EVALUATION OF SOIL FERTILITY STATUS AND POTATO (*Solanum tuberosum* L.) RESPONSE TO FERTILIZERS IN CENTRAL KENYA HIGHLAND

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A THESIS SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY IN SOIL SCIENCE

DEPARTMENT OF LAND RESOURCE MANAGEMENT AND AGRICULTURAL TECHNOLOGY

FACULTY OF AGRICULTURE

UNIVERSITY OF NAIROBI

2022

DECLARATION

This thesis is my original work and has not been submitted for the award of a degree in any other University.

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DEDICATION

To my parents Michael Mugo and Annet Wanjiru, for love and support. Still remember analogy created early in my education "I am the driver and your mother is the co-driver, if you wish to quit education just alert the co-driver and I will make a stop" I chose not to alight.

To Prof. Elmar Schulte-Gelderman for his desire to see his staff prosper.

To Prof. Nancy N. Karanja the push you gave me came when it was needed most I can't thank you more.

ACKNOWLEDGEMENT

I am grateful to Prof. Elmar Schulte-Gerdermann for giving me this opportunity, and for your continued guidance and support throughout all the research activities. Much regards to Prof. Nancy Karanja, you are a centerpiece to all this work, your way to guide, encourage, and open up minds is incomparable to none. Prof. Charles Gachene, your advice, comments and suggestions always opened up the unseen gaps. Am also grateful to Prof Klaus Dittert for your advice and support.

Dr. Harun Gitari, Dr. Shadrack Nyawade and My 'brother' Elly Ouma you offered helpful comments, advice mentorship and encouragement during manuscript publication process and thesis writing. I am also indebted to Susanne Koch, Ulrike Kierbaum, Kirsten Fladung, John Kimotho, Ferdinand Anyika, Herman Simindi and Beatrice Oucho for their technical support. The farmers who voluntarily provided information, land and routine husbandry for this study are highly acknowledged. I hold with high regard the support and love accorded by family members; especially, the immediate family members. I also recognize friends whose advice inspired this work: Dr. Monica Parker, Dr. Kalpana Sharma, Dr. Dinah Borus, Abigail Ngugi, Bruce Ochieng, Caroline Bett and Benson Kisinga.

The Department of LARMAT offered a great environment and critic to the study. I acknowledge the International Potato Center for supporting this study with the funds from the Federal Ministry for Economic Cooperation and Development (BMZ) of Germany, Consultative Group for International Agricultural Research (CGIAR) through Research Program on Roots, Tubers and Bananas (RTB).

Above all, I thank the Almighty God for the immeasurable love, protection and guidance throughout this journey.

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LIST OF ABBREVIATIONS AND ACRONYMS

AE : Agronomic Efficiency

AEZ : Agro-Ecological Zone

ANOVA : Analysis of Variance

CAN : Calcium Ammonium Nitrate

CEC : Cation exchange capacity

CGIAR : Consultative Group for International Agricultural Research

CIP : International Potato Center

DAP : Di Ammonium Phosphate

DAE : Days after emergence

DM : Dry Matter

DSSAT : Decision Support System for Agro-technology Transfer

EFMA : European Fertilizer Manufacturers' Association

EY : Environmental Yield

FAO : Food and Agricultural Organization

FAOSTAT : Food and Agricultural Organization Statistics

GPS : Global Position System

HSD : Honest Significant Difference

H_2SO_4 : Sulphuric Acid

ICP-OES : Inductively Coupled Plasma-Optical Emission Spectrometry

LAI : Leaf Area Index

LH : Lower Highland

KCl : Potasium Chloride

Masl : Meters above sea level

MI : Mavuno Improved

MoALF : The Kenya Ministry of Agriculture, Livestock and Fisheries

MRV : Mavuno Root tuber and vegetables

NH_4^+ : N Ammonium Nitrogen

NO_3^- :N Nitrate Nitrogen

QUEFTS : Quantitative Evaluation of Fertility of Tropical Soils

SD : Standard Deviation

SOC : Soil Organic Carbon

SOM : Soil Organic Matter

SSP : Single supper phosphates

TSP : Triple supper phosphates

UH : Upper Highland

UM : Upper Midland

GENERAL ABSTRACT

Increasing the low potato productivity due to declining soil fertility in Kenya requires an understanding of fertility status and potato response to site-specific fertilizer formulations.

This study was conducted in central Kenya highland; Meru and Nyandarua regions with the objectives as follows: i) identify limiting nutrients to potato production ii) determine response to the addition of the limiting nutrients, and iii) evaluate the effect of potato fertilizer blend(s) on yield of the potato crop. Soil and potato nutrient content were determined using inductively coupled plasma-optical emission spectrometry (ICP-OES) procedures and grouped into adequacy levels. Leaf area index (LAI) and aboveground biomass were determined during flowering and tuber bulking growth stages from the experimental trial. Tuber yields were determined during the bulking stage and at full maturity. Harvest index and nutrient use efficiency were estimated for the experimental trials. Cluster and factor analyses were performed on survey data while generalized linear models were used for data from the field trials using R software version 2.2.3. Means were separated using Tukey's Honest Significant Difference (HSD) at ($p \leq 0.05$). Pearson correlation and linear regression analyses were applied to determine the relationship between the measured variables. Soils from both Meru and Nyandarua with nutrient contents below critical levels constituted 66% and 20% for N, 46% and 85% for P, 67% and 31% for S, 9% and 51% for Cu, and 87% and 80% for B respectively. Subsequently, low tissue nutrient concentrations were observed for N, P, K, and S elements. A reduction in potato yields was observed when specific nutrients were omitted as follows; 9 t ha^{-1} when N was omitted and 3 t ha^{-1} when P was omitted. DAP fertilizer exerted the most significant effect on potato haulm (16 g $plant^{-1}$) on the variety Sherekea. The effect was also observed on potato yield in which 29.2 t ha^{-1} was recorded with DAP, and a yield of 26.6 t ha^{-1} with the application of new Mavuno on variety Sherekea. A significant positive interaction ($P < 0.05$) between fertilizer type and soil type was observed. Fertilizers had a significant effect on the agronomic efficiency of N (AE_N), P (AE_P), and K (AE_K).

These results show that N, P, K, S and B are the nutrients limiting potato productivity in central Kenya and their fortification would depend on specific soil nutrient requirements and associated applications.

CHAPTER ONE

INTRODUCTION

1.1. Background information

Potato (*Solanum tuberosum* L.) is the fourth most consumed stable food in the world after maize wheat and rice (Burke, 2017; FAOSTAT, 2019). In Kenya, it is the second staple crop after maize, and it is grown mainly in the highlands. The annual production is approximated at 9.4 tons with a production area of about 212,000 hectares (FAOSTAT, 2019). Small-scale farmers account for about 98% of potato producers (Janssens et al., 2013; Kaguongo et al., 2008). Production by small-scale farmers is about 83% of the national potato production with the rest of the production coming from large commercial growers (Gildemacher et al., 2009a; Janssens et al., 2013; Obare et al., 2010). The production cycle is mainly in the two seasons with minimal off-season production that is mainly practiced in areas around the slopes of Mt Kenya (Gildemacher et al., 2009a).

The production per unit in Kenya is very low compared to a potential of 30-40 t ha^{-1} under good management (Dieudonné et al., 2018; Gitari et al., 2018b; Mugo et al., 2013). Potato yield can be increased through the use of disease-free or certified seed potato, management of diseases such as bacterial wilt, late blight, potato cyst nematode and soil fertility management (Gildemacher et al., 2009b; Janssens et al., 2013; Mburu et al., 2018. Muthoni and Nyamongo, 2009).

Soil fertility management is key to sustainable potato production since potato is a high-feeding crop and requires the addition of nutrients to the soil (Burke, 2017; Koch et al., 2020; Westermann, 2005). As a result, organic and inorganic fertilizers are used in potato production (Gildemacher et al., 2009a; Powon et al., 2009). The majority of farmers (over 95%) in Kenya use mineral fertilizers in potato farming, with Di-Ammonium Phosphate (18:46:0) being the most commonly used fertilizer (Mugo et al., 2013; Muthoni et al., 2013b; Ogola et al., 2011). The use of the blanket recommended rate for nitrogen and phosphorous; 90 kg ha^{-1} and 230 kg ha^{-1} per season respectively has always been disregarded with most farmers using less than half of the recommended rates (Kaguongo et al., 2008; Mugo et al., 2020; Ogola et al., 2011). Only 10-15% of farmers have been observed to use the recommended rates (Ogola et al., 2011). The use of farmyard manure to improve soil fertility has also been observed as a common practice in Kenya with 45% of the farmers using it on potato crops (Gildemacher et al., 2009a; Mugo et al., 2020). To ensure a sustainable increase in production, the improvement of soil fertility management in Kenya should be taken into account. This can involve the good application of fertilizers that contain major and secondary micronutrients in proportions that ensure an adequate supply of essential nutrients for crop growth while conserving the environment (Kanyanjua and Agaya, 2006; Munoz et al., 2005). Specific fertilizer coupled with regional conditions is key to achieving sustainable soil fertility management.

General fertilizer use in Kenya is on the rise owing to several factors such as improved distribution, improved policies, and availability of credit (Ariga and Jayne, 2010). A large proportion of fertilizer used in Kenya is imported with about 10,000 metric tons annually produced by local manufacturers. Blending in the country stands at about 60,000 metric tons annually (Mathenge, 2009). Most of the fertilizer types in the country are general types for multipurpose crops with a few crop-specific blends available. Thus, the yield responses to these fertilizers would depend on a specific crop, soil nutrient requirements, and associated applications. This informs the need to develop fertilizer formulations that take into account the site-specific agronomic recommendations that fit local production conditions.

1.2. Statement of the problem and justification

Though potato is Kenyan's second most important food crop after maize (Lutaladio and Castaldi, 2009; Wang'ombe and van Dijk, 2013) its production is still below 10 t ha^{-1} owing to numerous constraints. Continuous cultivation without adequate replenishment of mined nutrients causes low soil fertility (Micheni et al., 2011; Obura et al., 2010; Muthoni and Nyamongo, 2009; Recke et al., 1997). Soil erosion and nutrient leaching aggravate the problem further (Nyawade et al., 2018, 2019). Small-scale farmers in Kenya replenish the soils through fertilizer application, but 70% of farmers apply rates that are below the national recommendations (Kaguongo et al., 2008; Mugo, 2013; Ogola et al., 2011; Ochieng' et al., 2021; Wang'ombe and van Dijk, 2013). Farmyard manure is used by about 45% of potato farmers, but in low quantities despite its low quality (Gildemacher et al., 2009a; Muthoni and Nyamongo, 2009).

The challenge of soil fertility issue among potato farmers is further compounded by the fact that farmers use diammonium phosphate (DAP) fertilizer which could lead to the limitation of elements not supplied (Kaguongo et al., 2008; Muthoni and Kabira, 2011; Ogola et al., 2011). Low levels of potassium have been reported in the highlands of Kenya (Kenya soil survey 2014, Micheni et al., 2011; Obura et al., 2010, Kanyanjua et al., 2006). Potassium is required in high amounts by potatoes, especially during tuber bulking thus its application could improve yields and tuber quality (Munoz et al., 2005; Mikkelsen 2006; El-Latif et al., 2011). DAP has also been associated with decreasing soil pH which may compromise the uptake of other nutrients. The lack of fertilizer blends formulated to replenish the nutrient removed by potatoes poses a challenge to soil fertility in terms of nutrient balances in the soil for sustainable production.

Soil and plant nutrient analysis is an important part of the development of crop-specific fertilizer blends (Hochmuth et al., 2012; Roy et al., 2006). Fertilizer applications that are guided by soil testing and plant nutrient uptake rates become essential in addressing the asymmetry between soil nutrient requirements and fertilizer application rates. These practices are nevertheless not adequately adopted by potato farmers in Kenya. Meru and Nyandarua are the major potato growing regions and present diverse soil types with Nitisols dominating in Meru and Planosols in Nyandarua (CIP, 2006; Jaetzold et al., 2006). The concept of nutrient omission trials (Huising et al., 2011; Nziguheba et al., 2009) presents crop responses to the addition of specific nutrient elements thus validating limiting nutrients. Fertilizers can be blended to produce a site and crop-specific nutrient needs (Roy et al., 2006). As a result, potato-specific blends are expected to increase productivity while conserving the environment and enhancing economical benefits to the farmers.

1.3. Objectives of the study

1.3.1. Main objective

Investigate the need to improve soil nutrients status and increase potato productivity through the use of crop-specific customized fertilizer blends in major potato-producing areas in Kenya.

1.3.2. Specific Objectives

i. To identify limiting nutrients for potato production in Kenya.
ii. To determine potato growth and yield response to limiting nutrients in Nitisols and Planosols.
iii. To evaluate the effect of fertilizer blend(s) on the yield of the potato crop.

1.3.2. Hypothesis

i. Potato productivity in Kenya is not limited by soil fertility.
ii. Potato crop will not respond to the addition of liming nutrients.
iii. Application of fertilizer blends will not improve potato yields.

1.4. Conceptual framework

The conceptual framework of this study was built on the major mechanisms that derive soil fertility in the major potato growing areas in central Kenya and was based on the overall goal of improving the soil nutrient status and potato productivity. The processes that guide soil fertility under potato production were clustered into three major dependent variables: specific nutrients, nutrient uptake, and potato yield-related parameters (Fig. 1.1). The specific elements hypothesized to affect the soil fertility were then aggregated into the macronutrients (N, P, K, S, Mg, Ca, S) and the micronutrients (Bo, Zn, Cu). Soil organic matter was discerned to influence both the macro and micronutrients, as well as the soil pH, while the latter (soil pH) was expected to influence all the major and minor nutrients.

The uptake and dynamics of these soil nutrients formed the independent variables explaining the nutrient levels in the soil and plant. The plant uptake would in turn affect crop growth and yield. Both crop growth and yield formed the major dependent variables explained by the changes manifested in the leaf area index, haulm biomass, harvest index, and tuber weights. The fertilizer and soil types were expected to directly influence the soil nutrient levels and dynamics and formed the independent variables interconnecting the specific limiting nutrients and potato crop responses to these nutrients. The key indicators explaining the effectiveness of each mechanism were generated by the interconnectivity of the variables. These resulted in processes that were related to changes in resource use efficiency, nutrient dynamics, and crop productivity.

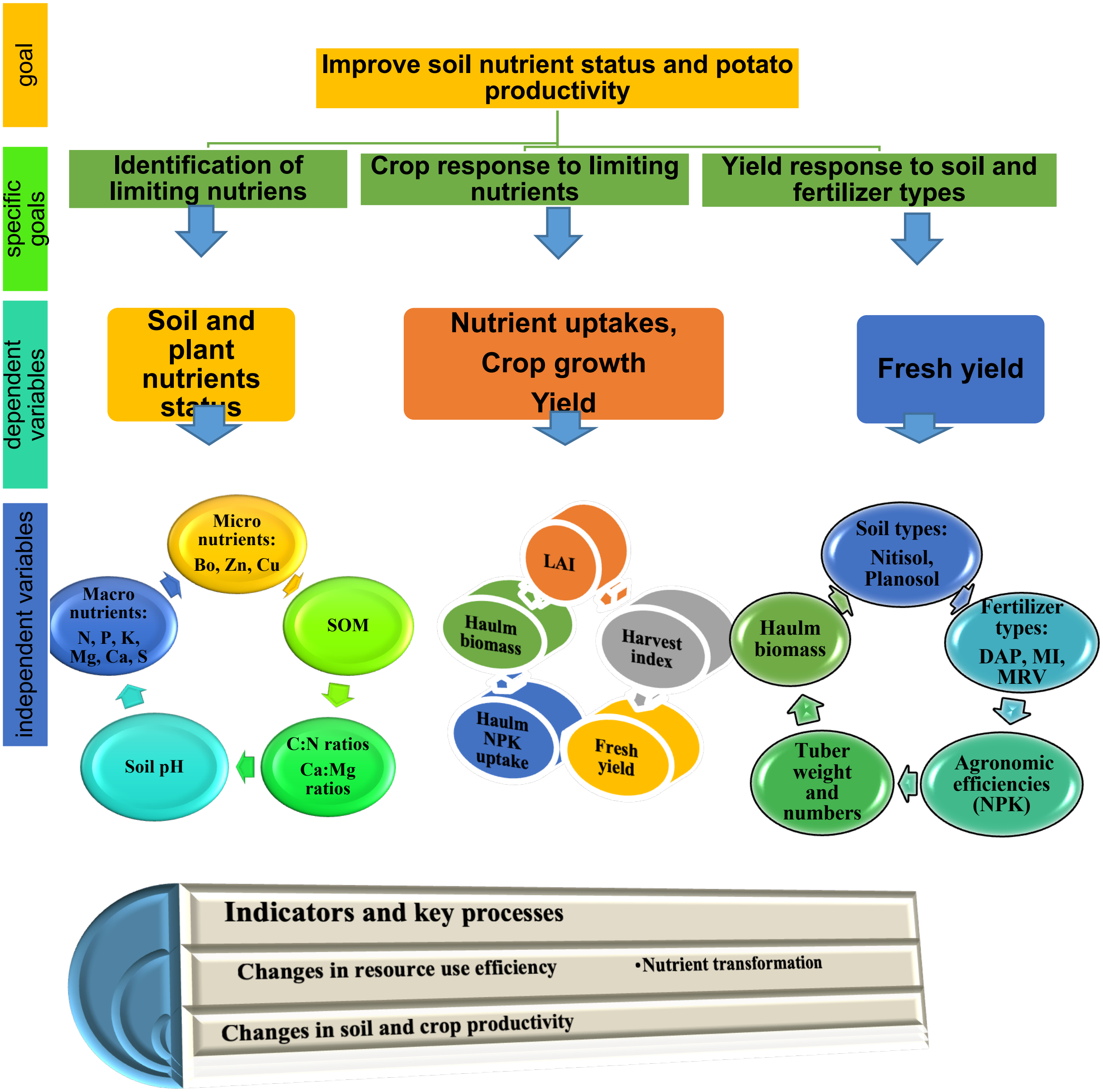


Figure 1.1: conceptual framework. DAP diammonium phosphate, MI mavuno improved, MRV mavuno root tuber and vegetables, SOM soil organic matter

1.5. Structure of the thesis

The thesis is organized into seven chapters, Chapter 1 gives a general introduction, problem statement and justification, objectives, hypotheses, and the conceptual framework of the study. Chapter 2 covers related studies and experiences as well as identifying knowledge gaps and Chapter 3 presents a description of the sites and methods and approaches as well as data management and analysis. Chapter 4 represents the results of the assessment of soil fertility and potato crop nutrient status in Kenyan highlands. Chapter 5 focuses on the response of potato crops to the omission of selected nutrients while Chapter 6 incorporates discussions on the response of potatoes to fertilizers applied to different soil types. Chapter 7 presents a summary of the results obtained in different experiments, conclusions, and recommendations.

CHAPTER TWO

LITERATURE REVIEW

2.1. Potato production in Kenya and its fertility related constraints

The potato crop (*Solanum tuberosum* L.) is an annual herbaceous dicotyledonous plant that originated in the highlands of the Andes in South America (Lisinka and Leszcynki, 1989). It belongs to the family *Solanaceae* and the specie *tuberosum*. The crop is currently produced in large quantities with China as the leading producer and consumed worldwide (FAOSTAT, 2019). In Africa, Kenya is among the top potato producer countries with Egypt leading in the list (FAOSTAT, 2019). The potato was introduced in Kenya primarily by British farmers and colonial officials in the 1880s (CIP, 2006; Durr and Lorenzl, 1980) and its cultivation is mainly in altitude areas above 1,500 m above sea level). It is the second most important food crop in the country and is produced for food and income generation (Muthoni et al., 2013a; Mwakidoshi et al., 2022; Lutaladio et al., 2009). The production of below 10t Ha^{-1} is low compared to about 40t Ha^{-1} achieved on the station (Muthoni et al., 2013b, Onditi et al., 2012). Potato production from Meru is estimated at 9 t ha^{-1} while the production in Nyandarua is slightly higher at 10 t ha^{-1} (MOALF, 2016). This yield gap is due to several production constraints among them low soil fertility.

Soil fertility is still a major challenge in potato production even though the majority of farmers in Kenya use mineral fertilizers in potato farming (Ogola et al., 2011; Muthoni and Nyamongo 2009). This is so because only about 10-15% of farmers use the recommended rates (Muthoni et al., 2013a; Ogola et al., 2011). The low fertilizer application could be attributed to inadequate funds as well as the lack of knowledge on the adequate amounts required (Obare et al., 2010; Ogola et al., 2011; Mugwe et al., 2009). Small-scale land ownership in potato growing zones is approximately 2 ha (Muthoni et al 2013a; Gildemacher et al., 2009; Kaguongo et al., 2008; Mugwe et al., 2009) and thus continuous farming is practiced on the available land leading to declining soil fertility. Manual harvest techniques disturb the soil thus encouraging soil erosion (Nyawade, 2015).

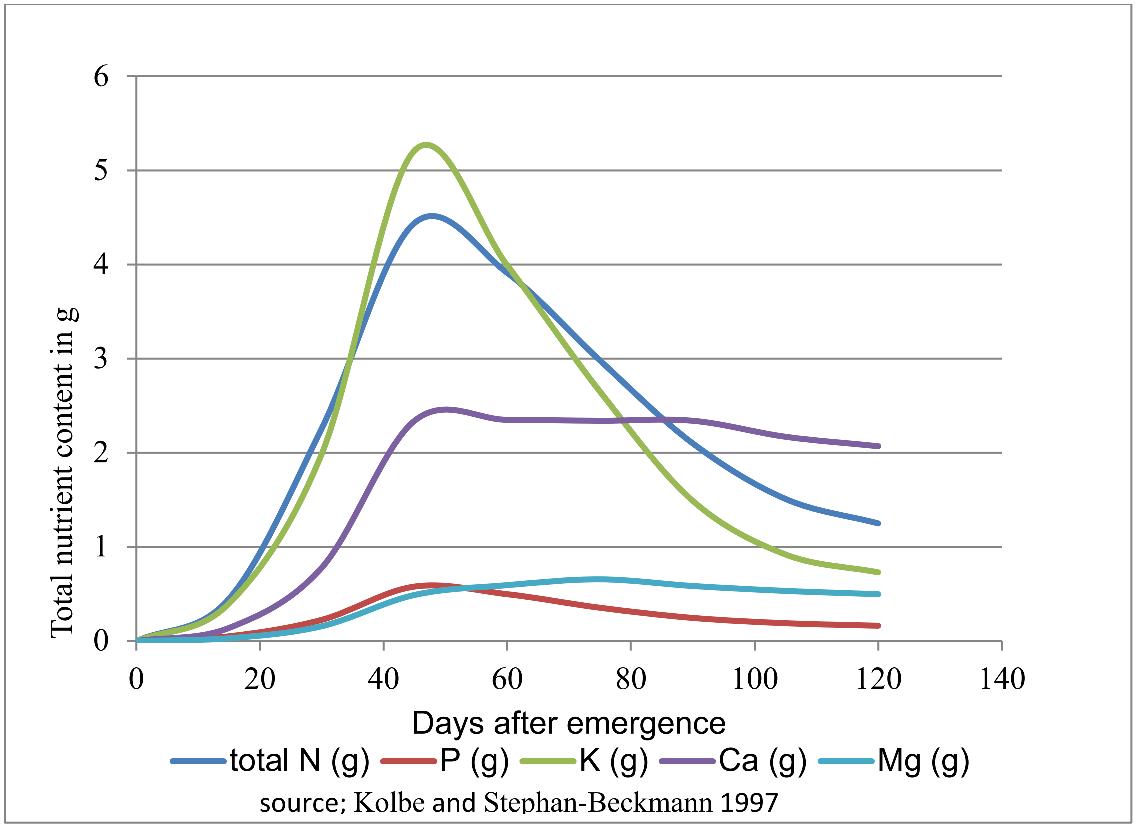
There is over-reliance on Di-Ammonium Phosphate as the main fertilizer blend by potato farmers in Kenya (Muthoni et al., 2013a, Ogola et al., 2011) this could be the reason for other nutrient limitations such as potassium and secondary nutrients as reported by some studies (Kenya soil survey 2014; Omanga et al., 2013; Recke et al., 1997; Wekesa et al., 2014). Long usage of Di-Ammonium Phosphate could also lead to the reduction of soil pH (Manoharan et al., 1995) which has also been reported by Wekesa et al. (2014). An additional cost is thus required to reduce the effect of reducing pH through liming.

2.2. Uptake and nutritional requirement of potato crop

Potato nutrition is important to achieving high yields and quality potatoes (El-Latif, et al., 2011; Mikkelsen 2006; Munoz et al., 2005; Westermann 2005), and the balance between macro and micronutrients is of great importance in nutrient supply (Koch et al., 2020; Naumann et al., 2020). Nitrogen is widely utilized by potatoes at the vegetative stage while potassium is widely utilized during the tuber bulking stage (Lakshmi et al., 2012), Phosphorous is needed in relatively large quantities during early growth to encourage rooting and tuber set, and also during the late season for bulking (Mikkelsen, 2006; Rosen et al., 2014). Calcium is critical to ensuring stress-free leaf growth while magnesium has a major role in maintaining tuber quality (Palta, 2010). Sulfur is needed at all growth stages and is important in reducing common scab. Boron ensures several key growth processes take place and is important in optimizing calcium utilization. Manganese and zinc influence the yield while Zinc also plays a key role in N-assimilation and metabolism and starch formation (Burke, 2017).

Nutrient uptake by the potato plant is generally low after germination and increases rapidly (Beringer et al., 1990; Kolbe and Stephan-Beckmann, 1997; Nunes et al., 2006) after the development of roots (Figure 2.1). The balance of soil chemical properties is of paramount importance to the uptake as it has been shown that the balance of individual elements can have a synergetic or antagonistic effect on the uptake of another element (Rietra et. al., 2015). The nutrient uptake by potato is also influenced greatly by the moisture levels as it has been shown in china that the highest nutrient uptake in the irrigated field was two weeks earlier when compared to the unirrigated field (Li and Jin, 2012). Crop age and health status affect nutrient uptake too. The nutrient levels in the haulm decrease during tuber bulking as a result of the source-sink relationship between the shoot and the tubers (Beringer et al., 1990; Kolbe and Stephan-Beckmann, 1997). According to Alva et al (2002) nitrogen partition in the leaves, tubers and stems before senescence is 19%, 69% and 12% respectively, which further highlights the source-sink relationship.

Chatterjee et al, (2010) indicated that potatoes need 132 kg N ha^{-1}, 20 kg P ha^{-1} P and 160 kg K ha^{-1} to produce 40t ha^{-1} of potato while Westermann (2005) summarized the macronutrient requirement as 235 kg N ha^{-1}, 31 kg P ha^{-1}, 336 kg K ha^{-1} to produce 56t ha^{-1}. On the other hand, Stark et al., (2004) indicated that potatoes need 108 kg N ha^{-1}, 15 kg P ha^{-1} and 145 kg K ha^{-1} to produce 62t ha^{-1}. This is a clear indication that Potassium and nitrogen are required by potato crop in high quantities and that different environment requires different levels of nutrients. Other nutrients required in relatively large amounts include calcium, magnesium, phosphorous and sulphur (Westermann, 2005; Kolbe and Stephan-Beckmann 1997). In reference to the tubers, Kolbe and Stephan-Beckmann (1997) indicated largest nutrient requirement occurs between 45 and 75 days after emergence. Data on nutrient uptake in major potato production areas have not been well presented. A review has indicate application of 150 Kg of N and K steadily increases potato yield (Otieno and Mageto, 2021). Nutrient management for potato production is thus important in terms of amount applied and timing to ensure increased productivity.



source; Kolbe and Stephan-Beckmann 1997

Figure 2.1: Macro and secondary nutrient uptake of potato (stems and leaves): Source (Kolbe and Stephan-Beckmann 1997)

2.3. Nutrient status and fertility management in potato production

Nutrient management for potato crops is crucial because of the high demand coupled with low nutrient-scavenging efficiency due to the shallow rooting system (Munoz et al., 2005). It is grown on well-drained soils that are prone to leaching and the harvesting method results in erosion due to extensive soil disturbance (Nyawade et al., 2018,2020).

Planosol and Nitisols are widespread in potato-producing areas of Kenya. Planosols are shallow and imperfectly drained and farmers in Kenya are compelled to employ cumbered beds to control waterlogging and flooding in these soils (Mati, 2012; Muchena and Gachene, 1988). Nitisols are well-drained but exhibit much N leaching, thus requiring higher fertilization to attain higher crop yields (Muchena and Gachene, 1988; Warren and Kihanda, 2001). Nitisols and Planosol have high P sorption, making P one of the most limiting nutrients (Gitari et al., 2020, Getie et al., 2021; Gichangi et al., 2008, Elias, 2017). Fertility management in this soil is thus necessary for better potato production.

Fertility management aid in maintaining soil nutrient status which in turn leads to adequate uptake by the plant. Adequate nutrient ranges have generally been published to aid in general result interpretation (Mangale et al., 2016; Mwadalu et al., 2021). The ranges are however general and not crop specific. Information on Critical nutrient concentration ranges for potato varieties grown in Kenya is scarce thus limiting the interpretation of results. General potato nutrient concentrations for various potato parts have been published elsewhere (Reuter et al., 1997). Determination of soil fertility status has largely been soil specific and focused for other crops. There is a need to conduct nutrient status for potato crops in Kenya.

According to Recke et al. (1997), critical nutrient levels of P and K in the soil for potato crops to respond are 15 ppm and 0.55meg/100g (modified Olsen) respectively. Studies by Wekesa et al (2014) found that potatoes planted on different sites responded differently to fertilizer addition depending on the site fertility levels. The response to mineral fertilizer has been shown, however, the most limiting nutrients have not been identified. Fertilizer evaluation trials have focused on various available fertilizer types and organic fertilizer against DAP applied at the recommended rate of 500 kg ha^{-1} as the main fertilizer. Muthoni and Kabira (2011) in a trial that evaluated DAP, N.P.K (20:20:20), Triple superphosphates (TSP), Calcium Ammonium Nitrate (CAN) and manure use reported potato yield as high as 80 t ha^{-1} with NPK and DAP. The use of CAN, Urea and Ammonium Sulphate nitrate has been evaluated when applied once or by split application by Gathungu et al., (2000) who recommended split application of nitrogen fertilizer. Umostart super Zn (11.46.0+2Zn) a zinc-fortified fertilizer, had a dismal performance as compared to DAP when evaluated at different rates (Lung'aho, et al., 2011). Organic fertilizers have also been evaluated with varying results. Green manure from purple vetch has shown comparable yields (above 20t ha^{-1}) to DAP (Mureithi et al., 2004). In a trial evaluating humate powders (Kelpak and Earthlee) the yields in trial were generally low (about 4-9t ha^{-1}) but they were comparable when organic and inorganic sources were used on potatoes. In addition, potassium-based fertilizers have been shown to improve potato yields and quality (Bansal and Trehan, 2011; Manjunatha et al., 2012; Shaaban and Kisetu, 2014). The comparable yields from other nutrient sources as compared to DAP might be one of the reasons farmers mainly use it, however more blends that are well balanced to meet crop need and soil nutrient deficits while increasing nutrient use efficiency might achieve better yields and quality. Fertilizer blends have recently been evaluated in Ethiopia and positive results have been reported (Bekele, 2018; Habte and Ayalew, 2017; Mekashaw et al., 2020). Nutrient use efficiency from fertilizer applied would help in deciding the best-fit fertilizer blends.

2.4. Nutrient use efficiencies under potato production

Effective nutrient use is important due to economic benefits as well as environmental benefits. Management factors maximizing nutrient uptake while minimizing nutrient losses will lead to high nutrient efficiency (Hailu et al., 2017). Application of 55.5 N and 39 P kg Ha^{-1} gave the highest NUE (about 70 kg kg^{-1}) while 55.5 N and 19.5 P kg Ha^{-1} had the highest PUE (100 kg kg^{-1}) in Ethiopia (Hailu et al., 2017). Precision agriculture management methods such as the right rate and the right timing of nutrient application are best suited to improve nutrient use efficiencies, traditional agricultural techniques such as intercropping improve nutrient use efficiency since different crops explore nutrients at different depths, while legumes also fix more nutrient into the soil (Gitari et al., 2020; Hailu et al., 2017). Gitari et al., (2018b) reported NUE of 180 and PUE of 400 Kg of potato equivalent yield when the potato is intercropped with dolichos lab lab. Well-balanced fertilizer in reference to soil supply capacity and crop need can lead to high nutrient use efficiency. Nutrient efficiencies of major fertilizer types used in potatoes in Kenya has not been researched thus research can be used to enhance these gaps.

Different potato varieties exhibit different nutrient efficiencies, nutrient use efficiency is thus as a result of uptake efficiency and utilization efficiency (Das et al., 2016; Hailu et al., 2017). At higher soil, fertility utilization efficiency is key to nutrient use efficiency while under nutrient limitation both uptake and utilization efficiency are key (Girma, 2017; Nieto, 2016). Das et al., (2016) found a high net gain with the application of 150 kg N ha^{-1}. Nutrient deficiency have been shown to be cultivar dependent as a result of utilization efficiency (Hailu et al., 2017). Hailu et al., (2017) also indicated application of more than 55 kg N ha^{-1} and 19 kg P ha^{-1} will not be beneficial under certain conditions. Fertilizer blends should thus be evaluated on their effects on nutrient use efficiency.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Description of the study area

Nutrient status studies and experimental trials were conducted in Meru and Nyandarua Counties due to their importance in potato production in the country (Figure 3.1). Both areas are located in the highlands, Meru is located on the North to Southeastern slope of Mt Kenya and Nyandarua on the Southwestern side of the Aberdare ranges. Nyandarua is mainly a plateau while Meru is dominated by sloppy terrains. Predominant soils in Meru are Nitisols while in Nyandarua the soils are mainly Planosols, Phaozems, Nitisols and Luvisols (Jaetzold et al., 2006). This study was conducted on Nitisol and Planosol mainly because potato is widely grown on these soils.

Rainfall in the two regions is bi-modal, with the long rain falling from March to July while the short rain falls from October to January. Annual rainfall in Meru and Nyandarua ranges from 800 mm to 2200 mm. Agroecological zones in Meru and Nyandarua range from the cold and wet (upper highlands) zones to the hot and dry lower zones. Potato is grown mainly between upper midland and upper highlands agro-ecological zones.

Farming in the region started during the colonial era and farmed land has been on the increase. Current farming is rain-fed with limited irrigation in both counties. Continuous farming is practiced since most farmers own less than 2 ha. Potato is mainly grown as a mono-crop and both for cash and food.

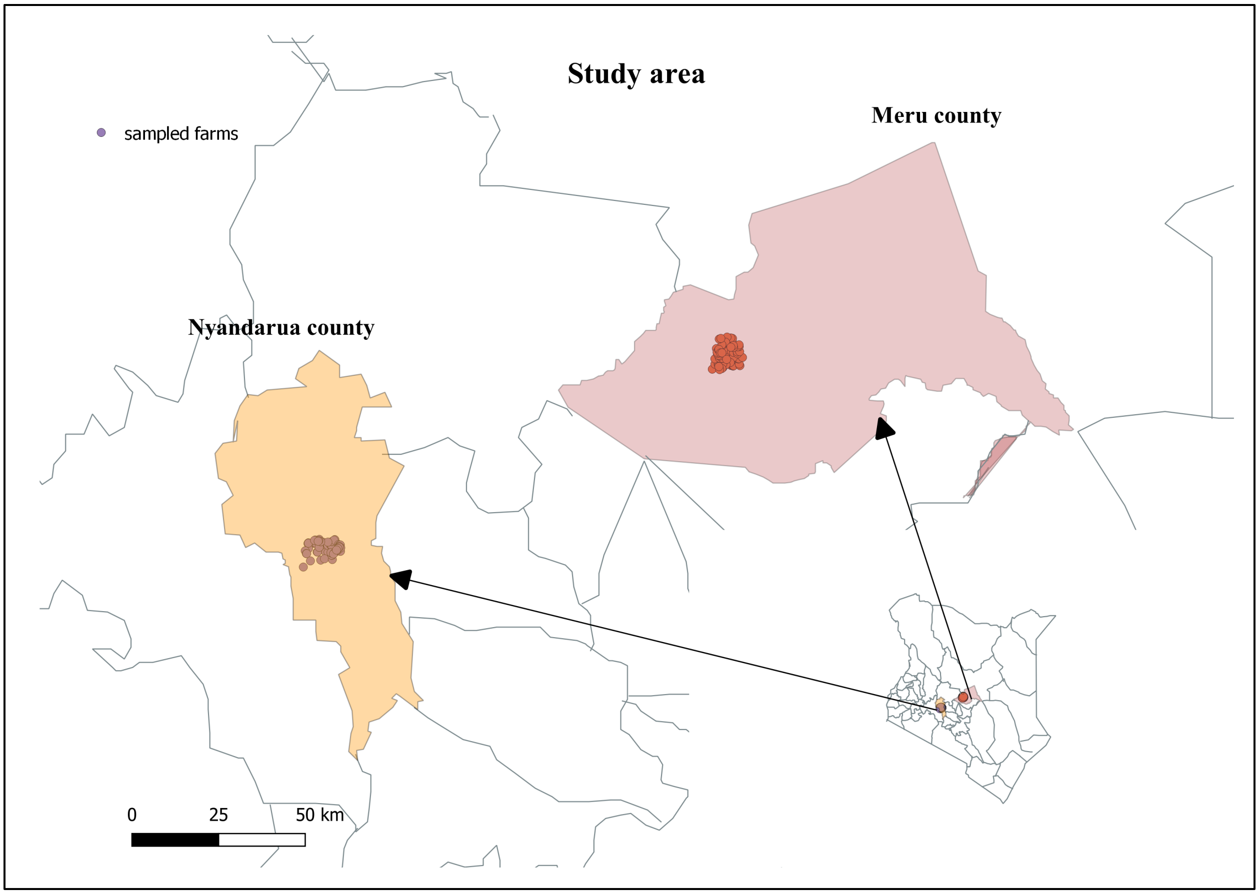


Figure 3.1: Map of the study area

3.2. Research approach

The study involved collecting soil and plant samples for nutrient status assessment, an on-field omission experiment for assessment of potato yield-limiting nutrients and fertilizer field trials conducted between short rains in 2015 and long rains in 2018 seasons.

3.2.1. Soil and plant sample collection

Soil and plant samples were collected from 198 farms during the short rains of 2015. Farmers who had potatoes at the flowering stage were randomly selected from a sampling frame. The sampling frame was created with the help of agricultural extension officers. The farms were within a 4 km wide transect ranging from lower to upper highlands agro-ecological zones. In Nyandarua agro-ecological zones UH2 (pyrethrum wheat zone), UH3 (wheat barley zone), LH3 (wheat/maize barley zone), and LH4 (cattle sheep barley zone) were covered while in Meru agro-ecological zones UH2, UH3, and LH4 were covered (Jaetzold et al., 2006).

Composite leaf samples of 50 leaves (50-70g) were collected from each farm by plucking the fourth compound leaf from the top of the main stem (Kelling et al., 2002; Kaiser et al., 2013). The sample in each farm was collected from a 0.1 ha portion of the total area under the crop by taking walks in a zigzag pattern (Katalin, 2004). Diseased, water-stressed, border plants and portions close to the homestead were avoided. The samples were placed in mafuko sampling bags (number 8) and silica gel was added to aid in the removal of excess moisture and prevent the leaves from rotting (Prendini et al., 2002).

At least five soil samples were collected from each farm at the depth of 0-30 cm using a soil auger, mixed thoroughly in a plastic bucket and a composite sample of about 500g was drawn and placed in a well labeled Ziplock paper bags (size 6” by 9”) (Carter and Gregorich, 2007; Katalin, 2004). Several soil samples will be placed in a ziplock polythene bag (size 9” by 12”), stored in a cool box then taken to the laboratory for analysis.

3.2.2. Field omission trials

Nutrient omission experiments were established in three sites during the two rainy seasons of 2016 in which the treatments were minus N, minus P, minus K, minus S, minus B, NPKSB, and negative control. The treatment was arrived at after analysis of data from the first study (section 3.2.1). The tested nutrients were low in several of the sampled farms. Elements were supplied using straight fertilizer at planting apart from boron supplied as a foliar application. The sites were in farmer’s field selected from of list of sampled farms in activity one. The farms selected had at least of two of the tested nutrients in low amounts. The treatments were laid in Randomized Complete Block Design (RCBD) with three replications.

Growth response was estimated by measuring leaf area index (LAI) using LAI-2200 plant canopy analyzer (LI-COR, Lincoln, NE, USA) at 30 and 45 DAE. Destructive sampling of 6 plants in the inner rows was done at 60 DAE to collect samples for determination of the fresh and dry weight of plant and tubers. The final yield was determined at full maturity between 90 – 100 DAE. Yield response percentage and harvest index were also calculated. The data from the trial were used to quantify potato response to the addition of the selected nutrients.

3.2.2. Fertilizer evaluation trial

The second set of experiments was established on Nitisol and Planosol during long and short rains of 2017 where the data was collected to evaluate three fertilizer blends. The treatment included di ammonium phosphate (DAP), mavuno root and vegetables (MRV), mavuno improved (MI) and control with no fertilizer application. Di ammonium nitrates was selected since it is widely used by potato farmers while MRV was selected since it is promoted to be used by potato farmers. Mavuno improved was used as a new improved blend. Early maturing (Shangi) and medium maturing (Sherekea) potato varieties were used. The treatments were laid in a split-plot design with variety being the main plot and fertilizer type being the subplot.

Haulm weight was measured by randomly selecting three plants per subplot at 35 days after emergence (DAE) as an indicator of potato growth. The final tuber yield was determined at full maturity. The agronomic nutrient efficiencies were calculated for nitrogen (AE_N), Phosphorus (AE_P) and potassium (AE_K).

3.3. Agronomic practices

Well sprouted potatoes were planted at a spacing of 0.3 m within a row and 0.75 m between rows targeting a plant density of 44,444 plants ha^{-1}. The first weeding and hilling-up for potato were carried out manually at around 15 DAE while the second weeding and hilling up was done at around 30 DAE. Disease and pest control were carried out by spraying the crop with Ridomil Gold MZ 68 WG (Mefenoxam 40 g kg^{-1} + Mancozeb 640 g kg^{-1}) alternated with Infinito (Fluopicolide 62.5 g L^{-1} + Propamocarb 625 g L^{-1}) after every 14 days starting at 30 days after planting to control late blight. The trials were conducted under rain-fed conditions.

3.4. Laboratory procedures

3.4.1. Determination of nutrient content in leaf

The leaf samples were oven-dried at 65 °C for about 24 hours, ground, then sieved through a 40-mesh sieve. 0.5g was weighted for extraction of P, K, Ca, Mg, S, Fe, Zn, Cu, and Mn using microwave digestion in a closed vessel extraction and determined using Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) (Kalra. 1997: Hou and Jones, 2000).

3.4.2. Description of procedures for chemical analysis of the soil

The soil samples were air-dried and sieved through a 2 mm sieve. Extraction of soil samples for analysis of P, K, Ca, Mg, Fe, Mn, B, Zn, and Cu done using Mehlich 1 procedures (Mylavarapu et al., 2002) and determined using inductively coupled plasma-optical emission spectrometry (ICP-OES) (Hou and Jones, 2000). Extraction for NO_3-N, NH_4-N, was done using 2 M KCl solution and determined by the distillation process. Soil pH was measured in a soil-to-water ratio of 1:2.5 using a glass electrode pH meter.

3.5. Data management and analysis

The data generated in this study were managed in Ms. Excel and analyzed differently for the different data sets. Descriptive statistics, Pearson correlations, and factor analysis were used for the nutrient status study. Stability analysis and linear mixed models in R software version 2.2.3 (R Core Team, 2018) were used for the nutrient omission study. The treatment means were compared using Least Significant Difference (LSD) at $p \leq 0.05$.

CHAPTER FOUR

Assessment of soil fertility and potato (*Solanum tuberosum* L.) crop nutrient status in Central and Eastern highlands of Kenya

Abstract

Inherent low soil fertility remains a hindrance to potato production in Kenya and continues to pose a threat to food security. A study was conducted in Nyandarua and Meru counties to assess the soil fertility status in smallholder potato farms. Soil and plant tissue samples were collected and analyzed for selected nutrients (pH, OC, N, P, K, S, Ca, Mg, Zn, B and Cu) from 198 farms. Critical nutrient levels (pH-5.5, SOC(g kg^{-1})-25, N (g kg^{-1})-2.5, P (mg kg^{-1})-30, K (Cmol kg^{-1})-0.2, S (mg kg^{-1})-4.5, Ca (Cmol kg^{-1})-0.9, Mg (Cmol kg^{-1})-0.3, Zn (mg kg^{-1})-0.6 and B (mg kg^{-1})-1) were used to assess the sufficiency levels of nutrients for potato growth. Soils in the sampled farms were weakly to strongly acidic (pH-$CaCl_2$ 3.9–6.6) and had low to high soil organic matter content (1.5–97.5 g Kg^{-1}). The percent of farms in Meru and Nyandarua with nutrient contents below critical levels were 66% and 20% for N, 46% and 85% for P, 67% and 31% for S, 9% and 51% for Cu, and 87% and 80% for B, respectively. Low tissue nutrient concentrations were observed for N, P, K, and S irrespective of the sites. Soil pH correlated strongly with the majority of the analyzed soil and tissue nutrients. These results affirm the need to design integrative soil fertility management strategies to correct the impoverished soil fertility status in the study area.

4.1. Introduction

The productivity of the potato crop (*Solanum tuberosum* L.) in sub-Saharan Africa is greatly constrained by the impoverished soil fertility caused mainly by poor soil nutrient management strategies (Bationo, 2004; Jonas et al., 2012). Potato is a heavy feeder crop with regard to the primary nutrients (N, P and K). For instance, to attain tuber yield of 48 tons ha^{-1}, potato tubers remove 47.6 kg N, 24 kg P, 103.4 kg K and 5 kg S, while the haulm requires 31.8 kg N, 8.2 kg P, 47.6 kg K and 3.2 kg S (Burton, 2018). These nutrient amounts can only be supplied through fertilizer application, a strategy that may be beyond the means of the resource constrained smallholder farmers (Gitari et al., 2018a; Obare et al., 2010). Nitrogen supply influences tuber bulking rate and the time of tuber growth (Honeycutt et al., 1996), K plays an important role in increasing tuber yield, size and quality (Trehan et al., 2009), while P enhances root development, tuber set and promotes tuber maturity (Burton, 2018). Sulphur is an integral component in proteins and activates many enzymes regulating potato growth. Soil pH, SOM, Ca, Mg, Fe, Zn, Mn, Mo, Ni, and B are also essential for potato growth and development (Burke, 2017; Burton, 2018).

In Kenya, the productivity of potato averages 8–15 t ha^{-1} which is far below the potential yield of 40 t ha^{-1} (Muthoni, 2016; Muthoni and Nyamongo, 2009). This yield constraint has been attributed to among other factors, poor nutrient management strategies, poor cropping systems, accelerated soil erosion rates, and high cost of inorganic fertilizers (Bationo, 2004; Gitari et al., 2018b; Muthoni, 2016; Nyawade, 2015). Fertilizer applications in Kenya is mainly blanket and is often below the recommended rates resulting in inadequate amount of nutrients that cannot meet the potato growth requirement (Kaguongo et al., 2008; Muthoni and Nyamongo, 2009; Ogola et al., 2011). Farmers apply mainly di-ammonium phosphate at planting and hardly top-dress with N fertilizer, a practice which has been associated with a reduction in soil pH (Muthoni, 2016; Nyawade, 2015). Once the soil pH drops below 4.9, nutrient deficiencies and toxicities become more common. In particular, Mn and Al toxicity and P, K, Ca, and Mg deficiencies (Fageria and Zimmermann, 1998; IPNI, 2010). The problem may not be prevalent throughout the entire field but may occur in smaller areas where the soil consists of higher sand or lower organic matter content (Westermann, 2005).

Continuous cultivation of crops without optimal nutrient replenishment has been associated with a deficiency of certain nutrients (Otieno et al., 2022; Nyawade et al., 2021). For instance, K which has been known to be adequate in Kenya highland soils has shown depleting levels partly because of high uptake by high K demanding crops such as potato (Kihara et al., 2017; Wekesa et al., 2014). Therefore, to achieve optimum potato yields in Kenya, there is a need to supply adequate amounts of both macro and micronutrients in their correct form, quantity and at the right time. Rosen emphasized that imbalances in the supply of nutrients may make certain micronutrients in the soil unavailable for potato uptake (Rosen, 2015). This reiterates the law of limiting nutrients which states that if one nutrient is limiting, an increase in the yield will be determined by the addition of the same nutrient and thus necessitates the need to identify the limiting nutrient (Hiddink and Kaiser, 2005).

Addressing the low nutrient use among the smallholder potato growers in Kenya should thus be based on the identification of limiting soil nutrients. Soil tests accompanied by plant tissue analysis provide a basis for predicting potential limiting nutrient supply and enable corrective action before serious nutrient deficiencies develop (Roy et al., 2006, 2003). Tissue nutrient analysis is based on the fact that the maximum yield and quality of tubers are associated with an optimum range of nutrients in the plant tissue (Munson and Nelson, 1990). Nutrient levels falling outside this optimal range are considered growth limiting and require corrective measures (Mangale et al., 2016). The critical nutrient level is the lower limit of the optimal nutrient range. The use of critical nutrient levels for the determination of limiting nutrients should be carefully done to take care of the several factors affecting it such as plant part sampled and sample preparation during analysis (Motsara and Roy, 2008; Schulte et al., 2005). Once well established, the critical nutrient level can be used widely for the same crop (Roy et al., 2006). Critical nutrient levels for potatoes at different growth times and plant parts have been described for use in the interpretation of plant analysis (Kaiser et al., 2013; Reis Jr. and Monnerat, 2000; Reuter et al., 1997). Soil nutrient sufficiency levels are largely influenced by soil extraction methods. Interpretation of the soil analysis results in Kenya has generally followed the general recommendations even though there are increasing calibrations of new test methods (Landon, 1991). The national research and partners have published a manual to guide researchers conduct their activities and interpreting their results (Mangale et al., 2016)

Individual examination of analyzed soil chemical elements can lead to the wrong interpretation of soil chemical property influencing soil fertility. Thus to determine the key nutrients affecting the nutrient status, there is a need for a more robust analytical method. Factor analysis has been used to analyze soil chemical properties in a bid to reduce the factors (Shukla et al., 2006). It enables the identification of key elements among the many that are analyzed.

Fertilizer application if based on key nutrient limitations will allow the growers to adjust nutrient applications according to crops' needs, growth rates, and length of the season. For most accurate fertilizer recommendations, soil test interpretations should be based on local or regional research (Rosen, 2015). Development of site-specific nutrient limit norms for potatoes will enhance the nutrient use efficiencies and avoid yield losses, and negative environmental impacts of fertilizer use (Fairhurst, 2012; Harou et al., 2018). It is in view of this background that this study was conducted to determine the nutrients status in two major potato-producing areas of Kenya. This information is useful for designing integrative nutrient management strategies appropriate to smallholder farmers.

4.2. Methodology

4.2.1. Sampling area

The study was conducted in Meru (Buuri sub-county) and Nyandarua (Kipipiri sub-county) counties of Kenya (Figure 3.1). The two counties are representative of the major potato-growing areas of eastern and central Kenya. Sampling in each county was done within a two-kilometer-wide transect. Transect in Meru was laid along the coordinate range of 0°07' N, 37°48' E to 0° 13' N, 37°53' E, and along 0°38' S, 36°50' E to 0°37' S, 36°45' E in Nyandarua. The Meru transect cut across agro-ecological zones; Upper highlands (UH3) (2100–2450 meters above sea level (masl)) and Lower highlands (LH4) (1850–2000 masl) whereas in Nyandarua it covered UH2 (2000–2150 masl), UH3 (2100–2450 masl) and LH3 (1900–2000 masl) (Jaetzold et al., 2006). Nitisols are the predominant soil type in Meru while Nyandarua is dominated by Andosols and Planosols (Jaetzold et al., 2006). Farms were selected purposively from a list of farmers generated with the assistance of agricultural extension officers. The overall sampling targeted farms with potatoes that had attained the mid flowering stage as this is the time when peak nutrient uptake by potato occurs. A total of 100 and 98 farms were sampled in Meru and Nyandarua counties, respectively.

4.2.1. Soil and tissue sampling

Soils were sampled from each target farm in zigzag pattern and at an interval of approximately10 m. On average, ten (10) soil replicates were taken within rows and inter rows of each farm with a 15 mm diameter soil auger at 0–30 cm depth. The samples were mixed into a composite for each farm and a sub-sample of 100 g of fresh weight was taken to the laboratory and frozen at 4°C until analysis. Extraction of soil samples for analysis of Ca, P, K, Mg, B, Zn, and Cu was done using Mehlich 1 procedures (Mylavarapu et al., 2002) and determined using inductively coupled plasma-optical emission spectrometry (ICP-OES) (Hou and Jones, 2000). Calcium chloride (0.0125 M) was used to extract soil minerals N and S (Houba et al., 2000).

To achieve an accurate nutrient assessment, tissue samples were collected at mid flowering stage by plucking the youngest fully expanded potato leaves (4th leaf from the top of the growing tip). (Westermann, 2005). The leaflets were placed in khaki paper bags No 8. embedded with silica gel to absorb excess moisture and prevent rotting. Foliar samples were oven dried at 60°C, ground using Wiley mill through mesh size 0.2mm, wet digested, and analyzed for mineral nitrogen calorimetrically using Skalar, and for Ca, P, S, K, Mg, B, Zn, S, and Cu using ICP-OES after dissolving the ashes (550°C, 4 h) in dilute HCl (Hou and Jones, 2000; Westerman et al., 1990).

In addition to plant and soil samples, information on the fertilizer type, amounts and manure used was collected using a check list to determine soil nutrient replenishment of the sampled farms.

4.3. Data analysis

Descriptive statistical analyses including means, range, and standard deviations were used to explore the data using STATA software and graphs plotted in MS Excel. Nutrient sufficiency ranges (low, adequate, and excess) (Table 4.1) were used to group the farms depending on respective nutrient levels (Mangale et al., 2016; Reuter et al., 1997). The proposed leaf nutrient sufficiency was adopted from elsewhere since no documented limits exist for potatoes in Kenya thus are used for general interpretation while critical soil nutrient levels were extracted from a manual published by national research (Mangale et al., 2016; Reuter et al., 1997). Factor analysis was performed to determine principal soil nutrient elements that influenced the soil fertility status. The data were log-transformed for standardization before running factor analysis. Standardization of the data was done since the elements were represented in different units and the concentration varied widely between the various elements. For a better interpretation of the results, the correlation matrix was rotated. Elements with a factor loading of more than 0.5 were considered to be the most influential within a factor. Relationships between soil nutrient content and leaf nutrient concentration and interrelations of soil nutrients were explored by correlation (r) analysis.

Table 4.1 Soil and tissue nutrient critical levels of macro and micronutrients used in this study

	Soil test	Tissue nutrient concentrations
Element	Critical level	Critical level
Soil pH ($CaCl_2$)	5.5	-
SOC (g kg^{-1})	25.0	-
N (g kg^{-1})	2.5	44.0
P (mg kg^{-1})	30.0	2.5
K (Cmol kg^{-1})	0.2	39.0
S (mg kg^{-1})	4.5	3.0
Ca (Cmol kg^{-1})	0.9	9.0
Mg (Cmol kg^{-1})	0.3	2.5
Zn (mg kg^{-1})	0.6	19.0
B (mg kg^{-1})	1.0	24.0
Cu (mg kg^{-1})	0.2	5.0

Source: Soil critical levels (Mangale et al., 2016), Tissue critical levels (Reuter et al., 1997)

4.4. Results

4.4.1. Fertilizer and manure use

Fertilizer was applied in the majority of the sampled potato farms in Meru (94%) and Nyandarua (95%) (Figure 4.2). This fertilizer was mainly in the form of di-ammonium phosphate. Manure was applied in 62% and 45% of sampled farms in Meru and Nyandarua respectively. Combined application of fertilizer and manure was done in 56% and 41% of sampled farms in Meru and Nyandarua respectively. With respect to N, which is considered the major limiting nutrient in Kenya, the majority of the farmers applied lower rates of this nutrient than the recommended rate of 90 Kg N ha^{-1} for these areas (Figure 4.3). Generally, the majority of the farmers in Meru applied N at rates greater than the recommended compared to farmers in Nyandarua.

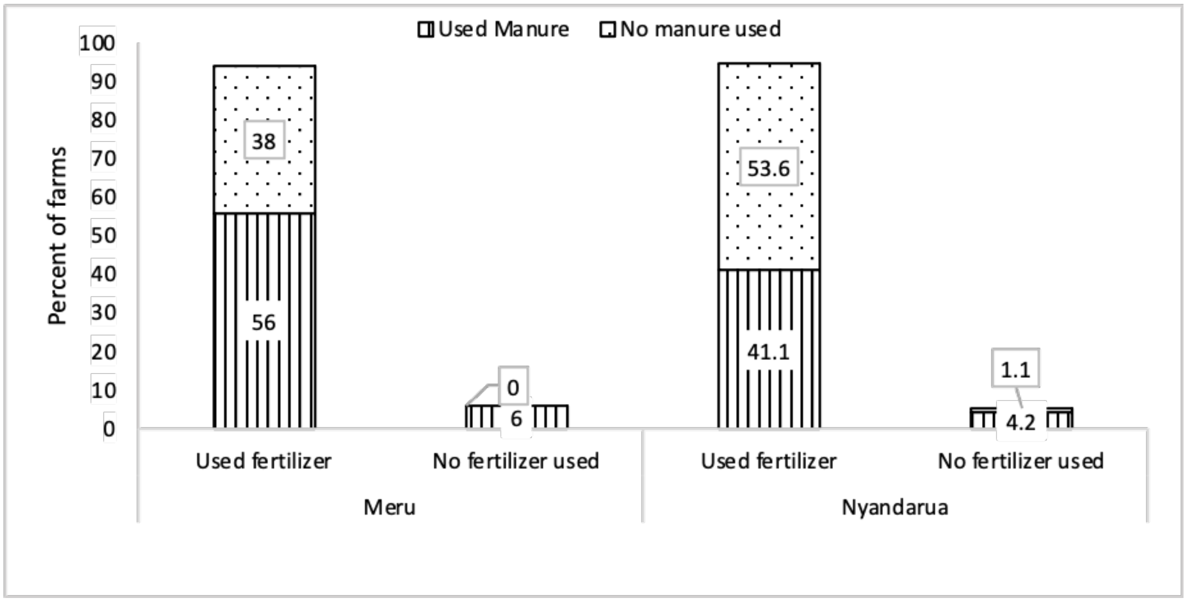


Figure 4.1: Percent of farms in which mineral fertilizer and/or cattle manure was used in Meru and Nyandarua.

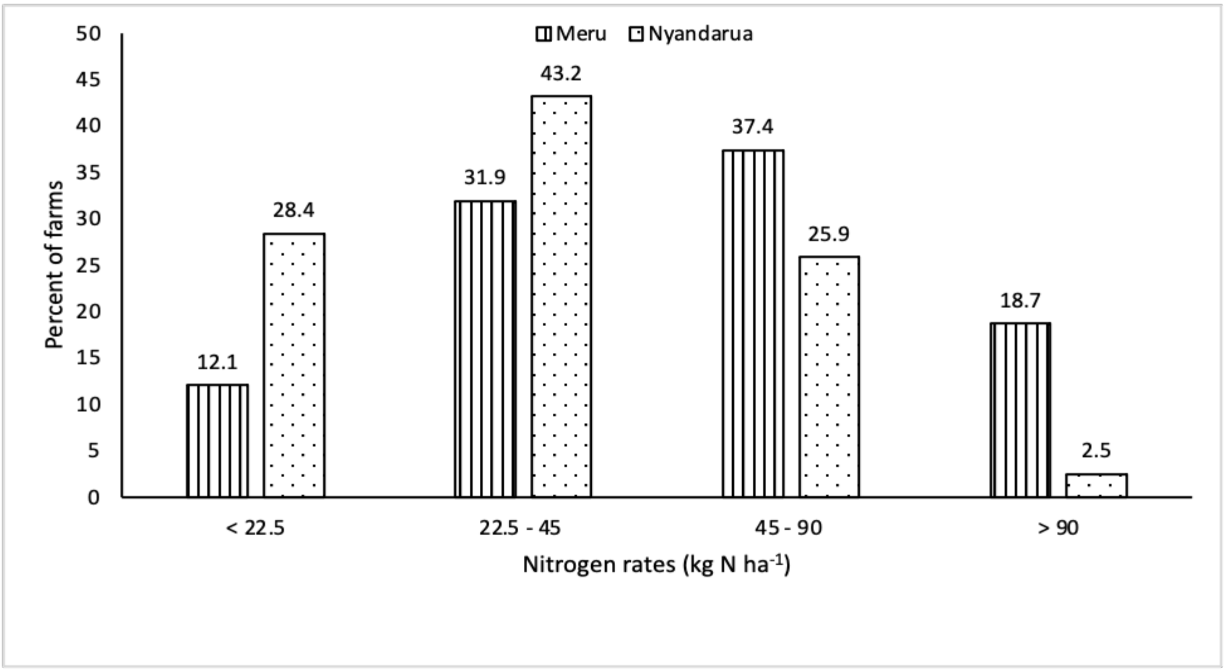


Figure 4.2: Percent of farms in which fertilizer was applied at various rate of nitrogen per hectare in Meru and Nyandarua.

4.4.2. Soil chemical characteristics

In Nyandarua, the soil pH ($CaCl_2$) ranged from 3.9 to 6.2, with an overall mean of 5.0 ± 0.5, with 86% of sampled farms having values below the critical level of 5.5 (Table 4.2). Similar results were observed in Meru which showed a soil pH range of 4.2–6.6 with 55% of the sampled farms showing pH values below the critical levels for potato production. The SOC contents ranged between 1.4–91.5 g kg^{-1} in Meru and 19.7–65.2 g kg^{-1} in Nyandarua and were below the critical levels for potato growth in 9% of sampled farms in Nyandarua and 30% of sampled farms in Meru. Total N varied widely between the sampled farms, both in Meru and Nyandarua, with 67% and 20% of the sampled farms recording values below critical levels, respectively. Soil P showed the highest variations between the sampled farms in Meru and Nyandarua with 47% and 85% of the sampled farms having this element at concentrations below the critical levels. Sulphur was below critical levels in 68% and 32% of sampled farms in Meru and Nyandarua respectively. Over 80% of the sampled farms in both regions had B below the critical levels. Zinc content showed similarity in Meru (5.1±3.5) and Nyandarua (5.6±5.3). Calcium and Mg were generally optimal in Meru and Nyandarua. Ca-Mg ratio was higher in Meru (3.63±0.88) compared to Nyandarua (1.98±0.77).

Table 4.2: Summary statistics (Mean, SD, Minimum and Maximum) and percent of farms below critical levels for potato growth in Meru and Nyandarua regions

	Meru (N=99)					Nyandarua (N=93)				
Variable	Min	Max	Mean	Std. Dev.	% farms below critical value	Min	Max	Mean	Std. Dev.	% farms below critical value
pH ($CaCl_2$)	4.2	6.6	5.4	0.6	54.5	3.9	6.2	5.0	0.5	86.2
SOC (g kg^{-1})	1.4	91.5	31.3	13.6	30.3	19.7	65.2	37.2	10.4	8.6
N (g kg^{-1})	<0.1	9.0	2.8	1.4	66.7	1.8	5.9	3.3	0.9	20.2
P (mg kg^{-1})	3.4	258.8	47.1	44.2	46.5	0.9	430.2	23.7	54.5	85.1
K (Cmol kg^{-1})	0.2	2.7	0.9	0.5	-	0.1	1.6	0.5	0.4	18.1
S (mg kg-1)	1.1	14.1	4.1	2.4	67.7	1.9	20.8	6.1	3.0	31.9
Ca (Cmol kg^{-1})	1.3	12.3	4.6	2.2	-	1.4	11.4	4.4	2.0	-
Mg (Cmol kg^{-1})	1.0	5.4	2.4	0.9	-	0.4	2.9	1.3	0.5	-
Zn (mg kg^{-1})	1.0	20.1	5.1	3.5	-	0.6	27.5	5.6	5.3	-
B (mg kg^{-1})	0.1	2.3	0.7	0.3	87.9	<0.1	2.6	0.7	0.4	80.9
Cu (mg kg^{-1})	<0.1	4.3	1.4	1.1	9.1	<0.1	1.7	0.3	0.2	51.0
C-N ratio	8.9	13.3	11.2	0.7		8.7	13.3	11.5	0.8	
Ca-Mg ratio	0.8	4.8	2.0	0.8		1.0	6.2	3.6	0.9	

4.4.3. Potato tissue nutrient content

Tissue N concentrations exhibited wide variations between the sampled farms with a mean of 40.27±5.32 g kg^{-1} in Meru and 47.39±4.98 g kg^{-1} in Nyandarua (Table 4.3). About 73% of the sampled farms had N below optimal levels in Meru compared to 23% in Nyandarua. Potassium variability was similarly high between the sampled farms averaging 47.33±10.92 g kg^{-1} in Meru and 51.64±12.52 g kg^{-1} in Nyandarua. The sampled farms with K levels below the optimal levels were 22% and 15% respectively in Meru and Nyandarua. Zinc concentrations varied between 18.3–78.9 mg kg^{-1} and 22.5–101.8 mg kg^{-1} which is within the optimal levels for potato growth. Boron and Cu similarly showed wide variations between the sampled farms averaging 31.45±3.08 mg kg^{-1} and 23.70±8.99 mg kg^{-1}, and 9.79±3.08 and 11.62±4.46 mg kg^{-1} respectively in Meru and Nyandarua. The sampled farms with B levels below critical limits were 17% and 55% respectively in Meru and Nyandarua.

Table 4.3: Summary statistics (mean, SD, Minimum and Maximum) and percent of farms below critical levels of plant nutrient content in Meru and Nyandarua regions

	Meru (N=99)					Nyandarua (N=93)				
Plant nutrients	Min	Max	Mean	Std. Dev.	% farms below critical value	Min	Max	Mean	Std. Dev.	% farms below critical value
N (g kg^{-1})	25.9	56.3	40.3	5.3	73.0	33.3	60.6	47.4	5.0	22.7
P (g kg^{-1})	1.9	5.3	3.2	0.8	24.0	2.4	5.8	3.7	0.7	1.2
K (g kg^{-1})	16.7	73.2	47.3	10.9	22.0	14.8	76.1	51.6	12.5	14.9
S (g kg^{-1})	2.7	5.3	3.5	0.5	18.0	2.8	12.4	4.5	1.3	1.2
Ca (g kg^{-1})	6.5	27.1	15.5	3.3	0.0	12.7	36.4	18.2	4.2	0.0
Mg (g kg^{-1})	5.0	16.6	9.0	2.6	0.0	4.4	16.6	7.8	2.3	0.0
Zn (mg kg^{-1})	18.3	78.9	31.9	9.4	2.0	22.5	101.8	37.7	10.6	0.0
B (mg kg^{-1})	15.8	44.7	31.5	6.5	17.0	6.5	42.1	23.7	9.0	55.2
Cu (mg kg^{-1})	3.5	16.3	9.8	3.1	5.0	5.0	26.0	11.6	4.5	1.2

4.4.4. Relationship between soil chemical properties and plant nutrient content

Tissue phosphorus was significantly positively correlated to pH (r=0.37), soil P and negatively correlated to soil Cu (r=-0.40) (Table 4.4). A significant positive correlation between tissue Ca and soil N (r=0.49) and tissue and soil Ca (r=0.49) were observed. Similarly, tissue K concentrations and soil K contents (r=0.32) correlated positively. Soil Cu concentrations correlated significantly and negatively with tissue P (r=-0.40) and N (r=-0.40).

Table 4.4: Correlations coefficients (r) between soil pH, soil chemical properties and plant tissue nutrients content in Meru region

Tissue nutrient	Soil nutrients									
	Soil pH	N	P	K	Ca	S	Mg	Zn	B	Cu
N	-0.02	0.22*	0.10	0.03	0.08	0.19	-0.07	-0.05	0.08	-0.08
P	0.37*	-0.01	0.49*	0.25*	0.31*	0.02	0.20*	0.04	0.18	-0.40*
K	0.20*	-0.27*	0.22*	0.32*	0.01	-0.23*	0.05	0.08	0.01	-0.12
Ca	0.27*	0.49*	0.13	0.01	0.49*	0.33*	0.07	0.08	0.34*	-0.40*
S	0.10	-0.14	0.11	0.01	-0.02	-0.10	0.13	-0.13	-0.07	-0.13
Mg	-0.21*	0.20*	-0.23*	-0.31*	-0.06	0.29*	-0.01	-0.15	0.03	0.30*
Zn	-0.09	-0.06	-0.08	-0.09	-0.11	0.01	-0.12	0.09	-0.03	0.06
B	-0.21*	-0.39*	-0.22*	-0.05	-0.36*	-0.06	-0.25*	0.06	-0.23*	0.26*
Cu	-0.30*	-0.59*	-0.24*	-0.18	-0.52*	-0.19	-0.09	-0.41*	-0.40*	0.44*

*level of significant $P < 0.05$

In Nyandarua, N uptake correlated negatively with the concentration of other nutrients in the soil (Table 4.5). The concentration of tissue K positively correlated with the concentration of soil P (r=0.25), Ca (r=0.22), Mg (r=0.27) and B (r=0.25). The tissue concentration of Cu was negatively correlated with the soil pH (r=-0.24) and concentration of N (r=-0.37), P (r=-0.3), Ca (r=-0.3), S (-0.33) and B (r=-0.37). An increase in soil pH and concentration of P, K and Zn increased the uptake of Zn by potato crops in Nyandarua.

Table 4.5 Correlations coefficients (r) between pH, soil chemical properties and plant tissue nutrients content in Nyandarua region

Tissue nutrient	Soil nutrients									
	Soil pH	N	P	K	Ca	S	Mg	Zn	B	Cu
N	-0.46*	-0.11	-0.22*	-0.38*	-0.26*	-0.07	-0.1	-0.18	-0.28*	0.29*
P	0.13	-0.18	0.41*	0.25*	0.16	-0.07	0.05	0.10	0.02	-0.09
K	0.40*	0.09	0.25*	0.57*	0.22*	0.16	0.27*	0.21	0.25*	-0.14
Ca	0.13	0.26*	0.12	-0.15	0.21	0.11	0.05	0.16	0.23*	-0.17
S	0.11	0.11	-0.03	0.07	0.04	-0.01	0.05	0.24*	0.02	-0.14
Mg	-0.30*	0.24*	-0.17	-0.49*	-0.1	-0.11	0.07	0.04	-0.07	0.12
Zn	-0.07	0.03	-0.22*	0.07	-0.1	-0.12	-0.04	-0.07	-0.09	0.04
B	0.34*	0.10	0.24*	0.25*	0.21	0.08	0.10	0.22*	0.19	-0.24*
Cu	-0.24*	-0.37*	-0.30*	-0.16	-0.30*	-0.33*	-0.18	-0.20	-0.37*	0.29*

*Level of significant $P < 0.05$

4.4.5. Interrelations of soil chemical properties

Soil pH positively correlated to soil P (r=0.49), K (r=0.47), Ca (r=0.79), Mg (r=0.69) and B (r=0.74) and negatively to Cu (r=-0.59) in Meru (Table 4.6). Copper was also significantly negatively correlated to N (r=-0.44), P (r=-0.39), Ca (r=-0.68), Mg (r=-0.38) and B (r=-0.37). The Ca levels were positively correlated to N (r=0.63), P (r=0.51), Mg (r=0.61), Zn (r=0.35) and B (r=0.66). Sulphur was not significantly correlated to other soil chemical properties in Meru while Zn was only significantly correlated to Ca.

The correlation of soil pH to other soil chemical properties in Nyandarua was positive for N (0.35), P (0.46), K (0.7), Ca (0.77), Mg (0.57) and B (0.75). Similarly, Cu was negatively correlated to all the nutrients and significantly with pH (-0.46), K (-0.37), Ca (-0.41) and B (-0.42). Boron was positively correlated to all analyzed nutrients apart from the correlation with Cu which was negative.

Table 4.6: Correlations coefficients (r) of soil chemical properties in Meru and Nyandarua region

Region		pH	N	P	K	Ca	S	Mg	Zn	B
Meru	N	0.31								
	P	0.49*	0.14							
	K	0.47*	0.18	0.36*						
	Ca	0.79*	0.63*	0.51*	0.27					
	S	-0.06	0.24	-0.06	0.10	0.10				
	Mg	0.69*	0.18	0.26	0.16	0.61*	-0.19			
	Zn	0.31	0.20	0.28	0.31	0.35*	-0.02	0.18		
	B	0.74*	0.49*	0.29	0.57*	0.66*	0.17	0.41*	0.31	
	Cu	-0.59*	-0.44*	-0.39*	-0.25	-0.68*	-0.08	-0.38*	-0.22	-0.37*
Nyandarua	N	0.35*								
	P	0.46*	0.28							
	K	0.70*	0.27	0.54*						
	Ca	0.77*	0.49*	0.47*	0.54*					
	S	0.33	0.28	0.36*	0.31	0.29				
	Mg	0.57*	0.55*	0.27	0.49*	0.76*	0.10			
	Zn	0.28	0.40*	0.27	0.25	0.43*	0.29	0.34*		
	B	0.75*	0.56*	0.45*	0.64*	0.77*	0.38*	0.58*	0.43*	
	Cu	-0.46*	-0.17	-0.20	-0.37*	-0.41*	-0.31	-0.22	-0.25	-0.42*

*Level of significant $P < 0.05$

4.4.6. Principal soil nutrients influencing soil fertility

Factor analysis for soil chemical properties in Meru retained 7 principal factors with the first three factors accounting for 91% proportion of the variance. Zinc and S were the most unique soil chemical properties in Meru (Table 4.7). The first factor was mainly weighted by soil pH, Ca, Mg and B whereas the second one was due to N and SOC. The Third factor was influenced by K and B. Soil Cu had a negative influence on the first factor (soil pH). Factor analysis results for the soil chemical properties in Nyandarua showed that the first three factors explained 90% of the variance. All the soil chemical properties (except Cu) which had a major influence on the first factor in Meru had a greater influence on the first factor in Nyandarua as well. The second factor in Nyandarua was dominated by SOC and N. Zinc and S were unique chemical properties in Nyandarua. In addition, Cu was found to be unique in Nyandarua.

Table 4.7: Factor loading for the first 3 factors and unique variances of soil chemical properties in Meru and Nyandarua

	Meru				Nyandarua			
Variable	Factor 1	Factor 2	Factor 3	Uniqueness	Factor 1	Factor 2	Factor 3	Uniqueness
pH	0.88	0.15	0.32	0.09	0.80	0.15	0.22	0.21
N	0.17	0.98	0.07	0.01	0.20	0.94	0.15	0.03
C	0.15	0.98	0.08	0.01	0.19	0.97	-0.03	0.02
P	0.41	0.05	0.21	0.52	0.38	0.08	0.69	0.37
K	0.23	0.09	0.63	0.51	0.62	0.11	0.40	0.33
Ca	0.77	0.50	0.06	0.07	0.85	0.29	0.17	0.13
S	-0.13	0.27	0.15	0.66	0.17	0.19	0.32	0.64
Mg	0.76	0.06	-0.03	0.37	0.72	0.47	0.00	0.17
Zn	0.22	0.15	0.28	0.77	0.31	0.30	0.16	0.65
B	0.56	0.36	0.57	0.21	0.68	0.38	0.25	0.24
Cu	-0.53	-0.35	0.01	0.42	-0.41	-0.04	-0.06	0.66

4.5. Discussion

4.5.1. Soil chemical characteristics in Meru and Nyadarua

The differences in soil chemical properties between Meru and Nyandarua were due to the differences in soil types and fertilizer and manure use. The farms examined in Meru were mainly dominated by Nitisols, which are acidic with soil organic matter content ranging from low to high (Gachene and Kimaru, 2003). Soils in the sampled farms in Nyandarua were dominated by Planosols which are formed from volcanic ash and are regarded as degraded with the surface soil being acidic (IUSS Working group WRB, 2015). Planosols due to their imperfect drainage and waterlogging, have poor soil organic carbon build-up capacity compared to the well-drained Nitisols in Meru. Organically bound nutrients, especially N and P are not available to plants because they cannot be absorbed into root cells without first being released from the organic molecule through mineralization (Ruttenberg, 2001). This process is regulated by soil microorganisms that work at optimal aeration that is not effectively provided in Planosols. Differences in soil nutrient levels and therefore tissue nutrient concentrations between Meru and Nyandarua suggest differences in cropping systems. Where the previous cropping system has caused a depletion of soil organic matter, the soils are more likely to be acidic with limited capacity to hold N, P, K, Ca and some essential micronutrients. This coupled with the low fertilizer and manure use, meant increased soil degradation. Long-term fertilization regime and manure use affect nutrient concentration, SOM, and microbial life in the soil (Cui et al., 2018). It can therefore be concluded that the farms in the two study areas had slight nutrient differences.

The low soil pH in both Meru and Nyandarua relates to the high rainfall amounts that probably caused cation leaching (Kisinyo et al., 2014a). Oxidation of DAP fertilizer commonly used by the farmers in these areas results in the formation of strong inorganic acids such as nitric acid which further lowers the soil pH (Muthoni, 2016). Low soil pH in turn affects the uptake of most macro and secondary plant nutrients by either its effects on microbial activity and dissolution of Al/Fe ions. Nitrogen, K, and S are less affected by pH but P is greatly affected, while micronutrients are mostly available in slightly acidic soil (Goulding, 2016).

4.5.2. Potato nutrient content on sampled potato farms

The relatively low soil N content in the sampled farms in Meru was reflected in the tissue N levels and could be attributed to the low soil pH coupled with the low soil organic carbon contents. Soil organic matter retains soil N and prevents it from leaching beyond the active rooting zones (Bingham and Cotrufo, 2016; Burton, 2018). Microbial activity that releases N from organic matter and certain fertilizers are particularly affected by the low soil pH since microbial activities occur best at the soil pH range of 5.5 to 7.0 (Lamb et al., 2014). In a study conducted to compare the yield response of potatoes to N levels, a larger response was exhibited in soils with higher soil organic matter content irrespective of the amount of N applied, and the recovery of the applied N was greater where the soil pH was slightly above 6.0 (Moulin et al., 2012; Faridvand et al., 2021). The large number of farms with N nutrients below optimum levels could thus be a result of nutrient leaching, low amount of N replenishment, and high nutrient mining as a result of continuous farming (Burton, 2018; Mohler and Johnson, 2009). According to Westerman (2005), potato takes up to 235 kg N ha^{-1}, which is mined out of the soil in a growing season.

The low soil P content was reflected in tissue P content suggesting reduced uptake. This observation could be ascribed to the predominating clay soils in these study areas (Gachene and Kimaru, 2003) as well as to the low soil pH. Both Nitisol and Planosols examined in this study had clay content >30% (Gachene and Kimaru, 2003). Clay soils and acidic soils have high Al and Fe contents which besides fixing the available soil P are associated with increased soil acidity, thus leading to an inconsistent response to soil P by potato leaf uptake (Mnthambala et al., 2016; Shen et al., 2011). The observed low soil phosphorus could be associated with the leaching of P, especially when the soil's sorption capacity is saturated (Haygarth et al., 1998). There is recent evidence that higher P concentrations are found in the soil water moving in the bypass flow pores within agricultural farms (Fisher, 2015; Nyawade et al., 2019). Poor P recovery through fertilizer application under acidic conditions is because the P applied in the form of fertilizers is mainly adsorbed by the soil (Mnthambala et al., 2016). Furthermore, P is largely transported offsite and attached to the sediment to be later released via dissolution or made available when anoxic conditions are present (Nyawade, 2015). The reduction of transport would also mean reduced uptake.

Soil K in Meru was adequate however this was not the case with the tissue K concertation. The differences between soil K and its uptake in Meru could be a result of cation balances. A study has shown Mg-induced K deficiency on Nitisol (Koch et al., 2019; Laekemariam et al., 2018). Soil moisture also affects the uptake of K since it helps in mass flow movement (IPNI, 1998). Lower soil moisture in Nitisol would thus mean reduced K uptake. Further to this, low soil pH indirectly affects K uptake. At low soil pH, Al becomes soluble thus dominating CEC hence lowering the soil capacity to hold K (Havlin, 2013). Potassium is of high importance in potato growing as it affects tuber yield and quality and it is the highest absorbed nutrient (Westermann, 2005).

Leaf S concentration was appreciably lower than the critical concentration. This was an indication that S deficiency is a problem in the potato-growing farms in Meru and Nyandarua. This observation is consistent with other findings that have established that potatoes do not respond to sulphur applications except in extremely deficient soils (Kenya Soil Survey, 2014; Sharma et al., 2011). If soil test S is less than 7 ppm and/or tissue S is less than 0.18%, then 20 kg S per hectare should be banded at planting (Burke, 2017; Reuter et al., 1997; Singh et al., 2016). Factors contributing to this increased incidence of S deficiency among the examined farms may be related to the use of S-free fertilizers such as urea and di-ammonium phosphate (Muthoni et al., 2013b; Muthoni and Nyamongo, 2009). This is despite the fact that potato tubers remove a high amount of S; typically 1 tonne of potato tubers will remove 4.5 kg of S (Burke, 2017). The low soil organic matter could also lead to low S as 95% of S is known to be associated with organic matter (Burke, 2017).

Boron and Cu were generally limited in the soils tested, an observation that was reflected in the potato tissues. This observation could be asserted to the limited supply of these nutrients in the soil and the overall low soil organic matter content of the sampled soils (Jones et al., 2017). Low soil pH would also be a contributing factor as a result of Al solubility that interferes with uptake and transport of other nutrients (Burke, 2017). The high level of B deficiency in the sampled farms in Meru could be associated with nutrient leaching coupled with low soil pH which hinders B uptake by potatoes (Ahmad et al., 2012). Elsewhere, B deficiency has been related to the low soil organic matter contents, especially under prevailing cold wet weather and in periods of drought (Burke, 2017; Jones et al., 2017).

4.5.3. Correlations between soil chemical properties and plant nutrient content

The significant positive correlation between leaf P and soil P relates to the low P ions in the soil solution at the root surface. This is in accordance with Morgan & Connolly (2013) who observed that potato responds to nutrient deficiency by changing its root structure to increase the overall nutrient acquisition. Burke (2017) similarly argued that the ability of potato crops to absorb P will depend on the concentration of P ions in the soil solution at the root surface. The significant interaction between tissue P concentrations and soil P contents indicates that this element was limiting in the majority of the sampled farms. Soil pH and tissue P content similarly showed significant associations implying their interactive effects. These relations could be linked to the low content of active P forms in the highly weathered clay dominating soils in this study sites (Gachene and Kimaru, 2003), since in acidic soils, P may be adsorbed by Fe or Al oxides, and various clay minerals (Burton, 2018).

The significant relationship between tissue K concentrations and soil K contents reflects soil K deficiency in several of the sampled farms. Though the tropical soils are generally considered to be sufficient in K, deficiency of this element was evident in this study. Potatoes take up more K than many other arable crops (Gitari et al., 2018b; Westermann, 2005). During peak vegetative growth, potatoes may require 10 kg K_2O ha^{-1} per day from the soil (Kolbe and Stephan-Beckmann, 1997). At about 80 days after emergence high yielding potato crop may remove more than 500 kg of K_2O ha^{-1} (Burke, 2017). At harvest, more than 75% of the K uptake is found in the tubers, which typically contain around 5.8 kg K_2O per tonne of tubers (Burke, 2017). As the potato crop is harvested and the tubers are removed from the field, K is taken away in that crop material. This must be replaced otherwise future crops will be grown in soil with a reduced K level, resulting in low yields.

Significant negative relations were exhibited between tissue Cu nutrient content and soil N, P, Ca, B, and Zn indicating that tissue Cu concentrations seem to level off at certain concentrations of these elements. Similar results have been reported elsewhere (Korkmaz et al., 2015). This would suggest that Cu toxicity is becoming a greater concern in Nitisols and Planosols. The significant correlation between tissue Cu concentrations and soil Cu content however indicated that Cu was a limiting nutrient requiring corrective measures. The positive association between tissue magnesium and soil Cu content showed synergy between these two nutrient elements. This would suggest that Mg uptake by potatoes increases with increasing levels of Cu concentrations in the soil. The positive correlation between tissue Ca and soil N, S, and B would mean Ca uptake by a potato is more efficient in soils with optimum N, S, Ca and B levels. The role of Ca and B on cell wall formation and auxin transport thus explains the correlation (Tariq and Mott, 2007).

Soil pH is the single factor affecting soil nutrients due to its effects on microbial activity and nutrient dissolution (Burke, 2017). High concentrations of Ca^{2+} in the soil solution increase the soil pH which reduces the solubility of Al and Fe ions and enhances the solubility and availability of certain micro-nutrient elements. Boron levels are associated with soil organic matter thus the low soil organic matter could be the reason for B correlations with other soil nutrients. This implies that the trend of soil nutrient element depletion is similar and that with continuous mining, other nutrients will become limiting. The negative effect of Cu levels on most of the other soil nutrients has been reported in other studies (Arora and Sekhon, 1982; Azeez et al., 2015). Copper has a negative effect on soil bacteria which would in turn affect other soil nutrient concentrations (Nunes et al., 2016).

4.5.4. Principal soil nutrients influencing soil fertility

Factor analysis results showed that soil pH and CEC related to soil chemical properties (K, Ca, Mg) influenced the first factor. The higher the bases (K, Ca, Mg) the higher the soil pH. This would thus reinforce that soil pH is a major factor to consider for sustainable nutrient management (Jones et al., 2017). The second factor affecting soil fertility in the two regions was soil organic matter. Soil organic matter retains nutrients especially N, P and S. Soil organic matter is subjected to change by cropping system and management practices and its influence on soil fertility is thus important (Burke, 2017; Jones et al., 2017). Management of the soil pH and soil organic matter factors would thus improve soil fertility in the studied region.

The low soil nutrient contents measured for N, P, K, S and B were reflected in the tissue nutrient concentrations which were consistently lower indicating that nutrient uptake by potato crop was influenced by soil nutrient concentrations. The correlations were however not very strong which could be explained by other confounding factors influencing nutrient uptake such as crop variety, farm management, climatic factors and crop health status (Fernandes et al., 2017; Nunes et al., 2006; Westermann, 2005). Similar relations have elsewhere been reported (Hailu et al., 2015; Mari et al., 2009). Nutrient interaction in the soil and within the plant also affects crop nutrient uptake (Farias et al., 2013; Korkmaz et al., 2015).

4.6. Conclusions

This study shows that N, P, K, S and B are the key nutrients limiting potato production in the highlands of Kenya. These nutrients need to be integrated in nutrient management programs for major potato-growing areas of Kenya. Soil pH was found to be low in all the sampled farms and was the major factor that influenced nutrient uptake by potato crops. Improved cropping systems and soil management practices are required to adjust the soil pH for enhanced soil fertility in the study areas.

CHAPTER FIVE

Response of potato crop to selected nutrients in Central and Eastern highlands of Kenya

Abstract

Low nutrients have been reported in potato growing areas of Kenya prompting a need for nutrient management research. A study was designed to determine the effect of omitting nutrients on potato growth, yield and harvest index. On-farm nutrient omission trials were set during the long rains (LR) and short rains (SR) of 2016 in which the treatments involves the judicious omission of N, P, K, S and B. Additional two treatments were included with one receiving all the nutrients and control where no nutrients added. The treatments were laid in a randomized complete block design with three replications. Potato yields were reduced by 6.6 and 11.2 t ha^{-1} in N omitted treatments in LR and SR, respectively when compared to the one receiving all the nutrients, while omitting P resulted in respective yield reduction of 3.8 and 2.0 t ha^{-1}. Stability analysis revealed that omission of N was more stable with a regression coefficient of 0.5, it was followed by P with a value of 1. Potassium, S and B were limiting nutrients only in some farms. N and P should continue to be included in potato nutrient management while K, S, and B should be added based on the soil test.

5.1. Introduction

The potato crop is widely grown by many communities living in the highlands of Eastern and Southern Africa (Gildemacher, et al., 2009). The increasing importance of the crop can be attributed to its potential contribution to income generation, nutrition and food security (Cromme, et al., 2010). Reaching the potential of potatoes in terms of productivity has been elusive for smallholder farmers due to constraints such as inappropriate use of yield-enhancing inputs (Gildemacher, et al., 2009; Janssens, et al., 2013; Muthoni & Nyamongo, 2009). Farmers are facing yield detrimental effects due to nutrient mining (Kaguongo et al., 2008; Muthoni, 2016; Nyawade, et al., 2018; Nyawade, 2015). Furthermore, harvesting of potatoes results in nutrient loss through erosion when soil particles are carried together with the tubers (Li et al., 2006, Parlak & Blanco-Canqui, 2015; Ruysschaert, et al., 2007). On the other hand, tubers export nutrients out of the farm system thus replenishment of lost nutrients is paramount (Koch, et al., 2019; Naumann, et al., 2020). There is also the tendency of growing potatoes in close rotation or even in mono-cropping due to limited available land (less than 2 ha) and lack of other alternative high-value cash crops in most potato-growing areas of Kenya (Muthoni, et al., 2013; Schulte-Geldermann, et al., 2012). Under such conditions, improvement in soil fertility can play a major role in increasing potato production of smallholder farmers (Gildemacher et al., 2009b).

Soil fertility management in Kenyan highlands is key since recent surveys have indicated a lower level of nitrogen (N), phosphorous (P), potassium (K), sulphur (S) and boron (B) in major potato-producing regions such as Meru and Nyandarua (Kenya Soil Survey, 2014; Mugo, 2013; Mugo et al., 2020). The Soil bulk density (g/cm3) in the area averages 1.03, cation exchange capacity 18.48 meg 100g-1, and total organic carbon 3.5%, while over 50% of potato-producing farms have pH below 5.5, this can severely limit the availability of important plant nutrients (Kenya Soil Survey, 2014; Mugo et al., 2020; Recke, et al., 1997). Farmers in the highlands apply inorganic fertilizer to boost their potato production and potato ranks third to maize and wheat in terms of fertilizer used (Oseko and Dienya, 2015).

Reported fertilizer use among potato farmers, however, does not reflect the expected level of productivity since low yields are still reported in farmers' fields (FAOSTAT, 2019), this has been attributed to fertilization among other challenges. Survey results indicate the majority of farmers apply below half of the recommended fertilizer (90 Kg N ha^{-1}) (Mugo, 2013; Mugo et al., 2020; Muthoni & Nyamongo, 2009). Farmers under fertilize the farms due to a complex of factors such as limited knowledge on soil status, high cost of fertilizers, poor quality manure, limited options on available fertilizers types, as well as low returns on investment in fertilizer application due to possible unresponsive soils (Bindraban et al., 2018; Fairhurst, 2012; Gildemacher, et al., 2009). In addition, there could be an unbalanced soil nutrient, which in turn affects the nutrient uptake thus affecting crop response to nutrient additions (Gitari et al., 2020; Ochieng' et al., 2021; Nyawade et al., 2020).

Over the years, constraints associated with fertilizer use by farmers ranging from the type of fertilizer, rates of application, patterns of application, and nutrient status have thus been the focus of research (FURP, 1994; Kenya Soil Survey, 2014; Mugo, 2013; Recke et al., 1997). Mainly compound fertilizers, DAP, NPK 17:17:17, NPK 23:23:0, and Calcium ammonium nitrate have been evaluated in combination with organic sources (Muthoni & Kabira, 2011; Rop, et al., 2019). A blanket recommended rate of 90 kg N ha^{-1} is mainly used as a reference, though the application of 75 kg ha-^{1} and above of N and P have however been reported to have yield responses on potatoes (Recke et al., 1997). In the recent past, the focus has been on limiting nutrients and crop responses which have revealed N and P as maize yield limiting (Kihara et al., 2016; Nziguheba et al., 2015). Further, surveys have revealed above 20% of farms are below in levels of N, P, K, B, Cu, and B for crop production (Mugo et al., 2020; Vanlauwe et al., 2017; Wortmann et al., 2019). Thus the question of how the potato crop responds to different nutrients remains unanswered.

Nutrient omission trials which follow Liebig's law of the minimum, have been used both on pot and field trials to determine crop response to the addition of specific nutrients thus determining the most limiting nutrient (Njoroge, et al., 2019; Rurinda et al., 2020; Valeva & Stamenov, 2017; Kihara et al., 2016). One nutrient is omitted while the rest are applied in adequate amounts, the effect of an omitted nutrient on crop growth and yield indicates the limitation of the nutrient (Huising, et al., 2011). The use of potatoes for nutrient omission trials has not been conducted in Kenyan highlands thus this study would add valuable information.

Unresponsiveness to the addition of limiting nutrients has been reported in studies using several crops (maize, sorghum, cassava beans, and pigeon peas) in different areas and including non-response to both macro and secondary nutrients (Kihara et al., 2016). Unresponsiveness has been attributed to the nutrient being strongly fixed in the soil (especially P) thus being unavailable to the plant (Fixen and Bruulsema, 2014; Muindi et al., 2015; Wilhelm, 2009). Most farmers do not have enough knowledge of their farms' soil fertility status (Muindi, et al., 2016). This means they run a risk of continuously adding the nutrients without any meaningful response on yields. This study was therefore set purposely to evaluate the response of potatoes to the application of selected nutrients in two major potato-producing regions of Kenya using on-farm nutrient omission trials.

5.2. Materials and methods

5.2.1. Site description

The study was conducted during the two rainy seasons of 2016 (long rains (LR) and short rains (SR)) in Meru and Nyandarua counties, which are among the largest potato-producing regions in Kenya. During LR planting was done in mid-March and harvesting in early July while in SR planting was done in mid-October and harvesting in January. Three (3) sites were used, 2 in Meru (Meru 1: 0.106ºN, 37.513ºE, 2384 meters above sea level (masl) and Meru 2: 0.091ºN,37.500ºE, 2348 masl) and 1 in Nyandarua (Nyandarua: 0.363ºS, 36.507ºE, 2463 masl). The sites were selected from a pool of previously sampled farms in a related study focusing on assessing the status of plant available soil nutrients in potato fields in the Meru and Nyandarua regions of Kenya (Mugo et al., 2020). The farms selected for the study had at least two major nutrients in an inadequate state for optimal potato production (Table 5.1). In Meru 1, P, S, and B were below critical levels while in Meru 2 P, K and B were below the critical level, in Nyadarua N, P and B were below the critical level.

5.2.2. Soil chemical properties

Soil types in Meru sites are Nitisol which is reddish-brown, very deep, and well-drained friable clay (Spaargaren, 2008). On the other hand, the Nyandarua site has Planosols as the dominant soil type, which is imperfectly drained with a pronounced and abrupt transition between relatively light-textured topsoil, part of which is whitish, and a heavy textured, compact and hard B-horizon. The chemical properties of the experimental site at 0−0.3 m depth are shown in Table 5.1.

Table 5.1: Soil chemical properties of the three study sites

	Meru 1	Meru 2	Nyandarua	*Critical nutrient levels
pH (0.01M $CaCl_2$)	4.8	4.3	4.6	5.5
SoC (g Kg^{-1})	28.0	30.4	27.2	25.0
Total N (g Kg^{-1})	2.5	2.5	2.4	2.5
P (mg Kg^{-1})	15.7	7.0	7.1	30.0
K (Cmol Kg^{-1})	0.4	0.2	0.4	0.2
S (mg Kg^{-1})	2.6	9.3	6.9	4.5
Ca (Cmol Kg^{-1})	2.7	2.0	1.8	0.9
Mg (Cmol Kg^{-1})	1.8	0.7	1.7	0.3
Zn (mg Kg^{-1})	6.7	2.1	1.3	0.6
B (mg Kg^{-1})	0.4	0.5	0.5	1.0
Cu (mg Kg^{-1})	1.6	0.4	4.0	0.2

*critical nutrient level source (Mangale et al., 2016)

5.2.3. Climate data

Rainfall in the two regions is bi-modal, with the long rain coming in March to July while the short rain coming in October to January. During the study period, the total rainfall per season was slightly high in Nyandarua (593 mm and 301 mm for LR and SR, respectively) region as compared to the respective values of 359 mm and 227 mm for Meru. It was also slightly cool in Nyandarua with an average seasonal maximum temperature of 25 ºC compared to 28 ºC in Meru while the respective average minimum temperatures were 17 ºC and 14 ºC (Figure 5.1).

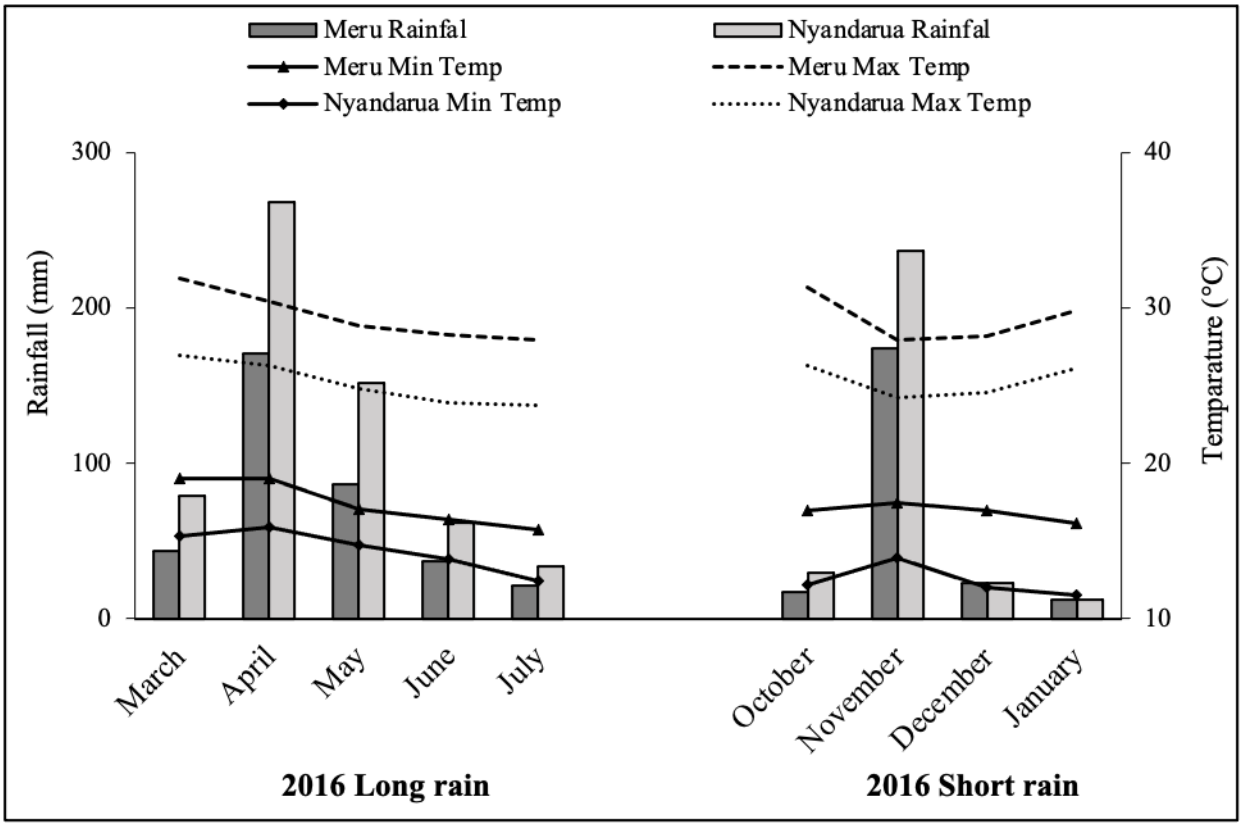


Figure 5.1: Rainfall, minimum and maximum temperatures in Meru and Nyandarua sites during the study period.

5.2.4. Experimental design and treatments

The trials were laid out in a randomized complete block design (RCBD) with three replications. The plots measured 4.5 m long by 3 m wide, with potatoes planted at a spacing of 0.3 m within a row and 0.75 m between rows targeting a plant density of 44,444 plants ha^{-1}. The treatments were composed of, i) no nutrients supplied (control), ii) all the tested nutrients supplied (NPKSB) and iii) five treatments in which one of the tested nutrients was omitted at a time while other nutrients were applied at adequate levels (Table 5.2). The nutrients tested were N, P, K, S and B. The rate of each nutrient applied was calculated based on the nutrient requirement for a target yield of 40 t ha^{-1} as described by Westermann (2006). Nitrogen was supplied using urea, P by triple superphosphate (TSP), K by murate of potash (MOP), S by sulphate of potash (SOP) and Boron by Solubor (disodium octaborate tetrahydrate).

Table 5.2: Nutrients application rate for each treatment

Treatment	Nitrogen	Phosphorus	Potassium*	Sulphur	Boron
			Kg ha^{-1}		
Control	0	0	0	0	0
Minus N	0	100	224	15	0.2
Minus P	130	0	224	15	0.2
Minus K	130	100	44	15	0.2
Minus S	130	100	224	0	0.2
Minus B	130	100	224	15	0
NPKSB	130	100	224	15	0.2

* Potassium was not completely omitted since sulphate of potash used to supply S contained K.

Potato variety Shangi was planted from well-sprouted seed. The variety is semi erect-medium tall which is an early maturing and planted by the majority of farmers (NPCK, 2019). At planting, potatoes were supplied with the respective fertilizer elements (Table 2). Urea was applied in two splits to avoid excessive leaching. 168 g TSP, 405 g MOP, 112.5 g SOP, and the first split of Urea (191 g) fertilizers were band applied and mixed with the soil properly before placing the tubers. Foliar application of B was done 15 days after emergence (DAE) while the second split of urea was applied 15 DAE.

The first weeding and hilling-up for potatoes were carried out manually at 15 DAE while the second weeding and hilling-up were done at 30 DAE. Potatoes were sprayed with Ridomil Gold MZ 68 WG (Mefenoxam 40 g kg^{-1} + Mancozeb 640 g kg^{-1}) alternated with Dithane M45 WP (Mancozeb (dithiocarbamate) 800 g kg^{-1}) after every 14 days starting at 15 DAE to control late blight. The trials were conducted under rain-fed conditions. However, supplemental irrigation was done in site 2 during LR and in site 1 in SR.

5.2.5. Growth and yield determination

Leaf area index (LAI) was measured using an LAI-2200 plant canopy analyzer (LI-COR, Lincoln, NE, USA) at 30 and 45 DAE and used as an indicator of potato growth. The measurement was made when the sky was clear with minimal uniform clouds at around mid-day local time. Destructive sampling of 6 plants in the inner rows was done at 60 DAE to collect samples for determination of the fresh and dry weight of plants and tubers. Fresh weight was measured immediately after sampling then a sub-sample of 500 g was weighed, oven-dried at 60 ° C for 72 hours, and eventually reweighed for dry weight determination. The final yield was determined by harvesting the 33 remaining inner plants at full maturity between 90 – 100 DAE. Yield response was calculated for each of the nutrient treatments for every site using equation 1.

$$\text{Yield response (\%)} = \frac{(\text{Y} - \text{Y0})}{\text{Y0}} * 100 \qquad (1)$$

Where Y = tuber yield of respective nutrients plots (t ha^{-1}), Y0 = tuber yield of the control (no fertilizer) (t ha^{-1}) of nutrient omission plots.

Harvest index (HI) was determined using data obtained during sequential harvest using equation 2.

$$\text{Harvest Index} = \frac{\text{Tuber DW}}{(\text{Tuber DW} + \text{Haulm DW})} \qquad (2)$$

5.2.6. Data analysis

The effect of the treatments on potato LAI, HI, and yield was tested using a mixed model where the season, site, and the treatments were considered as a fixed term while replications were considered random. Analysis was done in R Software version 3.5.2 (R Core Team, 2018). The treatment means were compared using Least Significant Difference (LSD) at $p \leq 0.05$. The effect of the treatment was regressed and plotted against the environmental/site yield calculated as the mean yield as described in the stability analysis approach (Raun et al., 1993). The stability analysis was done to determine how treatments were stable to the environmental factors by observing the linear regression coefficient. The smaller the regression coefficient the more stable the treatment effect (Raun et al., 1993).

5.3. Results

5.3.1. Leaf area index

Crop growth measured in terms of the leaf area index (LAI) was significantly affected by nutrient omissions (Table 5.3). The effect was significant at both growth stages in the two seasons ($p<0.001$). At flowering, the treatment in which all nutrients were added (NPKSB) had slightly lower LAI as compared to treatments where K and S were omitted, however, N and P had lower LAI compared to NPKSB treatment. On average, omitting N lowered potato growth the most at bulking stage (LAI of 0.75 and 1.01 in LR and SR respectively) followed by P which lowered the LAI at bulking by 0.71 and 0.88 in LR and SR respectively. NPKSB treatment increased potato growth as revealed by increased LAI from the control (no nutrient applied) treatment by 37 and 70% in LR and SR respectively at the flowering stage and 43 and 38% LR and SR respectively at the tuber bulking stage. Sites did not significantly influence potato growth at both the flowering and bulking stage during the two seasons. The seasonal differences could only be detected at the flowering stage and not at the tuber bulking stage.

Table 5.3: Potato leaf area index (LAI) at flowering and tuber bulking stages

		Flowering stage (30 DAE)		Bulking stage (45 DAE)	
Site	Treatment	2016 LR	2016 SR	2016 LR	2016 SR
Meru 1	Control	0.36b	0.34b	1.2a	1.3a
	Minus N	0.40b	0.49b	1.0a	1.3a
	Minus P	0.64ab	0.89a	0.8a	1.3a
	Minus K	0.81ab	1.16a	0.7a	2.53a
	Minus S	1.01a	1.22a	1.4a	1.92a
	Minus B	0.57ab	1.04a	0.9a	2.49a
	NPKSB	0.48ab	1.14a	1.5a	2.56a
Meru 2	Control	1.63a	0.25d	1.14a	1.11bcd
	Minus N	1.39a	0.29d	1.25a	0.74d
	Minus P	1.47a	0.75c	1.70a	1.05cd
	Minus K	2.17a	1.21ab	1.89a	1.90ab
	Minus S	2.64a	1.33a	2.11a	2.25a
	Minus B	1.21a	0.93bc	1.38a	1.78abc
	NPKSB	2.54a	0.99abc	2.63a	2.02a
Nyandarua	Control	0.44a	0.17a	0.55a	1.17a
	Minus N	0.80a	0.19a	0.73a	0.73a
	Minus P	0.69a	0.48a	0.63a	0.84a
	Minus K	1.14a	0.46a	1.13a	0.94a
	Minus S	0.42a	0.37a	0.79a	0.85a
	Minus B	1.17a	0.79a	1.43a	1.23a
	NPKSB	0.85a	0.42a	1.07a	1.23a

Analysis of variance (*p* values)

Factor	S	SI	T	S*SI	S*T	SI*T	S*SI*T
Flowering stage	<0.001	ns	<0.001	<0.001	ns	ns	ns
Bulking stage	ns	ns	<0.001	<0.001	ns	ns	<0.01

S= season, SI= site, and T= fertilizer treatment, DAE= days after emergence. Means followed by the same letter (within the same column and same site) are not significantly different ($p \leq 0.05$) by the LSD test.

5.3.2. Haulm dry weight and harvest index

Haulm dry weight was significantly different in Meru 1 during LR and in Meru 2 during SR (Table 5.4). Significant differences in Meru 1 were mainly because of the effect of control and omission of N treatments in relation to other treatments in which they reduced growth from NPKSB treatment by 41% and 37% respectively. In Meru 2, the significant differences were between control, omission on N and P against other treatments where they reduced growth from NPKSB treatment by 47%, 56%, and 48% respectively. Omission of B did not reduce potato growth in Meru 1 and Nyandarua. Treatments effects were significant between the seasons and between the sites. The HI was significantly lower in the control plots when compared to the omission of other nutrients in most sites during SR. It was lower than the NPKSB treatment by 15% in Meru and 30% in Nyandarua. Omission of N also lowered the HI in all the sites during the two seasons apart from Meru 1 in the LR. The reduction was high (25%) in Meru 2 in SR. The effect of omitting other nutrients varied from with sites and seasons. The effect of sites and season were found to be significant.

Table 5.4: Haulm dry weight (DW) and harvest index for potato at tuber bulking stage

		Haulm DW (Kg plant^{-1})		HI	
Site	Treatment	2016 LR	2016 SR	2016 LR	2016 SR
Meru 1	Control	8.81c	25.88a	0.74a	0.64b
	Minus N	9.39bc	27.03a	0.70a	0.68ab
	Minus P	21.50a	25.16a	0.69a	0.79a
	Minus K	22.28a	37.62a	0.68a	0.77ab
	Minus S	14.32abc	36.21a	0.67 a	0.74ab
	Minus B	17.47ab	41.26a	0.64a	0.69ab
	NPKSB	14.94abc	38.67a	0.67a	0.76ab
Meru 2	Control	28.15a	21.30c	0.75ab	0.48bc
	Minus N	27.03a	13.92c	0.72b	0.42c
	Minus P	35.65a	21.03c	0.70b	0.67a
	Minus K	24.59a	36.83ab	0.83 a	0.63ab
	Minus S	39.90a	45.69a	0.75ab	0.54abc
	Minus B	25.21a	34.19b	0.74ab	0.62ab
	NPKSB	36.70a	40.40ab	0.73ab	0.56abc
Nyandarua	Control	12.93a	20.93a	0.65ab	0.47b
	Minus N	23.81a	17.20a	0.55bc	0.56ab
	Minus P	21.65a	16.31a	0.58abc	0.66a
	Minus K	23.84a	18.36a	0.68a	0.53ab
	Minus S	26.29a	17.12a	0.54c	0.62ab
	Minus B	27.84a	23.81a	0.64abc	0.68a
	NPKSB	24.80a	21.94a	0.58abc	0.68a

Analysis of variance (*p* values)

Factor	S	SI	T	S*SI	S*T	SI*T	S*SI*T
Haulm DW	0.003	<0.001	<0.001	<0.001	ns	ns	ns
HI	0.001	<0.001	0.012	<0.001	<0.001	ns	ns

S= season, SI= site, and T= fertilizer treatment, HI= harvest index. Means followed by the same letter (within the same site and column) are not significantly different ($p \le 0.05$) by the LSD test.

5.3.3. Haulm macro-nutrient uptake

Uptake of N, P, and K were significantly different in the three sites and only N uptake was significant between the seasons and nutrient omission treatment (Table 5.5). In Meru 1, omission of N resulted in 10, 0.6, 1.2 t ha^{-1} lower N, P, and K uptake respectively compared with the wholly fertilized treatment (NPKSB) in 2016 LR whereas the respective values for SR were 30, -0.6, 1.2 t ha^{-1}. In Meru2, significant uptake was experienced for N and P while no significant uptake of K. Omission of N and control reduced uptake of N, P, and K while the omission of S treatment mostly had high N, P, and K uptake compared to NPKSB. There were no significant differences in uptake of N, P, and K in Nyandarua in all the two seasons. Omission of S and B mostly had higher N, P, and K uptake when compared to NPKSB treatment.

Table 5.5: Haulm N, P, K uptake under omission of selected nutrients

		N t ha^{-1}		P t ha^{-1}		K t ha^{-1}	
Site	Treatment	2016 LR	2016 SR	2016 LR	2016 SR	2016 LR	2016 SR
Meru 1	control	13.64b	40.26a	1.50b	4.39a	3.36b	8.78a
	minus N	14.06b	39.28a	1.20b	4.64a	2.06b	6.85a
	minus P	32.17a	38.01a	3.85a	4.25 a	6.41ab	4.46a
	minus K	32.32a	60.21a	3.53a	4.59a	9.89a	8.58a
	minus S	21.47ab	57.75a	2.14ab	4.49a	6.78ab	11.93a
	minus B	26.01ab	61.54a	2.38ab	5.63a	4.10b	8.07a
	NPKSB	24.15ab	58.56a	1.82ab	3.95a	4.25b	8.05a
Meru 2	control	43.72ab	29.42c	4.82a	3.15cd	8.91a	8.02a
	minus N	39.70b	14.14d	4.77a	2.09d	7.59a	3.64a
	minus P	54.64ab	28.94c	6.22a	2.46cd	7.44a	6.36a
	minus K	57.88ab	51.30ab	4.61a	6.44ab	10.27a	10.15a
	minus S	63.38a	62.45a	5.59a	8.30a	14.69a	9.48a
	minus B	37.84b	43.37b	3.12a	4.75bc	5.05a	11.44a
	NPKSB	55.27ab	61.12a	4.26a	4.01bcd	8.48a	9.52a
Nyandarua	control	17.8a	24.30a	1.85a	1.81a	4.80a	5.03a
	minus N	32.46a	21.76a	3.35a	3.09a	2.59a	5.83a
	minus P	29.80a	22.48a	2.81a	1.74a	6.19a	4.73a
	minus K	33.19a	23.09a	4.20a	1.47a	6.28a	4.66a
	minus S	35.86a	18.63a	4.84a	2.37a	4.98a	4.56a
	minus B	36.45a	27.15a	4.17a	2.16a	7.29a	6.17a
	NPKSB	33.03a	25.10a	3.55a	3.26a	7.24a	6.28a

Analysis of variance (*p* values)

Factor	S	SI	T	S*SI	S*T	SI*T	S*SI*T
Haulm N	0.04	<0.001	<0.001	<0.001	ns	0.018	ns
Haulm P	ns	0.002	ns	<0.001	ns	ns	ns
Haulm K	ns	0.029	ns	ns	ns	ns	ns

S= season, SI= site, and T= fertilizer treatment, HI= harvest index. Means followed by the same letter (within the same site and column) are not significantly different ($p \leq 0.05$) by the LSD test

5.3.4. Effects of omitted nutrient on potato yield

The yield was generally low in all the sites apart from where irrigation was done. Omitting N reduced yield most. For instance in LR, the omission of N reduced the yield by 3.3 t ha^{-1} (32%) and 6.6 t ha^{-1} (37%) at sequential and final harvest, respectively while in SR the reduction was8.9 t ha^{-1} (65%) and 11.2 t ha^{-1} (64%) compared to NPKSB during sequential and final harvests (Table 5.6). Phosphorus, which was the second most limiting nutrient, reduced yield from NPKSB treatment by 2 and 19% in LR and SR, respectively during sequential harvest, and 21 and 11% in LR and SR, respectively at final harvest. The final yield reduction from NPKSB with the omission of N was significant ($p<0.05$) in sites one and two during SR in which it reduced yield by more than 10 t ha^{-1}.

Table 5.6: Potato yield at 60 (sequential) and 90 (Final) days after emergence (DAE).

		2016 Long rains		2016 Short rains	
Site	Treatment	Sequential harvest	Final harvest	Sequential harvest	Final harvest
		t ha^{-1}			
Meru 1	Control	4.92a	5.29b	8.25a	10.79b
	Minus N	4.76a	4.92b	9.26a	11.84b
	Minus P	11.36a	10.57ab	19.58a	28.17ab
	Minus K	10.69a	13.87a	23.2a	32.95a
	Minus S	6.06a	12.68ab	21.01a	33.76a
	Minus B	7.31a	11.32ab	19.86a	39.04a
	NPKSB	6.90a	11.69ab	23.50a	32.37a
Meru 2	Control	13.31a	20.99a	3.88bc	4.82bc
	Minus N	12.02a	17.93a	1.86c	2.53c
	Minus P	14.94a	21.98a	8.16ab	11.92ab
	Minus K	19.05a	22.82a	11.53a	15.44a
	Minus S	18.65a	28.84a	10.28a	15.01a
	Minus B	12.03a	20.41a	10.22a	13.54a
	NPKSB	19.01a	26.71a	10.00a	13.41a
Nyandarua	Control	3.69a	5.53b	3.22b	3.62b
	Minus N	4.98a	11.4ab	3.58b	4.66ab
	Minus P	4.99a	10.13ab	5.91ab	6.82ab
	Minus K	8.57a	14.87a	4.08b	4.58ab
	Minus S	5.20a	14.29a	5.65ab	7.34a
	Minus B	8.02a	12.44ab	9.29a	7.26a
	NPKSB	5.89a	15.71a	7.89a	6.98ab

Analysis of variance (*p* values)

Factor	S	SI	T	S*SI	S*T	SI*T	S*SI*T
Sequential harvest	0.005	<0.001	<0.001	<0.001	ns	ns	ns
Final harvest	ns	<0.001	<0.001	<0.001	ns	ns	<0.001

S= season, SI= site, and T= fertilizer treatment, DAP= days after planting. Means followed by the same letter (within the same site and column) are not significantly different ($p \leq 0.05$) by the LSD test.

5.3.5. Comparisons of omitted nutrients treatments to control (no nutrient applied)

The omission of various nutrients led to reduced potato yields compared to the treatment where all the tested nutrients were applied. In reference to the sequential harvest yields, the omission of various tested nutrients gave higher yields than control apart from the omission of N which had lower yields than control in Meru 2. Nitrogen was the most limiting since the yields in plots where N was omitted were lower or slightly higher than plots with no nutrients added (Fig.5.2). Apart from Nyandarua in SR, the effects of the application of 44 kg K ha^{-1} gave a high percent yield difference from the control. The increasing K application from 44 to 224 kg ha^{-1} lowered the yield slightly. In Meru 1, omission of P had a higher yield than NPKSB treatment during LR. All the other sites revealed P as the second most limiting nutrient after N since it had the second lowest percent difference from the control (20% Meru2, 40% Nyandarua during LR, and 130% Meru 1, 100% Meru 2, and 80% Nyandarua during SR). Sulphur is also proofed to be a key nutrient influencing potato growth. Its omission revealed the third-lowest yield increase when compared to control in Meru 1 (25%) and Nyandarua (40%) in LR. Boron only seemed to affect potato yield in Meru 2 in LR and Meru 1 in SR.

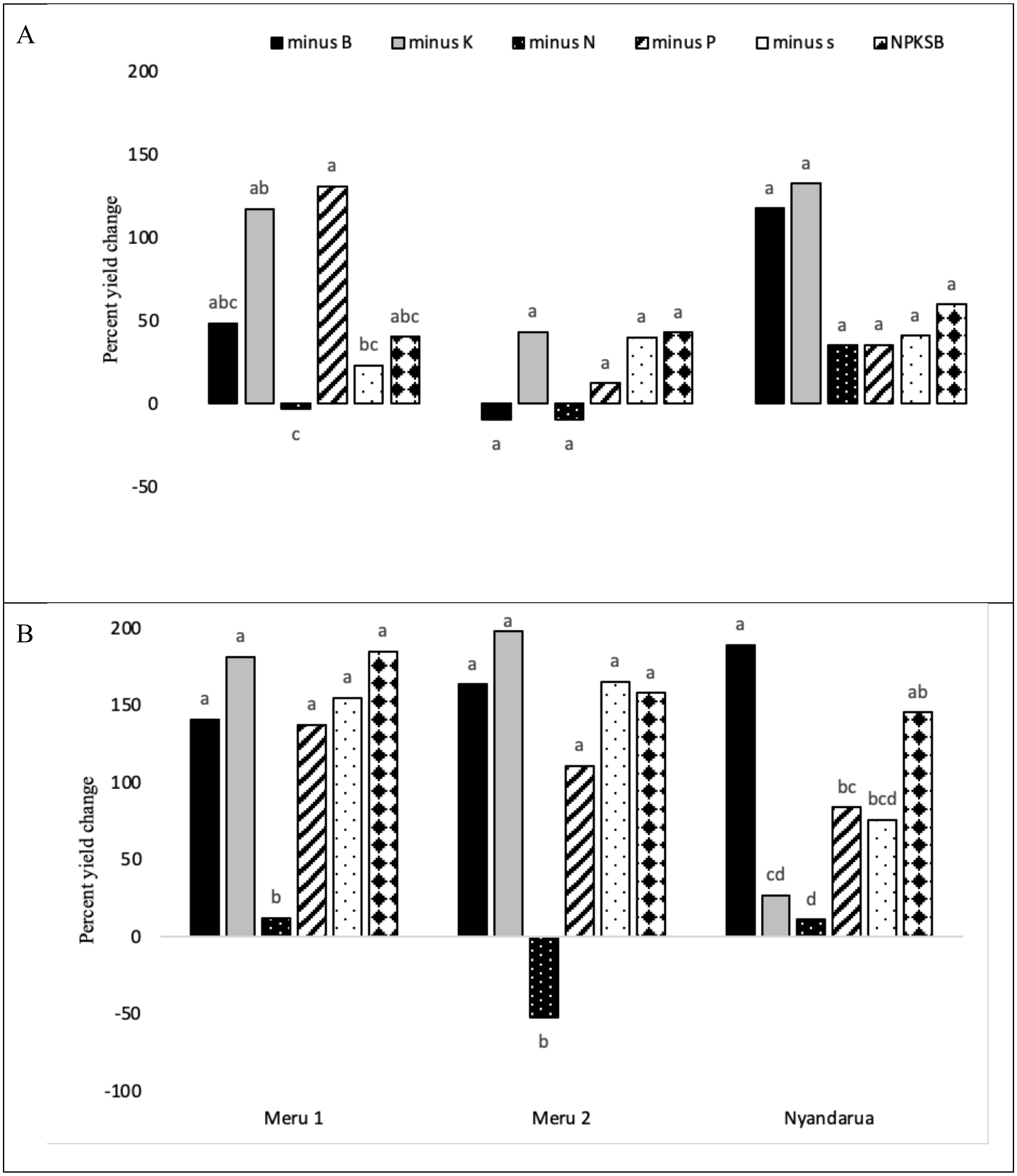


Figure 5.2: Percent potato yield response to the omission of N, P, K, S, and B compared to no fertilizer application treatment at 60 days after emergence in 2016 long rains (A) and 2016 short rains (B).

At the final harvest, the effect of omitting N had a yield gap of more than 5 t ha^{-1} when compared to the application of all nutrients (Fig. 5.3). The effect of S was observed as the third most limiting nutrients of the tested nutrient elements was not observed on analyzing the final yield data since the percent yield difference from the control was mostly higher than that of all the nutrients applied. Potassium was only found to be most limiting in site 3 in SR where it had a yield difference of 26% compared to the control while the omission of N at the same farm gave a percent yield difference of 28%. The effect of omitting boron gave varied results between the seasons and the sites. For instance, in site 2 in the LR, omitting B led to the crop not responding to the addition of other nutrients while in SR, there were no negative yield effects when it was omitted for site 1.

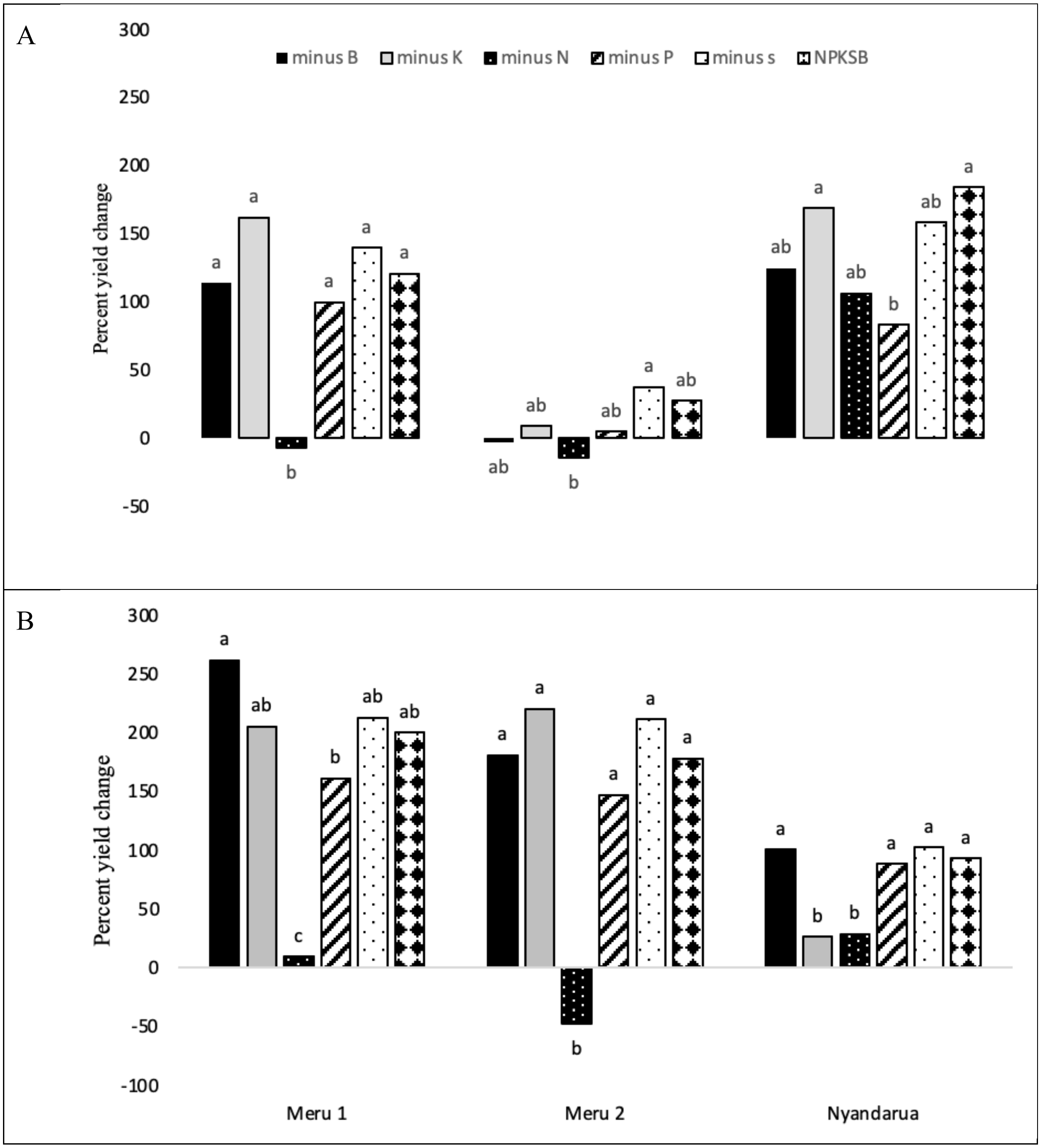


Figure 5.3: Percent potato yield response to the omission of N, P, K, S, and B compared to no fertilizer application treatment at final harvest in 2016 long rains (A) and 2016 short rains (B).

5.3.6. Comparisons of omitted nutrients treatments to NPKSB (all tested nutrients)

Nitrogen significantly decreased yield from NPKSB in all the sites in the two seasons (Figure 5.4). The yield gap was lowest (27%) in Nyandarua in LR and highest (81%) in site 2 during SR. phosphorus also reduce potato yields at 60DAE in all the sites in both seasons, the yield reduction ranged from 3% to 35%. There was no yield reduction with the omission of K in Meru 1 but reductions were experienced in Nyandarua. Sulphur omission also did not affect potato yield in all the sites

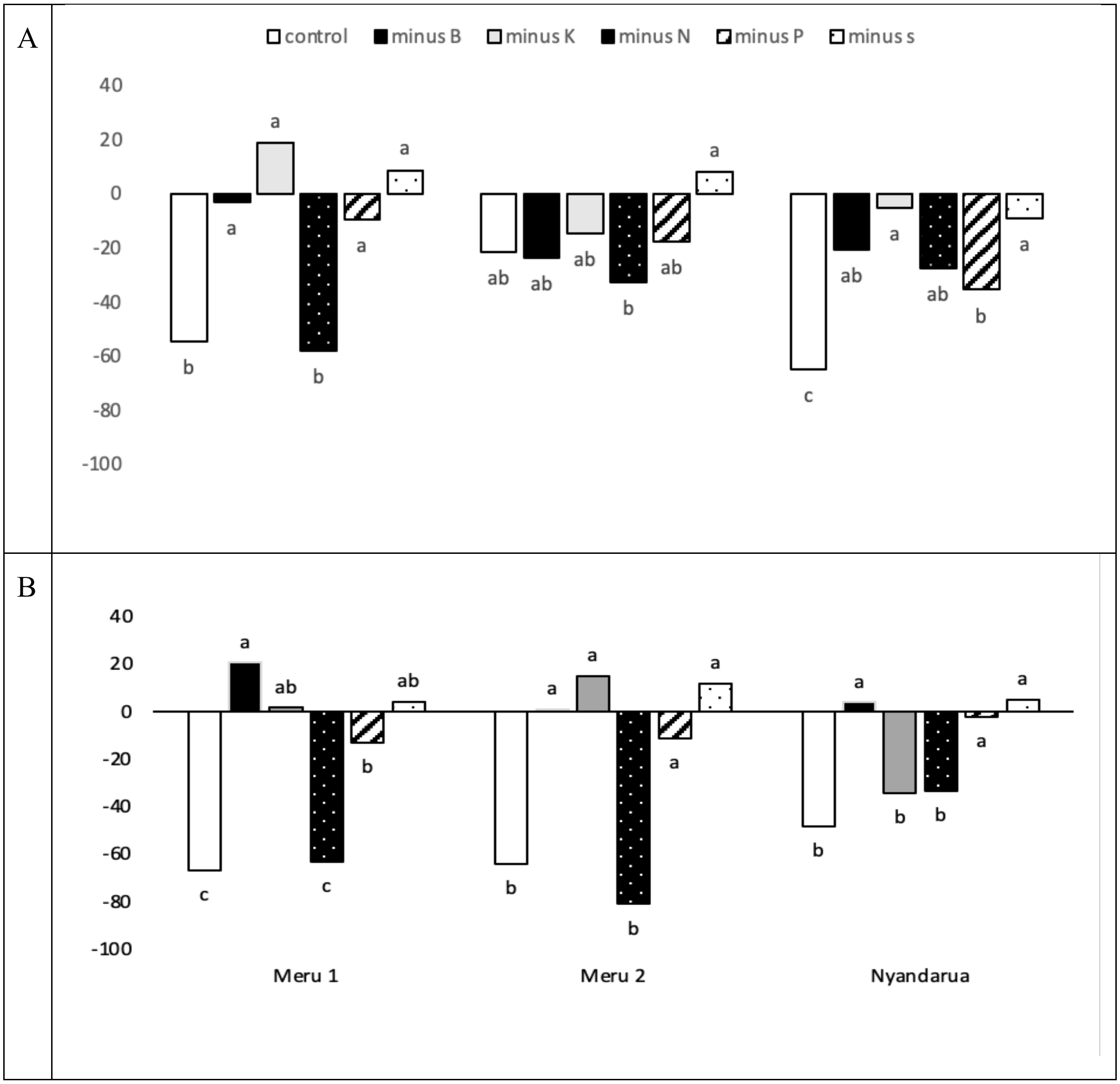


Figure 5.4: Percent potato yield response to the omission of N, P, K, S, and B compared to NPKSB treatment at 60 days after the emergence 2016 long rains (A) and 2016 short rains (B).

At 90 DAE, variations were observed between the seasons on most nutrient omission treatments. Apart from the omission of N which reduced potato yields in all the sites (Figure 5.5). Omission of P on average reduced in Meru 2 and Nyandarua by about 20% but no yield reduction was experienced in Meru 1 during LR. Omission of S was found to reduce the final yield from NPKSB treatment but B was found to have no major negative effect on the potato yield.

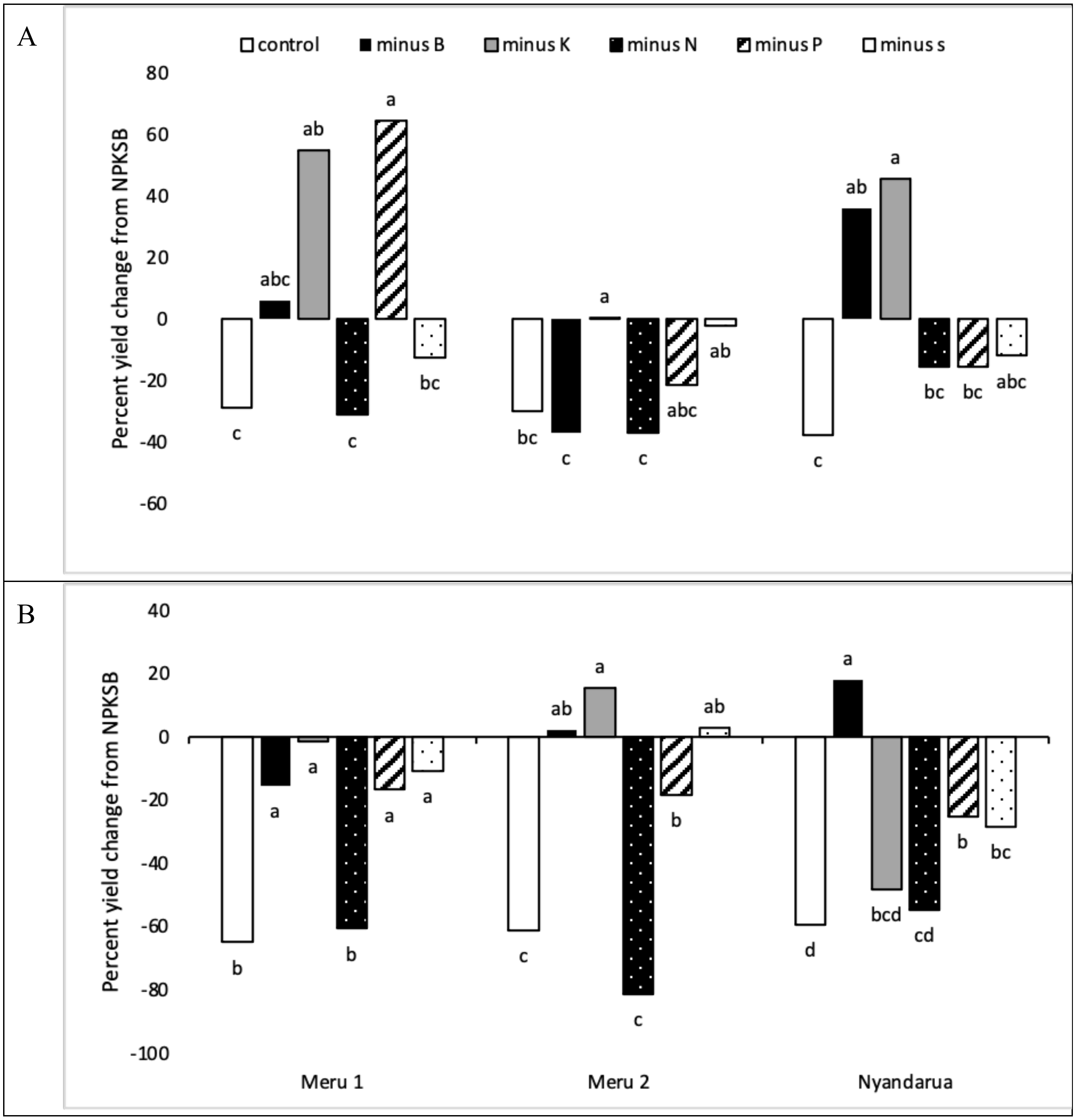


Figure 5.5: Percent potato yield response to the omission of N, P, K, S, and B compared to NPKSB treatment at final harvest in 2016 long rains (A) and 2016 short rains (B).

5.3.7. Stability analysis

Stability analysis revealed a relatively low regression coefficient for all the treatment. The control and minus N had the lowest regression coefficient of 0.6 and 0.5 respectively (Fig. 5.6). Boron had the highest regression coefficient of 1.3 implying that potato yield was affected differently by B omission in different sites. The coefficient for NPKSB and minus S treatments was 1.2 while that of minus K was 1.1. All regression equations were significant (p <0.05) though the R squared for minus N and control equations were relatively low (0.48 and 0.45 respectively). Omission of S had a better performance in all the environments while minus B performed better in the high yielding environment as compared to the low yielding environment.

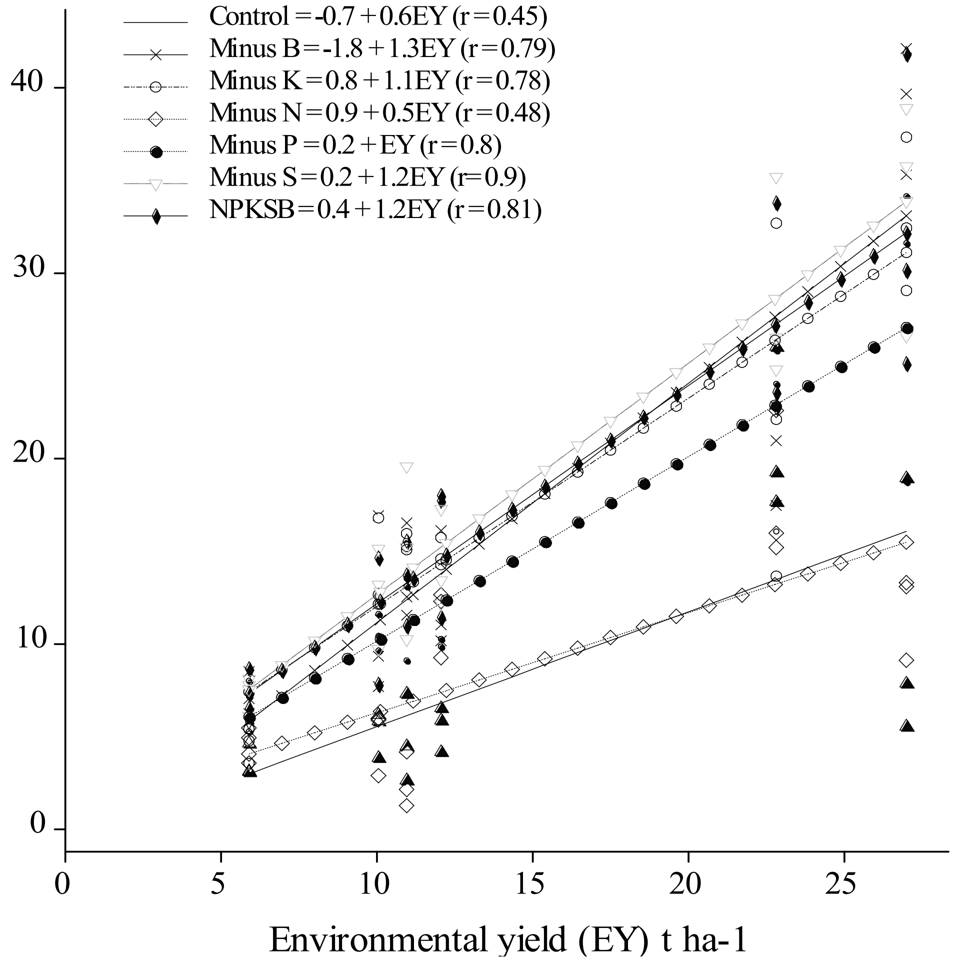


Figure 5.6: Regression of potato yields for various treatments against the environmental yield (EY) mean for the 2016 long and short rains seasons.

5.4. Discussion

5.4.1. Effects of N omission on potato growth and yields

The response of potato crop to the omission of N was imminent as indicated by uptake and yield parameter results, portraying N as the most limiting nutrient in potato growing areas of Kenya. Nitrogen as one of the major nutrients is responsible for key plant processes that influence the growth and yield of potatoes (Lamb, et al., 2014). The soils in the Kenyan highlands have been continually farmed which results in lots of N mining as well as losses through erosion and leaching (Gitari et al., 2019; Nyawade et al., 2020). Similar results have been reported from multi-location trials on different soil types, in several African countries including Kenya (Kihara et al., 2016). In slightly acidic to moderately acidic soils, higher responses to N and P addition have been identified (Shehu, et al., 2018). While using potato as a test crop, Banerjee et al., (2016) reported N as the most limiting yield. The nitrogen management dynamic is thus crucial and the levels in customized fertilizers are highly significant. The omission of N in some sites led to lower yields than the control, this might be a result of the synergetic effect of N with other nutrients (Aulakh and Malhi., 2005). Nitrogen and P addition have been shown to have a synergetic and additive effect on crop yield (Aulakh & Malhi., 2005; Rietra, et al., 2017). Aulakh & Malhi., (2005) also summarized the interaction between N and K and concluded that they are largely synergetic. Nitrogen and S affect many plant growth and tuber quality attributes since they are components of protein thus affecting the uptake and efficiency of each other (Singh, et al., 2016). The effect of N omission thus affected the yield the most, as a result, the application of N resulted in high agronomic nitrogen use efficiency.

5.4.2. Effects of P omission on potato growth and yield

The soil in most potato-growing regions of Kenya is mainly acidic. This has been attributed to the volcanic ash parent material as well as the continued use of acidifying fertilizers such as ammonia-based fertilizers (IUSS Working group WRB, 2015; Pansu and Gautheyrou, 2003; Recke et al., 1997; Spaargaren, 2008). Phosphorous is largely affected by the soil pH in which it is bound by the Al and Fe ions in low pH (Ekelöf, et al., 2014; Ndou, 2017). As a result, P was found to be a limiting nutrient to potato growth and yields as indicated by the percentage yield reduction from NPKSB treatment. This was also clear in the minus P regression line in the stability analysis graph, it lay in the middle after that of minus N and control treatments. Phosphorous has a role in root development and provides energy for photosynthesis factors that influence the growth of the crop (Ekelöf, 2007; Ndou, 2017). The phosphorous application increases P uptake leading to increased tuber numbers and yields thus the reason for reduced yields from NPKSB by over 15% with P omission. Omission of P has been found to affect the uptake of most essential plant nutrients on acidic to slightly acidic soils (Borges, et al., 2016; Fernandes, et al., 2017; Kumar, et al., 2018), this, in turn, affect most plant processes thus reducing the yield. Higher uptake of N, K, Ca, Mg, S, B, Cu, and Fe have been associated with P fertilization as a result of its effect on plant biomass (Fernandes, et al., 2015; Fernandes et al., 2017; Soratto, et al., 2020).

5.4.3. Effect of reduced K application on potato growth and yield

Potassium is a key nutrient in the potato crop, it is the nutrient needed in the highest amount by potatoes (Westermann, 2005). It leads to an increase in yield as well as the quality aspects of the product (Bhattarai and Swarnima, 2016). Despite this, the effect of reduction of K applied was not significant in most of the areas in terms of the LAI, haulm, and yield implying some K adequacy in the areas. Application of 224 Kg K ha^{-1} was demonstrated to decrease potato growth and yield in some sites, this could be because of excessive uptake of K since the initial soil K levels were above the critical level for potato growth (Mbuvi, et al., 2013; Rozo & Ñústez, 2011). Over-application of K (over 150 K_2O Kg ha^{-1}) has been shown to reduce growth and yield parameters in some potato varieties (Rozo & Ñústez, 2011; Zelelew, et al., 2016). The minimal effect on potato growth and yield parameter could imply that the application of 44 Kg K ha^{-1} was adequate for potato growth and also reinstate the fact that tropic soils are mostly K sufficient (Kanyanjua, et al., 2006; Mbuvi et al., 2013; Wekesa, et al., 2014). This would mean K needed in customized fertilizers is minimal. A recent study on tropical clay soil has shown that the benefits of K in improving uptake of other nutrients are reduced under medium and adequate levels of K in the soil (Soratto et al., 2020).

5.4.4. Effect of omission of S and B in potato production

The effect of omitting S was experienced at bulking stage, in both LAI and the tuber yield but not during the final harvest. The stability analysis equation for minus S was highest in all the environments, an indication of no negative effect on the yield when S was omitted, this was contrary to results from Ethiopia that have indicated responses to S addition (Mekashaw, et al., 2020). The low effect of omission of S may be attributed to the initial soil test since only Meru 1 site had low levels of S. Boron was found to reduce potato yields in the 2016LR, this effect was however not noticed in 2016SR and it led to a higher slope coefficient in the stability analysis. Boron has been shown not to have yield increases even in soils with as low as 0.5 mg Kg^{-1} of boron (Hopkins, et al., 2007), however, other studies have reported a slight yield increase (Moinuddin, et al., 2017). The adequate range of boron sufficiency is narrow with negative effects experienced at both extremes, potato crops can, however, adapt to excess levels of B (Ayvaz, et al., 2016; Tariq & Mott, 2007). Variability of potato responses to the omission of the nutrients was experienced in various sites as indicated by variation of measured parameters. Variability between sites is common in many omission trials (Kihara et al., 2016;

Shehu et al., 2018). This emphasizes the need for site-specific nutrient management which has been advocated for by other studies (Rurinda et al., 2020; Vanlauwe et al., 2017).

5.5. Conclusions

This study shows that nitrogen and phosphorous were the most limiting nutrients in the central highlands of Kenya. Potassium and boron were responsive in some of the sites. The potato crop was found to be unresponsive to the omission of sulphur fertilization. The response also varied between sites. Based on these results, for a potato-specific fertilizer to be formulated for the Kenyan highlands, N and P should continue to be included while K and B should only be added based on a soil test or just for fertility maintenance.

CHAPTER SIX

Response of potato (*Solanum tuberosum* L.) to fertilizers applied on different soil types in Kenyan Highlands

Abstract

Declining soil fertility in Nitisols and Planosols that dominate major potato growing areas of Kenya is a hindrance to the sustainable production of the crop. A study was conducted in Nyandarua County, to assess the performance of potato (*Solanum tuberosum* L.) and the agronomic efficiencies of three fertilizer types. Di Ammonium Phosphate (DAP) (N: P_2O_5: K_2O 18:46:0), Mavuno Peas, Beans, and Root Vegetables (MRV) (15N:8 P_2O_5:15 K_2O plus S, Ca, Mg, Fe, Cu, Zn, B, Mn, Mo), and new Mavuno blend (18N:24 P_2O_5:10 K_2O plus 5S, 0.04B, 0.02Zn). The experiments were established on Nitisol and Planosol soil types in farmers' fields, and two potato varieties were evaluated in a split-plot layout design. DAP had the highest and most significant influence on potato haulm giving 16.5 and 15.5 g plant^{-1} on variety Sherekea growing on Nitisol and Planosol, respectively. Fertilizer type significantly influenced potato yield which was recorded at 29.2 ton ha^{-1} with DAP and 26.6 ton ha^{-1} with new Mavuno on variety Sherekea grown on Nitisol. A significant positive interaction ($P < 0.05$) between fertilizer type and soil type was observed. Fertilizers also gave a significant effect on the agronomic efficiency of N (AE_N), P (AE_P), and K (AE_K). Potato yield and agronomic nutrient use efficiency were dependent on the fertilizer types used as well as soil type. DAP and new Mavuno were the best fertilizer types.

6.1. Introduction

Potato (*Solanum tuberosum* L.) is cultivated on a wide range of soils but preferably does best in deep well drained and friable soils with soil pH of 4.8 to 6.5 (Burke, 2017; NPCK, 2018; Westermann, 2005). Due to its shallow root system that makes it hard to explore the subsoil layers, potato requires fertile soils. The main soils in the highlands of east and central Africa are Nitisols, Cambisols, Phaozems, Planosols, Luvisols, and Andosols (Elias, 2017; IUSS Working group WRB, 2015). The highlands soils form the most productive though declining soil fertility has led to the need for the addition of organic and inorganic fertilizers. In Kenya, the potato is an important food and cash crop and its production occurs in the high-altitude areas between 1,500 and 3,000 meters above sea level (masl) and is mainly rain-fed. Nyandarua is one of the leading potato-producing counties accounting for up to 20% of the country's total potato production. It is covered by soils similar to the other highland areas, predominantly Planosols and Nitisols (Jaetzold et al., 2006; Kaguongo et al., 2008; Nyawade et al., 2021; Muchena and Gachene, 1988). Planosols are shallow and imperfectly drained and in many areas of the world are used for fodder (IUSS Working group WRB, 2015). Farmers in Kenya are compelled to employ cumbered beds to control waterlogging and flooding in these soils (Mati, 2012; Muchena and Gachene, 1988). Nitisols are well-drained but exhibit much N leaching, thus requiring higher fertilization to attain higher crop yields (Muchena and Gachene, 1988; Warren and Kihanda, 2001). Both soils exhibit high P sorption, making P one of the most limiting nutrients (Gitari et al., 2020, Getie et al., 2021; Gichangi et al., 2008, Elias, 2017). The soil pH in the county is low, contributing further to P adsorption and unavailability of other key nutrients (Mugo et al., 2020). High soil erosion and nutrient leaching further aggravate soil fertility problems in the highlands (Ministry of Environment and Natural Resources, 2016; Muchena and Gachene, 1988; Muzira et al., 2018; Nyawade et al., 2018). Continuous farming for many years has also been linked to declining soil fertility (Willy et al., 2019). It is estimated that 41 kg N ha^{-1}, 4 kg P ha$^{-1,}$ and 31 kg K ha^{-1} are mined from the soil in East Africa and this has led to negative nutrient balances (Bekunda et al., 2002). In recent studies nitrogen (N), phosphorous (P), sulphur (S), and boron (B) were found to be limiting potato production (Kenya Soil Survey, 2014; Mugo et al., 2020; EATA, 2014; Muzira et al., 2018). Fertilizer management in the region is thus key for sustainable crop production.

There has been efforts to promote the fertilization of potato in Kenya based on positive reports from studies. Recke et al (1997) summarized potato response to fertilizer application and indicated yield benefits to N and P addition in several sites and K in three sites out of 16 evaluated sites ranging from upper midland to upper high land agro-ecological zones. An increase in potato yield after the application of a fertilizer blend developed by a combination of several fertilizers including slow-release types has also been reported even where initial soil results indicate adequate K level (Mbuthia, 2018). The use of potassium chloride fertilizer as a source of potassium has been studied and the positive result reported (Ngomat, 2017). Additionally, application of diammonium phosphate and manure, NPK. (20: 20: 20) combined with triple superphosphate (TSP) + calcium ammonium nitrate (CAN) produced a higher yield compared to other fertilizers (Muthoni and Kabira, 2011). Although the use of fertilizer combined with manure is a common practice among potato farmers, Mugo et al. (2020) reported that they tend to apply low amounts compared to recommended rates, thus compromising the benefits. The fertilizer recommendation for potatoes is 90 kg N ha^{-1} and 230 kg P_2O_5 ha^{-1} and is based on commonly accessible di-ammonium phosphate (DAP) fertilizer. Site-Specific Fertilizer Management (SSFM) has been evaluated in recent years through nutrient omission trials to capture the potential presence of limiting nutrients and responses (Kihara et al., 2016; Nziguheba et al., 2009; Mugo et al., 2021). Fertilizer blending is used in the country to produce crop-specific and site-specific fertilizer (GIZ, 2016; Sitienei et al., 2018) and these fertilizer blends are available in the market. The fertilizers are based on crop nutrient removal as well as general soil chemical properties of various areas (GIZ, 2016; Kinyua et al., 2013; Mbuthia, 2018; Yara, 2020). This study aims to assess the effects of three fertilizers on potato yield and nutrient use efficiency on two soil types in Nyandarua County, Kenya. Balanced fertilizer types are expected to improve potato yield and nutrient use efficiency in various soil types thus increasing returns while conserving the environment (Jate, 2010).

6.2. Materials and methods

6.2.1. Site selection and description

The study was conducted in Nyadarua County, one of the leading and oldest potato-producing regions of Kenya (Figure 1). The majority of farmers are small-scale (< 2 ha) and produce potatoes as monocrop and the average yield is below 10 t ha^{-1} (Muthoni et al., 2013b). This study was conducted in eight small-scale farmer fields during the long rains (LR) and short rains (SR) seasons of 2017. The farms were selected with an aid of a soil map for the general area and farmers were contacted with the help of the area field extension officer (ISRIC, 2021). Four of the farms were located on a Nitisol and the other four farms were on Planosol as classified under FAO classification (IUSS Working group WRB, 2015). Nitisols are very deep soils and are well-drained, dark red friable clay while Planosols are shallow, light-colored soils with periodic water stagnation (IUSS Working group WRB, 2015). Nitisols were selected since it forms major soils in the Kenyan highlands while Planosols though poorly drained have been used for potato production in the county. The region receives bimodal rainfall, with March to June being LR season and October to December referred to as SR season (Jaetzold, et al., 2006). The annual average rainfall ranges between 700-1600 mm while the annual minimum and maximum air temperatures are 14 and 22 ºC, respectively.

6.2.2. Soil sampling and analysis

Soil samples were collected at the depth of 0.3m and composted to one sample from each study site using a 15mm soil auger. Composted samples were air-dried and ground to pass through a 2 mm sieve. Soil pH (soil: water ratio of 1: 2.5) was measured using a pH meter. total N by modified micro-Kjeldahl method (Bremner, 1996) and soil organic carbon (SOC) by modified Walkley and Black method (Nelson and Sommers, 1996). Extraction of soil samples for analysis of P, K, Ca, Mg, Fe, Mn, B, Zn, and Cu was done using Mehlich 1 procedures (Mylavarapu et al., 2002) and determined using inductively coupled plasma-optical emission spectrometry (ICP-OES) (Hou and Jones, 2000). Cation exchange capacity was analyzed following procedures provided by Polemio and Rhoades, (1977).

6.2.3. Experimental design and treatments

A factorial experiment comprising two soil types, two potato varieties, and three fertilizer types and a no fertilizer control was established. The fertilizer treatments comprised, DAP (N: P_2O_5: K_2O18:46:0), Mavuno Peas, Beans, and Root Vegetables (MRV) (15N:8 P_2O_5:15 K_2O plus S, Ca, Mg, Fe, Cu, Zn, B, Mn, Mo), and new Mavuno blend (18N:24 P_2O_5:10 K_2O plus 5S, 0.04B, 0.02Zn). Two potato varieties that were tested were Shangi which is an early maturing variety and Sherekea which is medium maturing taking 3-4 months (NPCK, 2019). The varieties were selected due to their growing popularity in Kenya. At planting, fertilizer was applied in the furrows and mixed with the soil thoroughly then seed tubers were sown. Fertilizer rates are presented in Table 6.1.

Table 6.1: Amount of nutrients (N, P, K) supplied by each fertilizer type.

Fertilizer type	Amount applied	N	P	K
		Kg ha^{-1}		
New Mavuno	556	100	58.2	8.3
MRV	666	100	21.8	12.4
DAP	556	100	111.6	0
Control	0	0	0	0

*Fertilizer application was based on 100 Kg N ha^{-1}, thus the amounts of the fertilizer applied corresponded to N grade in the fertilizer type. Similarly, this rate supplied the P and K shown in the table.

The experiments were laid out in a split-plot experimental design with farms considered as replication in each of the soil types. Soil type was the main plot, and potato variety and fertilizer were subplots. Each subplot size was 13.5 m^2, in which 15 tubers spaced at 0.3m within the rows spaced by 0.75m for each variety, one meter distance was left between the subplots.

First weeding and hilling were carried out around 20 days after planting while the second weeding and hilling were done around 35 days after planting. Disease and pest control were carried out by spraying the crop with Ridomil Gold MZ 68 WG (Mefenoxam 40 g kg^{-1} + Mancozeb 640 g kg^{-1}) alternated with Infinito (Fluopicolide 62.5 g L^{-1} + Propamocarb 625 g L^{-1}) after every 14 days starting at 30 days after planting to control late blight.

6.2.4. Field data collection and computation

Haulm weight was measured by randomly selecting three plants per subplot at 35 days after emergence (DAE). This parameter was used to give an indicator of potato growth. The haulm was chopped into small pieces and a sample of approximately 500g was placed in brown paper bags and placed in the oven to dry at 70°C for 48 hours and dry weight was recorded. At crop maturity plants were harvested and tubers counted and their respective weight was taken. A tuber sub-sample was collected and chopped into small pieces (approximately 5 cm) and was oven-dried at 70 °C to determine dry weight. Agronomic nutrient efficiencies defined as the additional potato yield per unit of added fertilizer were calculated using equations 1 to 3. The agronomic nutrient efficiencies calculated were nitrogen agronomic efficiency (AE_N), Phosphorus agronomic efficiency (AE_P), and potassium agronomic efficiency (AE_K).

$$AE_N = \frac{(Yi - Y0)}{(\text{soil N} + \text{fertilizer N})} \qquad (1)$$

$$AE_P = \frac{(Yi - Y0)}{(\text{soil P} + \text{fertilizer P})} \qquad (2)$$

$$AE_K = \frac{(Yi - Y0)}{(\text{soil K} + \text{fertilizer K})} \qquad (3)$$

Where Y_i is the yield under the respective fertilizer blend and Y0 is the yield from the control plot.

Total nutrient available for plant uptake was calculated by including soil available nutrients plus the amount added from fertilizer. Soil available nutrients (N, P, and K) from the initial soil sample were calculated using equation 4 (Brown and Wherrett, 2004). The amount supplied by fertilizer was calculated from the fertilizer grade ratio for the specific nutrient. The bulk density was estimated using soil data maps generated from kensoter project (ISRIC, 2021).

$$\text{Soil nutrient}(\text{Kg ha}^{-1}) = \frac{\text{soil test }(\text{mg kg}^{-1}) * \text{bulk density }(\text{g/cm}^3) * \text{sample depth}(\text{cm})}{10} \qquad (4)$$

6.2.5. Data management and analysis

Soil chemical properties data were subjected to a Turkey's t-test and the yield and AE using Genstat version 14 software (VSN International, UK, 2021). Generalized linear model analysis was used to analyze collected data, treatment mean differences were compared using Tukey HSD at $P<0.05$. Further, the relationship between agronomic efficiencies and potato yield was evaluated using linear regression.

6.3. Results

6.3.1. Soil chemical properties

Soil pH of the topsoil (0 - 30 cm) was significantly lower ($p < 0.05$) in Nitisol as compared to Planosol and consequently for Iron (Fe) (Table 6.2). Total N (1 g kg^{-1}), SOM (10 g kg^{-1}), and S (7 g kg^{-1}) were higher on Nitisols as compared to Planosols. Cation exchange elements (K, Ca, and Mg) varied widely under Planosol as revealed by the large standard deviation. The soil pH, total N, and B were low in both Nitisol and Planosol while the P, and C: N ratio were low in Nitisols.

Table 6.2: Soil chemical properties and their standard deviations of Nitisol and Planosol in the study sites in Nyandarua County, Kenya.

Soil type	Nitisol	Planosol	*Optimal range	t-test (P <0.05)
pH	4.8 ± 0.3	5.4 ± 0.5	5.5-6.6	0.08
SOM g kg^{-1}	47.0 ± 3	37.0 ± 7	25-60	0.04
Total N g kg^{-1}	20 ± 0.5	10 ± 2	25-40	<0.001
P mg kg^{-1}	12.8 ±7.8	62.4 ± 71.1	30-70	0.21
K mg kg^{-1}	472.5 ± 91.2	287.3 ± 252.9	35-120	0.21
Ca mg kg^{-1}	964.8 ± 95.5	1622.0 ± 1007.1	430-540	0.23
Mg mg kg^{-1}	180.0 ± 46.4	230.6 ± 149.6	25-45	0.54
S mg kg^{-1}	19.1 ± 3.0	12.3 ± 3.3	12-25	0.02
Fe mg kg^{-1}	162.5 ± 8.4	284.3 ± 61.5	30-300	0.008
Mn mg kg^{-1}	219.0 ± 82.0	129.7 ± 37.7	30-300	0.09
B mg kg^{-1}	0.5 ± 0.04	0.5 ± 0.2	0.8-2	0.95
Cu mg kg^{-1}	1.3 ± 0.2	1.3 ± 0.8	1.5-10	0.95
Zn mg kg^{-1}	8.5 ± 3.1	5.5 ± 3.6	2-20	0.24
C.E.C Cmol kg^{-1}	17.3 ± 2.8	16.9 ± 6.6	15-25	0.91
C:N ratio	13.6 ± 0.3	16.3 ± 1.2	15-20	0.01
Ca:Mg Ratio	3.3 ± 0.7	4.3 ± 1.0	3.5– 6.0	0.17

*(Cropnuts, 2019; Mangale et al., 2016), ± Standard deviation

6.3.2. Response of potato to fertilizer application

Vegetative growth of the aboveground haulm was increased with the application of fertilizers (Table 6.3). DAP gave the highest potato aboveground biomass followed by new Mavuno though no significant differences were observed between the three fertilizers. Fertilizer type interacted with both soil type and variety during SR, this was however not the case in LR. The three treatment factors also interacted during SR. No interactions were observed between soil type and variety in either season.

Table 6.3: Potato haulm dry weight at 35 DAE as affected by soil type and fertilizer.

Variety	Fertilizer type	Aboveground biomass (Haulm) dry weight (t ha^{-1})			
		2017 LR		2017 SR	
		Nitisol	Planosol	Nitisol	Planosol
Shangi	Control	0.10 a	0.25 ab	0.14 a	0.07 a
	DAP	0.40 abc	0.31 ab	0.30 b	0.30 b
	New Mavuno	0.21 ab	0.55 abc	0.24 ab	0.10 a
	MRV	0.34 abc	0.51 abc	0.21 ab	0.13 a
Sherekea	Control	0.15 a	0.49 abc	0.14 a	0.11 a
	DAP	0.73 c	0.68 c	0.46 c	0.31 b
	New Mavuno	0.61 bc	0.61 bc	0.26 ab	0.33 b
	MRV	0.36a bc	0.19 a	0.63 d	0.20 ab
Soil type		ns		<0.013	
Variety		0.032		<0.001	
Fertilizer		0.013		<0.001	
Soil type * Variety		ns		ns	
Soil type * Fertilizer		ns		0.007	
Variety * Fertilizer		ns		0.013	
Soil type * Variety * Fertilizer		ns		0.002	

*The Same letter after each means indicates no significant differences between means in the same column, ns- not significant at (P <0.05).

6.3.3. Potato tuber response to fertilizer application

During LR DAP gave the highest number of tubers per plant of Sherekea variety grown on Nitisol (Table 6.4). The effects on the tuber numbers were not as large in SR as LR with a double number of tubers being achieved in Sherekea for the three fertilizer types. Sherekea variety had higher tuber numbers (16 and 12 in LR and SR, respectively) than Shangi (11 and 7 in 2017 LR and SR, respectively). Potato planted in Planosol had high tuber numbers than those in Nitisol. In terms of tuber weight, a significant interaction between soil type and the fertilizer was observed. The highest tuber weight was achieved with Shangi variety with the application of DAP.

Table 6.4: Potato tuber number as affected by fertilizer in different soil types.

Variety	Fertilizer type	Tuber number per plant				Average tuber weight (g per tuber)			
		2017 LR		2017 SR		2017 LR		2017 SR	
		Nitisol	Planosol	Nitisol	Planosol	Nitisol	Planosol	Nitisol	Planosol
Shangi	Control	5.7a	9.1a	5.9a	6.2a	39.3a	64.3a	57.8a	37.0a
	DAP	12.2ab	13.0ab	8.1ab	8.8ab	75.3b	72.3a	81.4b	37.1a
	New Mavuno	11.3ab	13.7ab	9.4abc	7.8ab	65.2b	63.4a	74.3ab	47.7ab
	MRV	10.7ab	12.8ab	6.7a	7.8ab	71.0b	68.3a	72.0ab	40.5a
Sherekea	Control	6.0a	13.1ab	5.9a	9.4abc	39.2a	55.9a	65.0ab	38.2a
	DAP	23.5c	20.1b	15.7d	13.4cd	66.3b	58.2a	65.9ab	38.2a
	New Mavuno	18.6bc	18.7b	13.4cd	11.2bcd	65.2b	55.1a	62.5ab	55.9b
	MRV	12.4ab	17.0ab	12.4bcd	14.9d	71.4b	52.6a	66.6ab	35.3a
Soil type		ns		ns		ns		<0.001	
Variety		<0.001		<0.001		ns		0.007	
Fertilizer		<0.001		<0.001		0.004		0.001	
Soil type * Variety		ns		ns		ns		ns	
Soil type * Fertilizer		ns		ns		0.015		0.033	
Variety * Fertilizer		ns		ns		ns		ns	
Soil type * Variety * Fertilizer		ns		ns		ns		ns	

*Same letter after each means indicate no significant differences between means in the same column, ns- not significant at (P <0.05).

6.3.4. Potato yield as influenced by fertilizer and soil type

During LR DAP increased yield by 288% and 450% in Nitisol for variety Shangi and Sherekea above the control respectively (Table 6.5). Under Planosol during the same season, application of DAP fertilizer raised yield by 65% and 50% for Shangi and Sherekea, respectively. Similarly, the application of new Mavuno raised yield by 226% and 49% for variety Shangi on Nitisol and Planosol, respectively. The influence was lower in SR with DAP increasing yield by 94% and 151%, new Mavuno by 102% and 119%, and MRV by 44% and 118% under Nitisol for variety Shangi and Sherekea, respectively. Sherekea yields were significantly higher than Shangi. Similarly, yields in Nitisol were slightly higher than in Planosol.

Table 6.5: Potato yield as affected by various fertilizers on different soil types.

Variety	Fertilizer type	Yield (t ha^{-1})			
		2017 LR		2017 SR	
		Nitisol	Planosol	Nitisol	Planosol
Shangi	Control	4.5a	11.6 a	6.8 a	4.7 a
	DAP	17.5bcd	19.2 ab	13.2 bc	6.5 ab
	New Mavuno	14.7abc	17.3 ab	13.8 bc	8.1 abcd
	MRV	14.3abc	17.1 ab	9.8 ab	6.3 ab
Sherekea	Control	5.3ab	15.2 ab	7.6 a	7.1 abc
	DAP	29.2 d	22.9 b	19.1 d	10.3 bcd
	New Mavuno	26.3 cd	20.1 b	16.7 cd	11.0 d
	MRV	19.5 cd	19.3 ab	16.6 cd	10.8 cd
soil type		ns		0.006	
variety		0.007		<0.001	
Fertilizer		<0.001		<0.001	
soil type * Variety		ns		ns	
soil type * Fertilizer		ns		0.025	
Variety * Fertilizer		ns		ns	
soil type * Variety * Fertilizer		ns		ns	

*The Same letter after each means indicates no significant differences between means in the same column, ns- not significant at (P <0.05).

6.3.5. Agronomic efficiencies of fertilizer types under potato crop

Highest AE_N was mostly achieved with the application of DAP on Sherekea variety in both seasons and soil types, but the difference was mostly not significant (Table 6.6). The highest agronomic efficiencies were 101.2 Kg. yield $Kg.^{-1}$ N fertilizer after application of DAP, 333 Kg. yield $Kg.^{-1}$ P fertilizer on the application of MRV and 16.6 Kg. yield $Kg.^{-1}$ K fertilizer with the application of DAP. Mavuno root and vegetable fertilizer had the highest AE_P of 333 Kg. $Kg.^{-1}$and 204.5 Kg. $Kg.^{-1}$ on Nitisol during LR and SR, respectively. The AE_K was relatively low when compared to AE_N and AE_P and was not significant.

Table 6.6: N, P, and K agronomic efficiencies of potato on Nitisol and Planosols.

Variety	Fertilizer type	AE$_N$ Kg yield Kg^{-1} N				AE$_P$ Kg Yield Kg^{-1} P				AE$_K$ Kg yield Kg^{-1} K			
		2017 LR		2017 SR		2017 LR		2017 SR		2017 LR		2017 SR	
		Nitisol	Planosol	Nitisol	Planosol	Nitisol	Planosol	Nitisol	Planosol	Nitisol	Planosol	Nitisol	Planosol
Shangi	DAP	54.9a	44.4a	26.6ab	10.7a	90.5a	37.8a	47.9a	8.3a	8.7a	11.6a	3.2ab	2.9 a
	New Mavuno	52.8a	33.8a	29.1ab	20.2a	122.0a	39.9a	87.4ab	20.9a	9.2a	10.7a	3.5ab	5.3 a
	MRV	41.4a	32.3a	12.6a	9.5a	192.5a	51.5a	69.4ab	12.6a	6.7a	9.4a	1.5a	2.5 a
Sherekea	DAP	101.2a	42.6a	47.4b	18.7a	165.3a	37.1a	85.5ab	14.5a	16.6a	7.8a	5.8b	5.0 a
	New Mavuno	74.1a	27.0a	37.6ab	28.8a	211.3a	31.6a	112.8ab	29.7a	12.2a	5.9a	4.6ab	7.6 a
	MRV	60.3a	23.0a	37.2ab	21.0a	333.0a	31.2a	204.5b	29.2a	9.8a	5.4a	4.5ab	5.8 a
Soil type		ns		ns		ns		0.004		ns		ns	
Variety		ns		0.005		ns		0.004		ns		0.029	
Fertilizer		ns		ns		ns		0.035		ns		ns	
Soil type*Variety		ns		ns		ns		0.027		0.03		ns	
Soil type*Fertilizer		ns		ns		ns		ns		ns		ns	
Variety*Fertilizer		ns		ns		ns		ns		ns		ns	
Soil type*Variety* Fertilizer		ns		ns		ns		ns		ns		ns	

*Same letter after each means indicate no significant differences between means in the same column, ns- not significant at (P <0.05).

6.3.6. Nutrient efficiencies in relation to potato yield

A significant ($P < 0.05$) linear relationship was established between AE_N, AE_P, $AE_{K,}$ and potato yield in which yield increased with increasing agronomic efficiency (Figure 6.1). The coefficient of determination (R^2) were 0.61, 0.49, 0.46 on Planosol, and 0.50. 0.20, 0.49 on Nitisol for N, P, and K respectively, with $P < 0.001$. The slope of the regression line was similar for AEN and AEK in both soil types.

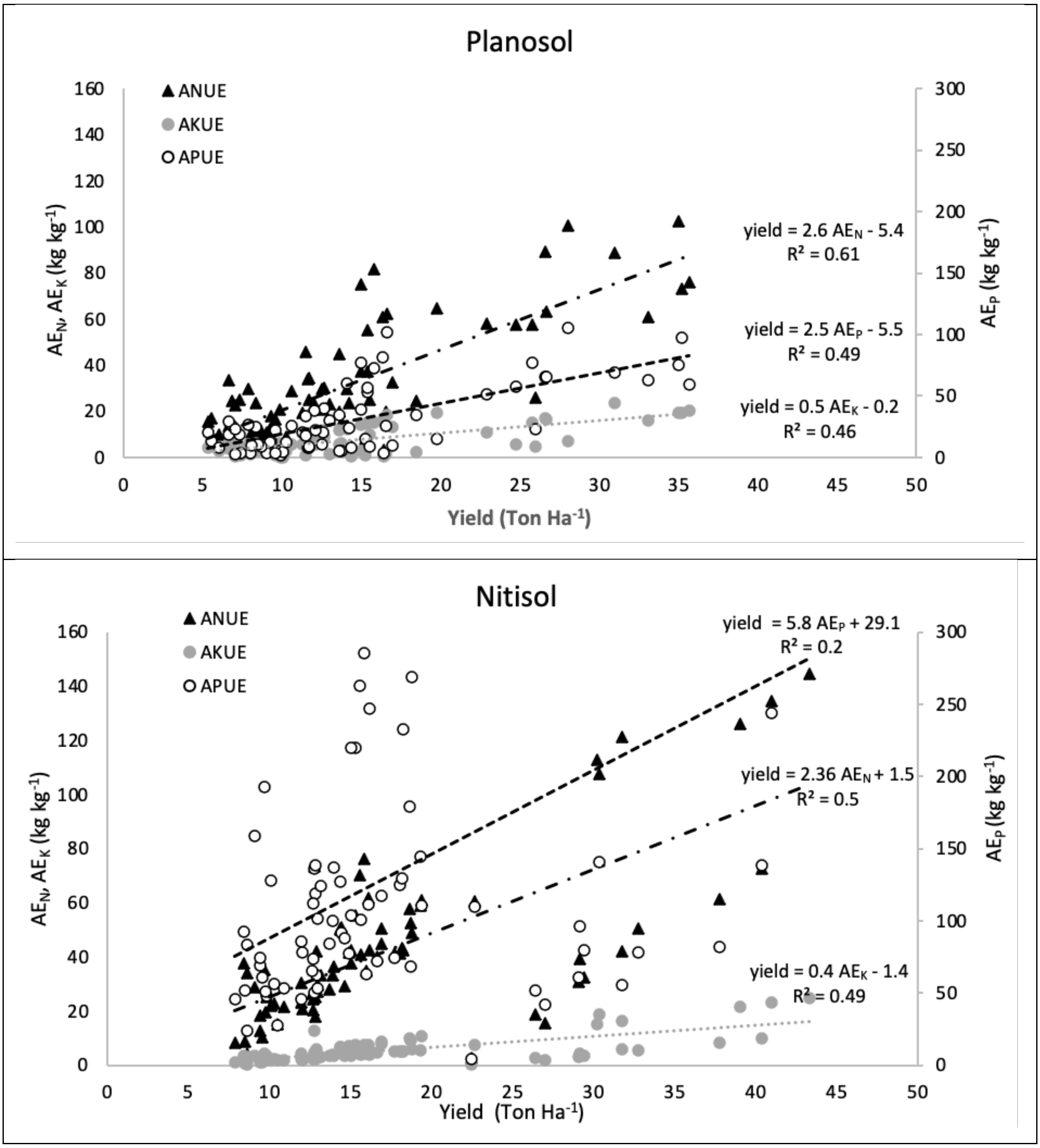


Figure 6.1: Relationship between potato yield and agronomic N (AE_N), P (AE_P) and K (AE_K) use efficiency.

6.4. Discussions

6.4.1. Effects of fertilizer blends on potato crop

The response to fertilizer addition significantly indicated a requirement for fertilizers in bridging potato yield gaps. DAP performance was among the best in terms of its effect on potato growth and yield attributes. A positive response to DAP fertilization has been reported

(Habte and Boke, 2017). Combining DAP with other fertilizers such as urea and murate of potash (MOP) is also beneficial to potatoes (Shunka et al., 2019). DAP is highly soluble thus making nutrients readily available thus enhancing the uptake (Nadarajan and Sukumaran, 2021). Temporal alkaline conditions that form around DAP molecule also enhance nutrient uptake, especially in acidic conditions (Jat et al., 2014; Nadarajan and Sukumaran, 2021). Phosphorus availability is particularly important at the tuber initiation phase to ensure maximum tuber set (Burke, 2017; Koch et al., 2019). Higher levels of phosphorus in the leaves stimulate the production of sucrose, which leads to more sucrose being translocated to the stolon, raising energy levels and stimulating earlier and greater tuber initiation, resulting in more tubers and hence higher yields (Koch et al., 2019). The high P content in DAP (46% P_2O_5) may also be attributed to the performance. In acid soils a lot of P is fixed into the soil particles making it not available for uptake, the high P level in DAP could have compensated for fixed P (Ayele et al., 2020; Muindi et al., 2015).

Mavuno blended fertilizers on the other hand contain gypsum and limestone, though not as soluble as DAP, the liming effect may have helped in raising the soil pH thus increasing nutrient uptake (Kisinyo et al., 2014b). Mavuno blended fertilizer has been shown to increase soil pH (Wamalwa, 2018). This would probably be the reason why the new Mavuno fertilizer blend performance was not significantly different from DAP despite the high P level on the latter. New Mavuno also contained other nutrients including K, which is taken up in relatively high amounts by root and tuber crops (Koch et al., 2020; Wortmann et al., 2020). Studies have revealed better crop performance with the application of compound fertilizer (Habte and Ayalew, 2017; Sitienei et al., 2018; van Erp et al., 2014). Apart from the immediate effect on the applied fertilizer, the maintenance of soil nutrients is crucial for sustainable production (Koch et al., 2020; Schut and Giller, 2020).

6.4.2. Influence of soil type on the potato crop

The two soil types are acidic though pH in Nitisol was lower than in Planosol and as such the biomass, tuber weight and yield obtained from the potatoes grown on the Planosol could be explained by the low N and SOM contents. Similar results were reported from the soil types (Andosols, Acrisol and Planosol) where a low response to organic amendments occurred with Planosol (Kevin et al., 2018). Higher yields have been reported with soils containing 5 g SOM kg^{-1} (Wang et al., 2019). Further, a linear relationship between potato yield and SOM has been reported (Zaeen et al., 2020). At low pH, the concentration of Fe and Al ion is higher thus the more the P is adsorbed to the soil (Abreu Jr. et al., 2003; Kim et al., 2006; Muchena and

Gachene, 1988). Adsorbed P is not available for plant uptake thus reducing the agronomic efficiency of P (Gitari et al., 2020).

Tropical soils, particularly in Kenya, generally have sufficient K, this is however rapidly changing due to nutrient mining with harvested crops (Mbuvi et al., 2013; Otieno et al., 2022). This was evident in the results since the K application showed some efficiency. In treatment where DAP was used, AE_K was slightly high than other blends implying available soil K which was above the optimum ranges, was efficiently used. Furthermore, the coefficients of the linear regression between AE_K and yield were low. The addition of K to potato fertilizer blends in Kenya should be added in small amounts to maintain soil K levels since potato is a high consumer of K (Koch et al., 2020; Naumann et al., 2020).

A high tuber number per plant may translate to high yield especially when the average tuber weight is high which was observed in the Sherekea variety. Thus high agronomic efficiencies especially of N and P were recorded. Nutrient use efficiency is affected by many factors including soil type and crop variety (Fixen et al., 2015; Zebarth et al., 2004). Li et al., (2009) also concluded that agronomic efficiencies in potatoes are affected by inherent soil conditions. The relationship between potato yield and the agronomic efficiency reported here is similar to those reported elsewhere (Li et al., 2009; Neshev and Manolov, 2016).

6.4.3. Interaction of fertilizer blends and soil type

Soil type and fertilizer type interactions were observed especially with respect to biomass, tuber number, and yield. Fertilizer performance is largely different in different soil types as a result of inherent soil fertility and adsorption capacity of added nutrients (Ayele et al., 2020; Haile and Boke, 2011; Muthoni and Kabira, 2011). In clay and sandy soil, P fertilization was found to significantly increase potato yield, the effect was however higher in clayey than sandy soil while P use efficiency was not different between the two soils (Martins et al., 2018). This is a clear indication that different fertilizer types should be recommended for the two soil types. Further, the agronomic efficiency on N and K was markedly higher with the application of DAP on Nitisol. This was probably one of the reasons why farmers prefer DAP fertilizer since its use has resulted in the efficient use of applied nutrients (Fixen et al., 2015; Mugo et al., 2020).

6.5. Conclusion

These results show that potato crop response to fertilizer types is largely a factor of the nutrient elements in the formulation and their ratios. The response is further influenced by site characteristics, especially the soil type. DAP and new Mavuno fertilizers had similar effects reflected by the majority of the measured attributes.

CHAPTER SEVEN

Discussion, Conclusions, Recommendations, and Policy Implications

7.1. General Discussion

Potato production is limited by inherent soil fertility that is influenced by continuous farming with minimal replenishment, nutrient leaching, and soil erosion. In Chapter 4, results obtained revealed that a substantial number of farms had soils that were deficient in N, P, K, S, and B. This could be attributed to fertilization as indicated by the high percentage of farmers applying fertilizer below national N recommended rates. Potato is grown as a monocrop mainly for commercial purposes thus mining high amounts of soil nutrients through the harvested tubers, this exacerbates the rate of soil fertility decline that is prevalent in the farms. Land-use changes such as continuous farming, have been associated with declining soil organic carbon, N, and B.

Apart from fertility management factors, soil type could also be linked with nutrient status. The high clay content in Nitisol and Planosol leads to fixation of nutrients especially P and S making them unavailable for plant uptake. Further, soil pH was low for potato production in over 50% of farms and correlated with most soil nutrients implying its vital influence on soil fertility. Under low pH, nutrients such as P are fixed by the Al and Fe ions thus making them unavailable for plant uptake. In addition, at low pH anaerobic bacteria, which plays a great role in the nitrogen mineralization process is inactivated due to low N levels. Low levels of residue incorporation in the soils account for low soil organic matter which impacts soil fertility. The first component in the analysis was influenced by pH, Ca, Mg and B while the second component was dominated by SOC and N. Calcium and Mg concentration influences the pH thus their domination of the first component of strong correlation and role of soil pH in nutrient management. Soil organic matter is also an important component in improving soil productivity thus explaining the correlation of SOC and N as the second component of factor analysis.

Raising soil fertility status in the region is crucial and chapter 5 of this study unveiled the effect of the addition of an adequate amount of N, P, K, S, and B on the growth of potatoes in the two main soil types in Kenyan highlands. Nitrogen was the single nutrient with the most significant effect on potato yield when omitted. Nitrogen plays a key role as a component of proteins, enzymes, and chlorophyll. It thus influences the yield growth and yield components. It had a synergistic effect on other nutrients tested as indicated by yield reduction when omitted, which was sometimes lower than the control plots. Due to its effects on plant growth, it leads to increased uptake of other nutrients such as K and S thus increasing yield. Phosphorus addition increased yields greatly. A lot of P is adsorbed under acidic conditions, and hence, the addition of P saturates adsorption points in the soil thus increasing levels of P available for uptake. Under low soil P, its addition has been shown to increase uptake of other nutrients due to its key role as a major component for energy transfer through adenosine triphosphate and being part of ribonucleic acid. While K is required in high amounts by potato crop, the yield limitation with its omission varied from various sites implying some levels of K adequacy in some sites. Tropical soils have long been classified as K-sufficient (Kanyanjua et al., 2006; Mbuvi et al., 2013; Recke et al., 1997). Nonetheless, the effect of K in some farms especially the Nyandarua site, implies that the addition of the same is necessary for some sites affirming the need for soil testing. Boron deficiency causes physiological and biochemical responses whereas when in excess it is toxic (Brdar-Jokanović, 2020). Given that its sufficiency ranges are narrow, this could explain the varying responses, a such inclusion in potato fertilizer blends is necessary after careful consideration. Correction of fertility status using inorganic nutrient source require integration of limiting nutrients for specific regions.

Crop-specific and farm-specific fertilizer are component of precision agriculture that matches the right source, rate, timing, and place (4 Rs) for ideal fertilizer management practices. Chapter 6 evaluated the right source component by evaluating the effects of selected fertilizer blends on their suitability to improve agronomic efficiency and yield of the potato crop. It was apparent that the application of DAP, which supplies N and P which were found to be the two most limiting nutrients, had better crop performance. This is a further emphasis on the impact of N and P on potato production in Kenya. The high P level in DAP coupled with the high solubility of the fertilizer could explain the performance. Application of Mavuno improved, which is a complete fertilizer enriched with micronutrients, performed equally well as DAP even with lower levels of P (24 P_2O_5 compared to 46 P_2O_5 in DAP), implying the positive effects of balanced fertilizer blends. Growth and yield effects on potatoes after application of Mavuno improved can also be attributed to the inclusion of micronutrients in the blend. Micronutrient applications improved the uptake of macronutrients. Further, Mavuno blended fertilizer with limestone as a filler material, raising the pH around the root zone thus enhancing nutrient uptake.

Agronomic efficiency based on the nutrients applied could be linked to the soil types, as the performances of evaluated fertilizer were different in the two soil types. Better N and P agronomic efficiencies were reported in nitisols as compared to planosol whereas no significant differences in K agronomic use efficiency were reported between the two soil types. These responses could be explained mainly by the levels of soil organic matter, the pH as well as the percent of clay content. Soil pH was lower on planosol as compared to nitisol and so was the organic matter content. The significant response differences of fertilizer on nitisols and planosol necessitate different fertilizer types and rate recommendations. The right nutrient balance is however an area of concern, MRV which had relatively low P content reported the highest P agronomic use efficiency.

7.2. Conclusions

i. Potato production in the Kenyan highlands is mainly limited by low levels of N, P, K, S, and B as well as low soil pH as indicated by survey and omission results.
ii. The addition of N and P to the basal fertilizer is necessary while K, S, and B should mainly be based on soil test results or to maintain the fertility status.
iii. Soil type played a crucial role in the performance of evaluated fertilizer blends and thus should be considered while developing fertilizer blends.
iv. Improved Mavuno fertilizer contains more nutrient combinations and low P content as compared to DAP yet there were no significant differences in their performances emphasizing the need for balanced fertilizers.

7.3. Recommendations.

i. Production of potato-specific fertilizer blend should be developed taking into consideration key factors such as soil type.
ii. Soil pH corrections have been conducted elsewhere but further studies on the same could strengthen the information.
iii. To better understand the long-term effect of fertilizer blend on soil nutrient balance as well as nutrient uptake by the human after consuming the food produced further should be conducted to bridge the knowledge gap.

There is a need for the government and private actors to invest in soil testing for individual farms to allow agronomists and extensionists to make customized recommendations as to the best type of product, application rate, and formulation to achieve optimal results with the minimum amount of fertilizer.

7.4. Policy implications

Bearing in mind the results from this study, the following policy recommendations are proposed:

1. Enactments are necessary to ensure that the production of fertilizers formulations shall be based on potato crop nutrient requirements for the different soil types and or agro-ecological zones.
2. Frameworks that enable the government to establish localized soil laboratories and soil testing facilities are necessary to generate site-specific information and provide site-specific agronomic recommendations. These services should be based on smallholder farming scenarios and must fit the local production conditions.
3. The government should build a regional framework with countries that already have soil and agro-specific fertilizer formulations to allow fertilizer blends matching specific soil types and gro-ecological zones a free entry.
4. Policy priorities that revitalize localized agricultural extension systems to help smallholder farmers obtain customized recommendations and hence maximize local production potential are priority areas.

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