosphate rock. MVN1 and MVN2= 0.24 t/ha (26 kg P/ha) and 0.48 t/ha (52 kg P/ha) Mavuno fertilizer. The error bars show significant difference between treatment means in terms of P availability*

4.3.3: Dry matter yield of maize tops

Dry matter yield ranged from 3.51 g pot^{-1} (control) to 6.88 g pot^{-1} (MVN2) in Sihay soils. General analysis showed no significance, however, contrast test indicated significant ($p < 0.05$) differences between control and treatments at Sihay as shown in Fig 11a. The treatments did not differ significantly from each other at 26 and 52 kg P ha^{-1}. At Tumbeni, treatments did not significantly influence dry matter yield. Maize dry matter yield ranged from 11.3 g pot^{-1} (control) to 15.02 (KL2). Application of P at 26 and 52 kg P ha^{-1} did not differ significantly from each other in influencing dry matter yield as shown in Fig 11b.

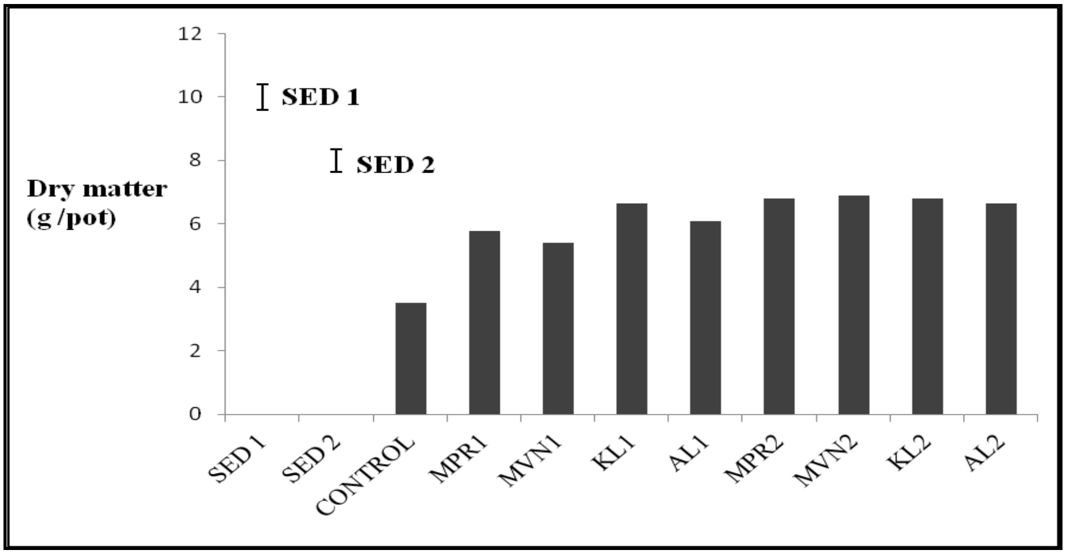

Figure 11a: Dry matter yield of maize as influenced by different lime and P sources in Sihay soils (SED 1= significant difference between P levels, SED 2= Significant difference between lime sources). *Where KL1 and KL2 = 0.4 t/ha koru lime + 26 kg P/ha and 0.8 t/ha koru lime + 52 kg P/ha. AL1 and AL2 = 0.2 and 0.4 t/ha Athi lime + 26 and 52 kg P/ha respectively. MPR1 and MPR2 = 0.2 (26 kg P/ha) and 0.4 t/ha (52 kg P/ha) Minjingu phosphate rock. MVN1 and MVN2= 0.24 (26 kg P/ha) and 0.48 t/ha (52 kg P/ha) Mavuno fertilizer.*

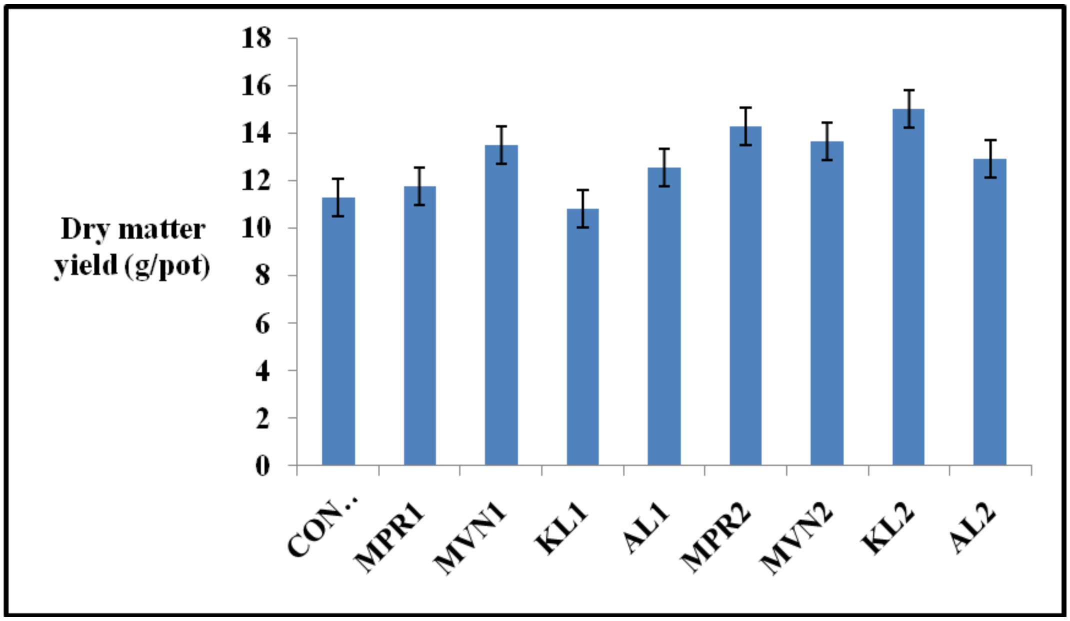

Figure 11b: Dry matter yield of maize as influenced by treatment application in Tumbeni soils. Where KL1 and KL2 = 0.4 t/ha koru lime + 26 kg P/ha and 0.8 t/ha koru lime + 52 kg P/ha. AL1 and AL2 = 0.2 and 0.4 t/ha Athi lime + 26 and 52 kg P/ha respectively. MPR1 and MPR2 = 0.2 (26 kg P/ha) and 0.4 t/ha (52 kg P/ha) Minjingu phosphate rock. MVN1 and MVN2= 0.24 (26 kg P/ha) and 0.48 t/ha (52 kg P/ha) Mavuno fertilizer. The error bars show significant difference between treatment means in terms dry matter yield.

4.3.4. Uptake of N and P as influenced by treatments

Generally, treatments did not show any significance in terms of N uptake in both soils, however, contrast test indicated that control differed significantly from the different fertilizer sources in Sihay as shown in Fig 12a. Lime application significantly ($p < 0.05$) increased P uptake at Sihay, while P was significant ($p < 0.05$) at Tumbeni as shown in Fig 12b and 12c respectively.

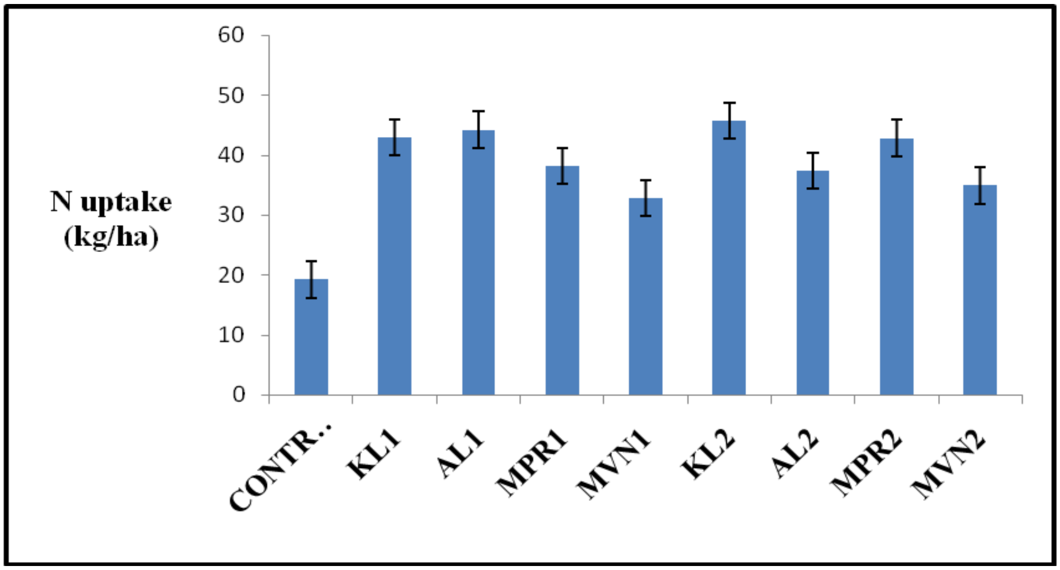

Fig 12a: N uptake as influenced by treatments in Sihay soils.

Where KL1 and KL2 = 0.4 t/ha koru lime + 26 kg P/ha and 0.8 t/ha koru lime + 52 kg P/ha. AL1 and AL2 = 0.2 and 0.4 t/ha Athi lime + 26 and 52 kg P/ha respectively. MPR1 and MPR2 = 0.2 (26 kg P/ha) and 0.4 t/ha (52 kg P/ha) Minjingu phosphate rock. MVN1 and MVN2= 0.24 (26 kg P/ha) and 0.48 t/ha (52 kg P/ha) Mavuno fertilizer. The error bars show significant difference between treatment means in terms N (11a) and P (11b) uptake respectively.

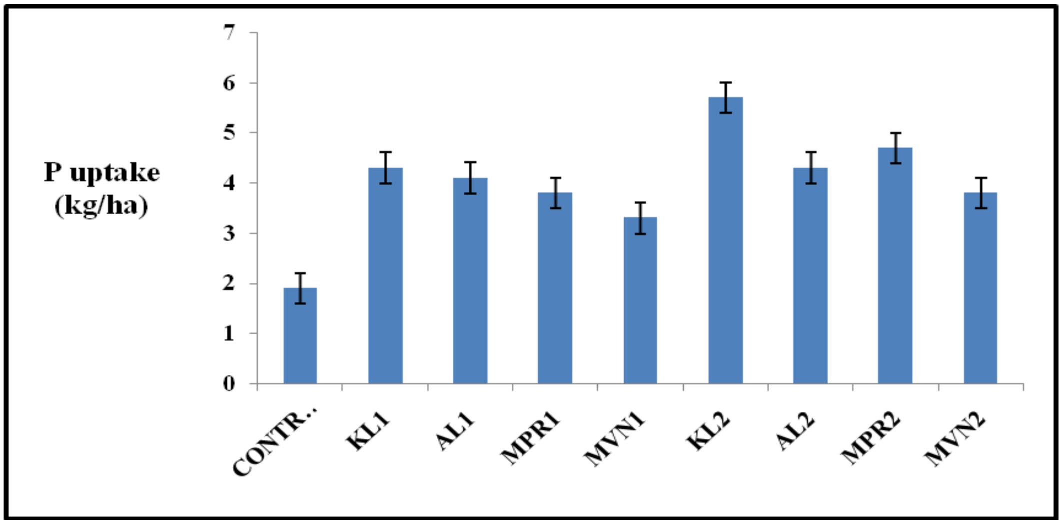

Fig 12b: P uptake as influenced by treatments in Sihay soil

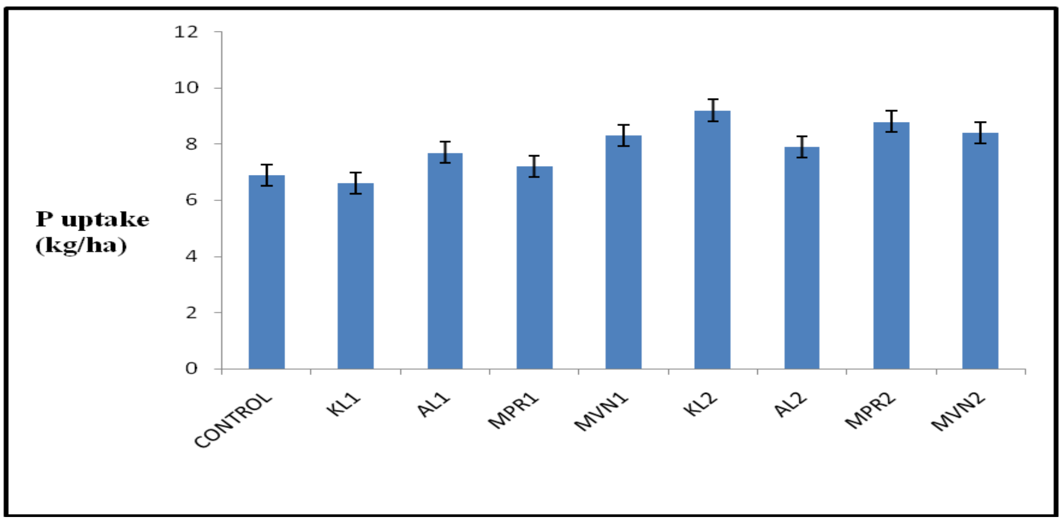

Fig 12c: P uptake as influenced by treatments in Tumbeni soil

Where KL1 and KL2 = 0.4 t/ha koru lime + 26 kg P/ha and 0.8 t/ha koru lime + 52 kg P/ha. AL1 and AL2 = 0.2 and 0.4 t/ha Athi lime + 26 and 52 kg P/ha respectively. MPR1 and MPR2 = 0.2 (26 kg P/ha) and 0.4 t/ha (52 kg P/ha) Minjingu phosphate rock. MVN1 and MVN2= 0.24 (26 kg P/ha) and 0.48 t/ha (52 kg P/ha) Mavuno fertilizer. The error bars show significant difference between treatment means in terms P uptake

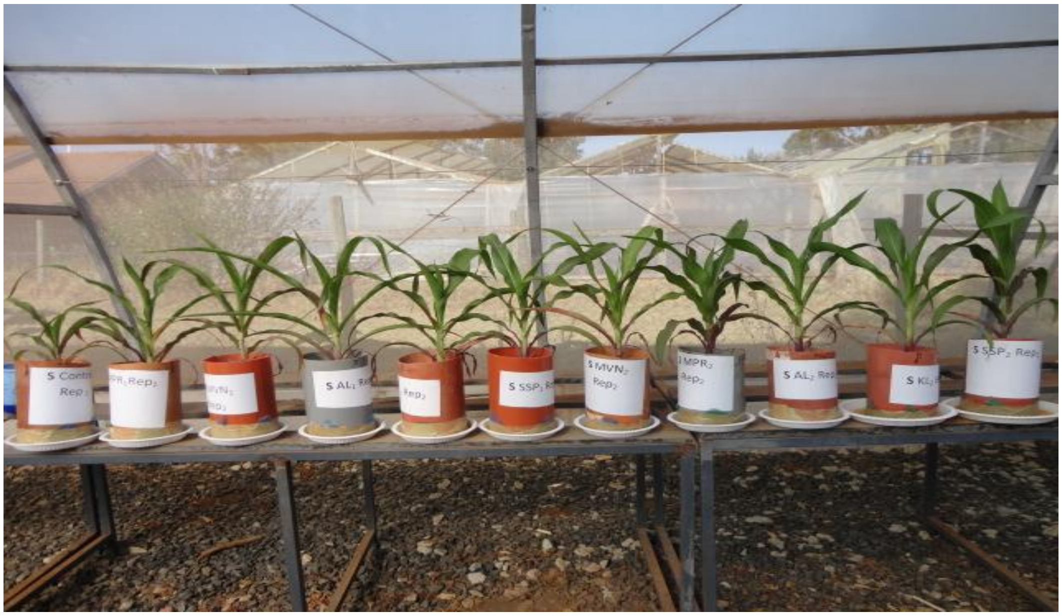

Plate 4: Green house pot experiment showing treatments in ascending order of P rates. Control (extreme left) to lower rate of 26 kg P/ha to higher rate of 52 kg P.

(Source: Omenyo, 2013)

Plate 5: Greenhouse pot experiment showing difference in growth of maize plants. L – Kakamega and R- Siaya counties.

(Source: Omenyo, 2013)

CHAPTER FIVE

DISCUSSION

5.1. Field experiments

5.1.1. Physical and chemical characteristics of the soils at the study sites

The low soil pH of these soils indicate that they require to be adjusted through liming and other appropriate practices if maize crop is to perform well. In a study by Gahoonia and Nisden (1992), it was reported that PR dissolution was enhanced in soils with pH < 5.5. Therefore, MPR could undergo a substantial dissolution in these soils. The low amounts of available soil P (less than 10 mg kg^{-1}) as suggested by Landon (1984) and Okalebo *et al.*, (2002), imply that these soils need supplemental P addition (Ndung'u *et al,* 2006). Since P availability is dependent on other factors like suitable soil pH, these soils would respond to application of both lime and P. The low levels of cations in all the sites suggest that the cations could have been leached down the horizons, and their place taken up by Fe and Al ions as indicated by the high levels of these ions. These soils therefore, have crop production problems since, oxides of Al and Fe, fix P making it unavailable for crop uptake (Tisdale and Werner, 1961). The result is manifested in the low yields as frequently experienced in this region (Nekesa *et al.,* 1999). Therefore, addition of micronutrients such as Zinc, Boron and Molybdenum to these soils can improve the yield response to macronutrients hence improved fertilizer – use efficiency and crop profitability (Sanginga and Woomer, 2009). The C: N ratios with values of 11:1, 9: 1, 8:1 and 12:1 were stable. Soil particle size analysis indicated that the soils at Got Nanga, Sihay and Tumbeni were heavy soils because they have higher clay percentage as compared to those at Chimoroni, and thus they possess the capacity to store nutrients (Kolay, 1993).

5.1.2. Soil profile characterization of the study sites

Soils of Siaya and Kakamega Counties are classified as Acrisols and partly Ferralsols. They are known to be highly weathered soils and are prone to leaching (Deckers, 1993). The leaching could explain why the cations concentration increased down the profile a process common to Acrisols (Somasiri, 1985) especially in Siaya soils. In as much as the leaching occurs, still the concentration of basic cations in some sites is below the recommended levels (Okalebo et al., 2002). This is prominent in such soils with low CEC. These soils are known to contain 2:1 low activity clays that are rich in hydrous Fe, Al oxides and Al hydroxides (Deckers, 1993). From the characteristic study that was carried out, Siaya soils were found to be Orthic Acrisols while Kakamega North soils were Ferralo – humic Acrisols. The soils in Kakamega North are inter-mediary soils that are still undergoing soil formation process. There is also the possibility of elements being transported down through erosion in this site, since it is found at the Nandi Escarpment Valley (C. Serrem, *personal communication, 2011*).

Discussion for experiment 1

5.1.3. Direct and residual effect of lime and P fertilizer application on soil pH

There was a significant increase in soil pH above the control due to application of lime in all the sites. According to Brady and Weil (2004), raising soil pH (reducing soil acidity), usually involves amending soil with alkaline materials that provide conjugated bases of weak acids that are capable of reacting with H^+ ions to form weak acids such as water. At Got Nanga, application of P significantly increased soil pH. It could be that this soil had a low buffer capacity such that the Ca element in TSP was capable of increasing soil pH. As explained by Brady and Weil (2004), buffering influences the amount of amendment required to bring about a desired change in soil pH and the lower the buffering capacity the faster the change and less amount of lime is required. During 2010 LRs, application of lime at 1.5 t ha^{-1} (Koru) or 0.7 t ha^{-1} (Athi) and 3 t ha^{-1} (Koru) and 1.4t ha^{-1} as (Athi) respectively did not differ significantly from each other in the levels of pH rise. This suggests that either of the two agricultural limes could be used to ameliorate soil acidity. However, there were significant differences between 1.5 and 3 t ha^{-1} KL, and between 0.7 and 1.4 t ha^{-1} AL at Sihay, suggesting that the lower rate of lime increases soil pH at Sihay but not significantly. A farmer at Sihay has to apply a higher rate to significantly influence soil pH change. At Got Nanga, there was no significance between 1.5 and 3 t ha^{-1} KL the same to 0.7 and 1.4 t ha^{-1} AL. A farmer at Got Nanga can apply the lower rate and still realize the benefits. The high pH at Got Nanga compared to Sihay could be that, initial status showed Got Nanga to have higher pH (5.49) value compared to Sihay pH (4.92). The negatively charged clay soils have a high tendency of holding cations on the exchange sites more firmly and longer (Brady and Weil, 2004). This could denote that more Ca^{2+} in the lime was held in the exchange sites for a longer time and more firmly hence reflecting stable soil pH at Got Nanga. At Chimoroni, 1.5 t ha^{-1} KL and 0.7 t ha^{-1} AL did not differ significantly from control in pH levels 120 DAP. However, there was significant difference between control and 3 t ha^{-1} KL and 1.4 t ha^{-1} AL. This showed that lime at 1.5 t ha^{-1} as KL or 0.7 t ha^{-1} as AL is not sufficient to influence pH change in these soils. At Tumbeni, the control treatment did not differ significantly from 1.5 t ha^{-1} KL, however, it differed significantly compared to 3 t ha^{-1} KL, suggesting that 3 t ha^{-1} KL sufficiently influences soil pH change in these soils as opposed to 2 t ha^{-1} suggested by Kisinyo (2011). The high pH values given by 3 t ha^{-1} KL application during the succeeding cropping seasons, could be due to the greater amount compared to 1.5 t ha^{-1} and its reactive nature.

5.1.4. Site differences in terms of pH change over time as influenced by lime and P application

Siaya county soils are classified as Orthic Acrisols. They are less weathered compared to the soils in Kakamega North (Ferralo humic Acrisols) (Deckers, 1993). Their capacity to retain nutrients is higher as compared to those with ferralic properties as in Kakamega North county because of the high clay percentage (Brady and Weill, 2004). This could explain why application of lime maintained soil pH above 5.5 for two and three consecutive cropping seasons in Sihay and Got Nanga sites, respectively. Additionally, Siaya county soils could be having low buffer capacity, thus, responded to lime application (Brady and Weil, 2004). Therefore, they were able to resist any acidifying effect of say acid rain or fertilizers. The soils in Kakamega North county probably require small doses of lime as compared to large massive application to supply calcium and to buffer the low soil pH.

5.1.5. Direct and residual effect of lime and P application on available soil P

Lime and P significantly gave high amounts of available soil P at Got Nanga, and Sihay, while lime was significant at Chimoroni in increasing P levels in soils. Phosphates are known to be sorbed at low pH (< 5.5) by oxides of Al and Fe in acidic soils (Sanginga and Woomer, 2009). Therefore, application of lime raised the soil pH thereby releasing the sorbed P hence making it available for plant uptake. In as much as lime is capable of influencing available soil P in Siaya, supplemental P addition is required in these soils (Ndung'u *et al*, 2006), just like it is required in the soils of Tumbeni for optimum crop production. The significant time x lime interaction in Kakamega North indicates that lime progressively changes the soil pH, resulting in favourable environment for nutrients such as P and micronutrients (Brady and Weil, 2004; Sanginga and Woomer, 2009). The reduced values of available soil P during 2010 SR and 2011 LR, indicate that application of 26 kg P

ha^{-1} may last for just one cropping season in these soils mainly because of the uptake by maize crop and P sorption. Therefore, higher rates of P fertilizer should be applied to achieve higher available P values in the soil during the following cropping seasons. This may however, be unattainable due to the acidic nature and high P fixation of these soils and the high cost of fertilizer.

5.1.6. Maize grain yield as affected by combination of lime and P application in all the sites during the three cropping seasons

During the 2010 LR, application of lime alone and lime in combination with P fertilizer increased maize yields above the control at Got Nanga. As reported by Adams, (1984), application of agricultural liming materials not only supplies Ca or Mg to the crops but also adjusts the soil pH to values that ensure availability of other nutrients. Consequently, the soil had close to adequate P for crop provided that the constraints due to acidity were eliminated. This could explain why 3 t ha^{-1} Koru lime application alone gave better maize yields in this site.

At Sihay, P significantly increased maize grain yield suggesting that lime alone was not sufficient, thus applying lime, P and N is the best way for optimum yield. These findings support work done in Rwanda by Rutunga *et al,* (1998), in which they observed that application of agricultural lime alone was not sufficient to replenish depleted soils and that a combination of lime, organic and/or inorganic fertilizers was the most effective way of addressing the problem of soil acidity and enhancing soil fertility. In Kakamega North county, application of soil amendment materials did not give any significance. However, application of lime alone increased maize yield above the control at Chimoroni and Tumbeni. Lime in combination with P and N gave higher maize yield at Chimoroni, indicating that cautious use of fertilizers in combination with lime is the best practice

(Biswas and Murkherjee, 1994). During the 2010 SR, maize yields were very low in all the sites. This could have been due to the inadequate rainfall experienced during that season as shown in Appendix 4. In the final season, the soil amendment materials still showed significance, though the yields had dropped in most of the sites. Koru lime + TSP (3 t ha^{-1} KL + 26 kg P ha^{-1}) application gave higher maize yields in all the sites compared to the other liming materials. As explained by Brady and Weill, (2004), CaO is quick in reacting, therefore could explain the higher yield by Koru lime in these sites. In addition, this was a 3 t ha^{-1} lime application and thus had a longer residual effect.

5.1.7. Correlations between maize grain yield, available soil P and soil pH

The significant and positive correlations observed at the third and fourth sampling stages were because at about 80 DAP to physiological maturity, maize is in the milk stage (a grain filling stage) where the kernels are filled with white, milky fluid. At this stage, sugar content decreases and the starch content increases. Also, water content decreases as dry matter content increases (Ritchie and Hanway, 1984). Maize grain yield was significantly correlated to available soil P at Sihay, Chimoroni and Tumbeni and not soil pH because application of lime alone was insufficient to replenish the depleted nutrients, but addition of P gave a stronger and significant correlation. The maize crop was also probably able to take up phosphorus during the period of fast growth that was later manifested in increased yields. If plant growth is poor due to a range of factors including nutrient deficiency, then the yield of the harvested crop will be low (Tisdale *et al*., 1990). It was observed from this study, however, that maize yields increased due to increased available soil P from the lime and P applications at planting. These results agree with those of Nekesa (2007) and Menon *et al*., (1989) who reported that available soil P was significantly correlated to grain and dry matter yield of maize in soils treated with TSP. At Got Nanga, maize grain yield was significantly correlated to both available soil P and soil pH. Application of lime (Ca^{2+}) is capable of releasing fixed P, making it available for plant uptake hence increased maize yield (Brady and Weil, 2004). This suggests that this site initially had P, which could have been fixed by oxides of Al and Fe and was later released into the soil solution as a result of increased soil pH. The positive and significant correlation between available soil P and soil pH in Siaya indicates that these soils initially had P that was fixed. As the pH increased, P became available because soil pH greatly affects P availability to plants, becoming fairly insoluble at both low (< 4) and high (> 8) pH levels (Sanginga and Woomer, 2009).

5.1.8. Uptake of N and P in Maize crop as influenced by P and Lime application

Generally, application of N and P significantly influenced N and P uptake in all the sites. There was a blanket application of N (75 kg N ha^{-1}), thus treatments like MPR and agricultural lime that do not contain N gave significant N and P uptake. Nitrogen is renowned for boosting P uptake and this most likely led to the increased uptake of these nutrients in the treated plots (Rowell, 1994). Application of lime alone also increased N and P uptake. Acidic conditions lessen the rate of release of mineral–N because certain microbes that are involved in N mineralization cannot survive in acidic soils. Liming, however, increases the rate of N mineralization and thus advances the supply of mineral–N to plants (Rowell, 1994). The higher N uptakes in Siaya than Kakamega North could possibly be due to the high rainfall experienced in Kakamega North during 2010 LR as shown in Appendix 4. High rainfall enhances leaching of NO_3^- N from the rhizosphere resulting in reduced N uptake (Rowell, 1994). The high P uptake at Got Nanga could be due to the well developed rooting system of the crop as a result of high initial available soil P status. Thus, the plants could possibly search for nutrients in larger soil volume as compared to the other sites.

5.1.9 Agronomic and physiological nitrogen and phosphorus use efficiencies

Both agronomic and physiological N and P use efficiency increased with increased lime rates because lime alleviates plants from pyhtotoxicity of Al which results in good root growth, required for nutrient uptake and utilization by plants (Kochian, 1995; Ligeyo *et al.*, 2006). Application of 3 t/ha lime gave the highest ANUE and APUE. This agrees with work done by Kisinyo, (2011) and Tabu *et al.*, (2007) who found that lime increased plant N and P use efficiencies in acid soils. ANUE, PNUE and PPUE increased with P application because application of lime alone is insufficient to replenish depleted soils (Rutunga *et al.*, 1998) such as these. Therefore, supplemental P addition is necessary (Ndung'u *et al.*, 2006) for optimum production.

5.1.10 Partial factor of productivity

Application of P fertilizer increased N uptake hence greater productivity. Increasing lime rates also resulted in higher productivity. This indicates that application of lime, N and P is the most productive cropping system in this region.

5.1.11 Economic analysis

Majority of treatments did not realize economically viable returns at Sihay, Chimoroni and Tumbeni sites possibly because of the high cost of inorganic inputs, a factor that has been cited (Okalebo *et al.*, 2006; Sanchez *et al.*, 1997) as the main cause for lack of adoption of the recommended soil fertility replenishment technologies among the smallholder farmers in western Kenya and SSA as a whole. Where lime was used together with N and P fertilizer, the returns were positive and higher in the long term (i.e during the third season) as compared to where lime was used with N alone. This could have been due to the longer residual effect of lime, since its effects have been reported to last for several years and not all the returns are realized in the first year (Havlin *et al.,* 2006). In all the sites it was observed that application of lime at lower rates of 1.5 t/ha Koru lime or 0.7 t/ha Athi lime was viable.

Discussion for experiment 2

5.2.1. Direct and residual effect of different lime and P sources on soil pH

Lime component in the different fertilizer sources significantly increased soil pH at Sihay, and Tumbeni implying that it was capable of neutralizing soil acidity and supplied calcium. Got Nanga had higher pH values as compared to Sihay. Initially this site had high pH values as compared to the other sites. It could also have a lower buffering capacity as compared to Sihay, thus succumbed to pH change a lot faster than Sihay as mentioned above. In Siaya, treatments did not differ significantly from each other at the end of the first season, suggesting that all these different lime and P fertilizer sources are capable of influencing pH change equally. However, 0.8 t ha^{-1} Koru lime + 52 kg P/ha (5.35) had higher pH values at Sihay and 0.2 t ha^{-1} MPR (5.69) at Got Nanga.

5.2.2. Direct and residual effect of different lime and P sources on available soil P

Koru lime + TSP gave significantly higher P values than MPR because TSP is highly a soluble source of P and would release P faster as compared to the sparingly soluble MPR (Szilas *et al* 2006; Ngoze, 2002)). In addition, the lime component (CaO) could have induced the release of precipitated P by increasing soil pH therefore, increasing P availability at Chimoroni. At Got Nanga, both lime and P application were significant in influencing P availability. This could be explained by the findings of Foster (1969), who reported that lime is effective by making more available the reserve of nutrients already present in the soil, plus the fact that lime was capable of releasing sorbed P by raising pH making it available. 0.8 t/ha Koru lime + 52 kg P/ha had higher P values because of the readily soluble TSP at a higher rate (52 kg P ha^{-1}) as compared to lower rate of 26 kg P/ha.

5.2.3 Maize grain yield as affected by different lime and P sources in all the sites during the three cropping seasons

All different lime and P sources in this study gave better maize yields than the control in all the sites during 2010 LR. Comparing Siaya and Kakamega North county, maize crop performed better in Siaya than Kakamega North. This could be attributed to the initial fertility status of the soils and the type of soils. From the soil characterization study, Kakamega North soils were found to be transition from Ferralsol to Acrisol. They are more weathered than Acrisol as in Siaya (Deckers, 1993) and since it is a transition, treating it could be a lot tricky. In addition, these soils had high Fe and Al levels that are likely to fix P, resulting in reduced crop yields (Kennedy, 1992). There was no significant difference between 26 and 52 kg P ha^{1-} application in these sites during this season suggesting that application of P at a lower rate is effective and hence economical. Comparison of the different sources in terms of maize yield showed that 0.48 t ha^{-1} MVN differed significantly from 0.2 and 0.4 t ha^{-1}MPR, 0.2 t ha^{-1} AL + 26 kg P ha^{-1} (AL3P1) and 0.4 t ha^{-1} AL + 52 kg P ha^{-1} (AL4P2) in Got Nanga and Tumbeni and from 0.4 t ha^{-1} KL + 26 kg P ha^{-1} (KL3P1), 0.2 t ha^{-1} MPR and 0.2 t ha $^{-1}$ AL + 26 kg P ha^{-1} (AL3P1) in Sihay. Nutrients such as Zn, B, S and Mg, included in Mavuno fertilizer can dramatically improve fertilizer use- efficiency and crop profitability when targeted to deficient soils (Woomer and Sanginga, 2009). This could be the reason as to why Mavuno gave higher maize yields as compared to the others. Additionally, in a study by Wendt *et al,* (1994), it was reported that supplementation by S, Zn, B and K increased maize yields by 40% over the standard N – P recommendation alone.

The low yields by MPR during this season could be explained by the slow release of nutrients (Szilas, 2006) by MPR.

The low and insignificant grain yield in the second season is attributed to the low and poorly distributed rainfall. Nonetheless, 0.2 t ha^{-1} Mavuno gave higher yields (3.69 t ha^{-1}) at Sihay during this season. In the final season (2011 LR), MPR gave higher yields as compared to the other previous cropping seasons. In a study by Semoka and Kalumuna (1991) on MPR research work conducted in Tanzania it was found that under favourable conditions of low soil pH, P and calcium and high rainfall, MPR was as effective as the inorganic P fertilizers such as TSP. However, conventional fertilizers were found to be better than MPR in the first season of application. But its effectiveness increased in the subsequent seasons as was seen in this study. From the third season of application onwards, yields obtained from MPR addition were higher than those from conventional fertilizers (Nekesa, 2007).

5.2.4 Uptake of N and P in maize crop as influenced by different lime and P sources

Application of lime and P in the different fertilizer sources still significantly influenced N and P uptake in all the sites. N uptake increased with increasing rate of P application. This suggests that the greater the amount of available soil P, the more the N uptake by plants. These findings corroborate with those of Nekesa (2007) who reported increased N uptake with increasing rate of P. Mavuno fertilizer gave the highest N and P uptake at Sihay, Got Nanga and Tumbeni sites. This could be due to the additional micronutrients it contains. As indicated by Woomer and Sanginga (2009), micronutrients can limit plant growth and substantially lower yields when deficient, though, they are required by plants in small quantities. Additions of these micronutrients, thus, can improve the yield response to macronutrients on deficient soils as shown in table 4a.

5.2.5 Agronomic and physiological N and P use efficiencies

Mavuno had the highest ANUE at Sihay, Got Nanga and Tumbeni sites. The reason for this could be that the micronutrients in Mavuno were able to improve on the yield response to macronutrients hence increased fertilizer use efficiency (Sanginga and Woomer, 2009). According to Liebig's Law of Minimum, the most limiting factor determines the yield potential (Giller *et al.*, 2002). Once the most limiting factor is minimized, the second most limiting factor and so forth dictate production. As was observed in this study, APUE decreased with increased rate of P application. Application of P increased available soil P, thus soil P was no longer the most limiting factor. Therefore, grain yield increase was now being dictated by other factor most limiting in Siaya. In Kakamega North however, P was not the most limiting factor at a higher rate of 52 kg P/ha. MPR had low ANUE and APUE values explained by the fact that it is sparingly soluble in the soil. As a result P release was likely slow and could not match up with uptake by the maize crop. These findings tally with those of Nekesa (2007), who also found out that MPR had very low internal P use efficiency.

The decrease in grain PPUE with increase in phosphorus rates is in accordance with the Liebig's Law of Minimum as above. Nekesa, (2007) reported similar decrease in PPUE as well as Kisinyo (2011) who also reported a decrease in both APUE and PPUE due to increase in P fertilizer, in western Kenya.

5.2.6 Partial factor of productivity and economic analysis

Application of P again increased N uptake hence greater productivity. Mavuno fertilizer was the most productive cropping system possibly because of the additional nutrient elements it contains as was observed in this study.

At Sihay, Chimoroni and Tumbeni sites a greater number of the different sources of lime and P used in this study were economically viable. The viability was realized both at 26 and 52 kg P/ha application. Therefore, application of small doses of lime, N at 75 kg N/ha and P at 26 kg P/ha would be economical for smallholder farmers in this region.

5.3. The Greenhouse pot Experiment

5.3.1. Soil pH

The results from this study agree with those of the field study where it was observed that 0.4 and 0.8 t ha^{-1} lime applications were sufficient to significantly influence pH change in Siaya, but not in Kakamega soils. This could be explained by the different soil types, buffering capacity and different agroecological zone. A soil with high buffer capacity requires greater amount of lime to bring it to the desired pH (Brady and Weill, 2004).

5.3.2. Available soil P

Application of P significantly influenced available soil P in both soils suggesting that, application of lime + N + P is the best practice for maximum crop yield. As reported by Ndung'u *et al.*, (2006), supplemental P additions are efficient in soils that have low extractable P values for better crop yields.

5.3.3. Maize biomass dry matter yield

From this experiment it was observed that the control treatment significantly differed from the L + P treatments at Sihay. However, there was no significant difference between the different lime and P sources as was observed in the field. This could explain why Mavuno fertilizer differed significantly from the other sources in the field, because in this experiment, both macro and micronutrients contained in Mavuno were supplied to the other sources. These findings agree with work of Grant (1981) who reported that enhanced yields were obtained by including selected nutrients in fertilizer blends. It is evident from this study that additions of micronutrients improve the yield response to macronutrients and crop profitability when targeted to deficient soils. In Kakamega North, P significantly influenced dry matter yield suggesting that these soils require supplemental P additions for optimum yield. Individual treatments did not differ significantly from each other as in Sihay above.

5.3.4. Uptake of N and P as influenced by treatments

There was no significance between treatments in N uptake because they all had equal amount of N (75 kg N ha^{-1}). However, control differed from all treatments because it did not receive N. Lime significantly influenced P uptake in Sihay soils indicating that there could have been P that was fixed but was made available through lime application. In Kakamega North, P fertilizer application significantly increased P uptake suggesting that lime application is not sufficient to replenish these soils, but additions of L + P greatly influence the uptake of phosphorus (Kisinyo, 2011).

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

- All the different lime (Koru and Athi River) and P fertilizer sources (MPR and Mavuno fertilizers) did increase soil pH across all sites however, the pH values were still below 5.5, the level implying the need for liming acid soils
- Application of agricultural lime (Koru at 1.5 or 3 t/ha and Athi River at 0.7 or 1.4 t/ha) increased soil pH above 5.5 and maintained it for two and three cropping seasons in Sihay and Got Nanga respectively in Siaya county. In Kakamega North county, these rates of lime did increase soil pH above the control but with values < 5.5, still suggesting lime application
- Mavuno fertilizer and MPR can be used both as liming and P fertilizer materials because results from this study showed increased soil pH at all sites and increased extractable soil P values resulting from their application.
- Lime in combination with P availed more P as compared to lime application alone in all the sites except for Got Nanga, where 3 t ha^{-1} Koru lime application significantly released extractable soil P.
- Lime application increased maize yields above the control in all sites, though the increases were not significant except for Got Nanga. A combination of lime and P gave better maize yields in all the sites. For the different fertilizer sources, Mavuno fertilizer gave the highest maize yield of 6.26, 5.13 and 3.57 t/ha at Sihay, Got Nanga and Tumbeni sites respectively during 2010 LR.
- Mavuno fertilizer performed better probably because it contains additional nutrients.

- Soil pH and crop yields showed significant residual effect of lime at Got Nanga and Sihay sites for 3 and 2 consecutive cropping seasons respectively.
- Application of lime at a lower rate of 1.5 t/ha as Koru lime or 0.7 t/ha as Athi lime + N + P is economically viable in the long run. These are suitable for use by farmers in western Kenya.
- Most of the different lime and P sources realized economically viable returns at Sihay, Chimoroni and Tumbeni.

6.2. RECOMMENDATIONS

- Lime requirement of Kakamega and Siaya County soils should be established in field trials and laboratory for future better management. This is because 3 t ha^{-1} lime was adequate at the two sites in Siaya but not Kakamega County sites
- Annual doses of lime such as 0.4 t ha^{-1} KL or 0.2 t ha^{-1} AL are preferable over one massive application that are normally enough to supply calcium as a nutrient and to buffer the low soil-pH of Ferralsols and Acrisols. As this is also economical.
- To maintain available soil P above the critical value of 10mg/kg (Olsen), for continuous high maize production, P fertilizer should be applied as follows:-
    - At Sihay, Chimoroni and Tumbeni, 26 kg P/ha + 1.5 or 0.7 t ha^{-1} KL or AL respectively, should be applied each cropping season.
    - At Got Nanga, 3 t/ha Koru lime, 1.4 t/ha Athi lime, 26 kg P/ha + 1.5 t/ha or 0.7 t/ha Koru and Athi lime respectively, should be applied every season.
- The following treatment combinations produced economically viable returns to investments in this study and are thus suitable for adoption by farmers.

- At Got Nanga, 30 bags Koru Lime (1.5 t/ha) + 3 bags TSP (26 kg P/ha) and 14 bags Athi lime (0.7 t/ha) + 3 bags TSP (26 kg P/ha) were economically viable
- At Sihay, 4 bags Athi lime (0.2 t/ha) + 3 bags TSP (26 kg P/ha) and 0.24 t/ha Mavuno (26 kg P/ha) were economically viable
- At Chimoroni, 8 bags Koru lime (0.4 t/ha) + 3 bags TSP (26 kg P/ha) and 0.24 t /ha Mavuno (26 kg P/ha) were economically viable.
- At Tumbeni, 30 bags Koru lime (1.5 t/ha) + 3 bags TSP (26 kg P/ha) were viable.

NB: 1 bag = 50 kg

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APPENDICES

Appendix I: ANOVA for soil pH

a) ANOVA for soil pH as influenced by lime and P additions during 2010 LR

General ANOVA for Got Nanga

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Plevel	1	2	344.82	0.0029
CaOmat	4	16	47.1	<.0001
P level*CaO mat	4	16	6.25	0.0032
CV (%) = 2.7				

Difference of least square means					
CaOmat	_Plevel	_CaOmat	Standard Error	t Value	Pr > |t|
CONTROL	Vs	AL1P0	0.1253	-2.95	0.0094
CONTROL	Vs	KL2P0	0.1253	-10.03	<.0001
CONTROL	Vs	L0P0	0.1253	-9.97	<.0001
CONTROL	Vs	AL2P1	0.1253	-15.24	<.0001
CONTROL	Vs	KL1P1	0.1253	-12.1	<.0001
AL1P0	Vs	AL2P0	0.1253	-6.44	<.0001
AL1P0	Vs	KL1P0	0.1253	1.49	0.1558
AL1P0	Vs	L0P0	0.1253	-7.02	<.0001
AL2P0	Vs	KL2P0	0.1253	-0.64	0.5322
AL2P0	Vs	L0P0	0.1253	-0.59	0.5666
KL1P0	Vs	KL2P0	0.1253	-8.57	<.0001
KL1P0	Vs	L0P0	0.1253	-8.51	<.0001
KL2P0	Vs	L0P0	0.1253	0.05	0.9582

General ANOVA for Sihay

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Plevel	1	2	6.52	0.1252
CaOmat	4	16	69.83	<.0001
P level*CaO mat	4	16	3.98	0.0198
CV (%) = 2.8				

Difference of least squares means					
CaOmat	**Plevel**	**CaOmat**	**Standard Error**	**t Value**	**Pr > |t|**
AL1P0	Vs	AL2P0	0.1179	-3.42	0.0035
AL1P0	Vs	KL1P0	0.1179	1.05	0.3113
AL1P0	Vs	CONTROL	0.1179	4.01	0.001
AL1P0	Vs	L0P1	0.1179	5.82	<.0001
AL2P0	Vs	KL2P0	0.1179	-0.11	0.9114
AL2P0	Vs	CONTROL	0.1179	7.43	<.0001
AL2P0	Vs	L0P1	0.1179	9.24	<.0001
KL1P0	Vs	KL2P0	0.1179	-4.58	0.0003
KL1P0	Vs	CONTROL	0.1179	2.97	0.0091
KL1P0	Vs	L0P1	0.1179	4.78	0.0002
KL2P0	Vs	CONTROL	0.1179	7.55	<.0001
KL2P0	Vs	L0P1	0.1179	9.35	<.0001
CONTROL	Vs	L0P1	0.1179	1.81	0.0893

General ANOVA for Chimoroni

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Plevel	1	2	1.38	0.3616
CaOmat	4	16	6.06	0.0036
P level*CaO mat	4	16	0.53	0.7151
CV (%) = 5.6				

Difference of least squares means					
CaOmat		**CaOmat**	**Standard Error**	**t Value**	**Pr > |t|**
CONTROL	Vs	AL2P0	0.2351	-3.54	0.0027
CONTROL	Vs	KL2P0	0.2351	-3.49	0.003
CONTROL	Vs	AL2P1	0.2351	-2.55	0.0213
CONTROL	Vs	KL2P1	0.2351	-2.72	0.0151
AL2P0	Vs	L0P1	0.2351	2.95	0.0094
AL2P0	Vs	AL1P1	0.2351	3.1	0.0068
KL2P0	Vs	LOP1	0.2351	2.89	0.0106
KL2P0	Vs	AL1P1	0.2351	3.05	0.0077
L0P0	Vs	KL2P1	0.2351	-2.13	0.0494
AL1P0	Vs	AL2P1	0.2351	-2.11	0.0507
AL1P0	Vs	KL2P1	0.2351	-2.28	0.0365

b) ANOVA for soil pH as influenced by different lime and P fertilizer sources during 2010 LR

General ANOVA for Got Nanga

Type 3 Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Plevel	1	2	7.02	0.1177
CaOmat	3	12	0.14	0.9318
Plevel*CaOmat	3	12	1.38	0.2964
CV (%) = 3.2				

Difference of Least Squares means							
CaOmat	Plevel	CaOmat	Estimate	Standard Error	DF	t Value	Pr > |t|
AL3P1	Vs	AL4P2	0.3833	0.1791	12	2.14	0.0536
AL3P1	Vs	MPR2	0.45	0.1791	12	2.51	0.0273
AL3P1	Vs	MVN2	0.4433	0.1791	12	2.47	0.0292
MPR1	Vs	AL4P2	0.4367	0.1791	12	2.44	0.0313
MPR1	Vs	MPR2	0.5033	0.1791	12	2.81	0.0158
MPR1	Vs	MVN2	0.4967	0.1791	12	2.77	0.0169
MVN1	Vs	MPR1	0.3967	0.1791	12	2.21	0.0469
MVN1	Vs	MVN2	0.39	0.1791	12	2.18	0.0502

General ANOVA for Chimoroni

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Plevel	1	2	0.04	0.8684
CaOmat	3	12	8.07	0.0033
Plevel*CaOmat	3	12	4.32	0.0277
CV (%) = 2.9				

Difference of least squares means							
CaOmat	**Plevel**	**CaOmat**	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
AL3P1	**Vs**	**MPR2**	0.3633	0.1233	12	2.95	0.0122
KL3P1	**Vs**	**AL4P2**	-0.2767	0.1233	12	-2.24	0.0445
KL3P1	**Vs**	**MPR2**	0.3033	0.1233	12	2.46	0.0300
MPR1	**Vs**	**AL4P2**	-0.3267	0.1233	12	-2.65	0.0212
MPR1	**Vs**	**KL4P2**	-0.2700	0.1233	12	-2.19	0.0490
MVN1	**Vs**	**AL4P2**	-0.3133	0.1233	12	-2.54	0.0259
AL4P2	**Vs**	**MPR2**	0.5800	0.1164	12	4.98	0.0003
AL4P2	**Vs**	**MVN2**	0.4433	0.1164	12	3.81	0.0025
KL4P2	**Vs**	**MPR2**	0.5233	0.1164	12	4.50	0.0007
KL4P2	**Vs**	**MVN2**	0.3867	0.1164	12	3.32	0.0061

Appendix II: ANOVA for available soil P

a) ANOVA for extractable soil P as influenced by different lime and P sources

General ANOVA for Sihay

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Plevel	1	2	15.17	0.0601
CaOmat	3	12	4.15	0.0312
Plevel*CaOmat	3	12	1.83	0.1952

Difference of Least square means						
CaOmat		**CaOmat**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
AL3P1	**Vs**	**KL4P2**	2.0629	12	-2.63	0.0218
KL3P1	**Vs**	**AL4P2**	2.0629	12	-2.78	0.0167
KL3P1	**Vs**	**KL4P2**	2.0629	12	-3.91	0.0021
MPR1	**Vs**	**AL4P2**	2.0629	12	-3.18	0.0079
MPR1	**Vs**	**KL4P2**	2.0629	12	-4.31	0.0010
MVN1	**Vs**	**AL4P2**	2.0629	12	-3.02	0.0106
MVN1	**Vs**	**KL4P2**	2.0629	12	-4.15	0.0013
AL4P2	**Vs**	**MPR2**	2.0629	12	2.38	0.0351
KL4P2	**Vs**	**MPR2**	2.0629	12	3.51	0.0043

Appendix III: ANOVA for Maize yield

a) ANOVA for maize yield as influenced by lime and P additions during 2010 LR

ANOVA for Sihay

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
CaOmat	4	16	1.22	0.3422
Plevel	1	2	123.33	0.008
P level * CaOmat	4	16	2.28	0.1052
CV (%) = 24.8				

Difference of least squares means					
Treatment		**Treatment**	**Standard Error**	**t Value**	**Pr > |t|**
CONTROL	**Vs**	**L0P1**	0.5435	-4.47	0.0004
CONTROL	**Vs**	**KL1P1**	0.5435	-4.69	0.0002
CONTROL	**Vs**	**KL2P1**	0.5435	-5.4	<.0001
AL1P0	**Vs**	**L0P1**	0.5435	-4.99	0.0001
AL1P0	**Vs**	**AL1P1**	0.5435	-7.07	<.0001
KL1P0	**Vs**	**AL2P1**	0.5435	-4.66	0.0003
AL1P1	**Vs**	**KL1P1**	0.5435	1.86	0.0816
AL1P1	**Vs**	**KL2P1**	0.5435	1.15	0.2658
AL2P1	**Vs**	**KL1P1**	0.5435	1.77	0.0964
AL2P1	**Vs**	**KL2P1**	0.5435	1.06	0.3044
KL1P1	**Vs**	**KL2P1**	0.5435	-0.71	0.4908

ANOVA for Got Nanga

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
CaOmat	4	16	5.47	0.0057
Plevel	1	2	1.31	0.3715
P level*CaOmat	4	16	3.09	0.0463
CV (%) = 20.9				

Difference of least square means					
Treatment		**Treatment**	**Standard Error**	**t Value**	**Pr > |t|**
CONTROL	**Vs**	**KL2P0**	0.6496	-2.9	0.0105
CONTROL	**Vs**	**L0P1**	0.6496	1.57	0.1359
CONTROL	**Vs**	**KL1P1**	0.6496	-2.47	0.025
AL1P0	**Vs**	**AL2P0**	0.6496	-0.46	0.6504
AL1P0	**Vs**	**KL1P0**	0.6496	0.16	0.8716
AL1P0	**Vs**	**AL1P1**	0.6496	-2.16	0.0467
AL2P0	**Vs**	**L0P0**	0.6496	2.39	0.0297
KL1P0	**Vs**	**KL2P0**	0.6496	-2.71	0.0155
KL1P0	**Vs**	**L0P0**	0.6496	1.76	0.0975
KL1P0	**Vs**	**AL1P1**	0.6496	-2.32	0.0339
KL1P0	**Vs**	**KL1P1**	0.6496	-2.28	0.0364
KL2P0	**Vs**	**L0P0**	0.6496	4.47	0.0004
L0P1	**Vs**	**AL1P1**	0.6496	-4.08	0.0009
L0P1	**Vs**	**KL2P1**	0.6496	-3.52	0.0029

ANOVA for Chimoroni

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Plevel	1	2	1.31	0.3703
CaOmat	4	16	2.12	0.126
P level*CaOmat	4	16	1.09	0.3931
CV (%) = 19.8				

Difference of least square means					
CaOmat		**_Plevel**	**Standard Error**	**t Value**	**Pr > |t|**
KL2P0	**Vs**	**L0P1**	0.5358	2.19	0.0437
L0P1	**Vs**	**AL1P1**	0.5358	-2.13	0.0493
L0P1	**Vs**	**AL2P1**	0.5358	-2.55	0.0214
L0P1	**Vs**	**KL1P1**	0.5358	-2.59	0.0196
L0P1	**Vs**	**KL2P1**	0.5358	-2.73	0.0148

b) ANOVA for maize yield as influenced by different lime and P fertilizer sources (2010 LR)

General ANOVA for Got Nanga

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Plevel	1	2	6.66	0.123
CaOmat	3	12	2.84	0.0829
P level *CaO material	3	12	1.37	0.3004
CV (%) = 27.8				

Difference of least square means					
CaOmat		**CaOmat**	**Standard Error**	**t Value**	**Pr > |t|**
AL3P1	**Vs**	**MVN2**	0.8009	-3.04	0.0103
KL3P1	**Vs**	**MVN2**	0.8009	-2.86	0.0144
MPR1	**Vs**	**AL4P2**	0.8009	-2.91	0.013
MPR1	**Vs**	**MVN2**	0.8009	-3.98	0.0018
MVN1	**Vs**	**MVN2**	0.8009	-2.86	0.0143
KL4P2	**Vs**	**MVN2**	0.6556	-2.83	0.0153
MPR2	**Vs**	**MVN2**	0.6556	-2.54	0.0261

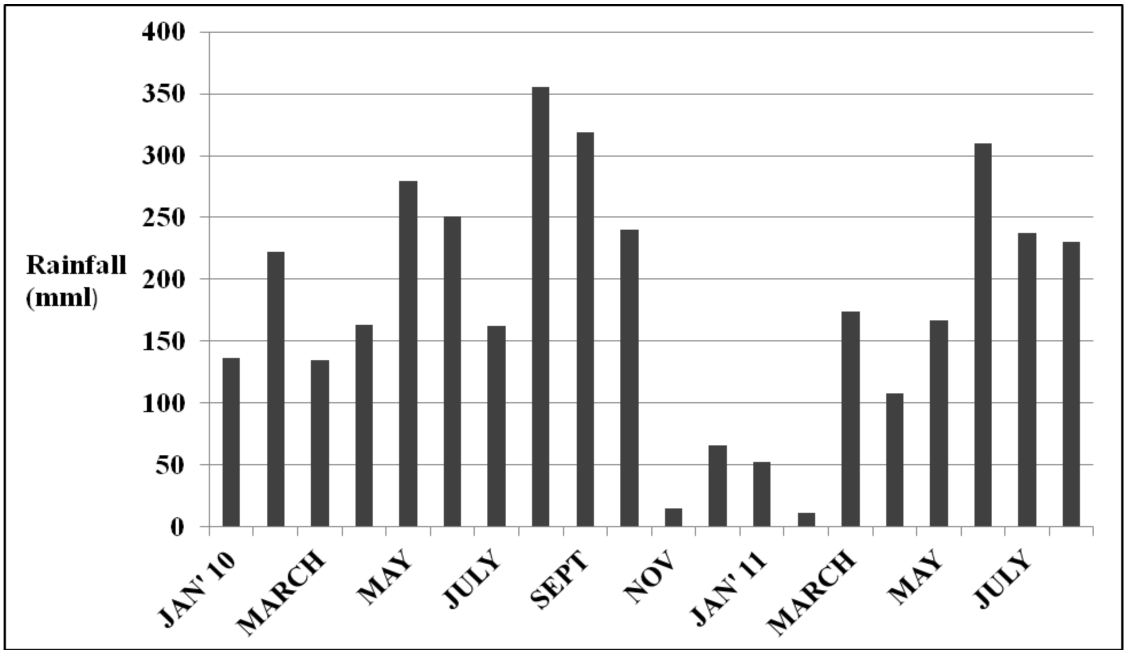
General ANOVA for Sihay

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Plevel	1	2	5.4	0.1457
CaOmat	3	12	4.16	0.0309
P level * CaO material	3	12	1.08	0.3952
CV (%) = 16.8				

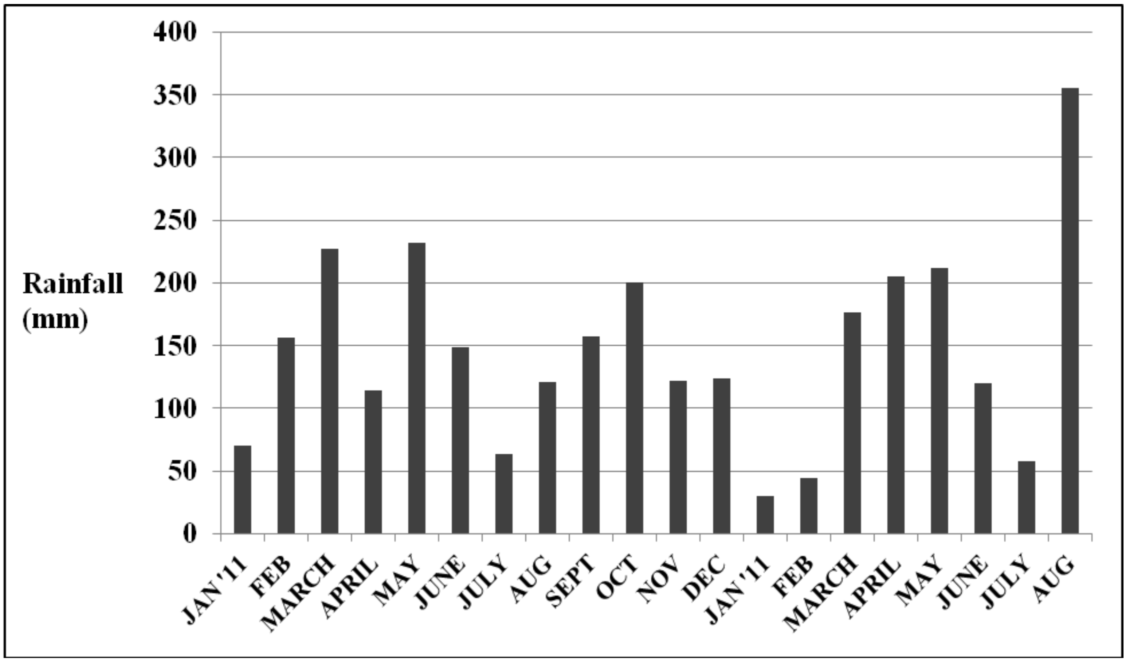
Difference of least square means					
CaO mat		**CaO mat**	**Standard Error**	**t Value**	**Pr > |t|**
AL3P1	**Vs**	**MVN2**	0.7207	-2.28	0.0413
KL3P1	**Vs**	**MVN2**	0.7207	-3.03	0.0104
MPR1	**Vs**	**MVN2**	0.7207	-2.75	0.0177
MPR1	**Vs**	**KL4P2**	0.7207	-2.69	0.0198
MPR1	**Vs**	**MVN2**	0.7207	-4.04	0.0016
AL4P2	**Vs**	**MVN2**	0.7207	-2.62	0.0225

Appendix IV: Rainfall distribution (mm) during 2010 and 2011LR

a) Kakamega North district



b) Siaya district



Appendix V: Plot layout

Experiment 1 Layout

REP 1		REP 2		REP 3	
P0	P1	P0	P1	P0	P1
AL1	AL1	AL1	KL2	0L	0L
0L	KL1	AL2	AL1	KL1	AL2
KL1	KL2	KL2	AL2	KL2	AL1
KL2	0L	0L	KL1	AL2	KL2
AL2	AL2	KL1	0L	AL1	KL1

Experiment 2 Layout

P1	P2	P1	P2	P1	P2
AL3	KL4	MPR1	AL4	AL3	AL4
MVN1	AL4	KL3	KL4	KL3	MVN2
KL3	MVN2	AL3	MPR2	MPR1	KL4
MPR1	MPR2	MVN1	MVN2	MVN1	MPR2

Appendix VI: ANOVA skeletons

ANOVA skeleton for field experiments

Source of variation	Degree of freedom	SS	Meansquare	Fprobability
Replication	r - 1			
Main plot factor (P)	p - 1			
Error (a)	r – 1(p – 1)			
Sub – plot factor (Lime)	L - 1			
Interaction (P x Lime)	(p – 1) (L – 1)			
Error (b)	p(r – 1) (L – 1)			
Total	rpL – 1			

ANOVA skeleton for the greenhouse experiment

Source of variation	Degree of freedom	SS	Meansquare	Fprobability
Replication	r - 1			
Treatment effect	p - 1			
Error	r – 1(p – 1)			
Total	rpL – 1			