FERTILIZER, LIME AND INTERCROPPING EFFECTS ON ACID SOIL, SORREL WEED (*Rumex acetosella* L.*)* GROWTH AND PERFORMANCE OF POTATO (*Solanum tuberosum* L.) IN MOLO, KENYA

MOSE KEMUNTO NAOM

A Thesis Submitted to the Graduate School in Partial Fulfilment of the Requirements for the Master of Science Degree in Soil Science of Egerton University

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DECLARATION AND RECOMMENDATION

Declaration

This thesis is my original work and has not been presented in this university or any other for the award of a degree.

Signature Date 4th April 2023

MOSE KEMUNTO NAOM

KM13/13637/19

Recommendation

This thesis has been submitted with our approval as university supervisors.

Signature…… …………. Date ……24/04/2023……………….

Prof. Joyce J. Lelei

Department of Crops, Horticulture and Soils,

Egerton University.

Signature… Date 25th April, 2023

Prof. Josephine P. Ouma

Department of Crops, Horticulture and Soils,

Egerton University.

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DEDICATION

This thesis is dedicated to God and my family.

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ABSTRACT

Soil fertility decline and soil acidity in potato (*Solanum tuberosum L.*) producing areas of Kenya have resulted in reduced tuber yields and sheep sorrel (*Rumex acetosella*) weed infestation. A two-season field experiment was set up in an acid mollic Andosol of Molo sub-county, Kenya. The objectives were to investigate (i) the effects of liming, intercropping and NPK fertilizer application on selected properties, (ii) the effects of liming, intercropping and NPK fertilizer application on sheep sorrel weed growth and (iii) the effects of liming, intercropping and NPK fertilizer application on potato growth, nutrient uptake and yield. A randomized complete block design with a split-split plot arrangement, replicated three times, was used. The compound Fertilizer NPK at two levels (0 and 0.2 t ha $^{-1}$), formed the main plots. Lime rates (0 and 2 t ha $^{-1}$) were assigned to the sub-plots and cropping system (sole potato and potato/dolichos intercrop) the sub-sub plots. Potato *Shangi* variety and dolichos hyacinth bean variety were used. Lime was applied 3 weeks before planting. The results showed that application of lime increased the soil pH by 5% while fertilizer application reduced soil pH by 2% over the control. Combined application of NPK fertilizer and lime increased available soil P up to 31.08ppm. Total soil N increased to between 0.26 and 0.28% where fertilizer was applied in potato cropping system across the seasons. The interaction between NPK fertilizer and lime potato/dolichos cropping system, reduced the sheep sorrel weed density, dry biomass and root length by 43%, 32% and 39% during the second season respectively. Higher plant height 74 and 77cm were obtained where fertilizer was applied and in the second season respectively. More shoots, 5, were observed in the second season. Season × fertilizer and fertilizer × lime interactions increased N uptake up to 140.73 and 146.77kg ha^{-1}, respectively, in potato/ dolichos intercropping system. Lime × cropping system and lime × fertilizer interactions increased P uptake up to 22.16 and 27.19kg ha^{-1} during the second season respectively. More tubers (11) per plant were obtained in cropping system × fertilizer, cropping system × season and fertilizer × season interactions. Higher tuber yields, 50,51 and 53t ha^{-1} were realized in cropping system × season × fertilizer, cropping system × season × lime and lime × fertilizer × season interactions respectively. The study therefore recommends application of 0.2 t ha^{-1} NPK fertilizer and 2 t ha^{-1} lime, and dolichos integration in potato systems for soil acidity amelioration, improving soil nutrient status, reducing sorrel weed infestation, and increasing potato nutrient uptake, growth and yield.

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LIST OF ABBREVIATIONS AND ACRONYMS

AAS	Atomic Absorption Spectrophotometry
ADC	Agricultural Development Corporation
BNF	Biological Nitrogen Fixation
DAE	Days After Emergence
DAP	Days After Planting
LER	Land Equivalent Ratio
LR	Lime Requirement
PD	Potato/ Dolichos intercrop
PEY	Potato Equivalent Yield
pH	Concentration of hydrogen ions
PS	Sole potato

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Potato (*Solanum tuberosum* L.) is the world's fourth most important food crop after rice (*Oryza sativa*), maize (*Zea mays*) and wheat (*Triticum aestivum*) (Chemeda *et al*., 2014). Globally, the area under potato was estimated to be 19 million hectares in 2017 with a production of 378 million tonnes (Campos & Ortiz, 2020).

In Kenya, potato is mainly cultivated in smallholder farms in the highlands. The major growing regions are Nakuru, Nyandarua, Bomet, Meru, Uasin Gishu, Kiambu, Nyeri, West Pokot, Narok, Kericho and Keiyo (Kasina & Nderitu, 2013; Musita *et al*., 2019). The average yield obtained in small holder farms is 4 t ha^{-1} which is very low compared to the global yield estimated at 19.9 t ha^{-1} (FAOSTAT, 2020). This gap is attributed to inadequate good quality seed, low soil fertility, soil acidity, limited use of agro-chemicals, attacks by leaf diseases (Komen *et al*., 2017) and weed infestation (Kołodziejczyk *et al*., 2017).

Soil acidity, low soil fertility and weed infestation, contribute significantly to low potato yields in small holder potato farms in Molo sub county, located in Nakuru Kenya (Komen *et al*., 2017). Soils in the region are acidic with pH of less than 5.5 (Muindi *et al*., 2016). The acidity is as a result of leaching of basic cations by rainfall and acidic parent material. Acid soils affect soil fertility and productivity through nutrient deficiencies and presence of phytotoxic elements (Al and Mn) (Muindi *et al*., 2016; Muthoni & Nyamongo, 2009; Nduwumuremyi, 2013).

Low soil fertility is widespread in Kenya and is the main limitation on crop yields (Sitienei *et al*., 2017). Application of chemical fertilizers plays an important role in replenishing depleted soil nutrients. However, only a small percentage of the smallholder farmers in high potential and low potential areas use fertilizers (Muthoni, 2016). Majority apply diammonium phosphate in potato production but in limited amounts due to high costs. The continuous use of diammonium phosphate (DAP) fertilizer in potato production has been shown to increase soil acidity (Muthoni, 2016).

Each crop has particular weed flora (Mahaut *et al*., 2019; Schonbeck, 2011) which can be influenced by site specific factors such as nutrients, soil conditions and climate. Potato yield losses as a result of weed infestation have been estimated to be between 20-80% (Kołodziejczyk *et al*., 2017). The sorrel weed also known as *Rumex acetosella* is a major weed in potato, which causes substantial yield losses (Kiiya *et al*., 2010). The weed thrives in infertile soils with low pH conditions, but is reduced on fertile soils (Stopps *et al*., 2011). It reproduces both sexually and asexually hence difficult to control through weeding. Seeds can remain viable for up to 20 years even after passing through the animal digestive system and are also easily dispersed by all seed dispersal agents (Kiiya *et al*., 2010).

Food security is threatened by low crop production and continued population increase in sub-Saharan Africa (SSA) (UNDESA, 2019). Continuous population increase and urbanization has rendered the traditional cultural practice of expanding farmlands to increase food production unsustainable (Lambin *et al*., 2013). In order to meet the food and nutritional demand for the growing population in coming decades, there is need to produce more food using the same or less resources (Campos & Ortiz, 2020). Due to small land sizes of less than 1 ha, intercropping can increase returns per cultivated area (Nyawade *et al*., 2019). Intercropping potato with other crops is a sustainable intensification strategy for improving soil fertility and production of the current croplands (Gitari *et al.*, 2018; Gitari *et al*., 2019; Nyawade *et al*., 2019).

Leguminous cover crops in potato production plays an important role in increasing the soil nutrient content and suppressing weed growth (Campiglia *et al*., 2009). Sowing different crop species that differ in their competitive ability may also achieve a better control of sorrel weed abundance by increasing the diversity of crop sowing dates across the crop sequence (Mahaut *et al*., 2019). Dolichos (*Lablab purpureus* L.) has a high ground cover hence efficient in weed suppression (Gitari *et al*., 2018).

Liming to raise soil pH inhibits sorrel weed growth since it prefers infertile soils with low pH. The use of agricultural lime has been shown to increase the soil pH, reduce Al and Mn toxicity and increase P uptake in high P fixing soil (Nduwumuremyi, 2013). Potato is a heavy feeder and due to its poorly developed and shallow root system, it requires high soil nutrient levels (Mishra, 2018). For a mature potato crop to yield 25–30 t ha^{-1}, it removes about 165–200 kg N, 14–17 kg P and 185–225 kg K ha^{-1} (Ghosh, 2015). The use of NPK fertilizer will supply adequate nutrients for its growth and yield.

1.2 Statement of the Problem

Potato production in Kenya has been on the decline since 2010 while the demand is rising due to an increase in population. The yield varied from 22.4 t ha^{-1} in 2010 to 8.6 t ha^{-1} in

2018, which is far below the potential yield of 30 – 40 t ha^{-1}. Low soil fertility and soil acidity are among the constraints limiting potato production in Molo sub county, Kenya. The low fertility has resulted from continuous cultivation without adequate replenishment of mined nutrients. Small holder farmers use mainly diammonium phosphate (DAP) fertilizer for crop production which exacerbates the soil acidity problem. Sheep sorrel weed (*Rumex acetosella* L.) infestation, favoured by soil acidity and low fertility, causes substantial yield losses. The use of lime to raise the soil pH is low due to limited awareness on its effectiveness among smallholder farmers. The study integrated dolichos in potato production, with application of lime and NPK fertilizer for the management of soil acidity, low soil fertility and sheep sorrel weed.

1.3 Objectives

1.3.1 General Objective

To contribute to food security by increasing potato production in acid soils of Molo Kenya through application of lime and NPK fertilizer, and dolichos integration in potato systems.

1.3.2 Specific Objectives

i. To determine the effects of lime, NPK fertilizer and intercropping on selected soil chemical properties in potato systems

ii. To evaluate the effects of lime, NPK fertilizer and intercropping on sorrel weed growth in potato systems.

iii. To determine the effects of lime, NPK fertilizer and intercropping on nutrient uptake, growth and yield of potato.

1.4 Hypotheses

i. Lime, NPK fertilizer and intercropping have no significant effects on the selected soil chemical properties in potato systems.

ii. Lime, NPK fertilizer and intercropping have no significant effect on sorrel weed growth in potato systems.

iii. Lime, NPK fertilizer and intercropping have no significant effects on nutrient uptake, growth and yield of potato.

1.5 Justification of the Study

Potato is an important food crop and source of income in Kenya, grown by more than 800,000 farmers generating more than KES50 billion to the country (AGRA, 2018). Potato is mainly grown in the Kenyan highlands by smallholder farmers (Gitari, 2018) who practice continuous cultivation without a fallow period with no or minimal application of fertilizers (Muthoni, 2016). Continuous cultivation of annual crops without adequate replenishment of mined nutrients has resulted in a rapid decline in soil fertility (Kiiya *et al*., 2010). Overdependence on nitrogen and phosphorus fertilizers, mostly diammonium phosphate, has been reported to cause gradual soil acidification and deficiency of micronutrients (Muthoni, 2016). Rapid decline in soil fertility together with low soil pH has resulted in sheep sorrel weed infestation in potato production fields (Kiiya *et al*., 2010).

To increase potato yields, there is need to focus on soil amendment practices that target on reducing soil acidity, prevalence of the sheep sorrel weed and increasing soil fertility. Liming of the acid soils has the potential of contributing to an increase of overall potato yield due to increase in soil pH. Increase in soil pH also improves the microbial status and hence their activity in soils. The use of leguminous cover crops will contribute to Biological Nitrogen Fixation (BNF) and sheep sorrel weed suppression.

Dolichos (*Lablab purpureus*) produces high biomass which provides a high ground cover hence competes with the weeds for resources such as light resulting in reduced germination and growth of the weeds. NPK fertilizer enhances nutrient availability, potato growth vigor as well as tuber yield. Use of NPK fertilizer, lime and leguminous intercrop will contribute to reduced soil acidity, sheep sorrel weed management and increased soil fertility. This will result in increased potato production to meet the increasing food requirements for the growing population and improve livelihood of smallholder farmers. This experiment will therefore contribute to reducing soil acidity, management of the sheep sorrel weed and increasing soil fertility by coming up with lime and potato cropping systems that will give high potato yields while maintaining soil fertility, reducing soil acidity and managing the sheep sorrel weed.

CHAPTER TWO

LITERATURE REVIEW

2.1 Potato Origin and its Distribution in Kenya

Potato originated from mountain ranges of south America, between the boarder of Bolivia and Peru about 8000 years ago. It is believed to have been first domesticated around the shores of Lake Titicaca at an altitude of 3800 m above sea level in southeast of Peru. In the 1570s, it was introduced into Europe and was distributed throughout the world from the late 17th century (Birch *et al*., 2012). The central highlands of Mexico are considered a centre of genetic diversity for both the potato late blight pathogen (Flier *et al*., 2003) and for germplasm of tuber bearing *Solanum sp*. (Spooner & Hijmans, 2001).

In Kenya, potato was introduced by European settlers for domestic consumption. New varieties, mainly Kerr's Pink, were introduced at the National Agricultural Laboratories and Plant Breeding Station, Njoro in 1907**.** The government started promoting potato production with varieties from Germany in 1963 and a potato development programme was established in 1967 (Komen *et al*., 2017). The major growing regions include; Mt. Kenya, mainly Meru Central, parts of Nyeri and Laikipia, Aberdares and Eastern Rift Valley, Kiambu, Nakuru, Nyandarua, Mau, Bomet, Narok, Mt. Elgon, Keiyo and Marakwet; and Taita Taveta (Kaguongo *et al*., 2008).

Potato is among the estimated 2,300 species in the family Solanaceae which consists of about 90 genera. The genus Solanum includes about 1000 species cultivated worldwide with potato (*S. tuberosum* L.), tomato (*Lycopersicum esculentum*), eggplant (*Solanum melongena*), pepino (*Solanum muricatum*), and naranjillo (*Solanum quitoense*) as the most popular species that are widely grown (Levy & Rabinowitch, 2017). It grows up to 90 - 100 cm tall producing white and pink or purple flowers with yellow stamens 3 - 4 weeks after sprouting. Being an herbaceous annual plant, it grows up to 100 cm tall, has weak stems that are angular and may be solid or hollow due to the disintegration of pith cells and produces a tuber that is commonly known as potato which is rich in starch (Flier *et al.*, 2003).

2.2 Potato Production

Potato (*Solanum tuberosum* L.) is the most important non-cereal crop globally consumed in various forms (Kahsay, 2019). It is the fourth most important food crop after rice (*Oryza sativa*), maize (*Zea mays*) and wheat (*Triticum aestivum*) in the world (Komen *et al*., 2017),estimated to be grown on 19.3 million hectares with an estimated production of 378 million tonnes globally (FAOSTAT, 2020). The crop is highly produced in the temperate zone of the northern hemisphere during the summer frost-free period mainly as a cash crop (Campos & Ortiz, 2020). In the tropics, the crop is grown in the highlands of the Andes, the volcanic mountains of West Africa and Southeast Asia, African highlands and the Rift valley where it is produced as a food and cash crop (Muthoni & Kabira, 2010). In the subtropics, potato is grown as a winter crop in the Mediterranean region, North India and southern China during the heat-free period (Campos & Ortiz, 2020). Potato is not a main staple crop in tropical lowlands because high temperatures in these regions do not favour growth and tuber development (Haverkort *et al*., 2013).

Increased potato production in East African countries over the past years has highly contributed to the local food systems. In Tanzania, potato supply almost tripled between the year 2000 and 2014. It plays a major role in national food security in Rwanda hence a national priority crop (Campos & Ortiz, 2020). As world population is shown to be on the greatest rise in Africa, increased contribution of potato to local food systems is of high significance (Birch *et al*., 2012).

In Kenya, potato is the mainly grown in the highlands by smallholder farmers for food and income and it performs better compared to maize which is a staple crop (Gitari *et al*., 2018). It is grown by approximately 800,000 smallholder farmers (AGRA, 2018 & Komen *et al*., 2017). The industry employs about three million people indirectly in the entire value chain and earns the country over KES50 billion annually (AGRA, 2018). The potato crop has capacity to feed large populations and provide more food per hectare compared to other staples due to its short maturity period allowing two crops annually (Wang'ombe & van Dijk, 2013). However, potato yield in Kenya is far below the potential and there has been a production decline since 2010 (Table 1). Being a potential crop for the country's mission to attain food security, there is need for improving its production.

Table 1: Potato area harvested, productivity and production trend between 2010 and 2018 in Kenya.

Year	Area harvested (ha)	Yield (tonnes/ha)	Production (tonnes)
2010	121542	22.4279	2725936
2011	123390	19.1690	2365263
2012	143325	20.3389	2915067
2013	152007	14.4262	2192885
2014	115604	14.0655	1626027
2015	133532	14.7043	1963495
2016	145967	9.1520	1335883
2017	192341	7.9019	1519870
2018	217315	8.6067	1870375

Source: FAOSTAT (2020).

2.3 Challenges Facing Potato Production

Despite the importance of potato in Kenya, yields have remained very low approximately between 7.7 to 9.5 t ha^{-1}against a potential of over 40 t ha^{-1} (Komen *et al*., 2017). The low yields are as a result of application of fertilizers below recommended rates (Kaguongo *et al*., 2008), use of low quality seeds, low soil fertility, limited use of fertilizers (Komen *et al*., 2017), diseases mainly bacterial wilt and late blight (Muthoni *et al*., 2013) and soil acidity (Muthoni, 2016).

In Kenya, low soil fertility is the major challenge in potato production (Muthoni, 2016). Soils in major potato growing areas in Kenya are deficient of soil phosphorus and total nitrogen (Recke *et al*., 1997). Potato being a heavy feeder, it requires adequate supply of nutrients for its growth and yield. It has a high nutrient requirement due to its relatively poorly developed and shallow root system in relation to yield (Mishra, 2018). Low soil fertility is as a result of continuous cultivation without adequate replenishment of required amount of mined nutrients (Muthoni, 2016). The situation is aggravated by the inherently low soil pH with values of between 4 to 5 being common (Muthoni, 2016). Due to small land sizes, farmers continuously practice intensive cropping systems on the same piece of land that mainly involve double and relay cropping of different crops without a fallow period.

The other challenges affecting potato production by reducing yields are weed infestation and diseases. The effects of weed infestation on crop yields depends on the abundance of the weeds and their biomass. Weeds are important growth reducing factors in crop production due to their competition for water, light and nutrients (Gu *et al*., 2021). Potato yield losses as a result of weed infestation have been estimated to be between 20-80% (Kołodziejczyk *et al*., 2017). Rapid decline in soil fertility coupled with low soil pH have favoured infestation of weeds particularly the sheep sorrel weed (Kiiya *et al*., 2010; Kiiya *et al*., 2015). The sorrel weed, is a major weed in potato production which causes substantial yield losses (Kiiya *et al*., 2010). The weed thrives in infertile and low pH soil conditions, but is highly reduced on fertile soils (Stopps *et al*., 2011). The weed thrives in infertile and low pH soil conditions, but is highly reduced on fertile soils (Stopps *et al*., 2011).

2.4 Soil acidity, its causes and effects on plant growth

Acidity is the concentration of hydrogen ions (H^+) in a solution (Dida & Etisa, 2019). Soil acidity is a major constraint in agricultural production worldwide and acid soils account for 4 billion ha of world land area (Muindi *et al.*, 2016). Approximately 43% of the world's tropical land area is classified as acidic (Buni, 2014) and Kenya accounts for 13% of this land area (Muindi *et al*., 2016). Soil acidity is one of the forms of soil degradation affecting sustainable crop production (Fekadu *et al*., 2019) and it involves nutrient deficiencies and toxicities, low activities of beneficial micro-organisms and reduced plant root growth which limits absorption of nutrients and water (Ameyu, 2019). Soil acidification is a natural process but it has been accelerated by agriculture, pollution and other human activities (Cabrales *et al*., 2020).

2.4.1 Soil acidity pools

Active acidity

This is the quantity of H^+ that are present in the soil water solution. The pool of H^+ in the solution is in equilibrium with the exchangeable H^+ that are held on soil's CEC (McBride, 1994). It is determined directly by a pH meter. It directly affects plant growth and development and soil microorganisms (Getaneh & Kidanemariam, 2021).

Exchangeable acidity

The amount of acid cations, Aluminium (Al^{3+}) and hydrogen (H^+) occupied on the CEC. It is determined by titration of a soil with a base thus used for lime requirement (McBride, 1994). There exists an equilibrium between the adsorbed and soil solution ions (active and exchange acidity), permitting the ready movement from one form to another form (Getaneh & Kidanemariam, 2021). It is the acidity caused by hydrogen and aluminium that are easily exchangeable.

Reserve acidity

Comprises of all bound Al^{3+} and H^{+} in soil minerals (clay and organic matter). It's the least available (Getaneh & Kidanemariam, 2021).

2.4.2 Causes of soil acidity

Soil acidity is influenced by the chemical composition of the parent material. Soil derived from granite rock is likely to be more acidic than soil from calcareous materials (Getaneh & Kidanemariam, 2021). Soils formed from volcanic ash are acidic. Excessive rainfall leaches the soil profile's basic elements (Ca, Mg, Na, and K) which are replaced by Al from the exchange sites and this results in increased acidity (Goulding, 2016). Application of ammonium-based fertilizers and elemental sulphur (S) fertilizer have resulted in soil acidification. Continuous use of acid-forming mineral fertilizer such as urea and diammonium phosphate (DAP) strongly acidify soil through the nitrification process (Getaneh & Kidanemariam, 2021; Goulding, 2016). Plant nutrient uptake also results in soil acidification due to harvest of high yielding crops.

2.4.3 Effects of soil acidity on plant growth

Crop plants differ in their tolerance to acidity. Soil acidity affects the availability of plant nutrients especially phosphorus (P) and hence affecting plant growth and yield (Goulding, 2016). Toxic levels of Al and manganese (Mn^{+}) affect plant root growth and soil microorganisms which results in poor plant growth. Poor plant growth as a result of soil acidity results in weed infestation and this reduces the overall crop yields (Getaneh & Kidanemariam, 2021). Acidic soils affect the growth of nitrifiers (Mkhonza *et al*., 2020) and this slows the nitrification process hence low N levels in the soil available for plant growth. Reduction in microbial activities also results in a reduction in organic matter breakdown reducing release and uptake of plant nutrients. Low soil P levels and high Al^{3+} in the soil affects the growth of the symbiotic nitrogen fixing bacteria resulting in low nitrogen fixation (Bakari *et al*., 2020).

2.5 Potato Intercropping Systems

Traditionally, crop lands were expanded to increase food production. This is no longer practiced in the sub-Saharan Africa (SSA) due to rapid population increase which results in decrease in land sizes (Lambin *et al*., 2013). To improve production of the current croplands, sustainable strategies such as intercropping have been adopted (Gitari *et al*., 2019). Due to small land sizes of less than 1 ha, farmers intercrop potato with other crops such as legumes to cushion against crop failure and increase returns per cultivated area (Nyawade *et al.*, 2019).

Intercropping is the cultivation of two or more plant species on the same land during the same growing period. It has a number of ecological benefits and results in high resource use efficiencies (light, water and nutrients) (Brooker *et al*., 2007). Intercropping is practiced globally due to its efficiency in soil water conservation and use (Gitari *et al*., 2018). Intercropping potato with a deep-rooted crop may increase complementary water use and increase water use efficiency of the system (Ren *et al*., 2018). Some legume species can fix atmospheric N which is used by the legume itself and will also be available to other plants in the system after decomposition of root nodules or plant material. Legumes are hence important in improving the fertility of the soil (Gitari *et al*., 2018).

Intercropping systems are viable when compatible crops are used as intercrops. Potato and maize can be grown as intercrop as they have different photosynthetic pathway, growth habit, growth duration and demand for growth resources (Begum *et al*., 2016). Gitari *et al*. (2019) reported higher Potato Equivalent Yields (PEY) values under intercropping compared to potato pure stand. Mushagalusa *et al*. (2008) also reported high soil moisture contents in a potato maize intercrop. However, the same author reported a decrease in potato yield, which was attributed to the shading effect of maize crops.

Variations in potato tuber yield in different cropping systems has been attributed to the differences in root architecture of the legume intercrops used (Gitari, 2018). Dolichos has a deep root system compared to beans and peas which have a shallow root system (Gitari, 2018). The low potato tuber yields recorded in potato bean, potato maize and potato radish cropping system have been attributed to increased competition for available water and nutrients of the intercrops with the potato crop.

2.6 Legume Integration in Potato Production

High poverty levels, declining soil fertility and food insecurity have compelled farmers to look for alternative ways of increasing crop production using the same land. This has resulted in farmers intercropping potato with other crops such as maize (*Zea mays* L.), beans (*Phaseolus vulgaris* L.), sulla (*Hedysarum coronarium* L.) and radish (*Raphanus raphanistrum* L.) (Gitari *et al*., 2018; Rezig *et al*., 2013). Intercropping involves cultivation of multiple crops in the same land in a single cropping season while mono cropping involves cultivation of only one crop in pure stand in a single cropping season. These multiple cropping systems have existed for decades globally playing a vital role in subsistence food production (Lithourgidis *et al*., 2011; Rezig *et al*., 2013).

Compared to pure stands, intercropping has several benefits including increased yields with higher combined returns and profitability per unit area of cultivated land (Gitari *et al*., 2018; Hinsinger *et al*., 2011). Intercropping potatoes with legumes is important in replenishing soil mineral nitrogen through the ability of legumes to biologically fix atmospheric nitrogen and not compete with potatoes for nitrogen resources (Sitienei *et al*., 2017). It also increases competitive ability of crops towards weeds due to a better ground cover which results in minimal soil erosion and nutrient leaching to lower horizons (Mucheru-Muna *et al*., 2010). Leguminous crops depend on atmospheric nitrogen hence, they are less likely to compete for N with potato and this results in improved soil fertility due to the addition of fixed nitrogen (Ojiem *et al*., 2007; Sitienei *et al*., 2017). Leguminous crops also provides smallholder farmers with food and fodder (Sennhenn *et al*., 2017). Legumes contain about three times more food protein than tubers (Maass *et al*., 2010) and their inclusion in potato-based cropping systems improves dietary supply for the rural household. Intercropping promotes higher resource capture by the component crops compared to monocrops hence reducing resources available for the weeds suppressing their growth (Gu *et al*., 2021). Some of the crops used as intercrops are allelopathic to weeds hampering their growth (Kocira *et al*., 2020). Intercropping potato with legumes will improve soil fertility and suppress weed growth resulting in increased yields (Kiiya *et al*., 2010).

2.7 Sheep Sorrel Weed

Sheep sorrel (*Rumex acetosella* L.) also known as red sorrel, field sorrel, horse sorrel, mountain sorrel, cow sorrel or sour dock is a major weed in Irish potato (*Solanum tuberosum* L.), maize (*Zea mays* L.) and pyrethrum (*Chrysanthemum cinerariaefolium* L.). It is a herbaceous perennial weed in the Polygonaceae family and reproduces by both sexual and asexual means (Kiiya *et al*., 2010) with male and female parts on separate plants (Hughes, 2012). The whole root system is capable of producing buds except for the fine terminal roots (Kiiya *et al*., 2010). The dense root system and ability of the weed to reproduce within 3 months from root fragments buried up to 10 cm deep makes the species successful (Frey *et al*., 2008). The well-developed root system also offers protection from drought due to the increased allocation of resources to vegetative growth (Fujitaka & Sakai, 2007). The low growth profile of the basal rosette of *R. acetosella* protects the plant from mowing or grazing and the larger and heavier seeds produce stronger and more competitive individuals than those from lighter seeds (Stopps *et al*., 2011).

The weed successfully competes under poor soil conditions, but is highly reduced on fertile soils (Fitzsimmons & Burrill, 1993). It exhibits a plastic morphology hence thrives in various soils but it is susceptible to shading (Stopps *et al*., 2011). Sole application of Fertilizers has shown to increase weed density (Hughes, 2012). Therefore, there is need for sustainable ways of controlling the sorrel weed.

2.8 Effect of Lime and Inorganic Fertilizers on Soil Fertility

Soil acidity is one of the most important soil factors which affect plant growth and eventually limit crop production and profitability (Dereje *et al*., 2019). Acid soils cover about 4 billion hectares of total world land area and this accounts for 30% of total world land area and 58% of land suitable for agriculture. In the sub-Saharan Africa (SSA), acid soils occupy 29% of the total land area (Muindi *et al*., 2016) and13% of the total land area in Kenya (Gitari *et al*., 2015). Soil acidity is mainly attributed to abundance of hydrogen (H^{+}), aluminium (Al^{3+}) and manganese (Mn^{2+}) cations in soil at levels that interfere with normal plant growth. This affects crops mainly through P unavailability in soils where the Fe and Al soil components fix P (Osundwa, 2013). Liming is an important practice in ameliorating soil acidity to improve crop yields (Kaitibie *et al*., 2002). Liming materials reduces soil acidity and Al, Mn, and H toxicity, improves soil structure and improves availability of P, Ca, Mo, and Mg, and N fixation. Also, it increases soil pH, cation exchange capacity (CEC) and decrease in toxic elements such as Aluminium and Manganese. Lime avails phosphorus that is added to the soil for plant growth (Gitari, 2013).

In Kenya, an average of 3 kg P, 42 kg N and 29 kg K per ha soil nutrients are lost annually (Wanjiru, 2018). Inorganic Fertilizers are mainly used due to their high nutrient concentration that are easily dissolved into available forms upon application (Masrie *et al*., 2015). Their application is one way of replenishing the lost soil nutrients as it increases nutrient availability in the soil solution hence enhancing their availability for plant uptake (Mugwe *et al*., 2010). However, the use of mineral Fertilizer is low due to their high cost (Muthoni, 2016). Application of P Fertilizer has been reported to have significant effects on available soil P in acidic soil conditions (Kisinyo *et al*., 2012).

2.9 Effect of Legumes on Weed Growth in Potato Production

Weed infestation, among plant pests, results in the highest potential crop yield reduction hence their control is important in the determination of crop profits (Kołodziejczyk *et al*., 2017). Globally, crop yield losses associated with weed infestation are estimated to be 43% (Singh *et al*., 2018) and their effect on crops plants yield depends on the abundance and biomass of weeds and their species composition. Potato yield losses caused by weed infestation are estimated at 20-80% (Kołodziejczyk *et al*., 2017). Weed control requires a complex approach to integrate the effect of both direct and indirect suppressive means. Fertilization and weed control enhance each other and are closely related (Campiglia *et al*., 2009). Weed growth basically depends on the competitive ability of the whole crop community, which in intercropping largely depends on the competitive abilities of the intercrops and the main crop (Matusso *et al*., 2014). Cover crops are important in enhancing crop nutrition and suppressing weeds. In a cropping system, they have a higher soil organic matter and available nutrient content, prevent erosion and nutrient leaching, suppress weeds and control soil-borne diseases (Campiglia *et al*., 2009). Legumes with a high ground cover are capable of smothering notorious weeds (Kiiya *et al*., 2015).

2.10 Effect of Legume Integration on Potato Nutrient Uptake

Potato production in Kenya is mainly carried out by smallholder farmers who depend on Agriculture for food and income (Gitari, 2018). Incorporation of legumes into potato production systems enhances better nutrient utilization, hence improving the productivity of the cropping systems (Nyawade *et al*., 2019). Rooting depth and canopy cover of the intercrop are the main factors that control N and P uptake for potato, and hence the productivity of the potato-legume cropping systems (Mushagalusa *et al*., 2008; Zhang *et al*., 2016). Any intervention that promotes uptake of these mineral elements increases their use efficiency (Musyoka *et al*., 2017; Nyiraneza *et al*., 2017). The type of intercrop used in potato-based intercropping systems, is important in determining nutrient uptake and use efficiency as well as the yield, and this can be partly associated with the growth attributes of this intercrop (Zhang *et al*., 2016).

An intercrop with a deep rooting system enables the crop to acquire nutrients outside the zone accessible to the less expansive potato root system, hence minimizing loss through fixation and leaching (Gitari *et al*., 2015). Dolichos has the ability to capture N and P from the subsoil hence minimizing the competition for these nutrients (Ojiem *et al*., 2007). It also produces phosphatase and carboxylate exudates which have a significant influence on the availability of nutrients in its rhizosphere and that of the main crop (Hinsinger *et al*., 2011). Phosphatases have a high affinity for clay colloids competes with phosphate ions from the charged surfaces, thus releasing P into soil solution (Giles *et al*., 2017; Hill *et al.*, 2015). They also play a major role in degrading organic matter though cleaving phosphate bonds hence, availing P in the rhizosphere (Richardson *et al*., 2009). The rhizodeposition of P increases its availability for uptake by potato (Nuruzzaman *et al*., 2005).

Canopy cover is also important in nutrient uptake and use efficiency. A high canopy cover increases soil moisture (Gitari, 2018). This results in increased N and P solubilisation reducing their lose hence, increasing their availability for potato uptake and this results in increased tuber yield (Sennhenn *et al*., 2017). Higher canopy cover also reduces solar radiation reaching the soil surface lowering soil temperatures (Webb *et al*., 2010). Low temperatures favour tuber initiation process and translocation of the produced sugars from the leaves to the tubers and this increases the number and weight of tubers, and thus increased total tuber yield (Kim *et al*., 2017).

2.11 Effect of Lime and Inorganic Fertilizer on Potato Nutrient Uptake

The use of lime in crop production enhances soil health status through improving soil pH, base saturation, Ca, Mg and enhancing P availability. Application of lime to acidic soils increases the availability of plant nutrients in the soil which results in improved crop performance (Dida & Etisa, 2019). Application of agricultural lime containing Ca and/or Mg compounds to acid soils increase Ca^{2+} and/or Mg^{2+} ions and reduces Al^{3+}, H^{+}, Mn^{4+}, and Fe^{3+} ions in the soil solution. This increases the soil pH, available P due to reduced P sorption and uptake of N and P improving crop productivity (Kisinyo *et al*., 2014b).

CHAPTER THREE

EFFECTS OF LIME, NPK FERTILIZER AND INTERCROPPING ON SELECTED PROPERTIES OF AN ACID MOLLIC ANDOSOL IN POTATO (*Solanum tuberosum*) PRODUCTION IN MOLO, KENYA

Abstract

Potato productivity in small holder farms of Molo sub county in Kenya is limited by soil acidity and low fertility. The objective of the study was to investigate effects of lime, NPK fertilizer and intercropping on soil pH, available soil phosphorus and total soil nitrogen in potato systems. A two-season field experiment was set up as a split-split plot in a randomized complete block design, with three replicates. Fertilizer, NPK, at two levels (0 and 0.2 t ha^{-1}) formed the main plots. Lime rates (0 and 2 t ha^{-1}) were assigned to the sub-plots and cropping system (sole potato and potato/dolichos intercrop) the sub-sub plots. Lime was applied 3 weeks before planting. The results showed that application of lime at 2 t ha^{-1} increased the soil pH by 0.34 over the control, by the end of the second season. Sole NPK fertilizer applied at the rate of 2 t ha^{-1} reduced the soil pH by 2% when compared to control without fertilizer. Combined application of 0.2 t ha^{-1} NPK fertilizer with 2 t lime ha^{-1} resulted in an increase in soil available P by 6.5, 8 and 6mgkg^{-1} in the first season, and 4.41, 3.91 and 3.58mgkg^{-1} in the second season over the control, sole lime and sole NPK fertilizer application, respectively. Application of 0.2 t NPK ha^{-1} fertilizer under the potato/dolichos intercrop increased the total soil N by 0.08% over the control without fertilizer, by the end of the second season. Therefore, in potato systems of Molo Kenya, application of 2 t lime ha^{-1} and 0.2 t ha^{-1} NPK fertilizer is recommended for reducing acidity and increasing N and P fertility of the soils.

3.1 Introduction

Acid soils occupy 13% of the Kenya's total land area (Gitari *et al*., 2015). The soils in Molo, a major potato producing area are acidic, with a pH of less than 5.2 (Lelei & Onwonga, 2013), and have low fertility (Komen *et al*., 2017). The causes of acidity are leaching of basic cations by rainfall and acidic parent material. At pH below 5.5, the hydrolysis of Al-hydroxides on the clay mineral surface release the Al^{3+} into soil solution which reacts with water molecules to form aluminium hydroxide and hydrogen ions (McBride, 1994). Acid soils affect soil fertility through nutrient deficiencies, mainly through phosphorus (P) fixation (Osundwa, 2013), and presence of phytotoxic elements (Al^{3+}, $Fe^{2+}$and Mn^{2+}) (Muindi, 2016; Nduwumuremyi, 2013).

Phosphorus reacts with Fe^{2+} and Al^{3+} in soil solution under these conditions to form insoluble phosphates making it unavailable for plant uptake (Opala, 2017). Low soil pH affects soil microorganisms which results in reduced soil microbial activities. Acidic soils affect the growth of nitrifiers (Mkhonza *et al*., 2020) and this slows the nitrification process hence low N levels in the soil available for plant growth. Reduction in microbial activities also results in a reduction in organic matter breakdown reducing release and uptake of plant nutrients. Low soil P levels and high Al^{3+} in the soil affects the growth of the symbiotic nitrogen fixing bacteria resulting in low nitrogen fixation (Bakari *et al*., 2020).

Application of organic manure to farm lands to increase soil fertility is limited since crop residues are used as animal feeds while animal manure is used in small quantities, and it is of low quality (Muindi *et al*., 2016). Fertilizer application is an effective means to increase plant nutrient uptake and improve yields (Girma *et al*., 2017). Small holder farmers in Molo practice continuous cultivation on their farms and they apply DAP or Urea fertilizers to correct nutrient deficiencies and increase plant nutrient uptake but in less than recommended rates (Gitari *et al*., 2015; Muthoni, 2016; Onwonga *et al*., 2014). This is due to high cost of fertilizer (Gitari *et al*., 2015). Continuous cultivation with inadequate replenishment of mined nutrients results in soil infertility (Bidai *et al*., 2020).

Liming acid soils is a long-term management practice that has been widely embraced as an acid amelioration strategy. Lime increases pH, reduces Al^{3+} and Mn^{+} toxicity, and increases P availability (Kisinyo *et al*., 2014; Meriño-Gergichevich *et al*., 2010; Nduwumuremyi, 2013). Lime supplies basic cations Ca and Mg, improves Molybdenum (Mo) availability and ensures optimal microbial activity (Bambara & Ndakidemi, 2010; Nekesa *et al*., 2011). Use of the acid forming DAP fertilizer in the small holder farms without liming contribute to increased acidity of soils (Muthoni, 2016; Opala *et al*., 2013). Liming is rarely practiced due to lack of awareness on its benefits (Bakari *et al*., 2020).

The traditional cultural practice of expanding farmlands to increase food production is no longer sustainable due to continued population increase and urbanization (Lambin *et al*., 2013). This has reduced the size of agricultural land even further. Due to small land sizes, intercropping can increase returns and guard against food insecurity in case of crop failure (Gitari *et al*., 2019). Intercropping potato with Dolichos enhances better nutrient utilization and thus improves productivity of the intercropping system. Dolichos (*Lablab purpureus*) has a deep rooting system which enables it to acquire nutrients outside the rhizosphere of the potato crop thereby minimizing loses through leaching and fixation (Gitari *et al*., 2018). Dolichos also produces exudates which are important in availing nutrients in the rhizosphere of the main crop (Hinsinger *et al*., 2011).

Identifying efficient and sustainable practices that reduce soil acidity, enhance soil N and P fertility and increase potato production are of importance to small holder farmers of Molo. The objective of this study was to determine the effects of lime, NPK fertilizer and intercropping on soil pH, available soil P and total soil N in potato intercropping systems.

3.2 Materials and Methods

3.2.1 Experimental Site

The experiment was conducted in Molo sub-County, Kenya, located at latitude 0° 12' S, longitude 35° 41' E, and altitude 2200 m asl, for two cropping seasons (2020 short rains and 2021 long rains). The area receives a mean annual rainfall of 1200 mm and mean temperature of 13.75°C. The main crops grown are pyrethrum (*Chrysanthemum cinerariifolium*), potatoes (*Solanum tuberosum*), barley (*Hordeum vulgare*) and maize (*Zea mays*). The soils are acidic, with pH of less than 5.2, well drained, deep, dark reddish brown with a mollic A horizon and are classified as mollic Andosols (Jaetzold *et al*., 2010).

3.2.2 Determination of initial soil physico-chemical properties

Soil was randomly sampled, using a soil auger, from six locations in the field in a zig zag pattern before land preparation, for characterization of initial physicochemical properties. The samples were collected from three soil depths (0-15, 15-30 and 30-45cm) and thoroughly mixed to obtain one composite sample for each depth. The samples were put in well labelled khaki bags, sealed to avoid spilling and transported to the laboratory. The soils were air dried in shallow trays in well-ventilated preparation room for one week. After drying, the soils were crushed to break large soil clods and then sieved using 2 mm sieve. Samples for analysis of total N were sieved through a 0.5mm. The sieved samples were then taken to the main laboratory for analyses. Soil texture was determined by hydrometer method and soil bulk density by core ring method as described by Okalebo *et al*. (2002). Soil pH was measured (soil : distilled water ratio of 1:2.5) using a pH meter (Make: Jenway, UK; model: 3510 pH meter), available soil P was determined by Mehlich Double Acid Method (Mangale *et al*., 2016), soil CEC and exchangeable bases by the ammonium acetate method and soil organic Carbon by the *Walkley-Black* procedure both as described by (Reeuwijk, 2002) and total soil N was determined by *Kjeldahl* method as described by Okalebo *et al.* (2002). The initial soil properties are presented in Table 2.

Table 2: Initial soil chemical and physical properties

	Soil depth (cm)		
	0 – 15	15 – 30	30 – 45
Parameters	value	value	value
Soil texture	SCL	SCL	SCL
Sand	56	56	56
Silt	16	14	12
Clay	28	30	32
Soil pH (H_20)	4.37	4.50	5.25
Exch. Acidity cmol kg^{-1}	0.2	0.5	0.4
Potassium cmol kg^{-1}	1.4	1.4	1.3
Calcium cmol kg^{-1}	10.2	12.4	12.6
Magnesium cmol kg^{-1}	1.6	1.9	2.0
Sodium cmol kg^{-1}	0.2	0.1	0.02
Total Nitrogen %	0.20	0.17	0.15
Total Organic Carbon %	2.17	1.92	1.74
Available phosphorus (mg kg^{-1})	23	19	19
CEC (cmol kg^{-1})	32.4	32.6	28.3
Bulk density (g cm^{-3})	1.06	1.15	1.24

Key: SCL- Sand Clay Loam, CEC- Cation Exchange Capacity, cmol kg^{-1}- centimoles per kilogram and mg kg^{-1}- milligrams per kilogram, g cm^{-3}- grams per centimetre cubed.

3.2.3 Experimental Design and Treatments

Land, previously with canola (*Brassica napus*), was ploughed manually using hand hoes and crop residues present were removed by raking before application of treatments. The experiment was laid out as a split-split plot arrangement in a randomized complete block design (RCBD). Compound Fertilizer (NPK 17:17:17) at two levels (0 and 0.2 t ha^{-1}) formed the main plots, granulated lime at two rates (0 and 2 t ha^{-1}) the sub-plots and cropping system (sole potato and potato/dolichos intercrop) the sub-sub plots. The treatments were replicated 3 times. Granulated lime was applied 3 weeks before planting. Potato sole crop was planted at a spacing of 75 cm × 30 cm. The dolichos intercrop was sown between the potato rows, at an intra-row spacing of 0.25 m. The sub sub-plots measured 5 × 4.5 m.

The compound fertilizer, NPK (17:17:17) was applied at a rate of 0.2 t ha^{-1} at planting to supply an equivalent of 34 kg N ha^{-1}, 34 kg P ha^{-1} and 34 kg K ha^{-1}. Topdressing was carried out 28 days after emergence (DAE) using Calcium Ammonium Nitrate (CAN 27%) at the rate of 0.2 t ha^{-1} in order to supply an equivalent of 54 kg N ha^{-1}. Weeding and earthing up was done manually 28 DAE to remove weeds and loosen up soil to allow tuber expansion and development. Fungal infections were managed by spraying Ridomil Gold® MZ 68 WG (Metalaxyl-M 100g ha^{-1} + Mancozeb 1600g ha^{-1}) and Infinito® (fluopicolide 100g ha^{-1} + propamocarb hydrochloride 1000g ha^{-1}alternately once every week. To manage insect pests, Thunder® OD 145 (imidacloprid 20g ha^{-1} + betacyfluthrine 9g ha^{-1}) was used. Drenching was done immediately after planting and after germination to control cutworms. Pesticide was applied once every week for the control bean aphids (*Aphis fabae*).

3.2.4 Seeds

Potato variety *Shangi* used in the study, is a semi- erect medium tall variety with moderately strong stems and light green broad leaves. It does well in altitudes of ≥1500 m.a.s.l. and the tubers are oval with white flesh containing medium to deep eyes with pink pigmentation. It has a very short dormancy and matures within 3-4 months, is moderately susceptible to late blight and its yield ranges between 30 – 40 tonnes ha^{-1} (N.P.C.K, 2019). Certified seeds (pre-sprouted tubers) size two were sourced from Agricultural Development corporation (ADC) Molo. The potato seed rate used was 2 t ha^{-1}. Dolichos *(Lablab purpureus)* used as an intercrop in the study**,** is a vigorously determinate herbaceous plant, resistant to disease and insect attack. Its leaves are large and trifoliate (Grotelüschen, 1999). Dolichos seeds were obtained from the local market and inspected for off types and damaged seeds. A germination test was conducted before planting. The seed rate used was 20 kg ha^{-1}.

3.2.5 Data Collection

Soil samples were collected randomly from four locations in each experimental unit at 30 cm depth at the end of each cropping season. The collected samples were thoroughly mixed to obtain one composite sample for each unit. The samples were put in well labelled khaki bags, sealed to avoid spilling put in a cool box and transported to the laboratory for soil pH, total soil N and available soil P analyses. In the laboratory the samples were air dried in shallow trays in a well-ventilated room. After drying, the samples were crushed and sieved using a 2 mm sieve for soil pH and available soil P determination while a 0.5mm sieve was used for samples that were used in total soil N determination. The methods used for analyses are explained in section 3.2.1.

3.2.6 Data Analyses

Data were then subjected to analysis of variance (ANOVA) using SAS software for windows 9.4 (SAS Institute, Cary, NC). using the following statistical model.

$Y_{ijklmn} = \mu + S_i + \beta_j + F_k + FS_{ik} + F\beta(S)_{ijk} + L_l + LS_{il} + LF_{kl} + LSF_{ikl} + LF\beta(S)_{ijkl} + C_m + CS_{im} + CF_{km} + CFS_{ikm} + CL_{lm} + CLS_{ilm} + CLF_{klm} + CSFL_{iklm} + \varepsilon_{ijklmn}$

Where:

Y_{ijklmn} = Overall observations, μ = Overall mean, S_i = Effect due to season, β_j = blocking effect, F_k= k^{th} fertilizer effect, FS_{ik} = Season and fertilizer effect, $F\beta(S)_{ijk}$ = Main plot error, L_l = l^{th} liming effect, LS_{il} = liming and season effect, LF_{kl} = liming and Fertilizer effect, LSF_{ikl}= liming, season and Fertilizer effect, $LF\beta(S)_{ijkl}$ = Sub-plot error, C_m = Cropping effect, CS_{im}= cropping and season effect, CF_{km} = cropping and Fertilizer effect, CFS_{ikm} = cropping, Fertilizer and season effect, CL_{lm} = Effect due to lime and cropping system, CLS_{ilm} = cropping, liming and season effect, CLF_{klm} = cropping, liming and Fertilizer effect, $CSFL_{iklm}$ = cropping, season, Fertilizer and liming effect and ε_{ijklmn} = Random error term.

Where the Fisher's protected F-test was significant, means of the main effects were separated using Tukey's honest significance test ($P<0.05$). Pearson correlation coefficient was carried out to test the significance of the relationship between soil pH and available soil P.

3.3 Results and Discussion

3.3.1 Effects of Lime and NPK Fertilizer on Soil pH

The main effects of NPK fertilizer and lime on pH were significant at $P<0.05$ (Table 3). Lime applied at the rate of 2 t ha^{-1} resulted in an increase in soil pH by 5% when compared to the control (Table 3). Application of 2 t ha^{-1} NPK fertilizer resulted in a significant ($P<0.05$) decrease in soil pH by 2% when compared to the control (Table 3).

Table 3: Main effects of lime and NPK fertilizer on soil pH in potato intercropping system in Molo, Kenya

Lime rates (t ha^{-1})	Soil pH
0	4.32b
2	4.539a
NPK fertilizer rates (t ha^{-1})	
0	4.46a
0.2	4.38b
Mean	4.42
CV	1.76
MSD	0.05

Means within a column followed by the same letter are not significantly different at $P \leq 0.05$.

Key: CV- Coefficient of Variation, MSD- Minimum Significance Difference

Application of lime tends to raise the soil pH and reduce acidity by displacement of H^+, Fe^{2+}, Al^{3+}, and Mn^{4+} ions from soil adsorption site (Osundwa *et al*., 2013; The *et al*., 2006)). Similarly, the anions $CO_3^{2-}$and OH^- present in lime neutralize the H^+ released from the exchange sites and hydrolyze Al to the soil solution (Fageria & Baligar, 2008). The observed liming effect on pH in the study concurs with the findings of other workers (Cabrales & Acosta, 2020; Dereje *et al*., 2019; Omollo *et al*., 2016; Otieno *et al*., 2018).

The NPK (17:17:17) fertilizer contains 5% N in ammoniacal form and 12% N in Urea form. Inorganic ammonium based fertilizers are not acidic but their application to soil result in increased acidification through the oxidation of NH_4^+ and NO_3^- during the process of nitrification which generates H^+ resulting in low soil pH (Schroder *et al*., 2011). Additionally, plants release excess H^+ when cation uptake exceeds anion uptake (Tang *et al*., 2011). The decrease in pH with NPK application was also observed by Ogundijo *et al*. (2015) and Beukes *et al*. (2012).

3.3.2 Effects of Lime and NPK Fertilizer on Available Soil P

The interaction effects of lime, fertilizer and season were significant at $P<0.05$ for available soil P (Table 4). Application of 0.2 t ha^{-1} NPK fertilizer and 2 t ha^{-1} lime resulted in a significant increase in available soil P content (31.08 mg kg^{-1}) at the end of the second season, compared to other treatments. The combined application of 0.2 t ha^{-1} NPK fertilizer and 2 t ha^{-1} lime resulted in an increase in soil available P by 20.41, 3.91 and 3.58 mg kg^{-1} in the second season over the control, sole lime and sole fertilizer application, respectively (Table 4).

Table 4: Season, Fertilizer and lime interaction effects on soil available P in potato intercropping system in Molo, Kenya

Seasons	Fertilizer levels (t ha^{-1})	Lime levels (t ha^{-1})	Available P (mg kg^{-1})
1	0	0	9.67 ± 0.82de
		2	9.17 ± 0.75e
	0.2	0	11.17 ± 0.98d
		2	17.17 ± 1.34c
2	0	0	10.33 ± 1.03de
		2	27.17 ± 1.34b
	0.2	0	27.50 ± 1.82 b
		2	31.08 ± 2.84a
Mean	-	-	19.95
CV	-	-	4.35
R^2	-	-	99.67

Means within a column followed by the same letter are not significantly different at P≤0.05.

Key: t ha^{-1}- tonnes per hectare, mg kg^{-1}- milligrams per kilogram, CV – Coefficient of Variation and R^2- coefficient of determination.

The release of P from NPK caused the increase in available soil P. Increase in soil available P due to liming is attributed to the decrease in soil acidity. Lime increased the soil pH leading to reduction in P sorption. Therefore, both the inherent phosphorous and fertilizer supplied phosphorus increased available soil P (Kisinyo *et al*., 2013). At low soil pH values, phosphorus is fixed by aluminium and iron oxides and hydroxides (Ameyu, 2019). Liming of acidic soils to increase the pH results in the release of phosphate ions fixed by Al and Fe ions into the soil solution (Kisinyo, 2016). Additionally, liming stimulates mineralization of soil organic P. Increasing the pH of acidic soils provides favourable environment for microorganisms which are important in the mineralization of soil organic phosphorus (Ameyu, 2019).

In a four-year study carried out on immediate and residual effects of lime and P fertilizer on soil acidity and maize productivity by Kisinyo *et al.* (2014a), sole application of 4t ha^{-1} lime was resulted in increase in available soil P. Kisinyo (2016) in a four year study on maize productivity in an acid soil, reported increased available soil P when 6t ha^{-I} lime was applied. Bidai *et al.* (2020) in his study on effects of soil amendments on selected soil properties reported an increase in available soil P above the control when 2 t ha^{-1} lime was applied. Therefore, both lime and P fertilizer should be used for long term management of acid soils deficient of P.

3.3.3 Correlation between soil pH and available soil P

Soil pH and available soil P had a positive correlation (r=0.4**). This implies that an increase in soil pH resulted in increase in soil available P. Kisinyo (2016) and Bidai *et al.* (2020) reported increases in soil available P as a result of liming. The slow change in soil pH (4.65) upon liming is attributed to the slow reactivity of lime to release Ca^{2+} and Mg^{2+} and this explains the weak correlation between soil pH and available soil P. Kisinyo *et al.* (2014a) reported that the changes in soil pH upon application of lime are more evident during the second year after lime application. Kisinyo (2016) reported that lime took 425 days to increase soil pH to maximum peak of 7.0. The current study took place for only two seasons. The applied P in form of NPK fertilizer also could have been fixed by the Al^{3+} and Fe^{2+}.

3.3.4 Effects of Lime and NPK Fertilizer on total soil N

The interaction of season, fertilizer and cropping system had a significant ($P<0.05$) effect on total soil N (Table 5). Application of 0.2 t NPK ha^{-1} resulted in higher total soil N in both the sole potato and potato/dolichos intercrop, in both cropping seasons, compared to where the fertilizer was not applied. Higher total soil N contents of 0.27% and 0.26% were observed during the first season and were not significantly ($P<0.05$) different from 0.27% and 0.28% observed in the second season under the potato sole crop and the potato/dolichos intercrop with fertilization, respectively (Table 5).

Table 5: Effects of NPK fertilizer on total soil N under Potato Intercropping systems for two seasons (mean ± SD)

Season	Fertilizer level (t ha $^{-1}$)	Cropping system	Total soil N (%)
1	0	P	0.20 ± 0.02b
		PD	0.23 ± 0.03b
	0.2	P	0.27 ± 0.03a
		PD	0.26 ± 0.03a
2	0	P	0.21 ± 0.02b
		PD	0.22 ± 0.03b
	0.2	P	0.27 ± 0.02a
		PD	0.28 ± 0.01a
Mean	-	-	0.24
CV	-	-	5.78
R^2	-	-	95.56

Means within a column followed by the same letter are not significantly different at $P \leq 0.05$

Key: t ha^{-1}- tonnes per hectare, P–Sole potato crop, PD–Potato-Dolichos intercrop, CV–Coefficient of Variation and R^2- coefficient of determination.

High total soil N was partly due to fertilization. N also increase plant growth and organic N inputs in the form of plant residues. Ge *et al*. (2018) also reported increase in total N where NPK fertilizer was applied when compared to the control. High total soil N due to fertilization was also reported by Aula *et al.* (2016). Lablab in the intercrop reduced N losses through leaching. Dolichos has a high canopy cover hence creates a cool microclimate that reduces the rate of N mineralisation (Gitari *et al*., 2018). In a study on the effects of potato legume intercrop on soil fertility and the use of dolichos and combined fertilizers to enhance soil nutrient availability Gitari *et al*. (2018) and Sitienei *et al*. (2017) reported a significant increase in total soil N under potato legume intercrop. The dolichos also has the ability to fix atmospheric N (Sitienei *et al*., 2017).

3.4 Conclusion

Lime application at the rate of 2 t ha^{-1} causes a slight increase in soil pH in two growing seasons. Sole application of NPK fertilizer (0.2 t ha^{-1}) increases soil acidity. The availability of P in soil is influenced by pH. Combined application of 0.2 t ha^{-1} NPK fertilizer and 2 t ha^{-1} lime in potato intercropping systems increased soil available P, with greater evidence in the second growing season. Sole NPK fertilizer application increases total soil N across growing seasons and cropping systems.

The study recommends application of 2 t ha^{-1} lime and 0.2 t ha^{-1} NPK fertilizer, and introduction of dolichos as intercrop in potato intercropping systems for improvement of soil pH, and N and P fertility in acid soils of Molo. This study also recommends long term research on soil amendments that can result in increased soil pH and avail soil nutrients in acidic mollic Andosols of Molo, Kenya.

CHAPTER FOUR

EFFECTS OF LIME, NPK FERTILIZER AND INTERCROPPING ON SORREL WEED GROWTH IN POTATO PRODUCTION SYSTEMS

Abstract

Low soil fertility, increased acidity and weed infestation among others are the factors contributing to reduced potato yields among smallholder potato farmers of Molo sub-county, Kenya. A two-season field experiment was set up in acid mollic Andosols of Molo sub county, Kenya. The objective was to investigate effects of lime, intercropping and NPK Fertilizer application on sorrel weed growth in a potato cropping system. A randomized complete block design with a split-split plot arrangement, replicated three times, was used. Fertilizer, NPK, at two levels (0 and 0.2t ha^{-1}) formed the main plots. Lime rates (0 and 2 t ha^{-1}) were assigned to the sub-plots and cropping system (sole potato and potato/dolichos intercrop) the sub-sub plots. Lime was applied 3 weeks before planting. The results showed that, fertilizer, lime and intercropping interactions had significant ($P \leq 0.05$) effects on sheep sorrel weed density, dry biomass and root length across the seasons. Combined application of 0.2 t ha^{-1} NPK and 2 t ha^{-1} lime under the potato/dolichos intercrop resulted in low weed density, lower dry weed biomass and lower weed root length,29 weeds,0.22kg and 161cm during the second season, respectively. The Pearson's correlation coefficient showed a positive significant (r=0.8***) relationship between sorrel weed density and biomass. Application of 0.2 t ha^{-1} NPK fertilizer, 2t ha^{-1} lime and intercropping potato with dolichos is important in reducing sorrel weed infestation among smallholder potato farms of Molo subcounty, Kenya and is recommended.

4.1 Introduction

Low potato yields in the smallholder farms in Kenya has been attributed to rapid decline in soil fertility among other factors. The decline in soil fertility is as a result of continuous cultivation of annual crops without adequate replenishment of mined nutrients (Muthoni, 2016). In Molo sub-county, Kenya, this problem has been exacerbated by low soil pH (less than 5.5) (Muindi *et al*., 2016). The soils in the Rift valley are derived from acid volcanic rocks and have been highly leached by high rainfall amounts (Komen *et al*., 2017). Together with low soil fertility and increased soil acidity, weed infestation also contributes to significant crop yield losses.

Rapid decline in soil fertility together with increased soil acidity have favoured weed infestation (Kiiya *et al*., 2010). Weeds are an important yield reducing factor in crop production due to competition with the crop for light, water and nutrients (Gu *et al*., 2021). Crop yield losses associated with weeds have been estimated to be 43% globally (Singh *et al*., 2018). In potato production, tuber losses due to weed infestation have been estimated to be between 20 and 80% (Kołodziejczyk *et al*., 2017). Crop yield losses as a result of weed infestation depends on the abundance and biomass of the weed species.

The sheep sorrel (*Rumex acetosella* L.) is a major weed in potato fields. It is also known as red sorrel, field sorrel, horse sorrel, mountain sorrel, cow sorrel or sour dock (Kiiya *et al*., 2010). It is a perennial weed belonging to the buckwheat (*Fagopyrum esculentum*) Polygonaceae family (Stopps *et al*., 2011). It is an herbaceous perennial weed that reproduces both sexually and asexually. Buds develop irregularly on creeping roots and rhizomes (Stopps *et al*., 2011). Seeds can be dispersed by wind, insects, water, and animals and can remain viable in the soil for up to 20 years and are viable even after passing through digestive tract of domestic birds and animals (Kiiya *et al*., 2010).

Weeds are commonly controlled by use of chemical herbicides, hand and mechanical weeding. However, the use herbicides is costly for resource poor farmers and the chemicals have negative impacts to the environment and the human health (Gu *et al*., 2021). Weeding is time consuming hence expensive and continued cultivation results in loosening up the soil and may result to losses through erosion. Sorrel weed has a dense root system that is difficult to remove through weeding together with its ability to reproduce within 3 months from root fragments buried deep in the soil (Frey *et al*., 2008) is key to the success of the species. The ability to reproduce vegetatively from creeping roots and its long-lived soil seed bank allows it to easily withstand fire disturbance. Both the male and female sorrel plants produce seeds and the male are more resistant to drought makes its control difficult (Stopps *et al*., 2011). A study on hexazinone and fertilizer impacts on sheep sorrel in wild blueberry Kennedy *et al*. (2010) reported that hexazinone reduced sorrel weed density, fertilizer increased weed density in absence of herbicide and had no effect on the density in the presence of the herbicide. He however concluded that despite the fact that hexazinone reduced sorrel weed density, its opportunity for use is narrow and its application did not result in increased yields. There is therefore need to come up with a sustainable approach to manage the weed.

Intercropping has been in use for long and its plays an important role in sustainable agricultural intensification. It is the cultivation of two or more crop species simultaneously in the same field during a significant part of their growing periods (Gu *et al*., 2021;Tang *et al*., 2021). Its advantages over monocropping is that there is land utilization efficiency, resource use efficiency, increased yields and has also been reported to suppress weed growth (Gu *et al*., 2021). Intercropping allows for higher resource capture when compared to monocropping leaving less for weed suppressing their growth (Kołodziejczyk, 2014). Some of the crops used as intercrops also have allelopathic properties against weeds hence suppressing their growth (Kocira *et al*., 2020).

The sorrel weed competes successfully on infertile soils with low soil pH but it is highly reduced on fertile soils (Stopps *et al*., 2011). Lime application has shown to increase the soil pH (Opala, 2017) and this results in increased availability of nutrients in the soil improving soil fertility status hence reduced sorrel weed infestation . Increased soil pH and nutrient availability also gives the associated crop a competitive advantage over the weed. The weed is highly susceptible to shading by associated plant species hence intercropping associated crops with a high biomass producing intercrop will suppress its growth. Application of inorganic fertilizers is also important in supplying required nutrients by the associated crop giving it a competitive advantage over the weed. The objective of this study was to investigate the effects of fertilizer, lime and intercropping on sorrel weed growth.

4.2 Materials and Methods

4.2.1 Experimental Site

The experimental site has been discussed in chapter three section 3.2.1.

4.2.2 Experimental Design and Treatments

Experimental design and treatments used in the study have been discussed in chapter three section 3.2.3.

4.2.3 Seeds

Seeds used in the study have been described in chapter three section 3.2.4.

4.2.4 Data Collection

Data on the sorrel weed was collected once before weeding (28 DAE of potato crop). In the determination of weed density, a quadrat measuring 50cm × 50 cm was randomly thrown in each plot and the number of the sorrel weeds within the quadrant counted and recorded as the weed density per square metre. The weeds were then uprooted and weighed and the weight was recorded as the fresh or wet biomass. The weeds were then put in well labelled khaki bags and transported to the laboratory for oven drying to obtain the dry weight. The weeds were oven dried at 65°C to constant weight and the weight recorded as dry weight/biomass. For the weed root length, one weed per plot was randomly selected from the uprooted roots within the one square metre after taking the fresh weight, put in a well labelled khaki bags, transported to the laboratory and scanned using the WinRHIZO (LA 2400) root scanner.

4.2.5 Data Analyses

Data were tested for normality using the Shapiro Wilk test at probability of ≤0.05 in SAS software using proc univariate plot.

$$W = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n} (x_i - \overline{x})^2}$$

Data were then subjected to analysis of variance (ANOVA) using SAS software for windows 9.4 (SAS Institute, Cary, NC) using the following statistical model.

$Y_{ijklmn} = \mu + S_i + \beta_j + F_k + FS_{ik} + F\beta(S)_{ijk} + L_l + LS_{il} + LF_{kl} + LSF_{ikl} + LF\beta(S)_{ijkl} + C_m + CS_{im} + CF_{km} + CFS_{ikm} + CL_{lm} + CLS_{ilm} + CLF_{klm} + CSFL_{iklm} + \varepsilon_{ijklmn}$

Where:

Y_{ijklmn} = Overall observations, μ = Overall mean, S_i = Effect due to season, β_j = blocking effect, F_k= k^{th} fertilizer effect, FS_{ik} = Season and fertilizer effect, $F\beta(S)_{ijk}$ = Main plot error, L_l = l^{th} liming effect, LS_{il} = liming and season effect, LF_{kl} = liming and Fertilizer effect, LSF_{ikl}= liming, season and Fertilizer effect, $LF\beta(S)_{ijkl}$ = Sub-plot error, C_m = Cropping effect, CS_{im}= cropping and season effect, CF_{km} = cropping and Fertilizer effect, CFS_{ikm} = cropping, Fertilizer and season effect, CL_{lm} = Effect due to lime and cropping system, CLS_{ilm} =

cropping, liming and season effect, CLF_{klm} = cropping, liming and Fertilizer effect, $CSFL_{iklm}$ = cropping, season, Fertilizer and liming effect and ε_{ijklmn} = Random error term.

Where the Fisher's protected F-test was significant, means of the main effects were separated using Tukey's honest significance test (P<0.05). Pearson correlation coefficient was carried out to test the significance of the relationship between weed density and weed biomass.

4.3 Results and Discussion

4.3.1 Interaction Effects of Season, Lime, Intercropping and NPK Fertilizer on Sheep Sorrel Weed Growth

Sheep sorrel weed density, dry biomass and root length were significantly (P≤0.05) affected by fertilizer, lime and cropping system interactions across the two seasons (Table 6 and 7). Higher sorrel weed densities of 144 and 125 weeds per square metre were obtained under sole potato without lime and NPK fertilizer (control) in the first and second seasons, respectively. In both sole potato and potato-dolichos cropping systems, the lowest density was obtained where there was combined application of lime and fertilizer in the first season and second season and also their sole applications in the second season (Table 6 and 7).

Highest weed dry weight of 1.82 kg was obtained in the second season without NPK fertilizer and lime application (control), under sole potato. This which was significantly (P≤0.05) higher than 1.54 kg obtained under potato/dolichos intercrop in the second season (Table 6 and 7). Least weed dry weights were observed in the second season in liming treatments with or without fertilizer application in both potato systems (Table 6 and 7).

Highest sorrel weed root lengths of 738.03 cm and 734.88cm were obtained in the potato/dolichos intercrop and potato sole crop controls, respectively in the first season, and 692.41 cm in sole potato without lime or fertilizer in the second season. The lowest root lengths were observed in the second season in potato/dolichos intercrop with sole lime or NPK fertilizer, and in both potato systems with combined application of lime and NPK fertilizer (Table 6 and 7).

Table 6: Fertilizer and lime interactions on weed density, biomass and root length under potato intercropping system in season 1 in Molo, Kenya (Mean ± SD)

	Fertilizer levels (t ha^{-1})	Lime levels (t ha^{-1})	Cropping system	Weed density ($m^{2\ -1}$)	Weed dry weight (kg)	Weed root length (cm)
	0	0	P	125 ± 37.50a	0.73 ± 0.11f	734.88 ± 43.73a
		0	PD	83 ± 21.70cd	0.59 ± 0.05g	738.03 ± 39.60a
	0	2	P	85 ± 13.86cd	0.93 ±0.01de	449.79 ± 59.38c
		2	PD	64 ± 6.08de	0.82 ± 0.02ef	439.19 ± 64.40cd
	0.2	0	P	89 ±5.29cd	1.34 ± 0.03c	479.61 ± 12.14bc
		0	PD	64 ±10.54de	0.95 ±0.03d	461.51 ± 22.85bc
	0.2	2	P	40 ± 7.64ef	0.59 ±0.02g	364.10 ± 21.23de
		2	PD	37 ± 2.00ef	0.43 ± 0.01h	350.64 ± 32.19e
Mean	-	-	-	67.27	0.73	412.25
CV	-	-	-	13.18	5.53	6.21
R^2	-	-	-	98.07	99.76	99.38

Means within a column followed by the same letter are not significantly different at P≤0.05

Key: t ha^{-1}- tonnes per hectare, $m^{2\ -1}$- per metre square, kg- kilograms, cm- centimetres, P- sole potato crop, PD- Potato-Dolichos intercrop, CV- Coefficient of Variation and R^2- Coefficient of determination.

Table 7: Fertilizer and lime interactions on weed density, biomass and root length under potato intercropping system in season 2 in Molo, Kenya (Mean ± SD)

	Fertilizer levels (t ha^{-1})	Lime levels (t ha^{-1})	Cropping system	Weed density ($m^{2\ -1}$)	Weed dry weight (kg)	Weed root length (cm)
	0	0	P	144 ± 33.15a	1.82 ± 0.07a	692.41 ± 134.31a
		0	PD	102 ± 17.93bc	1.54 ± 0.07b	543.33 ± 556.42b
	0	2	P	46 ± 9.29ef	0.34 ± 0.01hij	258.01 ± 4.25f
		2	PD	43 ± 6.08ef	0.32 ± 0.02hij	231.99 ± 7.65fg
	0.2	0	P	43 ± 11.59ef	0.38 ± 0.06h	262.70 ± 14.56f
		0	PD	41 ± 3.21ef	0.36 ± 0.05hi	238.52 ± 21.71fg
	0.2	2	P	33 ± 8.50f	0.24 ± 0.01ij	190.23 ± 13.55fg
		2	PD	29 ± 11.36f	0.22 ± 0.00j	161.07 ± 11.31g
Mean	-	-	-	67.27	0.73	412.25

Means within a column followed by the same letter are not significantly different at $P \leq 0.05$

Key: t ha^{-1}- tonnes per hectare, $m^{2\ -1}$- per metre square, kg- kilograms, cm- centimetres, P- sole potato crop, PD- Potato-Dolichos intercrop, CV- Coefficient of Variation and R^2- Coefficient of determination.

Sheep sorrel weed is commonly found in infertile and acidic soils (Kiiya *et al*., 2010). In order to inhibit its growth and give a competitive advantage to the associated crop, application of lime to increase the soil pH is recommended (Stopps *et al*., 2011). Reduced weed densities, weed biomass and root length due to lime application can be attributed to increased soil pH that made the conditions unfavourable for sorrel weed growth. Application of lime results in increase in soil pH (Kisinyo *et al*., 2014a) resulting in unconducive conditions for the sorrel weed growth. Combined application of lime and N fertilizer is also important in controlling the weed (Stopps *et al*., 2011). Low weed density, dry biomass and root length were observed where both 0.2t NPKha^{-1} and 2 t limeha^{-1} were applied. Application of 0.2 t NPKha^{-1} resulted in an increase in soil available nutrients improving the fertility of the soil hence reduced sorrel weed growth over the control. Kiiya *et al*. (2010) reported reduced sorrel weed biomass with increase in N fertilisation in combination with legume incorporation.

Slightly higher weed biomass and root length were observed under sole NPK fertilisation when compared to sole lime application. Kennedy *et al.* (2010) reported increased sorrel weed density and biomass under N fertilisation at the rate of 20 and 40 t N ha^{-1}. This can be attributed to the ability of N fertilizers to acidify soil hence creating favourable conditions for sorrel weed growth. Stopps *et al*. (2011) also suggested that crop rotation and intercropping using legume cover crops is effective in reducing the sorrel weed infestation. The use of high ground cover legumes as intercrops is important in suppressing weeds and affecting some of the soil properties positively (Kołodziejczyk *et al*., 2017). Cover crops used as intercrops prevent seed germination and emergence of weed seedlings hence reducing weed infestation and this limits weed growth and development and results in reduced number of weed seeds in the seed bank (Kocira *et al*., 2020).

The dolichos used as intercrop intercepted light preventing it from reaching the soil surface hence suppressing sorrel weed growth. It also produces high biomass hence competes with the sorrel weed for resources resulting in reduced Intercropping cereals with cowpea was reported to have significantly reduced striga weed infestation due to high ground cover of cowpea creating unfavourable conditions for striga germination (Matusso *et al*., 2014). Green manure also play an important role in improving soil fertility hence reducing sorrel weed infestation. Opala *et al*. (2012) reported increased soil pH upon sole tithonia incorporation or in combination with other inorganic inputs when compared to the control. Intercropping maize with beans and maize with groundnuts was reported to have resulted in reduced weed biomass (Matusso *et al.,* 2014). Sorrel weed is also reported to have a high demand for phosphorus (Stopps *et al*., 2011) resulting in extraction of P from the subsoil due to P fixation in the top soil by acidic cations. This can be attributed to the higher root length observed where either lime or both lime and fertilizer were not applied.

4.3.1 Correlation between weed density and dry biomass include root length

The results showed a strong positive correlation (*r*=0.8***) that was significant between sorrel weed density and dry biomass. This implies that a decrease in the number of weeds results in a decrease in the dry biomass and vice versa. (Stopps *et al*., 2011) stated that the weed is highly prevalent in acidic and infertile soils and its highly susceptible to shading.

4.4 Conclusion

Combined application of 0.2 t ha^{-1} NPK fertilizer and 2 t ha^{-1} lime with the integration of dolichos in potato systems resulted in reduced sorrel weed densities, dry biomass and lower root length. Low sorrel weed density per square metre, reduced dry biomass and lower root length were achieved in the application of both 0.2 t ha^{-1} NPK fertilizer and 2 t ha^{-1} lime with the integration of dolichos in potato systems and the effect was slightly higher during the second season. Lime reduced the soil acidity making the conditions unfavourable for sorrel weed growth. Addition of inorganic fertilizer into the soil increased the soil nutrient levels of the soil resulting in an increase in soil fertility and this hinders the germination and growth of the sorrel weed. Dolichos shared resources with the potato crop leaving little for the weed hence suppressing its growth. There was a high positive correlation between weed density and weed dry biomass.

The study recommends application of 2 t ha^{-1} lime and 0.2 t ha^{-1} NPK fertilizer, and introduction of dolichos as intercrop in potato systems for managing the sorrel weed in acid soils of Molo. This study also recommends long term research on soil amendments and legume intercrops/incorporation that can result in reduced sorrel weed growth in acidic mollic Andosols of Molo, Kenya.

CHAPTER FIVE

POTATO GROWTH, NUTRIENT UPTAKE AND YIELD AS INFLUENCED BY LIME, NPK FERTILIZER AND INTERCROPPING

Abstract

Soil fertility deterioration and increased acidity in potato growing areas have resulted in further decrease in potato growth and yields. A two-season field experiment was conducted in acidic mollic Andosols of Molo sub county, Kenya. The objective of the study was to investigate the effects of liming and NPK fertilizer application on potato growth, nutrient uptake and yield in a potato cropping system. A randomized complete block design with a split-split plot arrangement, replicated three times, was used. Compound fertilizer NPK at two levels (0 and 0.2t ha $^{-1}$) formed the main plots. Lime rates (0 and 2t ha^{-1}) were assigned to the sub-plots and cropping system (sole potato and potato/dolichos intercrop) the sub-sub plots. Lime was applied 3 weeks before planting. The results showed that plant height increased with season and fertilizer with higher plant height (73.53cm) being observed during the second season and where fertilizer was applied (76.97cm) both at 35 Days After Emergence (DAE). More shoots were obtained in the second season at 21 DAE. There was an increase in P uptake to 27.19 and 22.16 kg P ha^{-1} during the second season where there was combined application of 2t ha^{-1} lime and 0.2t ha^{-1} NPK fertilizer and sole application of 2t ha^{-1} lime under potato/dolichos intercrop, respectively. Significant ($P \leq 0.05$) increase in N uptake up to 140.73 and 146.77kg N ha^{-1} was observed where there was sole application of 0.2t ha^{-1} NPK fertilizer during the first season and combined application of 2t ha^{-1} lime and 0.2t ha^{-1} NPK fertilizer under potato/dolichos intercrop respectively. More potato tubers per plant (11) were obtained where 0.2t ha^{-1} NPK was applied during the second season under potato/dolichos intercrop. Significantly ($P \leq 0.05$) higher tuber weight (53t ha^{-1} and 51t ha^{-1}) was obtained where both 2t ha^{-1} lime and 0.2t ha^{-1} NPK were applied during the second season and under potato/dolichos intercrop respectively and 50t ha^{-1} under sole potato crop with sole 2t ha^{-1} lime in the first season. Application of both 2t ha^{-1} lime and 0.2t ha^{-1} NPK and incorporating dolichos in potato production in acid mollic Andosols of Molo is recommended for promoting potato growth and nutrient uptake and increasing yields.

5.1 Introduction

Potato is an important cash and food crop in the SSA which plays a major role in food security contributing to poverty alleviation through income generation and creation of employment in Kenya (Muthoni *et al*., 2013; Taiy, 2016). However, its production is highly constrained by low soil fertility (Komen *et al*., 2017) among other factors. Being a heavy feeder (Mugo *et al*., 2020), it has high fertilizer (N,P and K) requirement for growth and yield. Due to its shallow and poorly developed root system in relation to yield, it requires high soil nutrient levels (Mishra, 2018).

In Kenya, the potato crop is mainly produced by resource poor small holder farmers (Gitari *et al*., 2018) and its productivity is far much below the potential yield of 40 t ha^{-1} (Muthoni, 2016). Farmers need to timely apply fertilizers and in correct proportions in order to supply adequate nutrients at the proper time to achieve optimum yields of the potato crop (Mishra, 2018; Mugo *et al*., 2020). However, these farmers apply fertilizers below the recommended rates (Kiiya *et al*., 2015) due to their high costs and they barely top-dress (Nyawade, 2015). The continuous use of DAP has also shown to increase soil acidity (Muthoni, 2016).

The soils in most potato growing areas in Kenya are acidic (Komen *et al*., 2017) with soil pH of less than 5.5 and are deficient in N and P (Lelei, 2014). N and P are essential nutrients that are important in potato production supplied through inorganic fertilizers and their deficiencies results in noticeable yield losses (Musyoka *et al*., 2017). Low available P in soils is due to its adsorption to soil clays and organic matter (Opala, 2017). Available soil P is highly influenced by soil pH (Qaswar *et al*., 2020) hence application of P to low pH soils results in P fixation by Al and Fe ions (Gitari *et al*., 2018) rendering it unavailable for plant uptake. P is also highly immobile hence its uptake depends on root interception (Hill *et al*., 2015). In potato production, N and P nutrients are susceptible to leaching, immobilization and volatilization due to shallow potato rooting system (Hopkins *et al*., 2014) and high rainfall amounts in potato growing areas.

Agricultural lime is known widely as the most effective means of reducing soil acidity and increasing available soil P (Qaswar *et al*., 2020). Kisinyo *et al*. (2014b) reported that addition of lime to acidic soils increases the soil pH and available soil P. Kisinyo *et al*. (2012 and 2014a) also reported increased soil pH, available soil P and increased yields as a result of lime and P application. Increasing available soil P through liming and fertilizer application makes it available for plant uptake.

Due to exponential population growth and increased urbanization, which has resulted in decline in agricultural land, there is need to sustainably produce more food using the same or less resources to achieve food security. Intercropping is one of the integrated soil fertility management practice that is widespread among smallholder farmers (Matusso *et al*., 2014). Small holder farmers usually intercrop cereals and legumes in order to increase productivity and utilize labour per unit area of available land (Sitienei *et al*., 2017). Leguminous crops used as intercrops also play a significant role in sustainable agriculture through their ability to improve soil fertility through biological nitrogen fixation (Sitienei *et al*., 2017). The legumes used as intercrops supplies surplus nitrogen fixed to the companion crop making it available for plant uptake (Gitari *et al*., 2018). The roots of legumes also produce exudates that compete with phosphate ions for exchange sites hence solubilizing P making it available for uptake by the companion crop in the intercropping system (Sitienei *et al*., 2017). The objective of this study was to investigate the effects of liming, intercropping and NPK fertilizer application on potato growth, nutrient uptake and yield in potato cropping system.

5.2 Materials and Methods

5.2.1 Experimental Site

It is described in chapter three section 3.2.1.

5.2.2 Experimental Design and Treatments

The design and treatments of the experiment have been described in chapter three section 3.2.3.

5.2.3 Seeds

Planting materials used in the experiment have been discussed in chapter three section 3.2.4.

5.2.4 Data Collection

Six potato plants were randomly selected from the three inner rows and tagged for plant height and shoot number determination. Plant height was measured using a metre ruler from the soil surface to the tip of the actively growing central stem of the plant. The number of shoots per plant were determined by counting physically. Data for both plant height and number of shoots per plant was collected one week after emergence and thereafter weekly for four weeks.

Plant samples were taken at the mid flowering stage and at harvesting from the three inner rows and analysed for N and P concentrations. At mid flowering the most recent mature potato leaves were sampled from the tagged plants, put in well labelled khaki bags and transported to the laboratory for N and P analysis. At harvesting, nutrients uptake (N and P) was assessed by harvesting the haulms of the tagged plants which were weighed and cut into 0.05m long pieces. Tubers were dug out, weighed and two tubers randomly selected and sliced. A sample of the tubers and haulms, each weighing 500g were dried in an oven at 70°C for 72 h. The samples were ground and sieved using 1.0 mm sieve mesh for nutrient analysis. The content of nitrogen and phosphorus were determined in the digest obtained by treating plant samples with hydrogen peroxide, sulphuric acid, selenium and salicylic acid (Okalebo *et al*., 2002). Nutrient (N and P) uptake for tubers, leaves and haulms were determined as the product of tissue's dry weight and nutrient concentration and summing up the two gave the plant nutrient uptake.

Plant nutrient uptake = Haulm nutrient uptake + Tuber nutrient uptake

At physiological maturity, the tubers from the six plants were dug out and the number of tubers per plant were counted and weighed separately and the mean weight per treatment used to calculate yield in tonnes per hectare. Dolichos was harvested at physiological maturity where mature light reddish-brown pods with seeds were harvested. The fresh legume yield (kg) per subplot for each treatment was measured using weighing balance.

5.2.5 Data Analyses

Data were tested for normality using the Shapiro Wilk test at probability ≤0.05 in SAS software using proc univariate plot.

$$W = \frac{(\sum_{i=1}^{n} a_i x_{(i)})^2}{\sum_{i=1}^{n} (x_i - \overline{x})^2}$$

Data were then subjected to analysis of variance (ANOVA) using SAS software for windows 9.4 (SAS Institute, Cary, NC) using the following statistical model.

$Y_{ijklmn} = \mu + S_i + \beta_j + F_k + FS_{ik} + F\beta(S)_{ijk} + L_l + LS_{il} + LF_{kl} + LSF_{ikl} + LF\beta(S)_{ijkl} + C_m + CS_{im} + CF_{km} + CFS_{ikm} + CL_{lm} + CLS_{ilm} + CLF_{klm} + CSFL_{iklm} + \varepsilon_{ijklmn}$

Where:

Y_{ijklmn} = Overall observations, μ = Overall mean, S_i = Effect due to season, β_j = blocking effect, F_k= k^{th} Fertilizer effect, FS_{ik} = Season and fertilizer effect, $F\beta(S)_{ijk}$ = Main plot error, L_l = l^{th} liming effect, LS_{il} = liming and season effect, LF_{kl} = liming and fertilizer effect, LSF_{ikl}= liming, season and fertilizer effect, $LF\beta(S)_{ijkl}$ = Sub-plot error, C_m = Cropping effect,

CS_{im}= cropping and season effect, CF_{km} = cropping and fertilizer effect, CFS_{ikm} = cropping, fertilizer and season effect, CL_{lm} = Effect due to lime and cropping system, CLS_{ilm} = cropping, liming and season effect, CLF_{klm} = cropping, liming and fertilizer effect, $CSFL_{iklm}$ = cropping, season, fertilizer and liming effect and ε_{ijklmn} = Random error term.

Where the Fisher's protected F-test was significant, means of the main effects were separated using Tukey's honest significance test ($P<0.05$). Pearson correlation coefficient was carried out to test the significance of the relationship between plant growth and tuber yield.

5.3 Results and Discussion

5.3.1 Effects of Lime, Intercropping and NPK Fertilizer on Potato Growth

Plant height

Main effects of season and fertilizer on plant height were significant. The results showed that plant height differed significantly ($P\leq0.05$) across the seasons at 7, 14, 21, 28 and 35 days after emergence (DAE). The average plant height during the two growing seasons was higher in the second season when compared to the first season (Table 8). Application of NPK fertilizer significantly ($P\leq0.05$) affected potato plant height at 7, 14, 21, 28 and 35 DAE and ($P\leq0.05$) in DAE. Higher mean plant height was obtained where 0.2t ha^{-1} NPK fertilizer was applied in all sampling periods.

Table 8: Main effects of season and fertilizer on potato plant height in 7, 14, 21, 28 and 35 DAE in potato intercropping system in Molo, Kenya.

Plant Height					
	7 DAE	14 DAE	21 DAE	28 DAE	35 DAE
Season effect					
S1	14.10b	23.42b	38.51b	49.71b	59.94b
S2	38.55a	54.84a	60.44a	66.01a	73.53a
Fertilizer effect					
0	23.35b	33.33b	40.83b	48.29b	56.51b
0.2	29.29a	44.93a	58.10a	67.44a	76.97a
Mean	26.32	39.13	49.48	57.86	66.74
CV %	16.65	15.98	11.39	7.48	5.05
MSD	2.68	3.83	3.45	2.65	2.06

Means within a column followed by the same letter are not significantly different at $P \leq 0.05$

Key: DAE-Days After Emergence, S1-season one, S2-season two, CV-Coefficient of Variation and MSD- Minimum Significance Difference.

Fertilizer application corresponds with increased plant growth and yield. Adhikari (2014) in a study to evaluate effects of different nutrient levels on potato vegetative growth and yield, reported that plant height was significantly affected by different levels of fertilizer application and increased by 15-42 % with increase in fertilizer levels as compared to the control. He concluded that high nitrogen (N) dosage results in vigorous plant growth. Iraboneye *et al.* (2021) in his study on effects of different levels of a compound fertilizer and DAP on potato growth and yield reported that plant height was significantly affected by fertilizer levels. He concluded that NPK at the rate of 900 kg ha^{-1} increased plant height by 4% and 46% over DAP: 500 kg ha^{-1} and the control respectively.

Number of shoots per plant

The number of shoots per plant differed significantly ($P \leq 0.05$) with season at 14 and 21 DAE across the seasons (Table 9). Higher number of shoots was obtained during the second season at these sampling periods (Table 9). This concurs with the findings of Adhikari (2014) and Iraboneye *et al.* (2021) who reported that fertilizer did not have any significant effect on the number of stems on a study to evaluate effects of NPK on potato growth and yield. The number of shoots per plant is more attributed to the number of tuber eyes from which the shoots emerge. Higher number of shoots during the second season could be attributed to high soil moisture content during the season which favoured emergence of more shoots during the season.

Table 9: Season effects on number of potato shoots in 7. 14, 21, 28 and 35 DAE in potato intercropping system in Molo, Kenya

Number of Shoots					
	7 DAE	14 DAE	21 DAE	28 DAE	35 DAE
Season effect					
S1	3.22a	3.76b	4.38b	4.60a	4.60a
S2	3.39a	4.22a	4.85a	4.66a	4.76a
Mean	3.31	3.99	4.61	4.63	4.68
CV %	12.42	11.80	12.56	8.92	9.20
MSD	0.25	0.29	0.35	0.26	0.26

Means within a column followed by the same letter are not significantly different at $P \leq 0.05$

Key: DAE- Days After Emergence, S1- season 1, S2-season two, CV- Coefficient of Variation, MSD- Minimum Significance Difference.

5.3.2 Effects of Lime, Intercropping and NPK Fertilizer on N and P Uptake

The interaction effects due to fertilizer, lime and cropping system were significant ($P \leq 0.05$) for N uptake (Table 10). Significantly ($P \leq 0.05$) higher potato N uptake 146.77Kg ha^{-1} was observed under potato/dolichos intercrop with combined application of 0.2t ha^{-1} fertilizer and 2t ha^{-1} lime. N uptake in this treatment was higher compared sole potato with both fertilizer and lime and either fertilized or unfertilized treatments and those with or without lime across the cropping systems. (Table 10).

Table 10: Fertilizer, lime and intercropping system interaction effects on N uptake (Mean ± SD)

Fertilizer rate (t ha^{-1})	Lime rate (t ha^{-1})	Cropping system	N uptake (Kg ha^{-1})
0	0	P	84.01 ± 5.30ef
		PD	94.38 ± 5.38d
0	2	P	82.65 ± 9.20e
		PD	91.50 ± 8.48de
0.2	0	P	97.03 ± 9.83d
		PD	113.47 ± 10.18c
0.2	2	P	122.08 ± 20.00b
		PD	146.77 ± 27.33a
Mean	-	-	103.99
CV %	-	-	13.90
R^2	-	-	88.15

Means within a column followed by the same letter are not significantly different at $P \leq 0.05$

Key: t ha^{-1}-tonnes per hectare, Kg ha^{-1}-kilograms per hectare, P-sole potato crop, PD-Potato-Dolichos intercrop, CV-Coefficient of Variation and R^2- Coefficient of Determination.

Across the seasons and under the different intercropping systems, lime application had a significant ($P \leq 0.05$) effect on P uptake (Table 11). Application of 2 t lime ha^{-1} under the potato/dolichos intercrop resulted in significantly ($P \leq 0.05$) higher P uptake (22.16 kg P ha^{-1}) at the end of the second season. This was significantly ($P \leq 0.05$) different from results obtained from the potato sole crop with lime, and in both potato systems without lime during the second season and in both cropping systems with or without lime during the first season (Table 11).

Table 11**:** Effects of lime on P uptake under potato cropping systems for two seasons (Mean ± SD)

Season	Lime levels (t ha^{-1})	Cropping systems	P uptake (kg P ha^{-1})
1	0	P	7.59 ± 0.88e
		PD	9.48 ± 0.85d
	2	P	10.05 ± 1.47d
		PD	13.79 ± 2.21c
2	0	P	9.70 ± 0.50d
		PD	12.98 ± 0.48c
	2	P	19.81 ± 7.09b
		PD	22.16 ± 6.78a
Mean	-	-	13.19
CV %	-	-	8.53
R^2	-	-	98.79

Means within a column followed by the same letter are not significantly different at $P \leq 0.05$

Key: t ha^{-1} -tonnes per hectare, Kg ha^{-1}-kilograms per hectare, P- sole potato crop, PD- Potato-Dolichos intercrop, CV- Coefficient of Variation

Combined fertilizer and lime application had significant ($P \leq 0.05$) effects for P uptake across the two seasons (Table 12). There was significantly ($P \leq 0.05$) higher P uptake where both 0.2t NPK ha^{-1} and 2t lime ha^{-1} were applied at the end of the second season. The uptake was higher compared to similar treatment in the first season and sole application of either fertilizer or lime and also the controls in both seasons (Table 12).

Table 12: Fertilizer and lime effects on P uptake in two seasons (Mean ± SD)

Season	Fertilizer levels (t/ha)	Lime levels (t/ha)	P uptake (kg P/ha)
1	0	0	7.98 ± 1.32e
		2	10.46 ± 1.78cd
	0.2	0	9.09 ± 1.08de
		2	13.38 ± 2.68b
2	0	0	11.13 ± 1.84c
		2	14.78 ± 1.81b
	0.2	0	11.54 ± 1.86c
		2	27.19 ± 1.96a
Mean	-	-	13.19
CV %	-	-	8.53
R^2	-	-	98.79

Means within a column followed by the same letter are not significantly different at $P \leq 0.05$

Key: t ha^{-1}-tonnes per hectare, Kg P ha^{-1}-kilograms of phosphorus per hectare, CV-Coefficient of Variation.

Any practice that increases the availability of N and P nutrients in the soil will promote their uptake as well. Application of NPK fertilizer resulted in significant increase in N and P uptake. Increased N uptake under fertilization could be attributed to increase in N concentration in the soil which in return increases its mineralization (Ge *et al.*, 2018) and hence increased N uptake. High N uptake observed under liming can be explained by increased soil pH due to liming which increased soil microbial activity resulting in improved soil organic matter decomposition hence high levels of soil mineral nitrogen (Mkhonza *et al.*, 2020). Increased levels of mineral N in the soil could have influenced its uptake.

There was increased P uptake where NPK fertilizer and lime was applied. Opala (2017) in a study on effects of lime and P fertilizer application rates on maize growth in acid soil reported that fertilizer application increased P levels in the soil. Kisinyo *et al.* (2013) in a study on P sorption and lime requirements of maize growing in acid soils reported that liming increased the soil pH reducing P sorption making both the inherent and P fertilizer available for plant uptake.

Intercropping non leguminous crops with legumes is a practice that improves nutrient uptake and use efficiency without increasing fertilizer input (Gitari *et al*., 2018). Cereal legume intercrop is the most widely practised and has been promoted specifically for the complementary acquisition of N (Tang *et al*., 2021). Dolichos also has the ability to fix atmospheric N (BNF) hence replenishing soil mineral nitrogen (Sitienei *et al*., 2017). The type of intercrop used in potato cropping systems and its growth attributes is important in determining nutrient uptake (Zhang *et al*., 2016). High N uptake under potato/dolichos intercrop could be attributed to utilization of excess nitrates in the rhizosphere by the potato crop as a result of nitrogen fixed by dolichos (Sitienei *et al*., 2017). Legume canopy cover could have played an important role in nutrient uptake. High canopy cover under potato/dolichos intercrop could have resulted in increased moisture and this in return increased N and P solubilisation increasing their availability for potato uptake (Sennhenn *et al*., 2017).

Intercropping crops with different traits explore the various organic P sources in P deficient soils resulting in higher P uptake in the intercrop as compared to respective monocrops (Wang *et al*., 2014). Interaction of the roots between potato and dolichos could have also resulted in high N and P uptake. Dolichos produce root exudates which have significant influence on nutrient availability in both its rhizosphere and that of the companion crop (Hinsinger *et al*., 2011). According to Wang *et al*. (2014) phosphatases are important in cleaving phosphate bonds during organic matter degradation hence releasing P bound to organic matter into the soil. Phosphatases have high affinity for the clay colloids hence compete with phosphate ions from charged surfaces releasing P into the soil (Giles *et al*., 2017). Rhizodeposition increases the availability of P in the soil hence making it available for plant uptake and this can explain high P uptake observed under potato/dolichos intercrop (Gitari *et al*., 2018). Wang *et al*. (2014) in a study on intercropping enhances productivity and maintains most soil fertility properties than monocropping reported high P uptake in maize faba bean intercrop as compared to monocrops.

5.3.3 Effects of Lime, Intercropping and NPK Fertilizer on Potato Yield

Fertilizer application under the different cropping systems resulted in significant ($P \leq 0.05$) effects on the number of tubers per plant (Table 13). Application of 0.2 t NPK ha^{-1} under the potato/ dolichos intercrop resulted in more tubers per plant (11) which differed significantly

(P≤0.05) from 9 tubers obtained under potato sole crop and potato/dolichos intercrop without NPK fertilization and potato sole crop with NPK fertilizer (Table 13).

Table 13: Fertilizer effects on tuber yield under potato intercropping system (Mean ± SD)

Fertilizer levels ($t\ ha^{-1}$)	Cropping system	No. of tubers (Per plant)
0	P	9 ± 1.02c
	PD	9 ± 0.92bc
0.2	P	9 ± 1.57b
	PD	11 ± 1.82a
Mean	-	9.35
CV %	-	5.08
R^2	-	96.78

Means within a column followed by the same letter are not significantly different at P≤0.05

Key: $t\ ha^{-1}$-tonnes per hectare, P-sole potato crop, PD-Potato-Dolichos intercrop, CV-Coefficient of Variation and R^2- Coefficient of Determination.

The fertilizer and lime interaction had significant (P≤0.05) effects on the weight of potato tubers under the different cropping systems (Table 14). Higher tuber weight (51 $t\ ha^{-1}$) was observed where both 0.2t ha^{-1} fertilizer and 2t ha^{-1} lime were applied under sole potato and this weight was significantly (P≤0.05) different from 42 $t\ ha^{-1}$ obtained under potato/dolichos intercrop with both fertilizer and lime and from potato sole crop and potato/dolichos intercrop with either sole lime or fertilizer and from the control (Table 14).

Table 14: Fertilizer and lime interaction effects on potato tuber weight (t ha^{-1}) in potato intercropping systems in Molo, Kenya (Mean ± SD)

Fertilizer levels (t ha^{-1})	Lime levels (t ha^{-1})	Cropping system	Tuber weight (t ha^{-1})
0	0	P	36 ± 9.78d
	0	PD	31 ± 7.88f
0	2	P	34 ± 10.55ef
	2	PD	31 ± 11.06f
0.2	0	P	43 ± 12.53b
	0	PD	38 ± 11.02cd
0.2	2	P	51 ± 6.70a
	2	PD	42 ± 7.39bc
Mean	-	-	38.40
CV %	-	-	5.05
R^2	-	-	98.96

Means within a column followed by the same letter are not significantly different at $P \leq 0.05$

Key: t ha^{-1}-tonnes per hectare, P-potato sole crop, PD-Potato-Dolichos intercrop, CV-Coefficient of Variation

Increased crop productivity as a result of lime application has been reported due to positive effects of lime on soil physical, chemical and biological properties (Ameyu, 2019). Higher potato yields were obtained at the end of the second season where both lime and NPK fertilizer were applied. This can be due to the slow reaction of lime with soil attributed to the solubility and downward movement of lime with time and rainfall distribution throughout growing season (Ameyu, 2019). In a study on effects of agricultural lime on soil properties and wheat yield in acidic soils, Osundwa *et al*. (2013) reported increased wheat grain yield with lime application at the rates of 1, 1.5 and 2t ha^{-1}. In a study on interaction of lime and long-term fertilisation to increase crop yield and PUE through mediating exchangeable cations in acid soils under wheat-maize cropping system. Qaswar *et al*. (2020) reported increased maize and wheat yields where both lime at the rate of 2.5 t ha^{-1} and NPK fertilizer were applied when compared to where fertilizer alone was applied.

An increase in crop yields as a result of lime application can be attributed to the neutralisation of Al^{3+}, supply of Ca^{2+} and Mg^{+} and increasing availability of some plant nutrients like P (Alemu *et al*., 2017). Increase in soil pH due to liming also creates favourable conditions for microbial activities (Mkhonza *et al*., 2020), which improves the physico-chemical properties of the soil resulting in improved crop growth, nutrient uptake and increased yields. Application of inorganic fertilizers increases soil nutrient levels (Opala, 2017) making them readily available for plant uptake hence increasing plant growth and yield. Higher number of tubers observed under potato dolichos intercrop can be attributed to a microclimate created by dolichos due to high ground cover 47% and high soil moisture content of 21% resulting in more tubers as compared to 26% and 16% in potato sole crop (Gitari *et al*., 2018). High canopy cover in potato/dolichos cropping system intercepts light resulting in lower soil temperatures (19.9°C) that favour tuber initiation and translocation of food from haulms to tubers compared to 22.8°C in sole crop (Kim *et al*., 2017)

5.3.4 Correlation between plant growth and tuber yields

The Pearson's correlation coefficient analysis showed that, the number of tubers per plant were positively correlated with P uptake (r=0.65), plant height (r=0.65) and number of shoots (r=0.49) (Table 15). Potato tuber weight had a positive correlation with the number of tubers (r=0.57), P uptake (r=0.55), plant height (r=0.74) and number of shoots (r=0.39) (Table 15). Vegetative growth determines the potato tubers to be produced. The Pearson's correlation coefficient analysis showed that, plant height was positively correlated with number of tubers and tuber weight. This means that, the higher potato growth the more the number of tubers and tuber weight. The number of shoots had a positive but fair correlation with the number of tubers and tuber weight. This indicates that more shoots result in an increase in tuber number and weight. P uptake was strongly correlated to the tuber number and weight. This suggests that an increase in P uptake results in increased potato growth which translates to higher tuber yields. Increased nutrient uptake enhances the photosynthetic traits of plant leaves, stomatal conductance, transpiration rate and chlorophyll content, which results in increased yields (Guo *et al*., 2021). Adhikari (2014) and Iraboneye *et al.* (2020) reported potato tuber yield increase was associated with increase in the plant height as a result of NPK fertilizer application. In a study on effect of fertilizer manure and lime on growth and yield of Boro rice in acidic red soil Mitu *et al*. (2017) reported a positive correlation (r=0.80) between plant height and yield. In a study on response of nutrient uptake, photosynthesis and yield of tomato to biochar addition under reduced nitrogen application, Guo *et al.* (2021) reported increased tomato yield as a result of increased nutrient uptake.

Table 15: Correlation between yield and yield components in potato intercropping system in Molo, Kenya

	No. of tubers	Tuber weight
No. of tubers		0.57***
P uptake	0.65***	0.55***
Plant height	0.65***	0.74***
No. of shoots	0.49***	0.39**

(** and ***) shows significance at P≤0.01 and P≤0.001 respectively

5.3.5 Land Equivalent Ratio (LER)

Land Equivalent Ratio is the sum of the fractions of the intercropped yields divided by the sole-crop yield and it is important in evaluating the efficiency of intercropping systems (Dariush *et al*., 2006; Morales-Rosales & Franco-Mora, 2009). It was calculated using the formula;

LER = ∑ (Ypi/Ymi), where Yp is the yield of each crop or variety in the intercrop, and Ym is the yield of each crop or variety in the sole crop. For each crop (i) a ratio is calculated to determine the partial LER for that crop, then the partial LERs are summed to give the total LER for the intercrop (Dariush *et al*., 2006; Morales-Rosales & Franco-Mora, 2009). A LER value of 1.0, indicates no difference in yield between the intercrop and the collection of monocultures. Any value greater than 1.0 indicates a yield advantage for intercrop. A LER of 1.2 for example, indicates that the area planted to monocultures would need to be 20% greater than the area planted to intercrop for the two to produce the same combined yields. A total LER of higher that 1.0 indicates the presence of positive interferences among the varieties or crops components of the mixture, and also mean that any negative interspecific interference that exists in the mixture is not as intensive as the intraspecific interference that exists in the monoculture (Dariush *et al*., 2006; Morales-Rosales & Franco-Mora, 2009). The potato LER obtained in this study is less than 1 (Table 16). The dolichos LER was not determined because sole dolichos was not included in the experiment. The study shows that sole potato is not viable and recommends inclusion of sole dolichos in future studies in order to have a LER comparison between the two cropping systems.

Table 16: Land Equivalent Ratio in potato intercropping system in Molo, Kenya

Cropping system	Potato yield (t ha^{-1})	Dolichos yield (t ha^{-1})	Total
Potato sole crop	41.1076	-	-
Potato/dolichos	35.6893	11.3497	-
LER	0.8682		

Key: t ha^{-1}- tonnes per hectare, LER- Land Equivalent Ratio

5.4 Conclusion

Potato plant height increased with season and application of 0.2 t ha^{-1} NPK fertilizer. The number of shoots were only affected by season. Combined application of 0.2 t ha^{-1} NPK fertilizer and 2 t ha^{-1} lime, and the integration of dolichos in potato cropping system increased N uptake by the potato crop. Combined application of 0.2 t ha^{-1} NPK fertilizer and 2 t ha^{-1} lime, and sole application of 0.2 t ha^{-1} NPK fertilizer under the potato/dolichos intercrop increased P uptake by the potato crop in the second season, respectively. More potato tubers per plant were obtained under potato/dolichos intercrop with 0.2 t ha^{-1} NPK fertilizer. Higher tuber weight was obtained where there was combined application of 0.2 t ha^{-1} NPK fertilizer and 2 t ha^{-1} lime under the potato sole crop.

Agricultural lime is important in increasing the soil pH hence increasing the availability of nutrients especially P in the soil for plant uptake and this translates to improved yields. Increase in soil pH also creates unfavourable conditions for the growth of the sorrel weed. Lime also avails both calcium and magnesium in the soil for plant use. Use of inorganic fertilizers is important in timely application of nutrients and in adequate amounts. Inorganic fertilizers are also important in replenishing mined nutrients in the soil which are important for plant growth and improving yields. Increasing the soil fertility levels is also important in the reduction of sorrel weed infestation since the weed flourish in poor soils. Dolichos is a multipurpose legume that can be utilized as food (green pods, leaves and seeds), green manure and livestock feed. It has a high ground cover hence competes with weeds for resources reducing their germination and growth. Dolichos has the ability to fix atmospheric N hence improving soil fertility. It also does not compete with its companion crop for nutrients. There was a high positive correlation between plant height and tuber yield.

The study recommends application of 2 t ha^{-1} lime and 0.2 t ha^{-1} NPK fertilizer, and introduction of dolichos as intercrop in potato systems for improved potato growth, nutrient uptake and yield. There is also need for a long-term study on the different amendments together with legume incorporation that can result in improved potato growth, nutrient uptake and yield in acidic mollic Andosols of Molo, Kenya.

CHAPTER SIX

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1 Discussion

There was a reduction in soil pH with addition of sole NPK fertilizer. Addition of lime to the acidic mollic Andosol resulted in a slight increase in soil pH at the end of the second season. Changes in soil pH upon lime application takes place with time with changes being more pronounced during the second year after lime application (Kisinyo, 2016). Agricultural lime is important in hydrolysing acidic cations (Al^{3+} and Fe^{2+}) in the soil resulting in increased soil pH (Otieno *et al*., 2018).

Combined application of NPK fertilizer and lime resulted in increased total soil nitrogen. This can be attributed to release of nitrates from NPK and CAN fertilizer applied into the soil during planting and topdressing. Lime addition could have resulted in an increase in soil pH which created favourable conditions for microbial activities including decomposition and biological nitrogen fixation by Dolichos resulting in increased total soil N. Higher total soil N during the second season under potato/dolichos intercrop is attributed to the ability of dolichos to fix atmospheric N.

Higher available soil P contents observed under NPK fertilisation, liming and dolichos integration could be attributed to the release of phosphate ions from NPK fertilizer applied (Opala, 2017) and those fixed by acidic cations as a result of lime addition. Dolichos could have also contributed to increased available soil P due to its root exudates which aid in cleaving phosphate bonds hence releasing P into the soil (Gitari *et al*., 2018).

Sheep sorrel weed is characterised by being abundant in poor and acidic soils. Addition of both lime and NPK fertilizer resulted in reduced sorrel weed density, weed biomass and weed root length. Integration of dolichos in potato cropping system with either NPK fertilizer or lime application also resulted in reduced sorrel weed infestation since its highly susceptible to shading. Sorrel weed grows well in acidic conditions Lime application resulted in increased soil pH hence creating unfavourable conditions for growth of the sorrel weed (Stopps *et al*., 2011).

Potato growth was affected by season and fertilisation with higher plant height being observed during the second season and where NPK fertilizer was applied. This can be related to previous studies that reported increased plant growth due to fertilizer application. The number of shoots were affected by the season. This could be attributed to the differences in the rainfall patterns across the seasons. Higher number of shoots during the second season can be due to high amount of rainfall during this season compared to the first season.

Increased P and N uptake due to NPK fertilizer and lime application and dolichos integration can be attributed to the ability of the factors to make the nutrients available in the soil for plant uptake. Lime, NPK fertilizer and dolichos increased the availability of N and P in the soil and this resulted in increased uptake of the elements by the potato crop (Gitari *et al*., 2018).

The number of tubers per plant were highly affected by combined application of NPK fertilizer and lime. More tubers were obtained under potato/dolichos intercrop with combined application of NPK fertilizer and lime. More tubers were also observed during the second season compared to the first season. The weight of tubers was influenced by combined application of NPK fertilizer and lime across the seasons with higher tuber weight during the second season. Under the cropping system, higher tuber weight was obtained in the potato sole crop where there was combined application of both lime and NPK fertilizer.

6.2 Conclusions

i. Lime application at the rate of 2 t ha^{-1} causes a slight increase in soil pH in two growing seasons. Sole application of NPK fertilizer (0.2 t ha^{-1}) increases soil acidity. The availability of P in soil is influenced by pH. Combined application of 0.2 t ha^{-1} NPK fertilizer and 2 t ha^{-1} lime in potato systems increase soil available P, with greater evidence in the second growing season. Sole NPK fertilizer application increases total soil N across growing seasons and cropping systems.

ii. Application of lime (2 t ha^{-1}) and NPK fertilizer (0.2 t ha^{-1}), and intercropping potato with lablab reduces sorrel weed infestation in acid soils of Molo sub-County Kenya.

iii. Application of lime (2 t ha^{-1}) and NPK fertilizer (0.2 t ha^{-1}), and intercropping potato with lablab improves uptake of N and P by potato and results in improved growth and yields. in acid soils of Molo sub-County Kenya.

6.3 Recommendations

The study recommends that smallholder farmers in Molo subcounty;

i. Apply 2t ha^{-1} lime and 0.2t ha^{-1} NPK fertilizer and integrate dolichos as an intercrop into potato intercropping system to improve the chemical properties of the acid soils of Molo sub- County, Kenya.

ii. Integrate lablab as an intercrop and apply 2t ha^{-1} lime and 0.2 t ha^{-1} NPK fertilizer in order to reducing sorrel weed infestation in potato in the acid soils of Molo, Kenya.

iii. Apply 2 t ha^{-1} lime and 0.2t ha^{-1} NPK fertilizer and integrate lablab as an intercrop for improvement in potato growth, nutrient uptake and yield in acid soils of Molo sub-County, Kenya.

Further studies are recommended on the following;

i. Long term studies on soil amendments and inorganic fertilizers at different levels to establish the changes in soil chemical properties, sheep sorrel weed growth and performance of potato in acid soils.

ii. Long term studies on effects of legume incorporation on soil chemical changes and sheep sorrel weed growth.

iii. Alternative cover crops in potato intercropping systems under similar conditions.

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APPENDICES

Appendix I: ANOVA Table for Chapter Three

Analysis of Variance for soil chemical properties

Source of Variation	DF	pH	Total N	Available P
Replicate (Rep)	4	0.0161	0.0012	1.4635
Season (Ssn)	1	0.1587*	0.0006	3193.1718***
Fertiliser (Fert)	1	0.0784*	0.0403**	152.2968**
Ssn × Fert	1	0.0120	0.0006	16.9218
Rep × Fert (Ssn) (Ea)	4	0.0096	0.0011	2.7343
CV (%)	-	2.2232	14.2959	8.2895
Lime	1	0.5250***	0.0063**	68.8802***
Ssn × Lime	1	0.2160**	0.0000	1.5052
Fert × Lime	1	0.0040	0.0023*	68.8802***
Ssn × Fert × Lime	1	0.0016	0.0002	8.7552*
Rep × Fert × Lime (Ssn) (Eb)	8	0.0104	0.0003	1.2239
CV (%)	-	2.3147	7.8210	5.5460
Crps	1	0.0033	0.0013*	0.6302
Ssn × Crps	1	0.0056	0.0000	1.1718
Fert × Crps	1	0.0010	0.0004	0.6302
Ssn × Fert × Crps	1	0.0014	0.0011*	2.7552
Lime × Crps	1	0.0024	0.0001	1.8802
Ssn × Lime × Crps	1	0.0044	0.0005	11.5052***
Fert × Lime × Crps	1	0.0005	0.0004	6.3802**
Ssn × Fert × Lime × Crps	1	0.0261	0.0004	26.2552***
Error (Ec)	16	0.0060	0.0001	0.7448
CV (%)	-	1.7560	5.7846	4.3263
R^2	-	92.7016	95.5639	99.6690

(*, ** and ***) significance at 0.05, 0.01 and 0.001 respectively.

Appendix II: ANOVA Table for Chapter Four

Analysis of Variance for Sorrel weed growth

Source of Variation	DF	Weed No.	Weed weight	Weed root length
Replicate (Rep)	4	302.45	1523.95	2560.97
Season (Ssn)	1	7032.52*	5135084***	388522.84**
Fertiliser (Fert)	1	19886.02**	1258380.71***	467624.80**
Ssn×Fert	1	99.19	190500.66**	5242.13
Rep×Fert (Ssn) (Main Plot Error)	4	465.29	3363.73	7682.34
CV (%)	-	32.07		21.26
Lime	1	19561.68**	2732976.90***	545681.16***
Ssn×Lime	1	325.52	704678.67***	1365.12
Fert×Lime	1	3088.02*	100973.63**	170422.63***
Ssn×Fert×Lime	1	825.02	277.10	10643.96
Rep×Fert×Lime (Ssn) (Sub Plot Error)	8	508.25	2695.18	2466.67
CV (%)	-	33.83		12.05
Crps	1	3250.52***	24769.95***	13411.44**
Ssn×Crps	1	188.02	103409.83***	6727.96**
Fert×Crps	1	760.02**	148.509	1787.30
Ssn×Fert×Crps	1	35.02	13259.10**	3990.18*
Lime×Crps	1	927.52**	49636.38***	2226.32
Ssn×Lime×Crps	1	3.52	15923.18**	3033.72*
Fert×Lime×Crps	1	172.52	1195.30	2253.65
Ssn×Fert×Lime×Crps	1	487.69*	6857.62*	4020.14*
Error	16	78.60	1567.98	655.72
CV (%)	-	13.18	5.45	6.21
R^2	-	98.06	99.76	99.38

(*, ** and ***) significance at P≤ 0.05, 0.01 and 0.001 respectively.

Appendix III: ANOVA Tables for Chapter Five

a) Analysis of Variance table for plant height (cm)

Plant height						
Source of variation	Df	7 DAE	14 DAE	21 DAE	28 DAE	35 DAE
Replicate (Rep)	4	85.83	66.3	65.71	15.8	21.24
Season (Ssn)	1	7175.10***	11846.91***	5768.47***	3184.04***	2216.39***
Fertilizer (Fert)	1	424.23**	1612.75***	3569.72***	4400.67***	5027.23***
Ssn × Fert	1	79.83	98.53	75.35	61.7	30.19
Rep × Fert (Ssn) (Ea)	4	14.8	92.97	108.71	182.23	165.75
CV (%)	-	14.61	24.64	21.17	23.33	19.29
Lime	1	43.32	134.84	85.17	5.92	3.02
Lime × Ssn	1	63.3	88.64	39.85	43.4	12.27
Lime × Fert	1	3.02	1.13	1.25	15.98	2.94
Lime × Ssn × Fert	1	0.61	0.14	0.24	17.09	39.55
Lime × Rep × Fert (Ssn) (Ea)	8	41.75	93.82	108.65	70.89	49.62
CV (%)	-	24.55	24.75	21.07	14.55	10.55
Cropping system (Crps)	1	4.43	0.55	4.31	0.68	0.49
Crps × Ssn	1	7.6	15.08	14.54	68.35	35.93
Crps × Fert	1	28.37	137.87	124.55	114.98	42.04
Crps × Ssn × Fert	1	16.92	41.46	67.97	0.32	0.56
Crps × Lime	1	6.02	0.27	12.36	2.69	0.43
Crps × Ssn × Lime	1	18.9	14.07	25.17	18.38	16.58
Crps × Fert × Lime	1	0.79	0.36	2.06	15.78	2.46
Crps × Ssn × Fert × Lime	1	0.65	2.75	9.27	5.84	1.16
Error	16	19.2	39.12	31.79	18.74	11.37
CV (%)	-	16.65	15.98	11.39	7.48	5.05
R^2	-	96.55	96.09	95.74	96.89	97.93

(*, ** and ***) significance at 0.05, 0.01 and 0.001 respectively

b) Analysis of Variance for the number of shoots

Number of Shoots						
Source of variation	Df	7 DAE	14 DAE	21 DAE	28 DAE	35 DAE
Replicate (Rep)	4	0.64	0.63	0.79	1.79	1.30
Season (Ssn)	1	0.34	2.45*	2.75*	0.04	0.29
Fertilizer (Fert)	1	0.77	0.11	0.95	0.56	0.62
Ssn × Fert	1	0.09	1.26	0.60	0.47	0.78
Rep × Fert (Ssn) (Ea)	4	0.18	0.23	0.30	0.31	0.34
CV (%)	-	12.82	12.02	11.88	12.00	12.46
Lime	1	0.04	0.38	0.01	0.02	0.03
Lime × Ssn	1	0.03	0.26	0.04	0.33	0.06
Lime × Fert	1	0.35	0.49	0.00	0.05	0.07
Lime × Ssn × Fert	1	0.04	0.10	0.11	0.00	0.00
Lime × Rep × Fert (Ssn) (Eb)	8	0.47	0.43	0.15	0.10	0.06
CV (%)	-	20.71	16.43	8.40	6.82	5.23
Cropping system (Crps)	1	0.04	0.03	0.27	0.00	0.08
Crps × Ssn	1	0.00	0.07	0.27	0.04	0.02
Crps × Fert	1	0.07	0.67	0.92	0.02	0.22
Crps × Ssn × Fert	1	0.09	0.19	0.33	0.04	0.18
Crps × Lime	1	0.01	0.04	0.00	0.15	0.02
Crps × Ssn × Lime	1	0.01	0.08	0.00	0.02	0.16
Crps × Fert × Lime	1	0.07	0.01	0.12	0.00	0.01
Crps ×Ssn × Fert × Lime	1	0.01	0.01	0.00	0.02	0.19
Error	16	0.17	0.22	0.34	0.17	0.06
CV (%)	-	12.42	11.80	12.56	8.92	9.20
R^2	-	78.17	84.29	74.83	86.12	85.08

(*, ** and ***) significance at 0.05, 0.01 and 0.001 respectively

c) Analysis of Variance for potato nutrient uptake

Source of Variation	DF	N uptake	P uptake
Replicate (Rep)	4	228.5388	0.9304
Season (Ssn)	1	338.5125	422.7501***
Fertiliser (Fert)	1	12061.5332**	212.8998***
Ssn × Fert	1	1368.8556	57.9701**
Rep × Fert (Ssn) (Ea)	4	268.7261	1.4224
CV (%)	-	15.7644	9.0386
Lime	1	2195.5133*	509.2776***
Ssn × Lime	1	0.1838	117.1935***
Fert × Lime	1	2937.9746*	143.1407***
Ssn × Fert × Lime	1	119.9853	77.6989***
Rep × Fert × Lime (Ssn) (Eb)	8	407.1801	1.8821
CV (%)	-	19.4051	10.3974
Crps	1	2732.3463***	180.44***
Ssn × Crps	1	12.9273	0.0001
Fert × Crps	1	359.9813***	0.0729
Ssn × Fert × Crps	1	209.3763**	0.2174
Lime × Crps	1	33.9865	0.6371
Ssn × Lime × Crps	1	8.2585	5.8311**
Fert × Lime × Crps	1	71.8586*	0.4163
Ssn × Fert × Lime × Crps	1	16.4854	0.7575
Error (Ec)	16	15.1630	0.5284
CV (%)	-	3.7447	5.5090
R^2	-	99.1396	99.4961

(*, ** and ***) significance at P≤ 0.05, 0.01 and 0.001 respectively.

d) Analysis of Variance for Potato yield

Source of variation	Df	No. of tubers	Tuber weight (t ha^{-1})
Replicate (Rep)	4	0.60	3.99
Season (Ssn)	1	45.12**	3566.45***
Fertiliser (Fert)	1	17.21**	1268.59***
Fert × Ssn	1	11.08*	4.54
Rep × Fert (Ssn) (Main plot error)	4	0.79	2.29
CV (%)	-	9.51	3.94
Lime	1	0.05	68.66**
Lime × Ssn	1	0.14	22.84*
Lime × Fert	1	0.01	159.53***
Lime × Fert × Ssn	1	5.11	121.11***
Lime × Rep × Fert (Ssn) (sub plot error)	8	0.61	3.23
CV (%)	-	8.35	4.68
Cropping system (Crps)	1	7.04***	352.30***
Crps × Ssn	1	1.85**	2.65
Crps × Fert	1	3.49***	32.68**
Crps × Ssn ×Fert	1	0.01	0.21
Crps × lime	1	1.74*	8.64
Crps × Ssn × lime	1	1.16*	17.12*
Crps × Fert × lime	1	0.00	44.60**
Crps × Ssn × Fert ×lime	1	4.00***	0.12
Error	16	0.22	3.76
CV (%)	-	5.08	5.05
R^2	-	96.78	98.96

(*, ** and ***) significance at P≤ 0.05, 0.01 and 0.001 respectively.

Appendix IV: SAS Codes for Chapter Three

```
DATA YIELD;
INPUT SSN REP $ FERT $ CRPS $ LIME $ pH SN SP;
CARDS;



PROC PRINT;
PROC GLM;
CLASS SSN   REP FERT LIME CRPS;
MODEL pH SN SP = SSN REP(SSN)FERT SSN*FERT REP*FERT(SSN) LIME
LIME*SSN LIME*FERT LIME*SSN*FERT REP*LIME*FERT(SSN) CRPS CRPS*SSN
CRPS*FERT CRPS*FERT*SSN CRPS*LIME CRPS*LIME*SSN CRPS*FERT*LIME
CRPS*FERT*LIME*SSN/ss4;
TEST H=FERT SSN FERT*SSN E=REP*FERT(SSN);
TEST H=LIME LIME*SSN LIME*FERT LIME*SSN*FERT E=REP*LIME*FERT(SSN);
LSMEANS SSN FERT FERT*SSN/pdiff STDERR LINES ADJUST=TUKEY;
LSMEANS LIME LIME*SSN LIME*FERT LIME*SSN*FERT/pdiff STDERR LINES
ADJUST=TUKEY;
LSMEANS CRPS CRPS*SSN FERT*CRPS LIME*CRPS CRPS*SSN*FERT
SSN*LIME*CRPS FERT*LIME*CRPS CRPS*SSN*FERT*LIME/pdiff STDERR LINES
ADJUST=TUKEY;
run;
```

Appendix V: Chapter Four SAS Codes

```
DATA SORREL WEED;
INPUT SSN REP $ FERT $ CRPS $ LIME $ DENSITY BIOMS RTLT;
CARDS;



PROC PRINT;
PROC GLM;
CLASS SSN   REP FERT LIME CRPS;
MODEL DENSITY BIOMS RTLT = SSN REP(SSN)FERT SSN*FERT REP*FERT(SSN)
LIME LIME*SSN LIME*FERT LIME*SSN*FERT REP*LIME*FERT(SSN) CRPS
CRPS*SSN CRPS*FERT CRPS*FERT*SSN CRPS*LIME CRPS*LIME*SSN
CRPS*FERT*LIME CRPS*FERT*LIME*SSN/ss4;
TEST H=FERT SSN FERT*SSN E=REP*FERT(SSN);
TEST H=LIME LIME*SSN LIME*FERT LIME*SSN*FERT E=REP*LIME*FERT(SSN);
LSMEANS SSN FERT FERT*SSN/pdiff STDERR LINES ADJUST=TUKEY;
LSMEANS LIME LIME*SSN LIME*FERT LIME*SSN*FERT/pdiff STDERR LINES
ADJUST=TUKEY;
LSMEANS CRPS CRPS*SSN FERT*CRPS LIME*CRPS CRPS*SSN*FERT
SSN*LIME*CRPS FERT*LIME*CRPS CRPS*SSN*FERT*LIME/pdiff STDERR LINES
ADJUST=TUKEY;
run;
```

Appendix VI: Chapter Five SAS Codes

a) SAS CODES FOR PLANT HEIGHT ANALYSES

```
DATA HEIGHT;
INPUT SSN REP $ FERT $ CRPS $ LIME $ HT1 HT2 HT3 HT4 HT5;
CARDS;



PROC PRINT;
PROC GLM;
CLASS SSN  REP FERT LIME CRPS;
MODEL HT1 HT2 HT3 HT4 HT5= SSN REP(SSN)FERT SSN*FERT REP*FERT(SSN)
LIME LIME*SSN LIME*FERT LIME*SSN*FERT REP*LIME*FERT(SSN) CRPS
CRPS*SSN CRPS*FERT CRPS*FERT*SSN CRPS*LIME CRPS*LIME*SSN
CRPS*FERT*LIME CRPS*FERT*LIME*SSN/ss4;
TEST H=FERT SSN FERT*SSN E=REP*FERT(SSN);
TEST H=LIME LIME*SSN LIME*FERT LIME*SSN*FERT E=REP*LIME*FERT(SSN);
LSMEANS SSN FERT FERT*SSN/pdiff STDERR LINES ADJUST=TUKEY;
LSMEANS LIME LIME*SSN LIME*FERT LIME*SSN*FERT/pdiff STDERR LINES
ADJUST=TUKEY;
LSMEANS CRPS CRPS*SSN FERT*CRPS LIME*CRPS CRPS*SSN*FERT
SSN*LIME*CRPS FERT*LIME*CRPS CRPS*SSN*FERT*LIME/pdiff STDERR LINES
ADJUST=TUKEY;
run;
```

b) SAS CODES FOR SHOOT NUMBER ANALYSES

```
DATA SHOOTS;
INPUT SSN REP $ FERT $ CRPS $ LIME $ ST1 ST2 ST3 ST4 ST5;
CARDS;



PROC PRINT;
PROC GLM;
CLASS SSN  REP FERT LIME CRPS;
MODEL ST1 ST2 ST3 ST4 ST5= SSN REP(SSN)FERT SSN*FERT REP*FERT(SSN)
LIME LIME*SSN LIME*FERT LIME*SSN*FERT REP*LIME*FERT(SSN) CRPS
CRPS*SSN CRPS*FERT CRPS*FERT*SSN CRPS*LIME CRPS*LIME*SSN
CRPS*FERT*LIME CRPS*FERT*LIME*SSN/ss4;
TEST H=FERT SSN FERT*SSN E=REP*FERT(SSN);
TEST H=LIME LIME*SSN LIME*FERT LIME*SSN*FERT E=REP*LIME*FERT(SSN);
LSMEANS SSN FERT FERT*SSN/pdiff STDERR LINES ADJUST=TUKEY;
LSMEANS LIME LIME*SSN LIME*FERT LIME*SSN*FERT/pdiff STDERR LINES
ADJUST=TUKEY;
LSMEANS CRPS CRPS*SSN FERT*CRPS LIME*CRPS CRPS*SSN*FERT
SSN*LIME*CRPS FERT*LIME*CRPS CRPS*SSN*FERT*LIME/pdiff STDERR LINES
ADJUST=TUKEY;
run;
```

c) SAS CODES FOR NUTRIENT UPTAKE AND YIELD ANALYSES

```
DATA YIELD;
INPUT SSN REP $ FERT $ CRPS $ LIME $ NUP PUP TNO TWT;
CARDS;



PROC PRINT;
PROC GLM;
CLASS SSN   REP FERT LIME CRPS;
MODEL NUP PUP TNO TWT = SSN REP(SSN)FERT SSN*FERT REP*FERT(SSN)
LIME LIME*SSN LIME*FERT LIME*SSN*FERT REP*LIME*FERT(SSN) CRPS
CRPS*SSN CRPS*FERT CRPS*FERT*SSN CRPS*LIME CRPS*LIME*SSN
CRPS*FERT*LIME CRPS*FERT*LIME*SSN/ss4;
TEST H=FERT SSN FERT*SSN E=REP*FERT(SSN);
TEST H=LIME LIME*SSN LIME*FERT LIME*SSN*FERT E=REP*LIME*FERT(SSN);
LSMEANS SSN FERT FERT*SSN/pdiff STDERR LINES ADJUST=TUKEY;
LSMEANS LIME LIME*SSN LIME*FERT LIME*SSN*FERT/pdiff STDERR LINES
ADJUST=TUKEY;
LSMEANS CRPS CRPS*SSN FERT*CRPS LIME*CRPS CRPS*SSN*FERT
SSN*LIME*CRPS FERT*LIME*CRPS CRPS*SSN*FERT*LIME/pdiff STDERR LINES
ADJUST=TUKEY;
run;
```

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Appendix VIII: Publication

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Full Length Research Paper

Effects of lime, NPK fertilizer and intercropping on selected properties of an acid mollic andosol in potato (*solanum tuberosum*) production systems

Naom K. Mose*, Joyce J. Lelei and Josephine P. Ouma

Department of Crops, Horticulture and Soils, Egerton University, P. O. Box 536-20115 Egerton, Njoro, Kenya.

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This study investigated the effects of intercropping, liming, and NPK fertilizer application on soil pH, available soil phosphorus (P), and total soil nitrogen (N) in potato production system during a two season's field experiment in Molo sub-county, Kenya. A randomized complete block design with a split-split plot arrangement of treatments and three replicates was used. Main plot factors were NPK fertilizer levels (0 and 0.2 t ha^{-1}). Lime rates (0 and 2 t ha^{-1}) formed the sub-plots and cropping system (sole potato and Potato-Dolichos intercrop) the sub-sub plots. Application of lime increased the soil pH by 0.34 over the control. Sole NPK fertilizer application reduced the soil pH by 2% when compared to the control. Combined application of NPK fertilizer with lime increased soil available P by 6.5, 8 and 6 mg kg^{-1}, and 20.41, 3.91 and 3.58 mg kg^{-1} in the first and second season over the control, sole lime and sole fertilizer application, respectively. Application of NPK fertilizer under the Potato-Dolichos intercrop increased the total soil N by 0.08% over the control. The study concluded that intercropping, application of lime and NPK fertilizer to mollic Andosols of Molo Kenya is important in increasing soil pH, available P and total N.

Key words: Available P, dolichos, lime, NPK fertilizer, pH, total N.