

**EFFECTS OF SELECTED LIMITING NUTRIENTS ON GROWTH AND
YIELD OF MAIZE AND THEIR VARIABILITY IN SMALLHOLDER
FARMS OF KANDARA, MURANG'A COUNTY**

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DECLARATION

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

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DEDICATION

I dedicate this thesis to my dear Mother Alice Kanana, Father Lazarus Mukindia, Sisters Roseline, Caroline, Emily, and Doreen.

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ACRONYMS AND ABBREVIATIONS

CBS	Central Bureau of Statistics
FAO	Food and Agriculture Organization of the United Nations
FYM	Farm yard manure
H ₂ PO ₄	Di-hydrogen Phosphate
HPO ₄	Hydrogen Phosphate
ICRISAT	International Crops Research Institute for Semi-Arid Tropics
ISFM	Integrated Soil Fertility Management
KARI	Kenya Agricultural Research Institute
LR13	Long rains season of year 2013
SOM	Soil Organic Matter
SSA	Sub Saharan Africa
SSSA	Soil Science Society of America
SR13	Short rains season of year 2013
TSBF	Tropical Soil Biology and Fertility
CART	Classification and Regression Tree
ICP-AES	Inductively Coupled Plasma Atomic Emission Spectrometer
ANOVA	Analysis of Variance
SAS	Statistical Analysis Software
SPSS	Statistical Program for Social Sciences
ICRAF	International Centre for Research in Agro forestry
NUE	Nutrient Use Efficiency

ABSTRACT

Nutrient mining and mismanagement of farmers' fields has led to a decline in soil fertility in smallholder farms. In order to increase the productivity and subsequently improve food security in Sub-Saharan Africa (SSA), there is a need to identify soil nutrients limiting maize growth and production. The objectives of the study were; (i) to determine the most limiting nutrients for maize production in Kandara and establish the effect of selected soil amendments (CaMgS, manure and lime) on growth and yield of maize, (ii) to establish the influence of farm management history on soil variability in nitrogen, phosphorus and potassium levels. This study was carried in 2013 during the long rains season (March-May) and the short rains season (October- December) in Kandara Sub-County, Murang'a County in Kenya. Twenty three farmers were randomly selected for the trials. The experiment was laid out in randomized complete block design (RCBD) with 8 treatments (control, NPK+ CaMgS, NPK+ Manure, NPK+ Lime, NPK, NP, NK, and PK) in 23 farmers' fields, which were considered as replicates. Soil was sampled at a depth 0 – 20 cm in all the fields before the establishment of the trials and analyzed for pH, total carbon, macro, and secondary nutrients. Treatment inputs were applied at rates equivalent to 60 kg ha⁻¹N, 30 kg ha⁻¹ P, 60 kg ha⁻¹ K, 10 kg ha⁻¹ Ca, 10 kg ha⁻¹ Mg, 5 kg ha⁻¹ S, 10t ha⁻¹ manure and 1t ha⁻¹ lime in all the 23 replicates. Data on maize growth parameters; plant height, leaf number, and basal diameter was collected at intervals of two weeks at 14, 28, 42, 56 and 70 days after planting (DAP). Plant height and basal area were used to determine crop bio-volume. Grain and stover yield data was collected at physiological maturity. A semi-structured questionnaire was used to collect data on the farmers' management history of the 23 fields. Information on the number of seasons of manure use, the number of seasons of fertilizer use, field positions, fallow type, and land conversion history was sought. Maize growth and yield data were subjected to Analysis of Variance (ANOVA) using SAS 9.2 software. Fisher's LSD test was used to separate maize growth and yield means at 5% significance level ($P < 0.05$). Plant growth results showed that control, PK and NK treatment achieved means that were significantly different ($p < 0.05$) for leaf number and bio-volume in both seasons of growth. The grain and stover yields for, control, NK and PK showed significant differences ($p < 0.05$) during the two seasons of growth. Nutrient response analysis indicated that omission of N and P led to a yield loss of 1.8 Mg ha⁻¹ and 1 Mg ha⁻¹, respectively. The regression models indicated that manure use and land conversion history influenced N, P, and K variability in the soils of Kandara area. The regression tree for nitrogen indicated that the number of seasons of manure use (NSMA) was the predictor variable, which achieved the highest improvement value (0.10) among root competitor splits. The regression tree for phosphorus and potassium had LCH as the predictor variable, which achieved the highest improvement value 1.06 and 11.22, respectively. The regression tree indicated that the number of seasons of manure use (NSMA) had the greatest influence on soil nitrogen stocks. Soil P and K stocks were greatly influenced by land conversion history. Results from nutrient omission trials indicated that N and P are the most limiting nutrients for maize production in Kandara area. Additionally, manure use and land conversion history are the major management factors influencing nitrogen, potassium and phosphorus variability in farmers' fields. Farmers are therefore advised to use N and P fertilizers to replenish those specific limiting nutrients.

CHAPTER ONE

INTRODUCTION

1.1 Background information

Soil infertility has been considered a serious threat to agricultural productivity in Sub-Saharan Africa (SSA). Continuous cultivation of land, rising population and limited use of organic and inorganic fertilizers has led to soil fertility decline in Sub-Saharan Africa (Henao and Baanante, 2006). This situation is manifested by declining crop yields, decreasing vegetation cover, and increasing soil erosion. Consequently, farm productivity and agricultural incomes are falling and migration to urban centers is on the rise, while both household and countrywide food securities are continuously declining (AGRA, 2007).

Sub-Saharan Africa region faces interrelated problems; declining per capita food production and continuous deterioration of the environment (FAO, 2002). A World Bank report estimated the rate of cereal yield increase in Africa over the years at a very low. The increase is at a rate of 0.7% compared to growth rates in other developing regions of the world of 1.2-2.3% (AGRA, 2007). Sub-Saharan Africa is, the only region in the world where per capita agricultural productivity has remained stagnant over the past 40 years. This is because of persistent soil degradation and soil infertility across much of the agricultural area (Sanchez and Swaminathan 2005a, b).

Yet other parts of the developed world have registered improved per capita food production it continues to decline in SSA (Bationo *et al.*, 2004).

Smallholder farms in SSA are highly diverse often operating in complex natural and social economic environments. Much of the soil fertility variation within farming systems is caused by spatial soil heterogeneity (Tittonell *et al.*, 2005). The processes of nutrient depletion and soil degradation however are spatially heterogeneous as determined by the underlying parent materials, geomorphology and current and historical management. Causes of variability in soil fertility status are both biophysical and social economic (Tittonell *et al.*, 2005a, b) and are at different scale (region, village, farm, and field). The variability at regional scale is determined by climate, dominant soil type, and historical, social, cultural, and ethnic aspects of land use. The variability between different farm types (resource endowment groups) is associated with differences in soil fertility management between poor and wealthy households (Tittonell *et al.*, 2008). The restoration of soil fertility is now recognized as the key entry point for increasing agricultural productivity in smallholder farms (Sanchez and Swaminathan, 2005a, b; Martens, 2005).

The smallholder farming community in Kenya plays a major role in domestic food production. It is responsible for meeting up to 80% domestic food requirements in the country (Makokha *et al.*, 2001). However, maize yield in smallholder farms in Kenya has steadily declined because of deteriorating soil fertility. Indeed most soils are characterized by nutrient mining, high evaporation rates while other soils are fragile and

unsuitable for sustainable rain-fed agriculture (Angima *et al.*, 2003). The bottlenecks faced by smallholder farmers are compounded by inadequate use of agricultural inputs to replenish the mined nutrients. This inadequacy has been caused by shortage of capital and lack of access to credit facilities. This has hampered the use of inorganic fertilizers to replenish soil nutrients (Makokha *et al.*, 2001). Local economic policies and the slowing global economy have led to high fertilizer prices. The result is expensive fertilizers subsequently depressing maize yields in smallholder maize fields (Heerink, 2005). This situation is made worse by continuous cropping without returning the plant residues back into field.

Soil fertility depletion remains the major biophysical cause of declining crop productivity on smallholder farms in central Kenya (Bationo *et al.*, 2004; Kimani *et al.*, 2004). The central highlands of Kenya are associated with significant soil degradation. This phenomenon is aggravated by rapid population growth, cultivation of fragile ecosystems and continuous cropping. This has resulted in low returns to agricultural investments, declining food security and general high food prices (Angima *et al.*, 2003; Mugendi *et al.*, 2003). A study by Okalebo *et al.* (2006) indicated that, decline in soil fertility is multifaceted. It is caused by a myriad of factors such as high rates of soil erosion, nutrient leaching, removal of crop residues and continuous cultivation. In another study by Gachimbi (2002), it was revealed that the skyrocketing prices of inputs resulted in many smallholder farmers lowering or ceasing use of chemical fertilizer. This scenario does not portend well to status of soil health since it exacerbates soil fertility decline.

Further, Lekasi *et al.* (2003) showed that farmers in central Kenya do not mix manure well during their preparation, which leads to low mineral nitrogen (N) concentration and a higher carbon. This leads to low quality manure, yet smallholder farmers turn to locally available manure believing it can replace inorganic fertilizers. Another study by Kimani *et al.* (2004) reported that soils in central Kenya are more acidic due to continuous cultivation and widespread use of phosphatic fertilizers. The status of soil fertility is also influenced by socioeconomic status of smallholder farmers. A study by Murage *et al.* (2000) in central Kenya showed that differences in chemical and biological soil properties in productive and non-productive fields are influenced by the social-economic status of the household.

Central Kenya has high potential for food production because of favorable seasonal precipitation. However, most of the soils are deficient in essential nutrients particularly nitrogen (N) and phosphorus (P) (Murage *et al.*, 2000). Nitrogen is the major nutrient limiting cereal growth (Snapp *et al.*, 1998). To sustain high crop yields in intensive crop production system, nitrogen fertilizer input is required. Further, phosphorus limitation in smallholder farms is also widespread in Kenya (Kwabiah *et al.*, 2003). Indeed phosphorus (P) deficiency is a nutrient limiting crop production in most smallholder maize fields in tropical and sub-tropical soils. In addition, potassium (K) is an emerging nutrient limiting crop production in humid and sub humid regions of Kenya (ICRAF, 1997). This is attributed to greater losses than gains of soil nutrients leading to a negative balance in intensively cropped soils (Smaling *et al.*, 1997). Potassium losses through leaching, soil erosion, runoff and crop uptake are higher than addition through

weathering of parent material and application of organic and inorganic fertilizers (Weil and Mughogho, 2000).

1.2 Problem statement and justification

Nutrient limitation in soils has led to a drastic decline in maize yields in most smallholder farms. This is characterized by low levels nitrogen, phosphorus, and potassium in smallholder farmers' fields. This is caused by decline in soil fertility (Nziguheba *et al.*, 2002a, b), which inevitably leads to low agricultural productivity. It is evident that agricultural output is fundamentally affected by productivity status of soil (Liasu *et al.*, 2008). Poor soil management practices and the fragile nature of tropical soils account for heavy nutrient losses through soil erosion and nutrient leaching (Hossner and Juo, 1999). Unsuitable soil management activities including deforestation, and use of marginal lands for agricultural purposes often lead to degradation of soil resources (Henao and Baanante, 2006). Poor cultivation practices have resulted in reduction of soil organic matter (SOM), and increase in occurrence of acidified soils (Aihou *et al.*, 1998). This decline in soil fertility has decreased farmland productivity in most smallholder farming communities (Amede, 2003). Escalating rates of soil nutrient mining makes nutrient losses highly variable in agricultural areas. This variability ranges from moderate to severe loss of nutrients (Henao and Baanante, 2006). Continuous cropping in Kandara has led to nutrient mining which has resulted to decline in soil fertility subsequently lowering maize yields due to the emergence of limiting nutrients.

Limiting nutrients in smallholder fields of Kandara have not been established. Further, field management practices play a critical role in determining the status of soil fertility. Farm management activities directly influence variability of nitrogen, phosphorus, and potassium. The study sought to determine the limiting nutrients in the production of maize in Kandara and how field management practices influence the variability of those nutrients.

1.3 Research questions

The study sought to answer the following questions:

- i. How do nitrogen, phosphorus, and potassium limit maize production in Kandara and the influence of selected soil amendments (CaMgS, manure and lime) on growth and yield of maize?
- ii. How does field management history influence the variability of soil nitrogen, phosphorus and potassium levels in smallholder maize fields of Kandara?

1.4 Research objectives

The objectives of the study were:

- i. To determine the limiting nutrients for maize production in Kandara and establish the influence of selected soil amendments (CaMgS, manure and lime) on growth and yield of maize.
- ii. To evaluate the influence of history of management on nitrogen, phosphorus and potassium variability in smallholder maize fields of Kandara

1.5 Research hypotheses

The study was guided by the following hypotheses:

- i. Nitrogen, phosphorus, and potassium are the nutrients limiting maize production in Kandara and selected soil amendments (CaMgS, manure and lime) influence growth and yield of maize.
- ii. History of management influences the variability of soil nitrogen, phosphorus, and potassium in smallholder maize fields of Kandara.

1.6 Significance of the research output

The knowledge generated will help to develop succinct recommendations that will be used to advise farmers on what nutrients formulations to use on their fields. The results will be used by research institutions such as Kenya Agriculture and Livestock Research Organization (KALRO) and other stakeholders to inform fertilizer formulations. The determination of the limiting nutrients will help farmers replenish their soil with the correct nutrient and thus produce maize sustainably. This will lead to restoration of soil fertility and consequently farmers will achieve high yields. Food security in Kandara will improve thus help in alleviating poverty. In addition, the establishment of the influence of history of field management on variability of nitrogen, phosphorus, and potassium will help farmers change how they manage their farms and thus start the process of soil rehabilitation.

1.7 Conceptual Framework

Smallholder farmers in Kandara face challenges of declining soil fertility. This has led to depressed maize yields thus exacerbating food insecurity. The decline of crop yields in most smallholder farmers' fields can be attributed to low soil fertility (Murwira, 2003). Soil fertility is conceptualized to be influenced by the nutrient mining and poor field management practices (Figure1.1). These factors interact in synergy to determine

the status of soil fertility. When soil is severely degraded and farmers fail to manage their fields well. This results to widespread soil infertility leading to depressed yields.

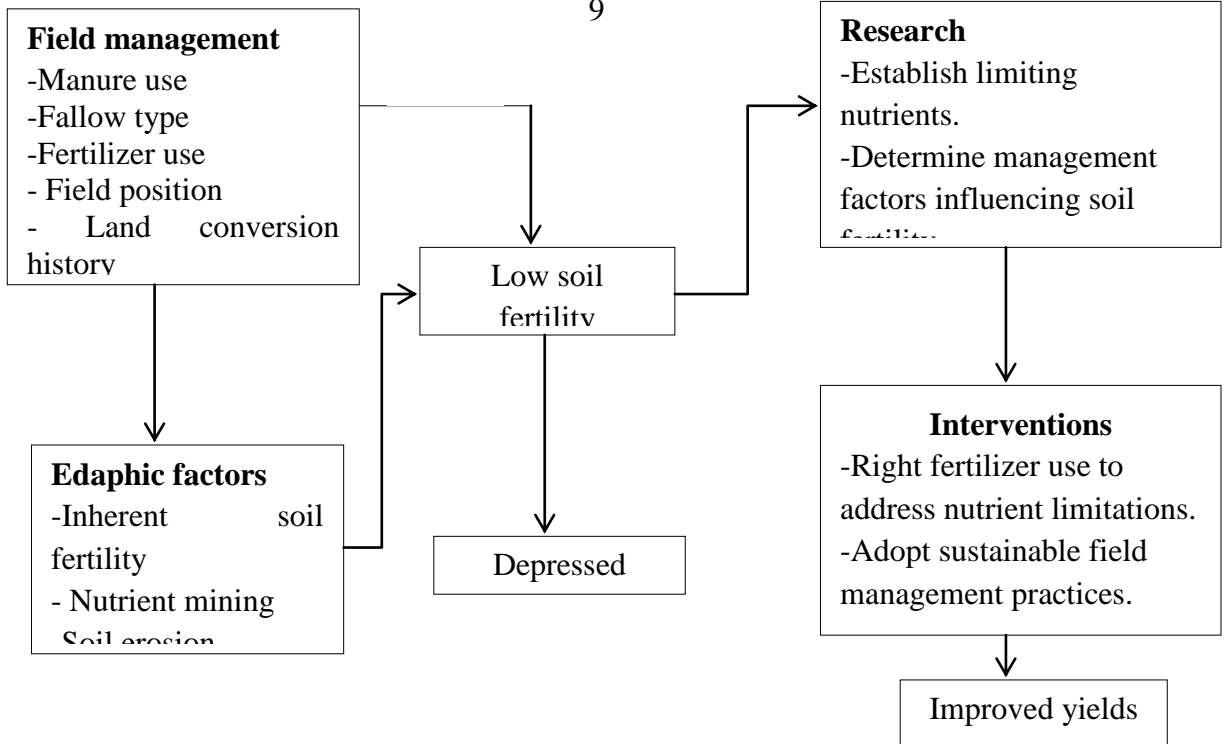


Figure 1.1 Conceptual framework

The experiments sought to establish the limiting nutrients depressing maize yields and establish how management practices influence variability of those nutrients in smallholder fields. Further, the influence of soil amendments inform of secondary nutrients, lime, and manure was sought in order to establish whether there is limitation of these soil amendments. Identifying the limiting nutrients will inform nutrient formulation and application to correct these nutrient imbalances and thus improve maize yields

1.8 Definition of terms

Inherent soil fertility - This is the existing status of soil in farmers' fields before the experiments were set.

Amendments - These are soil additives meant to improve soil quality during the trials period. They include lime to modify pH and manure to add onto soil carbon content.

Secondary nutrients/micronutrients - These are elements such as magnesium, sulphur, calcium that are required by crops in small quantities during growth.

Soil quality - The soil capacity to function within natural or managed ecosystem boundaries with capacity to sustain plant and animal life; while enhancing water and air quality to support both human and animal health and habitation.

Plant bio volume -Product of plant basal area multiplied by height.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview

This chapter reviews relevant research and literature on soil fertility, plant nutrition, and effects of farmer practice on nutrient variability. Critical points touching on above thematic topics are discussed in depth by reviewing current knowledge and scholarly contributions to the subject matter. The themes discussed herein include, soil quality, and fertilizer use in smallholder farms. The roles of plant mineral nutrients such as nitrogen, phosphorus, potassium, and secondary nutrients are discussed. The effects of soil pH, soil organic matter, and land degradation on soil fertility are also highlighted. In the course of the review, gaps are identified that inform this research theoretically and add value to the experimental design and methods.

2.2 Nature of soil; paradigm of soil quality

Soil quality concepts have been evolving and the last decade saw soil scientists develop modern theories to define soil quality (de Haan *et al.*, 1990; Davidson, 2000; Tóth *et al.*, 2007). The Soil Science Society of America (SSSA) proposed a definition (Allan *et al.*, 1995), which integrated scientific and practical approach. The SSSA defined soil quality as the capacity of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal production, enhance water and air quality and support human health and habitation.

Some may critique that this scientific concept is biased by our current perception of the services provided by soil (Sojka and Upchurch, 1999). Rather, than being based solely and purely on theoretical ground (with possible windows towards applicability). It is generally accepted that apart from studying its natural phenomena, soil is a compound whose characteristics cannot be directly measured (FAO, 1976; Karlen *et al.*, 2001). Therefore soil quality assessment within the framework of its functions is well justified. Soil quality is a concept developed to characterize the usefulness and health status of soils. Consequently, are fundamental to the well-being and productivity of agricultural and natural ecosystems (Rodrigues de Lima *et al.*, 2008). Soil quality is the ability of the soil to provide ecosystem and social services through its capacities to perform its functions under changing conditions (Tóth *et al.*, 2007).

A profound challenge is faced in evaluating and sustaining the broader ecological services that soils can provide with proper management, while still maintaining sufficient food and energy production for a population projected to reach 9 billion by 2050 (Tilman *et al.*, 2002; Rockstrom *et al.*, 2009a; 2009b). Regional variation in soil properties and management ensures that no single set of soil characteristics can be universally adopted to quantify these definitions (Robertson and Swinton, 2005). Soil quality is often equated with agricultural productivity and sustainability. It is commonly defined, as a soil's potential to perform ecological functions in a system, for example, to maintain biological productivity, partition, and regulate water and solute flow (Palm *et al.*, 2007).

Subsequently, Sanchez *et al.* (2009) argued that an ongoing effort to map soil properties globally and evaluate the condition of soils in conjunction with management recommendations for preventing soil degradation are critical for the protection of ecosystem services.

The concept has been applied throughout the world for a multitude of purposes (Ouedraogo *et al.*, 2001; Tian and Feng, 2008). Soil quality concept is crucial for the success of sustainable agriculture and ecological management (Karlen *et al.*, 2001; Wienhold *et al.*, 2004; Kibblewhite *et al.*, 2008). Soil quality is an attribute of a soil that is inferred from soil characteristics or indirect observations. Soil characteristics representing soil quality need to be selected and quantified (Karlen *et al.*, 2001). These may include biological, chemical, or physical soil characteristics (Idowu *et al.*, 2008). Characteristics used by both farmers and scientists to identify degraded soils include visual, tactile and morphological characteristics (Doran and Parkin, 1994). Farmers rely largely on observation to judge soil quality (Romig *et al.*, 1995; Mwesigye, 1996); Pien *et al.* (1995) reported farmers' knowledge of detecting soil depletion symptoms associated with land and plant production. They included local means of detecting leaf symptoms and soil chemical imbalances. Soil chemical imbalances are a challenge to sustainable crop production. These chemical discrepancies portend absence of the essential nutrients to support sustainable crop production. This scenario is not good for efforts to achieve food security in Sub-Saharan Africa.

2.3 Nutrient use in small hold farms of Sub-Saharan Africa

Soils in highly productive areas of Sub-Saharan Africa have been degraded by continuous cropping without replacement of nutrients a phenomenon referred to as nutrient mining (Murwira, 2003). According to Sanders *et al.* (1996), population explosion has pushed smallholder farmers to cultivate marginal lands that are prone to soil erosion and environmental degradation. Moreover, Nandwa (2001) noted that it is also no longer feasible to use extended fallow periods to restore soil fertility leading to non-sustainability of the production systems.

Mueller *et al.* (2010) noted that the capacity of soil to produce plant biomass remains a pivotal role. He added that this function is closely associated with food security, and can only be delivered by a fertile and/or a healthy soil. According to Millennium Ecosystem Assessment (2005), a soil is said to be fertile if it has the capacity to retain, cycle, and supply the essential nutrients for plant growth over many years. Alley and Vanlauwe (2009) described a healthy soil as one that is capable of supporting ecosystem services on a sustained basis. They added that soil fertility should ensure robust plant growth and good crop yields. Sanchez *et al.* (1997) observed the role of soil in Africa is fast waning because of the severe nutrient depletion and the widespread decline in the fertility of African soils.

Sanchez *et al.* (1997) observed that fertilizer use has been responsible for a large part of sustained increases in per capita food production that have occurred in Asia, Latin America, and southern Africa. But according to Kazombo-Phiri (2005), most

smallholder farmers in SSA appreciate the value of fertilizers although they rarely apply them at the recommended rates and at the appropriate time because of high costs and low variable returns. Heisey and Mwangi (1996) noted since 1960s fertilizer use has been growing in SSA at around 6.7% annually but growth in application rates per hectare has slowed down since the 1990s. In southern Africa, current fertilizer use varies from 3.5 kg ha⁻¹ in Mozambique, to 49.3 kg ha⁻¹ in Zimbabwe compared to 80 kg ha⁻¹ per year in the rest of the world.

According to Ahmed *et al.* (1997) and Rusike *et al.* (2003), less than 5% of farmers commonly use fertilizers in Zimbabwe due to the fear to risk investment in fertilizer. ICRISAT (2006) observed the need to improve fertilizer use efficiency so that mineral fertilizer use is financially attractive to farmers. Appropriate fertilizer usage will address problems of limiting nutrients in most smallholder maize fields once the nutrients are established. Most smallholder farmers and researchers in Kenya appreciate the value of mineral fertilizers in replenishing the dwindling nutrients. A study carried out in western Kenya reported 63% increase in maize yields using mineral fertilizers (Ayoke *et al.*, 2006). Kihanda (1996) reported that less than 25% of farmers in Central highlands of Kenya use mineral fertilizers with most of them applying less than 20 kg ha⁻¹.

2.4 Limiting nutrients in smallholder maize fields

Soil fertility decline in SSA has contributed to the loss of nitrogen (N) phosphorus (P) and potassium (Amede, 2003). According to Roy *et al.* (2003), negative nutrient balances for nitrogen and phosphorus have been found in smallholder farming systems in SSA. Henna and Baanante (2006), computed per hectare nitrogen (N), phosphorus (P) and potassium (K) nutrient balances for the whole of Africa for 2002- 2004. They found that the average annual depletion rate of all Sub-Saharan African countries was 54 kg NPKha^{-1} , ranging from $23 \text{ kg ha}^{-1}\text{yr}^{-1}$ in South Africa to as much as $88 \text{ kg ha}^{-1}\text{yr}^{-1}$ for Somalia.

Shepherd *et al.* (1997) observed that nitrogen and phosphorus are the main limiting nutrients in food crop production in western Kenya. Hartemic *et al.* (2000) reported that nitrogen fertilizer input was required in order to sustain high crop yields in intensive crop production system. Further, nitrogen deficiency can be ameliorated through application of inorganic, organic fertilizers and biological nitrogen fixation. According to Lungu and Dynoodt (2008), one of the ways of addressing the impact of soil mining is use of inorganic fertilizers. However, use of these inputs among smallholder farmers is currently very low. Nitrogen is one of the key nutrients for crop production. It is the most mobile, volatile and the most exhausted nutrients due to its ability to exist in different forms and its easy leach ability (Palm *et al.*, 1997). Snapp *et al.* (1998) observed that maize removes about 40 kg N ha^{-1} to produce 2 to 2.5 t of grain yield per hectare in the tropics.

According to Kwabiah *et al.* (2003) phosphorus is a limiting nutrient in maize production due to the low native soil P and high P fixation. In addition, Fairhurst *et al.* (1999) observed that phosphorus unlike nitrogen couldn't be replenished through biological fixation. For many cropping systems in the tropics, application of P from organic and inorganic sources is essential to sustain high crop yield. Further, Kwabiah *et al.* (2003) concluded that phosphorus (P) deficiency is a factor limiting crop production in tropical and sub-tropical soils. Correcting P deficiency with application of phosphatic fertilizers is a challenge for most poor smallholder farmers in SSA due to high costs of mineral fertilizers.

ICRAF (1997) found that potassium (K) is an emerging limiting plant nutrient in humid and sub humid regions of Kenya. This is attributed to greater losses than gains of soil nutrients leading to a negative balance in intensively cropped soils (Smaling *et al.*, 1997). Potassium losses through leaching, soil erosion, runoff and crop uptake are higher than addition through weathering of parent material and application of organic and inorganic fertilizers (Weil and Mughogho, 2000).

2.5 Importance of nitrogen in maize growth

According to Jones (2003), nitrogen occurs in soil in organic and inorganic forms. Organic nitrogen originates from living organisms and is a part of the organic compounds remaining after their death and decomposition.

Inorganic N in soils refers to all forms of N that have been freed by mineralization from organic compounds including or have been added to the soil in the form of chemical fertilizers (Zhu and Chen, 2002). Tisdale *et al.* (1985) observed that plants absorb nitrogen mainly in the nitrate (NO_3^-) and ammonium (NH_4^+) forms. Mengel and Kirkby (1982) observed uptake of nitrate and ammonium by plants is influenced by soil water availability, microbial activities, and soil chemical reactions. Nitrate uptake is encouraged when soil pH is low and depressed when soil pH is high. This is due to the competitive effect of OH^- ions, which suppress the NO_3^- uptake and transport. Further, plant uptake of ammonium proceeds best at neutral pH values and is depressed by acidity due to competition between hydrogen (H^+) and ammonium (NH_4^+) on plant roots. According to Splittstoesser (1990), nitrogen is more responsible for variability in plant growth than any other element.

Nitrogen plays a vital role in nutritional and physiological status of maize and promotes changes in mineral composition of the crop (Zhu and Chen, 2002). Malhia *et al.* (2001) and Murshedul *et al.* (2006) reported that increasing nitrogen levels up to 120 kg N ha^{-1} leads to a significant increase in grain yield and its components. However, most plants only utilize less than one-half of fertilizer N applied, and the loss of fertilizer N is high (Zhu, 2000; Zhu and Chen, 2002). Nitrogen management in agro-ecosystems has been extensively studied due to its importance in improving crop yield and quality (Hillin and Hudak, 2003; De Paz and Ramos, 2004; Alam *et al.*, 2006; Dambreville *et al.*, 2008).

Soil exchangeable inorganic N is the common source of various N losses (Zhu, 2000). The immobilization and release of fertilizer N in soil organic N and fixed NH_4^+ pools are important processes regulating fertilizer N transformation in soil (Mubarak *et al.*, 2001; Macdonald *et al.*, 2002; Elmaci *et al.*, 2002; Lu *et al.*, 2010). Therefore, a key challenge in minimizing loss of chemical fertilizer N is how to decrease the superfluous accumulation of soil exchangeable inorganic N and synchronize the supply of available N with plant uptake during peak periods of crop N demand (Zhu, 2000; Lin *et al.*, 2007). Understanding the accumulation of fertilizer N in soil inorganic N pool is of considerable importance in minimizing fertilizer N loss while maximizing its use efficiency (Lu *et al.*, 2008). Smallholder maize farmers in the Kenya highlands face severe biotic and abiotic challenges (Ariga *et al.*, 2006). The major abiotic challenge is low nitrogen (N) and stress during critical stages of crop growth. Poor N nutrition may be due to inadequate N fertilization or temporal mismatch between N availability in soil solution and crop uptake needs. In the absence of site-specific recommendations, N management poses a serious challenge in the highlands (Shanahan *et al.*, 2008). Sangoi *et al.* (2007) found that application of total N before or at sowing results in reduced grain yield. N losses through volatilization, leaching, and denitrification are likely to be high as the cropping season is very long with maize taking up to 240 days to physiological maturity (Sangoi *et al.*, 2007). Matching N availability in soil solution and crop uptake needs is critical to Nitrogen Use Efficiency (NUE) and economic viability (Shanahan *et al.*, 2008). According to Samira *et al.* (1998) and Torbert *et al.* (2001) N₂ application increased yield and yield components of maize. Jones (2003) observed that plants suffering from N deficiency mature earlier and the vegetative

growth stage is shortened. Further, Wolf (1999) observed nitrogen deficiencies are most common in mineral soils that are subject to leaching.

2.6 Importance of Phosphorus in maize growth

Jones (2003), described phosphorus (P) has a naturally occurring element that can be found in the earth's crust, water and all living organisms. Powers and McSorley (2000) highlighted that forms in which phosphorus occurs in soils as inorganic phosphorus ions, strongly bound P, organic P in humus and soluble, adsorbed phosphates, including P in solution. These four different forms of soil P are in equilibrium in an aqueous solution, and the predominant form of P depends on the soil pH.

Plants absorb phosphorus largely as primary and secondary orthophosphate ions (H_2PO_4 and HPO_4^-) present in the soil solution (Jones, 2003). Phosphate compounds adenosine di-phosphate (ADP) and adenosine tri-phosphate (ATP) act as energy currency within plants (Wolf, 1999). Good supply of phosphorus increases root development. It is also associated with early maturity and strength of crop tissues, improving quality of final yields (Parker, 2000). Grant *et al.* (2001) found that plants require adequate P from the very early stages of growth for optimum crop production. Yet this element is frequently limited in most Africa soils. According to Tang *et al.* (2007) dynamics of soil P are characterized by interactions between physico-chemical (sorption and desorption) and biological (immobilization and mineralization) processes. The rate and direction of these reactions are influenced by chemical conditions and biophysical dynamics as well as by the agricultural crops adopted (Blake *et al.*, 2000; Krishna, 2002; Bunemann *et*

al., 2004). Soil P undergoes biological (Hedley *et al.*, 1982) and pedological (Smeck, 1985) transformations, which are short- and long-term transformations, respectively.

Biological transformation of P is governed by the bio-cycling of organic matter (Nziguheba *et al.*, 2000). During the process of transformation and losses of bases, carbonates and silicates, some of the P released into solution is taken up by soil and plant biomass (Kpongor, 2007). In addition, the release of organic exudates by soil microbes and plant roots or added organic material may affect sorption P and the exchangeability of added P by competing for the sites of P sorption (Nziguheba *et al.*, 1998).

In highly P fertilized soils, the P concentration in soil solution is high, and the depletion zone is readily replenished. The replenishment is slow when soil solution P is low especially for soil solid phase with a low buffer capacity (Kpongor, 2007). The quantity of P ions in soil solution at any given time generally represents less than 1% of P annually taken up by crops. Approximately, 99% of P taken up by plants is bound to soil constituents before uptake (Schneider and Morel, 2000). The importance of adequate tissue P concentrations during early-season growth has been reported in many different crop species (Grant *et al.*, 2001). Studies in Ontario have shown that maize grain yield was strongly affected by P supply and tissue P concentration in the L4 to L5 stage, rather than by P concentration later in growth (Barry and Miller, 1989; Lauzon and Miller, 1997). Gavito and Miller (1998) reported that enhanced early-season P

nutrition in maize increased the dry matter partitioning to the grain at later development stages. Plénet *et al.* (2000) reported the maximum difference in biomass production of corn under P deficiency in field conditions where the aboveground biomass accumulation was severely reduced (–60%) during early stages of maize growth. Only slight differences were observed on biomass accumulation at harvest and grain yield.

The spectacular effect of P deprivation on early reduction in shoot growth is explained by a slight although rapid stimulation of root growth, which has been reported (Mollier and Pellerin, 1999). The ultimate effect of initial reductions in growth related to P deficiency on the final crop yield is influenced by other growth-limiting factors experienced by the crop through the remainder of the growing season. Plénet *et al.* (2000) observed that phosphorus deficiency results in plants that grow slowly with poorly developed root systems and small leaves of greyish-green color. Phosphorus deficiency is most common in acid soils rich in aluminium (Al^{3+}). Excess supply of phosphorus affects plant growth indirectly by reducing the availability of Fe, Mn and Zn. Excess phosphorus occurs in soils subject to heavy phosphorus applications, particularly where aluminium levels are low (Wolf, 1999).

2.7 Importance of potassium in maize growth

Potassium (K) is another macronutrient required for crop growth. In the soil, K exists in exchangeable and non-exchangeable forms, which are in dynamic equilibrium with each other (Cox *et al.*, 1999). Archer (1985) observed that potassium in solution and

exchangeable potassium are replenished by non-exchangeable potassium when these forms of K are depleted by plant removal or leaching

Plants can only absorb potassium as the potassium ion K^+ (Dong *et al.*, 2010). The observed potassium (K) plays a particularly critical role in plant growth and metabolism. It contributes greatly to the survival of plants that are under various biotic and abiotic stresses. According to Shaballa and Pottosin (2010), concentration of K^+ in the cytoplasm has consistently been found to be between 100 and 200 mM. Apoplastic K^+ concentration may vary between 10 and 200 or even reach up to 500 mM (White and Karley, 2010).

Potassium plays a vital role as macronutrient in plant growth and sustainable crop production (Bukhsh *et al.*, 2012). It maintains turgor pressure of cell which is essential for cell expansion. It helps in osmo-regulation of plant cell, assists in opening and closing of stomata (Mengel and Kirkby, 1987). It plays a key role in activation of more than 60 enzymes (Tisdale *et al.*, 1990). Its application has a positive effect on growth and development (Bukhsh *et al.*, 2011) and grain yield in maize (Bukhsh *et al.*, 2009). It not only affects the transport of assimilates but also regulates the rate of photosynthesis in maize. It is known for its interaction both antagonistic and synergistic with essential macro and micro nutrients (Dibb and Thomson, 1985). K is very important for efficient N utilization and has a consistent effect on lowering tissue concentration of Ca and Mg (Bukhsh, 2010). According to Wolf (1999), K deficiency typically results in stunted plants with weak stalks that lodge easily. When the deficiency is very acute, the leaves

show yellow spots followed by necrosis on the tips and edges. K deficiency is common in sandy soils with low exchange capacities and in soils with high potassium fixing capacities. Excess potassium can lead to Ca and /or Mg deficiencies in plants (Sanjuán *et al.*, 2003).

2.8 Land management history and soil fertility

A major part of the cultivable land in SSA (72%) suffers from low fertility, loss of soil nutrients, poor soil drainage and steep slopes, and is unlikely to support the population (FAO, 1993). According to Voortman *et al.* (2000), land degradation exacerbates soil degradation eventually causing poor agricultural performance. The most important forms of degradation are soil erosion and soil nutrient depletion (Wopereis *et al.*, 2006). It is estimated that 65% of SSA's agricultural land is degraded because of water and soil erosion, chemical and physical degradation (Olderman *et al.*, 1990; Scherr, 1996). The areas experiencing the most rapid degradation are densely populated areas with young and relatively fertile volcanic soils. These areas are on steep mountain slopes found in the highlands of eastern and central Africa (Smaling *et al.*, 1997; Voortman *et al.*, 2000; Henao and Baanante, 2006).

Forms of degradation vary with the causative factor: loss of topsoil, loss of nutrient and organic matter, chemical deterioration and physical deterioration (Scherr, 1996). Of the total degraded area, overgrazing, agricultural mismanagement, deforestation and overexploitation of natural resources are said to account respectively, for 49, 24, 14, and 13 percent (Olderman *et al.*, 1990). According to Barbier (2000a), human-induced soil degradation; through overgrazing, deforestation, and inappropriate agricultural

activities, it poses a serious threat to land productivity. Response to declining land productivity has been the abandonment of existing degraded pasture and cropland and the move to new land for grazing and cultivation (Barbier, 2000a).

Research has shown that soil nutrient depletion with insufficient replacement of macro-nutrients removed from the soil is a major problem in low income countries. It is a fundamental biophysical constraint to steady growth of food production (Donovan and Casey, 1998; Borlaug, 1995). On a per ha basis, 22 kg N, 2.5 kg P, and 15 kg K are being lost annually because of long-term cropping with no external nutrient inputs and returned crop residues (Weight and Kelly, 1998). Severe land degradation in SSA has threatened the agricultural productivity of smallholder farmers and thereby hindering efforts to reduce poverty (Lufumpa, 2005). The Kenyan highland, where Kandara is located has high agricultural potential. Several studies conducted in the region confirm that agricultural productivity is decreasing because of declining soil fertility (Palm *et al.*, 1997; Kapkiyai *et al.*, 1999; Solomon *et al.*, 2007). Decreasing soil fertility is a result of imbalance between nutrient inputs and nutrient removals through harvesting, erosion, and leaching (Lynam *et al.*, 1998; Zingore *et al.*, 2005; Lal, 2007). The depletion rates of specific nutrients depend on a number of factors including management, soil type, and climate (Davidson and Ackerman, 1993; Wopereis *et al.*, 2006; Zingore *et al.*, 2007).

Smallholder farmers in the Kandara pursue a wide range of crop and livestock enterprises in variable humid and sub humid agro-ecozones (MOA&RD, 2001; Jaetzold *et al.*, 2006). Variability in soil fertility can occur at different scales, including field

level land use, distance of fields from the homestead, and among households (Vanlauwe *et al.*, 2002a; Tittonell *et al.*, 2005a; Tittonell *et al.*, 2005b; Tittonell *et al.*, 2006; Vanlauwe *et al.*, 2006; Tittonell *et al.*, 2007a). Household characteristics, exogenous economic forces, and biophysical factors interact in a complex way resulting in highly diverse smallholder agriculture systems (Shepherd and Soule, 1998; Wopereis *et al.*, 2006). Tittonell *et al.* (2007a) observed that differences among households in labor availability; resource endowments give rise to different approaches to managing resources. These management differences affect the type and growth of plants, the use of fertilizers, and the functioning of soil micro- and macro fauna, which in turn influence soil fertility (Tittonell *et al.*, 2007). Consequently, soil fertility management usually is related to access to resources, history of local farming, access to markets and agricultural policy (Vanlauwe *et al.*, 2006).

De Costa and Sangakkara (2006) observed that success in alleviating hunger and poverty through soil fertility improvement requires a comprehensive insight of the climatic, edaphic, and socio-economic factors determining the process of soil fertility depletion and repletion. Socio-economic and political factors have forced many countries in SSA to bring new land under cultivation and to reduce fallow periods to meet the food and fiber needs of the rapidly increasing population (Davidson and Ackerman, 1993). This extensive approach is reflected in low cropping intensity and poor yields per hectare (ha) in SSA. Cropping intensity is 55 percent in SSA compared with 110 percent in South Asia and the average yield of cereals is about 1 ton per ha in SSA while it is 2.3 tons per ha for the rest of the developing countries (World Bank and FAO, 1995). Much of the un-utilized land in many parts of SSA is of marginal quality

in fragile ecosystems. Intensification of agriculture often results in depletion of soil fertility and in land degradation.

2.9 Importance of pH in maize growth

Soil acidity is widespread in the tropics and could be partially responsible for low maize yield in several parts of Kenya (Onyango *et al.*, 1997). Soils with pH <5.5 have high exchangeable aluminium and outright toxicity to most crops (Carver and Ownby, 1995). Plant growth, and especially root growth, in acid soils is retarded by toxicities of Al^{3+} , Mn^{2+} , and H^+ . The degree of toxicity depends upon how high the concentration of soluble or exchangeable Al^{3+} is and how low the pH is (Crawford *et al.*, 2008).

Soil pH is an important factor influencing the growth of most crops (Alam, 1981). Often the effects of pH on the growth of plants are complex. It is difficult to separate direct effects of excess hydrogen (H^+) or hydroxyl (OH^-) ions from indirect effects associated with numerous chemical changes occurring at the root rhizosphere (Wagatsuma *et al.*, 1988). Among the various plant parts, the roots are directly affected by the pH of the growth medium. Low pH injury or H^+ injury is one of the factors responsible for growth retardation in acid soils. Hydrogen ions (H^+) increase the solubility of Al^{3+} , Mn^{2+} , and Fe^{3+} in acid soils (Rhodes, 1978). The presence of hydrogen ions in the growth medium generally inhibits root elongation, and this phenomenon is observed at extremely low pH (Alam and Adams, 1979).

It has generally been considered that H^+ injury is negligible in a medium at a pH above 4. However, even in this case, the contents of mineral nutrients in plants decrease with the decrease of the pH (Crawford *et al.*, 2008). In some cases, mineral ions flow out of the roots. Excess H^+ in the growth medium affects plant growth by two processes. First, nonspecific inhibition of root elongation, lateral branching, and water absorption. Second, specific effects on root ion fluxes via H^+ competition with base cations for uptake and H^+ damage to the ion-selective carrier in root membranes (Rhodes, 1978).

It is generally recognized that poor growth in acid soils is not caused by the Ca^{2+} deficiency of the soils but by other factors such as excessive Al^{3+} or Mn^{2+} . Plant growth does not improve by the addition of calcium sulfate to the acid soils (Inoue *et al.*, 1988). In acid soils, it may be difficult to observe the ameliorating effect of Ca^{2+} , because Al^{3+} injury is predominant (Wagatsuma *et al.*, 1988). In solution culture, however, a high Ca^{2+} concentration in the growth medium alleviates Al^{3+} injury or low-pH injury (Crawford *et al.*, 2008) and prevents K^+ loss associated with H^+ injury.

Calcium plays an important role in raising the pH of the growth medium. It is required to sustain cell membrane integrity plus facilitate the active uptake of otherwise competitive cations. This “Viets” effect of Ca^{2+} can be demonstrated with other polyvalent cations (including Al^{3+}) (Clarkson and Sanderson, 1971). It has been shown to alleviate the toxic effects of high H^+ activities. At pH levels of less than 4, H^+ may out compete Ca^{2+} , preventing their absorption, and even displacing Ca^{2+} present in the root apoplast (Inoue *et al.*, 1988). Once Ca^{2+} absorption is repressed, cell membranes

lose integrity. The selective ion carrier mechanism dysfunctions, resulting in reduced base cation absorption and efflux of cations (Rhodes, 1978). Loss of root membrane integrity can also produce the wilting symptoms of low turgor pressure observed with H^+ toxicity (Clarkson and Sanderson, 1971).

The important role of Al^{3+} in acid soil chemistry has been reviewed. Al^{3+} affects plant growth in acid soils by three general processes. First, reduced divalent cation especially Ca^{2+} uptake by plant roots due to the presence of excess Al^{3+} in the root apoplast. Dysfunction of cell division in the root meristematic tissue caused by penetration of Al^{3+} into the root protoplasm is the second process (Crawford *et al.*, 2008). The production of abnormal root morphology and decreased anion (SO_4^{2-} , Cl^-), adsorption by roots due to increased positive adsorption sites in the rhizosphere and root apoplast is the third one (Inoue *et al.*, 1988).

Aluminium is believed to facilitate monovalent cation uptake (especially K^+ uptake via the Viets effect), and increased P sorption, as hydroxyl-Al-P-complex (Clarkson and Sanderson, 1971). Several studies have shown that solution pH greatly affects the absorption of inorganic nutrients by plants (Smith, 1971). Short-term studies have shown that, at low pH, ion transport may be impaired, especially at low Ca^{2+} concentrations, and sufficient membrane damage may occur to allow the loss of previously absorbed solutes. Similarly, long-term studies on several plant species have shown in extreme cases, to death of the root tips caused by low pH (Smith, 1971).

Legumes increase soil acidity, because they absorb more cations than anions from soil (Adams and Martin, 1985). Nitrogen, in the NO_3^- form, seems almost universally to lead to an increase in pH. The observed effect of pH on NO_3^- uptake suggests that both H^+ and OH^- are involved in the absorption process. At low pH values, H^+ may cause injury to the root tissue, whereas at higher pH values, competition with OH^- reduces NO_3^- uptake. Breemen *et al.* (1983) indicated that nitrification of NH_4^+ and accompanying soil acidification can occur even at a pH of less than 4.

Lowering of pH has been found to be associated with the uptake of N as NH_4^+ (Riley and Barber, 1971). Uptake of NH_4^+ by the roots results in a release of H^+ , the rhizosphere, (or nutrient solution) becomes acidified and root integrity is impaired. This type of NH_4^+ toxicity can be avoided by pH control of the rooting medium. In their experiment with Kentucky bluegrass (*Poa pratensis* L.) and using N sources, Davis and Dernoeden (1991), observed that soil pH was affected by N sources and the NaNO_3 treated plots had the highest pH; whereas SCU (sulphur-coated urea) and NH_4Cl treated plots had the lowest pH.

2.10 Importance of secondary and micronutrients nutrients in maize growth

Soil nutrient mining remains a challenge in smallholder farmers' fields where secondary nutrients and micronutrients are removed without replacement (Alley and Vanlauwe, 2009). Secondary nutrients play an active role in the plant metabolism process starting from cell wall development to respiration, photosynthesis, chlorophyll formation, enzyme activity and nitrogen fixation (Das, 2000). Micronutrient requirements of the

maize crops are relatively small and ranges of their deficiencies and toxicities in plants and soils are rather narrow (Brady and Weil, 2002). Expectation of higher maize productivity using adequate amount of fertilizer nutrients may lead limitation of some micronutrients in the soil (Das, 2000).

The importance of essential micronutrients in Nepal was realized about two decades ago when wheat sterility problems were encountered in the eastern part of the country. At that time, the micronutrient identified was boron. In areas where intensive cultivation is, practiced application of Zn^{2+} has become a regular feature in maize cultivation. Khatri-Chhetri and Schulte (1984) found that B^{2+} and Zn^{2+} were the most limiting micronutrients for the soils of the Chitwan valley. Further, Khatri-Chhetri and Schulte (1985) reported that maize respond to the application of N and P, secondary nutrients and micronutrients. Joshy (1997), reported that the critical limit of some micronutrients on maize. He mentioned the critical limit for sulphur was 14 ppm, boron 95 ppm, zinc 82 ppm and for manganese 0 ppm for maize crop. These limits were obtained from plant samples which were grown on the soils which were below critical limit values (Joshy, 1997). Micronutrients are becoming increasingly important to world agriculture as crop removal of these essential element increases (Das, 2000). Micronutrient deficiencies are due to not only to low contents of these elements in the soil but more often to their unavailability to growing plants (Brady and Weil, 2002).

The importance Ca and Mg soils cannot be understated for their role in plant nutrition is crucial since they constitute plants protoplasm (Szulc *et al.*, 2008). Calcium is part of

every plant cell. Much of the Ca in plants is part of the cell walls in a compound called calcium pectate. Without adequate Ca, cell walls would collapse and plants would not remain upright. Calcium is not mobile in plants therefore it does not easily move from old leaves to young leaves (Fageria *et al.*, 2002). Magnesium is an important constituent of chlorophyll, hence vital in photosynthesis (Jones and Huber, 2007). Plants that are deficient in Mg^{2+} have an overall light green color. In maize, the veins are mainly white when concentrations are inadequate. Calcium also has a positive effect on soil properties (Lipinski, 2005). Both Ca and Mg have two positive electrical charges and the clay-size particles and soil organic matter have negative electrical charges on their surface (Fageria *et al.*, 2002). This charge balance improves soil structure thereby increasing water penetration, and providing a more favorable soil environment for growth of plant roots and soil microorganisms (Sifri *et al.*, 2003).

Sulfur (S) is often the third limiting nutrient in soils after N and phosphorus (P) (Randhawa and Arora, 2000). Yet it is seldom included in the fertilizers commonly available. The widely available calcium–ammonium- nitrate, di-ammonium phosphate, Triple Super phosphate, and urea do not contain S (Randhawa and Arora, 2000). Therefore, an important use must be made of the sulfur-bearing agro-minerals, such as elemental sulfur, pyrite, or iron sulfide, and gypsum or calcium sulfate, in the supplementation of imported mineral fertilizers that lack sulfur (Das, 2000). Studies across SSA indicate that many soils become deficient in Zn, Fe, and S once macronutrient status is corrected (Lipinski, 2005). Obviously, sustained removal of nutrients means that nutrients will have to be replaced after some time (Giller *et al.*, 2006).

2.11 Importance of manure in maize production

Soil organic matter (SOM) is any material produced originally by living organisms that is returned to the soil and goes through the decomposition process (Woomer *et al.*, 1994). Its functions vary from nutrient supply, water retention, soil structure maintenance and carbon sequestration (Palm *et al.*, 2000; Craswell and Lefroy, 2001; Merckx *et al.*, 2001). According to Mukonyweet *et al.* (1996), manure adds SOM to soil which is an important source of plant nutrients. There is a need to explore the efficient utilization of the available nutrient resources that lead to improved crop yields. The use of organic resources in combination with mineral fertilizers offers potential for improving soil fertility and crop yields (Vanlauwe *et al.*, 2002b). The release of nutrients and the efficiency of nutrient availability to the plant can be manipulated by controlling the quality and quantity of organic resources. This can facilitate the retention of added mineral fertilizers and the timing of nutrient availability (Myers *et al.*, 1994). Research by Nyamangara *et al.* (2003) and Mtambanengwe *et al.* (2006) showed that combinations of organic resources and mineral fertilizers result in greater crop yields. This increase in grain yield has been attributed to improved N synchrony with combined inputs through direct interactions of the organic resources and N fertilizers as observed by Vanlauwe *et al.* (2002b).

Nitrogen is an essential component of SOM, which holds 90-95% of total N (Smith, 1994); hence, maintenance of SOM is of paramount importance (Kang and Van der Heide, 1985; National Research Council, 1993). Increasing the SOM content of soil is the key to building soil N capital (Buresh and Giller, 1998). Murwira (1994) observed that the most efficient use of manure is to combine it with some inorganic fertilizer.

Further, Munguri *et al.* (1996) showed that station-placement or dribbling into the planting furrow, rather than broadcast application, are promising ways of increasing the crop yield benefits from cattle manure

A study by Murwira *et al.* (2001) showed strong yield responses to manure in Tsholotsho sands and reported 2.5 t ha⁻¹ maize yields when applying 3 and 6 t ha⁻¹ of amended pit and heap treated manure. But they did not explain the responses in terms of nutrient supply. In high rainfall areas high maize yield responses to manure were reported by Murwira *et al.* (1998) and Waddington and Karigwindi (2004). The results from this study have shown that the yield responses were probably not related to P effects, as the soils did not seem to be P limited (Murwira *et al.*, 1998; Waddington and Karigwindi, 2004). An earlier study by Grant (1967) attributed the manure effects to an increase in cation availability with manure in soils. Similar benefits of N top-dressing with manure application have been found for maize production in Zimbabwe on granitic sands (Grant, 1976; Thiessen, 1979; Chikowo *et al.*, 2004) and elsewhere in Africa (Carsky *et al.*, 1998; Sherchan *et al.*, 1999; Roose and Barthes, 2001).

2.12 Classification and regression analysis

Classification and regression tree (CART) analysis is a robust model building application that uses recursive partitioning method to unravel commonality in continuous and categorical variables and build predictor models that can be used to decode the importance of the variables in the set hypotheses, (Tittonell *et al.*, 2008a). CART is intrinsically non-parametric and no assumptions are made on the primary distribution of values of the predictor variables. Consequently, CART can analyze

numerical data that are vastly skewed or multi-modal, as well as category predictors with either ordinal or non-ordinal structure (Tittonell *et al.*, 2007). In medical studies, CART has been handy in development of clinical decision rules as observed by Crichton *et al.*, 1997; and to advance risk assessment tools as applied by Steadman *et al.*, 2000. In agronomy CART, analysis has been infrequently applied though few studies have been done using CART analysis. A study by Shepherd and Walsh (2002) used classification trees related soil fertility case definitions to reflectance spectra for an extensive library of African soils. Martius, 2004 used CART analysis to characterize the habitat structure of termites in agroforestry systems. Further, Zheng *et al.*, (2009), used CART to analyse agronomic factors affecting Soybean yield variability's among fields in North East China. In a study by Zhang *et al.*, (2012),

CART analysis was used to analyze the effects of soil properties and agronomic properties on wheat yield variability in China. Tittonell *et al.*, (2007) used CART analysis to unravel the effects of soil and crop management on maize productivity in smallholder agricultural systems in western Kenya. In analyzing nitrogen, phosphorus and potassium variability at farm scale, use of CART analysis may help to stratify such variability into classes that reflect interactions between management factors and nitrogen, phosphorus and potassium variability, and thus may have practical use for targeting soil and crop management interventions and advice to farmers Zhang *et al.*, (2012). For example, the relation between input use and yields (i.e. crop response) has been shown to vary for different soil quality classes indicated by variability of nitrogen potassium and phosphorus (Vanlauwe *et al.*, 2006).

CART analysis (Salford Systems Inc., San Diego, CA, USA) is used to explain response of categorical variables or continuous variables from predictor variables using binary partitioning rules (Breiman *et al.*, 1984). CART is robust in model generation than conventional statistical methods. First, there are no statistical assumptions for independent and dependent variables. Secondly, it allows analysis of a mixture of categorical and continuous explanatory variables. Third, there is no sensitivity on outliers, multi-collinearity, heteroskedasticity, and distributional error structures that affect other parametric methods. Finally, variable interactions are easily revealed (Tittonell *et al.*, 2007a, b).

CART sets values of the predictor variables by searching all alternative variables to maximize the quality of a split of the target variable. When the best split is established, CART recursively repeats the search process for each child node and a tree structure is generated. Relative errors (RE) derived using cross validation or hold-out validation are used to prune very large trees and to an optimal sized tree (Breiman *et al.*, 1984). The trees are made of intermediate, splitting nodes (SN) and a succession of terminal nodes (TN) that represent homogeneous groups of interpretations in terms of the response variable (nitrogen, phosphorus and potassium). The variables explaining the model appear in the consecutive splitting nodes in a hierarchy of diminishing explanatory power.

2.13 Identified study gaps

Soil fertility is multifaceted discipline, cutting across biophysical, climatic, and anthropogenic factors. Despite the massive investment in research and fertilizers, yields

in smallholder fields are on a downward trend. The review of literature identified a dearth of critical research on effects of limiting nutrients on the growth and yield of *Zea mays*. From the published work on research done in other regions of SSA it is evident that deteriorating soil fertility leads to depressed yields among smallholder farmers’.

Although poor maize yields are because of numerous interrelated bottlenecks such as climate change, nutrient mining remains one of the major impediments. It ultimately leads to emergence of limiting nutrients. This problem is further compounded by mismanagement of smallholder fields. Determination of the limiting nutrients to maize growth and yield of maize in Kandara is crucial in helping to develop solutions to arrest the dwindling soil fertility. Further establishment of management practices that influence the variability of nitrogen, phosphorus, and potassium in soils of Kandara is important in developing local solutions.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Study area

The experiment was set up in Kandara Sub-county in Murang'a County, which covers an area of 235 km² of which 193 km² has been put under agricultural production. Kandara is located on geographical coordinates 0° 54' 0" South and 37° 0' 0" East (Figure. 3.1).

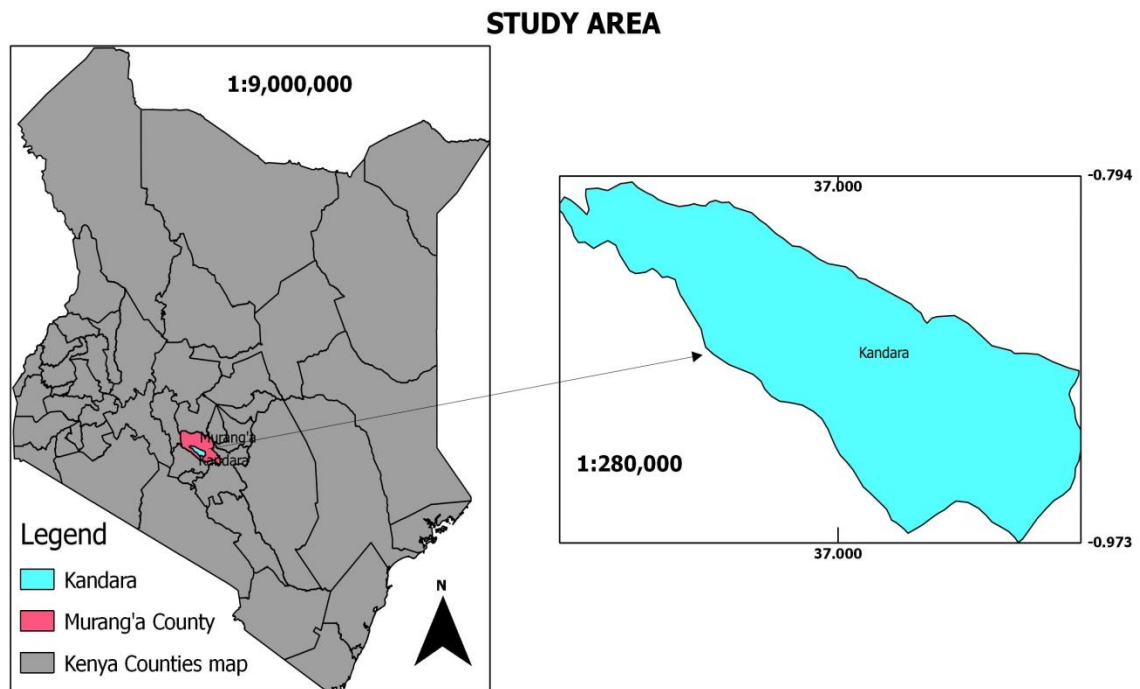


Figure 3.1: Map of Murang'a County showing Kandara Sub-county

Kandara lies across four agro-ecological zones (AEZ) namely, lower highland (LH), upper midland 1 (UM1), upper midland 2(UM2) and upper midland 3 (UM3), which support maize production (Jaetzold *et al.*, 2006). Average annual rainfall is variable and

ranges 1400- 2000mm (Jaetzold *et al.*, 2006). The rainfall pattern is bimodal and rainy seasons are clearly separated with long rains season in March – May and short rains season in October - December. According to Jaetzold *et al.* (2006), the area of Kandara area has medium to long cropping days (155 - 174 days) and medium to short (115 - 134 days) cropping days in a cropping season. Kandara has mean annual temperatures ranging from of 18 - 21⁰C. The soils are deep, well drained; weathered Humic Nitisols (locally known as red Kikuyu loams) with moderate to high inherent fertility (Jaetzold *et al.*, 2006). However, soil fertility has been declining due to continuous cropping without adequate nutrient addition.

3.2 Experimental design and management

This experiment was carried out during the long and short rains seasons of 2013. Trials were established on-farm in 23 selected fields. Choice of experimental fields was limited to farmer fields currently in crop production. Each field was divided into eight plots measuring 5m by 5m. The 23 fields were treated as replicates. The treatments were laid out in a randomized complete block design.

Land preparation was done by hand ploughing at a depth of 15-20 cm using hoes. Planting was done at the onset of the rainy season. Maize was planted at a spacing of 75 cm (inter-row) and 25 cm (intra-row). Two seeds were planted per hill and thinned to one 10 days after emergence. Gapping was done 5 days after emergence.

Straight fertilizers were used to supply nitrogen (N), phosphorus (P) and potassium (K). The source of N was Urea, P was Triple Super Phosphate (TSP), and K was Muriate of Potash (MOP). The source of secondary and micronutrients was Mavuno fertilizer, which is available as a multi-nutrient fertilizer. It contains N, P and K, and Calcium (Ca), Magnesium (Mg) and Sulphur (S) as secondary. The rates of nutrient application are shown in Table 3.1.

Table 3.1: Rate of nutrient application for the different treatments in Kandara

Treatment	Rate of nutrient application (kg ha ⁻¹)
Control	No fertilizer inputs
NPK	60N+30P+60K
NPK+ lime	60N+30P+60K+1,000 Lime
NPK+ manure	60N+30P+60K+10,000 Manure
NPK+ CaMgS	60N+30P+60K+10Ca+10Mg+3S
NP	60N+30P
NK	60N+60K
PK	30P+60K

There are different types of Mavuno fertilizer that contain different amounts of N, P, and K in addition to the secondary and micronutrients. Mavuno planting fertilizer (10:26:10 +10Ca + 4Mg + 4S), which is recommended for cereal planting was used. The application rates of Urea, TSP, and MOP in the NPK + CaMgS treatment were adjusted to factor in the amount of N, P and K supplied by Mavuno fertilizer. Lime and manure were applied pre-planting, by broadcasting over the 5 x 5 m plot and incorporation into the surface soil by digging. Basal fertilizer was applied in the

planting holes at sowing. The applied fertilizer was covered with some soil before placing the seeds to avoid direct contact of seed with fertilizer. Top dressing using urea was done by spot-application in two equal split applications, at three and six weeks after emergence. This was done for all treatments requiring nitrogen. Weeding was done using a hoe as necessary to keep the trials free from weeds.

3.3 Data collection

3.3.1 Soil sampling and analysis

Soil samples were collected before planting at 0 - 20 cm depth using a soil auger. From each plot, a composite sample of three cores was taken using a soil auger. The three cores were taken along one of the diagonals of the plot by taking one core at the center of the 5m x 5 m plot and the other two 1.75 m away from the center of the diagonal in both directions. The sample cores were placed into a basin, thoroughly mixed and about 300 g taken as the final composite sample. Samples were put in polythene sample bags and well labeled before being dispatched to the laboratory. At the laboratory, the samples were air-dried by spreading out each sample as a thin layer in shallow trays. Internationally recognized methods of soil laboratory analysis were used.

Soil pH was determined using potentiometric method i.e. soil: water at a ratio of 1:2. 20g of soil was weighed using a scale and added to a sample cup. Two times volume of water that is was added to one part of the soil sample. The mixture was stirred vigorously and the slurry was allowed to set from 15 minutes to 1 hour. pH meter and electrode were calibrated using pH 4 and 7 buffers. The electrode was placed in the soil slurry to measure pH. Adequate time was allowed for pH to reach a stable reading (Miller and Kissel, 2010).

For soil nutrients (P, K, S, Ca, Mg), atomic emission spectrometry (ICP), using Mehlich 3 was adopted. Mehlich 3 (M3) estimates most macro- and micronutrients on soils acid to neutral pH using a dilute acid-fluoride-EDTA solution of pH 2.5 (Schroder *et al.*, 2010). Phosphorus and cations was determined by ICP-AES instrumentation (Pittman *et al.*, 2005). 2.5 g of Soil was extracted into a glass or plastic Erlenmeyer. 20 mL of Mehlich 3 extracting solution was added into the soil. The extraction flask was placed on a reciprocating mechanical shaker (200, recip/minute) for five minutes. The suspension was filtered immediately and the extract was collected in 40 mL plastic vials. ICP instrument was calibrated using multiple element standards following manufacturer's recommendations in the operation and calibration of the instrument. Readings were made from the machine.

Total nitrogen was analyzed by the modified Kjeldahl oxidation method where salicylic acid is added during digestion to include nitrate-N and nitrite-N. A sample weighing 0.3 g was placed in a clean dry digestion tube and, after addition of the oxidising reagents, sulphuric acid + salicylic acid + catalyst; the tubes were placed in a digestion block at 360 °C for 3 h until the remaining digest was white. The tubes were removed and left to cool and diluted to 50 ml. 10 ml of the digest was taken for N determination by the distillation and titration method (Okalebo *et al.*, 2002).

Soil total carbon was determined by the Walkley Black (WB) method (Nelson and Sommers, 1996). 1.0g of mineral soil was put into a 250-mL wide mouth graduated Erlenmeyer flask. 10.0 mL of Potassium dichromate solution was pipetted into the flask containing the soil sample. Mixing was done by carefully rotating the flask to wet all of the soil. 20 mL of concentrated sulphuric acid was added under a fume chamber, to the

flask and mixed gently. The flask was allowed to stand for 5 min under the fume chamber. Pure water was added to the flask such that the final volume was approximately 125 mL. Mixing was done by swirling gently. The sample was allowed to cool and return to room temperature and the volume was rechecked after 30 minutes. 5 -6 drops of Phenanthroline complex were added to the mixture and titration with the Ferrous Sulphate solution was performed. A mixing bar was used to properly mix the sample as it was being titrated. Volumetric readings were recorded at end-point, which was reached when the greenish solution turned reddish-brown. The laboratory methods used are summarized in Table 3.2

Table 3.2: Methods of laboratory analysis used in soil chemical determination

PARAMETER	METHOD/EQUIPMENT	DESCRIPTION
Soil pH	Potentiometric/pH metre	Soil: Water 1:2
Soil Nutrients – P, Ca, Mg, K, S	Atomic Emission spectrometry (ICP)	Mehlich 3 – Diluted ammonium fluoride and ammonium nitrate
Soil Total Nitrogen %	Kjeldahl acid digestion	Sulphuric –salicylic wet digestion
Soil Total Carbon (*1.72 for Organic matter %)	Walkley – Black (Nelson – Sommers)	Dichromate – Sulphuric acid Oxidation

3.3.2 Maize crop emergence

Data collection commenced on the second day after the first coleoptile emerged from the soil. The total number of blocks with emerged plants within the total plot area (5m x 5m) was recorded. Recording stopped on the date when half of all stations had emerged plants. This date was recorded as the 50% emergence date.

3.3.3 Maize plant height, leaf number and basal diameter

Data on plant height, leaf number and basal diameter of 8 random maize plants per plot from the net plot area consisting of 3 middle rows (leaving out 2 rows from each end) was obtained at 14, 28, 42, 56 and 70 days after planting. The measurement for basal diameter was obtained at about 1 cm from the soil surface using vernier calipers. Plant height was taken from the soil surface to the highest tip of the emerging leaf or the highest tip of the tassel. For each of the growth stages for which height and basal diameter were measured, the number of leaves on the 8 selected plants was counted. All leaves were counted including those that were senesced as long as this could be identified.

3.3.4 Harvest grain and crop residue yield

Harvesting was done after the crop had reached physiological maturity. Grain yields in each treatment were determined from a net plot of 3mx 3m. The cobs were removed, counted, and recorded. Five cobs were randomly selected and fresh weight determined. The grains and cores of the 5 selected cobs were separated and their fresh weights determined separately. The grain sub-sample was oven dried (at 60 °C for 48 hours) and reweighed to determine moisture content. After drying to 12.5% moisture content the final dry weight was determined and recorded. Five fully established stovers were

randomly selected from the net plot. They were cut into small pieces and fresh weight was determined. The stover sub-sample was oven dried (60 °C for 48 hours) after which it was weighed to determine the final dry weight.

3.3.5 Field management history

For the 23 experimental fields, management history (previous 5 seasons) was collected using standard survey forms (Appendix 1). The following data was collected; (i) field position (ii) land conversion history (iii) fertilizer use in the past 5 seasons (iv) manure use in the past 5 seasons (v) fallow type (vii) cropping system used.

3.4 Data analysis

3.4.1 Plant growth data

Data collected was analyzed using statistical analysis software (SAS) 9.2 (SAS Institute, 2009). Analysis of variance (ANOVA) was carried out to determine whether there were significant differences among treatments on plant growth parameters over the entire growth period. Fisher's LSD (t-test) was used to separate means at ($P < 0.05$) significance level. Correlation analysis was done to establish the relationship between plant growth parameters and grain yield. The results were presented graphically. Further analysis, was carried out on grain yield to deduce nutrient responses and the result was presented graphically.

3.4.2 Field management history data

Historical data was keyed in an excel sheet together with amounts of total nitrogen, phosphorus and potassium extracted from soil analysis results. This data was matched to represent the results for each individual farmer. Classification and Regression Tree Analysis (CART) software (Salford Systems Inc., San Diego, CA, USA) (Breiman *et*

al., 1984) was used to develop regression models to determine how management practices influenced the variability of soil nitrogen, phosphorus and potassium in farmers' fields.

The levels of nitrogen, phosphorus, and potassium constituted the target variables while the predictor variables were the recorded management parameters which were: i) field position (ii) land conversion history (iii) fertilizer use in the past 5 seasons (iv) manure use in the past 5 seasons (v) fallow type and (vi) cropping system used. The results were presented using regression tree models. The model was developed from the following variables as shown in Table 3.3.

Table 3.3: Management variables used in Classification and Regression modeling

Category	Variable	Detail
Management (Predictor variables)	Fertilizer use	Fertilizer use in the previous five seasons (NSFA).
	Manure use	Manure use in the previous five seasons (NSMA).
	Fallow type	Type of fallow (If any) since conversion (FT).
	Land conversion	Predicted time when land was converted into farmland (LCH).
	Field position	Slope, flat and bottomland (FP)
Soil (Target variables)	Total nitrogen (%)	Results from soil nutrient analysis.
	Phosphorus (ppm)	Results from soil nutrient analysis.
	Potassium (ppm)	Results from soil nutrient analysis.

The analysis of the variables was done using the following model.

$$X=f(lch+fp+nsfa+cs+ft+ nsma)$$

Where; x= nitrogen, phosphorus or potassium, lch=land conversion history, fp=field position, nsfa=number of seasons of fertilizer use, cs =cropping system, ft=fallow type and nsma= number of seasons of manure use.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Overview

This chapter presents a summary of the findings of the study. The results are presented chronologically as per the research objectives.

4.2 Site Characterization

4.2.1 Average precipitation in Kandara

Total precipitation recorded for the entire 2013 is presented in Figure 4.1. During the long rains season March to May the cumulative precipitation received was about 617 mm (Figure 4.1).

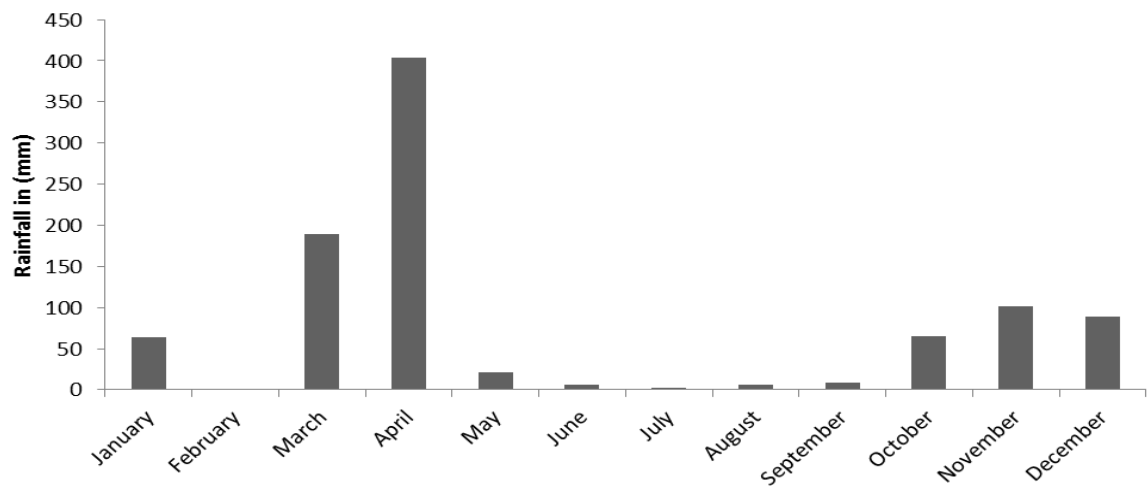


Figure 4.1: Average precipitation of Kandara experimental fields during the long rains of 2013 and short rains of 2013 seasons

During the short rains, running from October to December, the cumulative amount of rainfall received was about 354 mm. The rainfall amount during the two cropping systems was adequate.

4.2.2 Soil Characterization

Before establishing the trials, soil characterization was carried out. The results from the analysis indicated the pH ranges from extremely acidic (4.57) to slightly acidic (6.87) (Table 4.1). About 65% of the sampled fields have their pH between 5- 8, which is optimum for maize production. However, only 17% fields were below the recommended pH levels for maize production. Total C and N were found to be inadequate in most of the fields. 87% recorded low levels of total N and 91% had inadequate levels of total C. P (ppm) was low in 34% fields while, K (ppm) deficiency was not observed in any of the sampled fields (Table 4.1). The fields that recorded low levels of Ca were 17%. Magnesium and sulphur recorded no deficiency in the sampled fields (Table 4.1).

Table 4.1: Chemical properties determined at the start of the experiment in 2013 (top soil 0 - 20 cm)

Source: Soil Suitability Evaluation for Maize Production in Kenya. A Report by NAAIAP in Corroboration with KARLO

Results for soil chemical analysis at the start of the trials							
Soil Parameter	Max	Min	Nutrient critical levels	Fields with below critical levels	Fields with optimum levels	Fields with above critical levels	% of 23 samples with below critical levels
pH	6.87	4.57	≥ 5.5	8	15	-	34
Total N (%)	4.1	1.2	≥ 2.4	20	3	-	87
Total C (%)	9.7	4.9	≥ 9.5	21	2	-	91
P (ppm)	208	5.22	≥ 30	8	12	3	34
K (ppm)	1170	126	≥ 126	-	13	10	-
Ca (ppm)	3600	334	≥ 513	4	16	3	17
Mg (ppm)	517	119	≥ 216	-	16	7	-
S (ppm)	86.7	10	≥ 14.4	-	17	6	-

Department of Soil Survey, Feb 2014.

The results further, indicate that nitrogen is the most limiting nutrient with 87% of the fields with below critical levels. Phosphorus is also limiting with 34% of the farms with below critical levels. This implies that most of the fields would get a positive yield response if fertilizers containing N and P are used. As regards potassium, calcium, magnesium, manganese, copper and iron they are adequately supplied in the soil in most of the fields. However to maintain adequate levels of nutrients, regular applications of organic and inorganic inputs to replenish the removed nutrients through crop harvest and nutrients lost through avenues such as leaching, vaporization encouraged.

4.3 Maize growth responses to different nutrient treatments

4.3.1 Leaf response to different nutrient treatments at different sampling times in Kandara

The results presented show the trend observed in the number of leaves produced by the plant in different stages of growth during the two seasons of the experiment. Leaf number is a good indicator of crop potential yields because it carries chlorophyll. Data in Table 4.2 indicates significant differences among different treatments for leaf number during both seasons of crop establishment ($p < 0.05$). At 14, DAP there were significant differences in number of leaves among control, NK, NPK+ manure and NPK+ CaMgS during the first season (LR13). NPK+ manure had the highest leaf count followed by NPK+ lime and PK treatments. Conversely, control treatment had the lowest leaf count. During the second season, the treatment that achieved the highest leaf number was NPK (7.3) and control achieved the lowest leaf count (6.6). At 28 DAP; during LR13 season

of growth, treatment NPK+ CaMgS achieved the highest leaf number (9.7) while control achieved the lowest (7.8). The treatments that indicated consistent significant differences for the entire growth period were control, NK, and PK treatments during LR13 season of crop growth. The absence of all applied nutrients in control led to the consistently low number of leaves.

Table 4.2: Leaf response to different nutrient treatments at different sampling times in Kandara in LR13 and SR13 seasons

Treatment	LEAF NUMBER									
	14 DAP		28 DAP		42 DAP		56 DAP		70 DAP	
	LR13	SR13	LR13	SR13	LR13	SR13	LR13	SR13	LR13	SR13
Control	5.3 ^c	6.6 ^b	7.8 ^d	8.9 ^d	8.6 ^e	10.0 ^f	11.6 ^d	12.4 ^d	11.7 ^c	12.6 ^c
PK	6.8 ^{ab}	7.2 ^a	8.4 ^c	9.3 ^{cd}	9.2 ^d	10.5 ^e	11.7 ^d	12.7 ^d	11.7 ^c	12.9 ^{bc}
NK	6.1 ^d	7.2 ^a	8.1 ^{cd}	9.8 ^c	9.9 ^c	11.4 ^d	12.7 ^c	13.5 ^c	12.4 ^b	13.3 ^b
NP	6.6 ^{bc}	7.2 ^a	9.2 ^b	10.9 ^a	10.8 ^{ab}	12.1 ^{bc}	13.7 ^a	14.5 ^a	13.3 ^a	14.2 ^a
NPK	6.7 ^{abc}	7.3 ^a	9.1 ^b	11.0 ^a	11.0 ^a	12.6 ^a	13.8 ^a	14.6 ^a	13.4 ^a	14.3 ^a
NPK+ lime	6.8 ^{ab}	7.2 ^a	9.2 ^b	11.0 ^a	10.8 ^{ab}	12.1 ^{bc}	13.4 ^{ab}	14.4 ^{ab}	13.5 ^a	14.4 ^a
NPK+ manure	6.9 ^a	7.2 ^a	9.4 ^{ab}	10.3 ^b	10.8 ^{ab}	11.7 ^{cd}	13.1 ^{bc}	14.1 ^b	13.4 ^a	14.3 ^a
NPK+ CaMgS	6.5 ^c	7.2 ^a	9.7 ^a	11.0 ^a	10.4 ^{bc}	12.3 ^{ab}	13.7 ^a	14.7 ^a	13.4 ^a	14.3 ^a
LSD. 5%	0.2024	0.1186	0.4807	0.4668	0.5066	0.5001	0.4433	0.4434	0.4717	0.4721

Same superscript letters appearing in the same column indicate no significant difference between the treatments.

Treatment NPK+ CaMgS indicated significant differences for most of the growth period except at 42 DAP. This indicates that addition of secondary nutrients positively influences crop growth. During SR13 season of crop growth, NK, PK and control treatments indicated significant differences for the entire growth period. NK treatment achieved low number of leaves during both cropping seasons, which is an indicator to the deficiency of phosphorus in farmers' fields. PK treatment performed poorly for both crop establishment seasons, an indicator of nitrogen limitation in farmers' fields. At 56, DAP the following treatments; NPK and NP showed no significant difference between them in SR13 and LR13 seasons however, they indicated significant differences from control, PK and NK in both seasons. PK, NK, and control treatments indicated significant differences from the rest of the treatments during SR13 and LR13 seasons of crop establishment. Control treatment achieved the lowest number of leaves at 11.6 and 12.4 for SR13 and LR13 seasons respectively. The number of leaves at 70 DAP showed no significance differences in treatments NPK, NPK+ lime, NPK + manure, NPK + CaMgS and NP. However, the treatments indicated significant differences with treatments; NK, PK and control. This was observed in both SR13 and LR13 seasons. Further, control and PK showed no significance difference between them over the two seasons. The treatment that produced the maximum number of leaves for both SR13 and LR13 was NPK+ lime at 13.5 and 14.4.

Stefano *et al.* (2004) reported that fertilizer application resulted in luxuriant growth of leaves, which is a precursor for improved photosynthesis. This was observed in NPK treatment, NPK+ manure, NPK+ Lime, NPK+ CaMgS and NP. According to Bray and Bailey-Serres (2000), higher number of leaves on fertilizer treated plants contributes to

a better canopy and suppression of weeds. However, continuous cultivation of crops in make the arable soils deficient of nitrogen and other important nutrients. Maize crop grown in poor soils has numerous deficiency symptoms that lead to poor growth and depressed yields. These are poor growth; chlorosis, necrosis of leaves and many physiological and biochemical shortcomings (Bray and Bailey-Serres, 2000). This was observed in control and PK treatments, which achieved low number of leaves. Because of the considerable uptake and utilization of nitrogen nutrient, its deficiency frequently occurs in most soils (Ashraf and McNelly, 1994; Marschner, 1995). This was indicated by the number of leaves achieved by PK and control treatments, which were low for the entire growth period.

Nitrogen deficiency is known to effectively interfere with metabolic process in plants (Drew and Morgan, 2000). For instance, Reddy and Dakota (2007) recognized that nitrogen deficiency leads to disruption of the fine structures of chlorophyll and instability of the pigment protein complex. Graham and Vance (2000) observed that an increase in the nitrogen supply stimulates growth as observed in treatments NPK, NP, NPK + manure, NPK + CaMgS and NPK + lime. In maize, it has been observed that local NO_3^- application induces root proliferation due to an increased growth of leaves (Zhang and Forde, 2000). Gastal (2002) reported that an increase in number of leaves and canopy is brought about by a large effect of nitrogen supply on the expansion of individual leaves and on branching, or tillering in grasses (Cruz and Boval, 2000). In all instances, the impact of nitrogen on leaf expansion rate of grasses was related more to

the effect of nitrogen on cell production than cell elongation rate (Drew and Morgan, 2000).

High N has shown higher leaf numbers and slower rate of senescence (Sumi and Katayama, 2000). According to Bonhomme (2000), light interception by crop canopy is a major factor influencing dry matter productivity where leaves contribute more than 80%. Therefore negative N deficits in maize fields lead to depressed yields, since leaf growth is highly dependent of availability of adequate levels.

Phosphorus deficiency is invariably a common crop growth and yield-limiting factor in unfertilized soils (Ibrikci *et al.*, 2005). According to Rehman *et al.* (2011) nutrient P affects leaf growth dynamics in maize. Treatment NK indicated reduced number of leaves for both seasons of growth. Amanullah *et al.* (2009) observed that P is one of the most important factors affecting crop growth and yield of maize. This corroborated by treatments NPK, NP, NPK + manure, NPK +CaMgS and NPK + lime. These treatments showed robust growth with adequate leaf numbers. Alias *et al.* (2003) reported that leaf number was significantly increased by increasing dose of the phosphorous by 125 kg ha⁻¹.

In this study, it was established that trials with P (NPK, NP, NPK + manure, NPK +CaMgS and NPK + lime) achieved robust growth and good leaf development. This is a good indicator, since proper leaf establishment precedes good yields if environmental and management factors are kept constant. Application of different P improved growth and yields as compared with control (P not applied) (Amanullah *et al.*, 2009).

In maize, vegetative phase 12 (V12) and vegetative phase13 (V13) stages of growth are critical in determining the final crop yield (Strachan, 2001). Approximately 6 weeks after the plant emerges, the V12 stage begins. This stage begins at 42 DAP, where nutrient and moisture use by the plant is very high. Moisture or nutrient deficiencies at these stages reduce yields drastically (Bolanos and Edmeades, 1996). Brace roots are developing from the fifth node and the first aboveground node (White, 2003). Cultivation of plants at this time will destroy some of the plant roots. By the V12 stage, the potential number of kernel rows and the potential number of ovules is established (Cakir, 2004).The meristematic dome is no longer present, so ovule formation is now complete (Colless, 1992). Paired ovule formation is apparent along nearly the entire length of the ear. If an ear has the proper number of kernel rows around the ear but the ear is shorter than normal, then the crop is under either water stress or experiencing nutrient deficiency (Huang *et al.*, 2006).

During LR13 season of crop establishment, Coefficient of Determination (R^2) for grain yield and leaf number correlation at 42 DAP was 0.9 (Figure 4.2) which indicates a

strong linear relationship between the number of leaves in maize and the achieved grain yields.

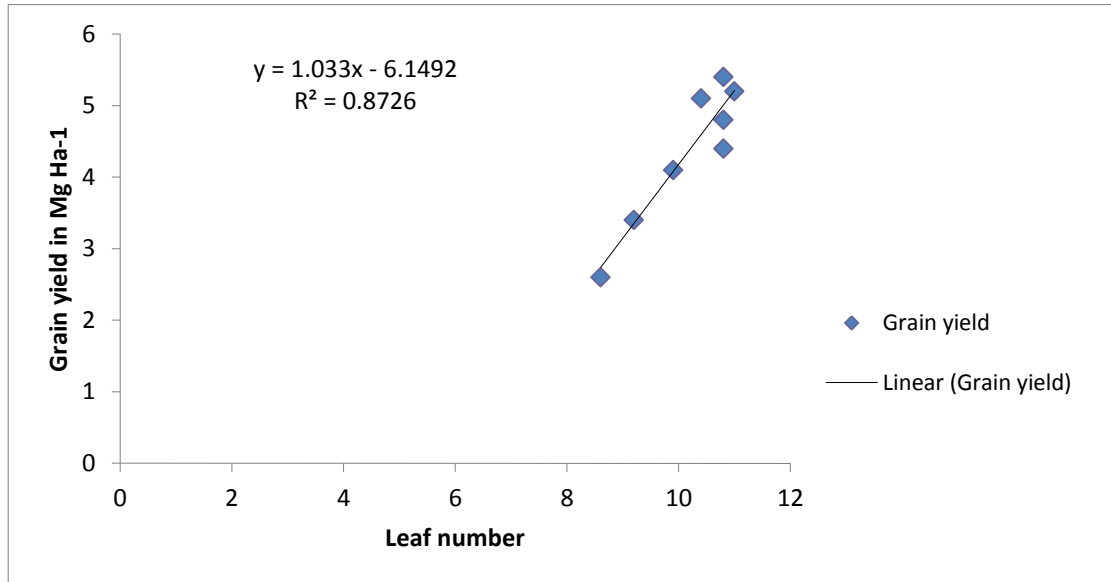


Figure 4.2: Linear regression of grain yield and leaf number at 42 DAP in LR13

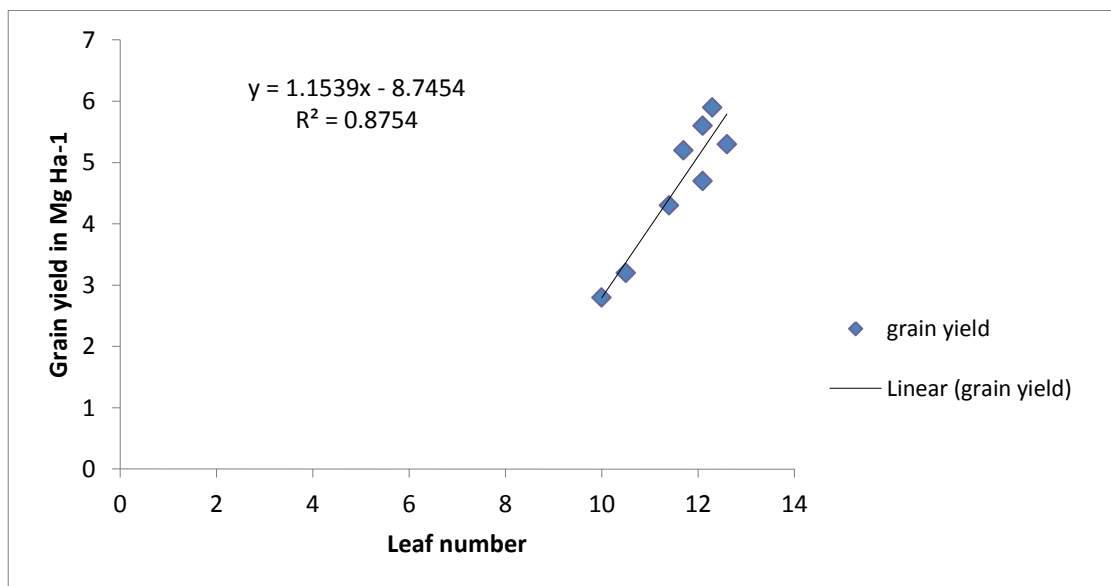


Figure 4.3: Linear regression of grain yield and leaf number at 42 DAP in SR13

During SR13 season, coefficient of determination (R^2) was 0.9(Figure 4.3) indicating a strong linear relationship between leaf numbers and the achieved yield at the end of the cropping systems. This is a clear indicator of the effects of ample and precise nutrient supply in maize for the entire growth period. From the results, it was indicated that NPK, NPK+ manure, NPK+ lime and NPK+ CaMgS had good leaf establishment, however PK, NK and control treatment achieved poor leaf establishment. The only notable exception was NP treatment, which achieved good leaf establishment. This is a clear indicator that potassium absence did limit leaf development in Kandara. Further, these results show the treatments that achieved proper leaf formation achieved good yields in the long run.

4.3.2 Bio-volume response to different nutrient treatments at different sampling times in Kandara

The results show the mean bio-volumes achieved for the two seasons of crop establishment. At 14 DAP, only bio-volume was significant ($p<0.05$), in control and NPK treatment. The other treatments showed no significant differences during LR13 season (Table 4.3). During SR13 season, the treatments that indicated significance differences were control, PK and NK. These differences can be attributed to the absence of nutrients in control, the omission of nitrogen in PK treatment and omission of phosphorus in NK treatment. The importance of full fertilizer application in maize cannot be understated. Treatments, NPK, NPK + manure, NPK +CaMgS and NPK + lime achieved high bio-volumes over the two seasons. The treatments had no significant differences although NPK + manure achieved the largest bio-volume at 1314. 4 cm³ at 70 DAP during SR13 season of crop establishment. This was closely followed by NPK

+ CaMgS which achieved 1300.2 cm³ during the same period. Treatment NPK+ CaMgS consistently achieved huge bio-volumes during LR13 and SR13 seasons.

Table 4.3: Bio-volume response to different nutrient treatments at different sampling times in Kandara in LR13 and SR13 seasons

Treatments	BIOVOLUME (cm ³)									
	14 DAP		28 DAP		42 DAP		56 DAP		70 DAP	
	LR13	SR13	LR13	SR13	LR13	SR13	LR13	SR13	LR13	SR13
Control	19.5 ^c	22.6 ^d	126.4 ^c	128.4 ^b	255.0 ^c	288.3 ^c	435.7 ^c	506.5 ^c	437.2 ^c	565.0 ^c
PK	29.3 ^b	30.9 ^c	180.6 ^{bc}	201.4 ^b	373.6 ^c	411.0 ^c	547.9 ^c	585.4 ^c	588.1 ^c	679.7 ^c
NK	30.6 ^{ab}	31.6 ^{bc}	220.1 ^b	219.9 ^b	593.7 ^b	660.3 ^b	816.3 ^b	928.6 ^b	958.1 ^b	1003.9 ^b
NP	30.0 ^{ab}	34.5 ^{ab}	327.8 ^a	361.2 ^a	727.3 ^{ab}	806.5 ^{ab}	1057.1 ^a	1161.3 ^a	1159.1 ^{ab}	1209.1 ^{ab}
NPK	32.2 ^a	35.9 ^a	348.4 ^a	373.4 ^a	785.5 ^a	848.1 ^a	1143.7 ^a	1185.4 ^a	1119.6 ^{ab}	1190.4 ^{ab}
NPK+ Lime	28.1 ^b	34.6 ^a	332.7 ^a	347.7 ^a	800.0 ^a	817.7 ^{ba}	1134.6 ^a	1157.6 ^a	1181.6 ^{ab}	1142.9 ^{ab}
NPK+ Manure	28.5 ^b	35.0 ^a	354.9 ^a	349.3 ^a	857.5 ^a	877.7 ^a	1166.5 ^a	1190.5 ^a	1291.2 ^a	1314.4 ^a
NPK+ CaMgS	28.2 ^b	35.2 ^a	412.3 ^a	427.3 ^a	864.6 ^a	885.6 ^a	1236.4 ^a	1260.7 ^a	1273.7 ^a	1300.2 ^a
LSD. 5%	2.32	2.98	93.31	103.99	167.30	179.18	185.12	201.66	202.91	224.72

Same superscript letters appearing in the same column indicate no significant difference between the treatments.

During the two seasons of crop establishment, control, PK and NK indicated significant differences in biomass accumulation. These significant differences were consistent in 28, 42, 56 and 70 DAP. This indicated that absence of key nutrients highly influences biomass accumulation in maize crops. The other notable observation was treatment NP, performed as well as other full fertilizer treatments. Adequate bio-volume was observed in NPK treatments across both seasons of crop establishment. Moreover, full fertilizer treatments with amendments, i.e. NPK +manure, NPK +lime, NPK +CaMgS achieved good bio-volumes over the two seasons of crop growth. The only exception observed in this experiment is in NP treatment since it achieved high bio volumes despite the absence of potassium.

On further analysis, simple linear regression results indicated that bio-volumes achieved by specific treatments directly impacted on the yields realised at the end of the season. This was the case in LR13 and SR13 season. Indeed, there was strong linear relationship between mean bio-volume at 42 DAP and grain yield achieved for both LR13 and SR13 seasons of crop establishment (Figure 4.4 and 4.5). During the LR13 season, the coefficient of determination was R^2 was 0.8 while during the SR13season; R^2 was 0.9 (Figure 4.4 and 4.5).

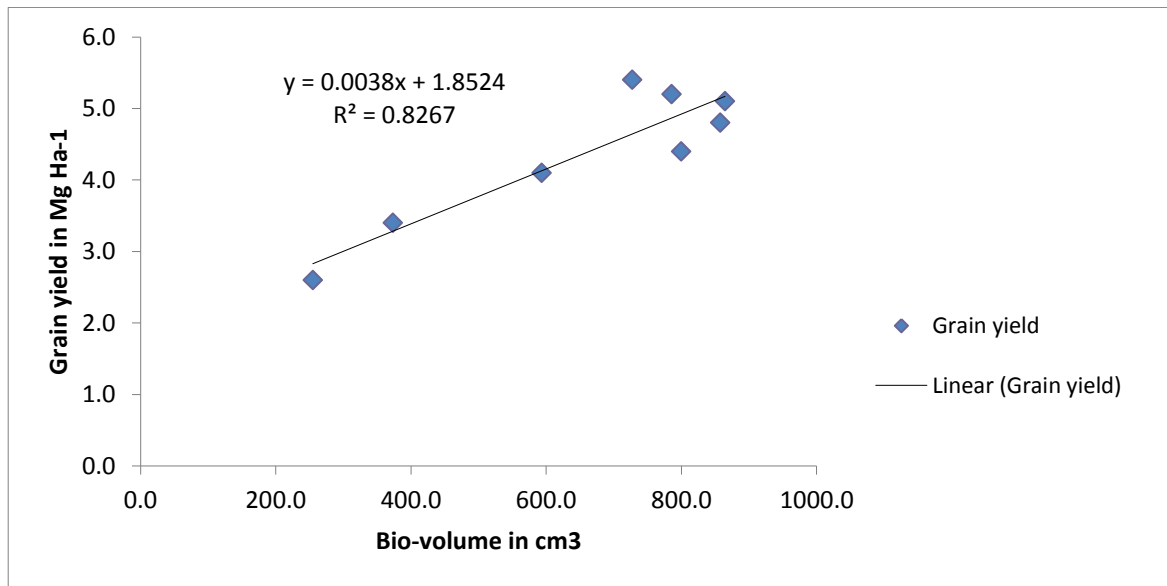


Figure 4.4: Linear regression of grain yield and bio-volume at 42 DAP in LR13 season

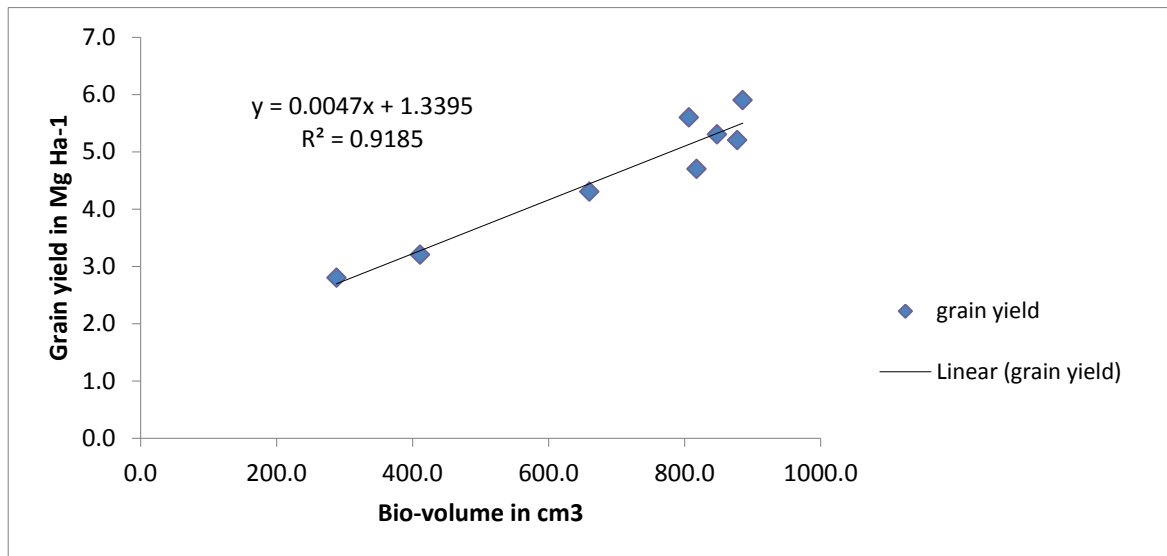


Figure 4.5: Linear regression of grain yield and bio-volume at 42 DAP in SR13 season

This is a clear indication that robust growth crop growth is directly proportional to the achieved yields. This growth is dependent on the nutrient supply. This relates well with the high bio-volume results achieved by full fertilizer treatments (NPK, NPK + manure,

NPK +CaMgS and NPK + lime) with the exception of NP treatment, which achieved high bio-volume values. Control, PK, and NK treatments consistently achieved low bio-volume values. This emphasizes the need for fertilizer application and it is a clear indicator that inherent soil fertility is not an adequate source of nutrients. The correlation results indicate that biomass accumulation in maize is a strong indicator of potential yields. Crop yield is influenced by multiple factors such as crop genotype, weather and management (Zingore *et al.*, 2007). Nutrient use is an aspect of management. The results indicate the importance precise nutrient use in maize crop fields.

Studies have shown that applications of N accelerate plant growth resulting in taller and greener plants (Zhang *et al.*, 2007; 2008a; 2010a, b). This observation was made in treatments with full supply of NPK, i.e. NPK, NPK + manure, NPK + CaMgS and NPK + lime and NP treatment. The findings indicated absence of K limitation in Kandara, since NP treatment performed robustly similar to other full fertilizer treatments. Nitrogen is typically the most limiting nutrient for maize production and a high-yielding crop requires 308 kg N ha⁻¹ to reach physiological maturity (Joern and Sawyer, 2006). Maize removes 78 kg P₂O₅ ha⁻¹ and 56 kg K₂O ha⁻¹, to reach physiological maturity (Laboski, 2007).

According to Fashina *et al.* (2002), the availability of sufficient growth nutrients from inorganic fertilizers lead to improved cell activities, enhanced cell multiplication, enlargement, and luxuriant growth. Lush plant growth resulting from full nutrient

application leads to larger dry matter production (Obi et al., 2005) owing to better utilization of solar radiation and more nutrient (Saeed *et al.*, 2001). This was observed in NPK, NPK + manure, NPK +CaMgS and NPK + lime and NP treatments. However, PK treatment and control showed stunted growth over the two seasons. Plant bio-volume is an important growth character directly linked with the productive potential of plants in terms of grains. According to Saeed *et al.* (2001), an optimum plant bio-volume is positively correlated with yield of plant. Adediran and Banjoko (2003) observed that there was substantial depletion of nutrients with the yields where no NPK fertilizer was applied; this was observed in all treatments that omitted N and P in the experiment, i.e. PK and NK treatments. This position was reported by Uyovbisere *et al.* (2001) who reported that there was substantial depletion of nutrients when no NPK fertilizer was applied and nitrates and available phosphorus were substantially reduced with cropping in humid zone of South-western Nigeria. According to Abbas *et al.* (2003) different bio-volumes of the varieties is genetic but N being a primary nutrient when applied early and adequately leads to taller plants that have been shown to achieve high yields. Increase in plant height with nitrogen application has also been reported by Ayub *et al.* (2002) and Sharar *et al.* (2003).

Studies conducted by Stewart *et al.* (2005) and Niehues *et al.* (2004) revealed that starter nitrogen was able to stimulate the growth and yield of maize. This was observed in all treatments with full fertilizer treatment namely, NPK, NPK + manure, NPK +CaMgS, NPK + lime and NP. However, treatment PK and control had stunted growth. According to Ogunlela *et al.* (2005), synergistic relationship between N and P may convert relatively unavailable native and residual P to chemical forms, which are

susceptible for uptake by plants after dissociation. This was evident in treatment NK, which performed dismally despite having N, since the synchrony between N and P was lacking. This indicted a P limitation in Kandara. This process may also produce CO₂ from urea, which forms weak carbonic acid, H₂CO₃, in soil solution, resulting in the dissolution of primary P-containing minerals thus releasing mineral P to be utilized by the plant. This synchrony of N and P is crucial in ensuring crops achieve optimum growth as indicated by full fertilizer treatments. Supply of these nutrients is critical especially in soils exhibiting their limitation.

Gastal and Lemaire (2002) reported that N uptake of field crops varies significantly with seasons, sites and soil types, and with crop types. Limited N or absence decreases rates of cell division, cell expansion and cell permeability, photosynthesis, leaf production, and ultimately depressing yields (Zhao *et al.*, 2003; 2005a, b; 2007). In this experiment, all the treatments (control and PK) lacking nitrogen achieved stunted growth as indicated by their achieved bio-volumes. Indeed, PK treatment means were significant ($p < 0.05$) from other treatments. The observations indicated a possibility of N limitation in Kandara. Similarly, the results emphasized the need for fertilizer use since inherent soil fertility cannot support crops as indicated by the performance of control treatment.

According to Busman *et al.* (2002) and Sahoo and Panda, (2001) adequate availability of the phosphorous increases the early plant growth and hastens the maturity. This was evident in NPK, NPK + manure, NPK +CaMgS, NPK + lime and NP treatments which achieved high bio-volumes. Saeed *et al.* (2001) reported that all the growth parameters

such as plant bio-volume, number of leaves per plant, leaf area per plant, fresh and dry weight of the plant increased by application of the phosphorous alone or in combination with the nitrogen. This was not the case in treatment NK and PK, where stunted growth was observed from the recorded bio-volume values. This observation was further affirmed by Ayub *et al.* (2002), who indicated that growth and yield increased with increase in the rate of phosphorous application.

Nitrogen internal efficiency does not only depend on its total amount taken up by the crop, but also on the concomitant supply of secondary nutrients (Jones and Huber, 2007) (Potarzycki and Grzebisz, 2009). Although NPK +CaMgS showed no significant differences from other full fertilizer treatments, keen observations show the treatment achieved high bio-volumes which reached 1300.2 cm³ at 70 DAP during the SR13 season. Nitrogen metabolism is strictly related to the presence of magnesium in the chlorophyll and its role as a cofactor of the activity of enzymes responsible for the remobilization and transportation of metabolites (nitrogen among others) from the vegetative plant parts to the developing kernels (Rasheed *et al.*, 2004). Moreover, since magnesium activates a large number of enzymes in the plant, its simultaneous supply increases the rate of mineral nitrogen transformation into proteins (Pessaraki, 2002).

Manure temporarily immobilizes nutrients from mineral fertilizers and may release them in synchrony with crop nutrient uptake (Vanlauwe *et al.*, 2002a). This observation was made in NPK + manure treatment which achieved the highest bio-volume i.e. 1314.4 cm³ at 70 DAP during season 2. N mineralization of manure is improved with the

combined application of manures and nitrogenous fertilizers (Sakala *et al.*, 2001). Indirect interactions may also enhance crop growth by improving the soil environment for root growth through increased SOM, increasing the nitrogen demand, which can be met by nitrogenous fertilizers (Vanlauwe *et al.*, 2002b). The nutrient resource most readily available to smallholder farmers is cattle manure although the small nutrient contents of manures makes them poorly effective in improving crop yields (Mugwira and Murwira, 1998). One of the greatest research challenges is to develop technologies that are effective within farmer resource constraints, resource levels and acceptable risk (Snapp *et al.*, 2003). Recent research emphasizes options that combine mineral fertilizer and organic manures (Palm *et al.*, 2001; Mucheru-Muna *et al.*, 2007).

Results from this experiment show that limiting nutrients affect maize growth and yield in the study area. Plant leaf number and crop bio-volume showed significant differences in treatments NK and PK. These results were highly significant ($p < 0.05$) which indicated that nitrogen and phosphorus were the limiting nutrients depressing maize yields in Kandara. The results further indicate that use of secondary nutrients and manure improves growth and yield of maize. Although this was not significant, it has a role in determining the final yields.

4.3.3 Grain and stover yields response to different nutrient treatments in Kandara

The mean grain yield and were significantly different between the different treatments ($p < 0.05$). The control, PK, and NK treatments indicated significant differences in grain and stover yields were (Table 4.4). During cropping LR13 season, the treatment that achieved the highest mean grain yield was NP at 5.5 Mg ha^{-1} while the control had the

lowest mean grain yield 2.6 Mg ha^{-1} . The treatment that achieved the highest stover yield was NPK with 6.2 Mg ha^{-1} while control achieved the lowest stover yield (2.8 Mg ha^{-1}) (Table 4.4).

Table 4.4: Grain and stover yields response to different nutrient treatments in Kandara in LR13 and SR13 seasons

LR13			SR13			
Treatments	Grain yields Mg ha ⁻¹	Stover yields Mg ha ⁻¹	HI	Grain yields Mg ha ⁻¹	Stover yields Mg ha ⁻¹	HI
Control	2.6 ^f	2.8 ^e	0.48	2.8 ^d	3.4 ^c	0.50
PK	3.4 ^e	3.9 ^d	0.47	3.2 ^d	4.2 ^c	0.43
NK	4.1 ^d	4.5 ^c	0.48	4.3 ^c	4.4 ^c	0.49
NP	5.5 ^a	5.6 ^{ba}	0.50	5.6 ^a	6.0 ^b	0.48
NPK	5.2 ^{ba}	6.0 ^a	0.46	5.3 ^b	6.1 ^b	0.46
NPK+ Lime	4.4 ^{dc}	5.3 ^b	0.45	4.7 ^{ba}	6.1 ^b	0.44
NPK+ Manure	4.8 ^{bc}	6.1 ^a	0.44	5.2 ^b	6.5 ^a	0.44
NPK+ CaMgS	5.1 ^{ba}	5.7 ^{ba}	0.47	5.9 ^a	6.4 ^a	0.48
LSD. 5%	0.6411	0.7032		0.6984	0.8549	

HI= Harvest index. Same superscript letters appearing in the same column indicate no significant difference between the treatments.

During cropping LR13 season, the treatments, which showed significant differences in grain yield were; control, PK, NK, and NPK +CaMgS. The treatments that indicated significant differences in stover yields were; control, PK and NK. The treatment, which achieved the highest grain yield was NPK+ CaMgS (5.9 Mg ha^{-1}), while control treatment achieved the lowest grain yield (2.8 Mg ha^{-1}). For stovers, NPK+ manure achieved the highest yield (6.5 Mg ha^{-1}) while control achieved the lowest (3.4 Mg ha^{-1}). The grain and stover yields recorded by NK and PK treatments were consistently low. This indicated that absence of P and N in the above treatments played a critical role in determining the actual yields. NP treatment was showed no significant difference from other full fertilizer treatments, which implies that K is not a limiting nutrients in farmers' fields.

There is no wide variation for the harvest index during the two cropping seasons. The harvest index generally hovers around 0.50 for a normal cropping season. The observed variation in harvest indexes within the same season can be explained by variability in soil types, treatment effects and to a lesser extent, management of the maize crop.

On further analysis of grain yield, the results indicated that absence of N in PK treatment led to a loss of 2 Mg ha^{-1} over the two seasons of crop establishment. The net loss recorded in the NK treatment was about 1 Mg ha^{-1} for both seasons (Figure 4.6). The loss recorded by absence of CaMgS secondary nutrients was about 0.5 Mg ha^{-1} . The rest of the treatments had a loss below 0.5 Mg ha^{-1} with the exception of NP treatment which achieved a gain in grain yields of between 0.3 Mg ha^{-1} and 0.4 Mg ha^{-1} in LR13 season and SR13 season respectively.

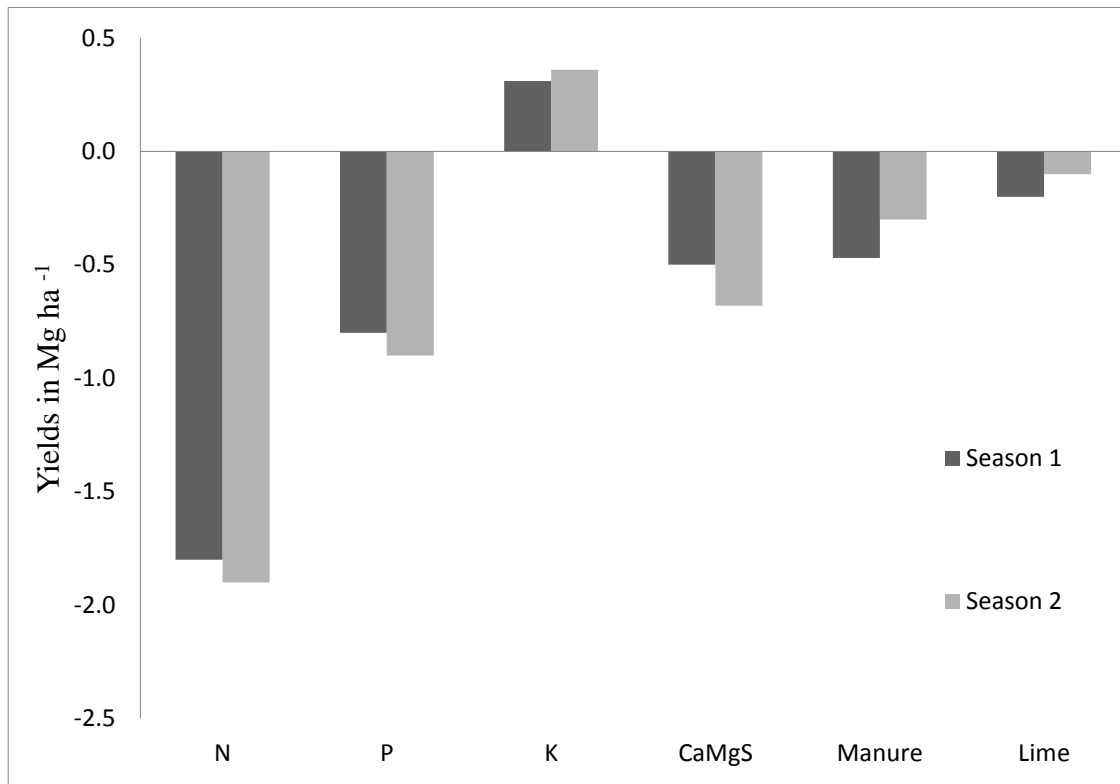


Figure 4.6: Grain yields response to different treatments in LR13 and SR13 seasons

These findings are in line with the view of Adediran and Banjoko (2003) who reported high yields in treatments with full fertilizer treatment. This may be attributed to NPK being part of the essential nutrients required for the production of the meristematic and physiological activities such as leaves, roots, shoots, and dry matter production, leading to an efficient translocation of water and nutrients, interception of solar radiation and carbon dioxide (Adediran and Banjoko, 2003). These physiological activities promote greater photosynthetic activities of adequate assimilates for subsequent translocation to various sinks and hence higher yields (Jaliya *et al.*, 2008). Optimum utilization of solar light, higher assimilates production and its conversion to starches resulted higher grains number and grain weight (Derby *et al.*, 2004).

Kogbe and Adediran (2003) found that the application of inadequate P depressed maize yield as observed in treatment NK of this experiment. While observing that higher rates of P lowered the phosphorus use efficiency of the maize crop, they added that the efficiency of maize in P utilization decreased as P fertilizer rate was increased (Kogbe and Adediran, 2003). In line with the observed increased in maize yield with fertilization, in a trial conducted by Plenet *et al.* (2000) on the growth analysis of maize field crops under P deficiency, they observed that grain yield was significantly reduced in the control treatment.

Inorganic fertilizer generally increased yields relative to the control on farmers' fields. The yield differences noted in agreement with an earlier report (Tittonell *et al.*, 2008). Data reported by Aitken *et al.* (1999) show that magnesium fertilizer application significantly increased grain yield in magnesium-deficient Australian acid soils. This observation was evident in NPK+ CaMgS treatment where there is an indication of high grain yields in comparison with other treatments. The improvement of mineral nitrogen efficiency after supplementing NPK fertilizers with magnesium has been reported by Rasheed *et al.* (2004). These authors applying to the soil $15 \text{ kg Mg}\cdot\text{ha}^{-1}$ obtained maize grain yield increment by 1.1 t ha^{-1} i.e. by 13%.

Under tropical conditions, in a three year field trial with maize, magnesium applied as sulphate gained yield increments of 16.5% respectively (Abunyewa and Mercer-Quarshie, 2004). In another study by Jones and Huber (2007), it was revealed that externally applied magnesium, considered as the NPK-Mg fertilizer supplement, gained

its yield forming effect only under a condition of lower N rate. This phenomenon can be related to the physiological function of Mg^{2+} , which is responsible for nitrate anions uptake by plant roots from soil solution. The gain from use of secondary nutrients in Kandara was about 0.6 Mg ha^{-1} . Indeed, NPK +CaMgS achieved the highest grain yield at 5.9 Mg ha^{-1} which implies that addition of secondary nutrients had a positive yield response. Balanced nutrition is an essential component of nutrient management and plays a significant role in increasing crop production and its quality. For the major processes of plant development and yield formation the presence of nutrients like N, P, K, S and Mg in balanced form is essential (Randhawa and Arora, 2000).

Research has shown that combinations of manure and mineral fertilizers result in greater crop yields compared with sole manure or sole mineral fertilizers (Mtambanengwe *et al.*, 2006; Nyamangara *et al.*, 2003) with grain yield increases of up to 400% over the control. NPK+ manure achieved the highest stover yields of 6.5 Mg ha^{-1} and the treatment had grain yield response of almost 0.4 Mg ha^{-1} . This increase in grain yield could be attributed to improved N synchrony with combined inputs through direct interactions of the manure and N fertilizers (Vanlauwe *et al.*, 2002b). The results agree with the findings by Nziguheba *et al.*, (2000); Kimetu *et al.*, (2004) and Mucheru-Muna *et al.*, (2007) who observed improved maize grain yields because of applying organic inputs with combination mineral fertilizers as compared to sole application of mineral fertilizers.

Nitrogen is an essential component of soil organic matter, which holds 90-95% of total N (Smith, 1994), hence maintenance of SOM is of paramount importance (Kang and Van der Heide, 1985; National Research Council, 1993). Its functions vary from nutrient supply, water retention, soil structure maintenance and carbon sequestration (Palm *et al.*, 2000; Craswell and Lefroy, 2001; Merckx *et al.*, 2001). Increasing the SOM content of soil is the key to building soil N capital (Buresh and Giller, 1998). The results indicated that nitrogen and phosphorus were the limiting nutrients to growth and yield of maize in Kandara. Further, addition of secondary nutrients, manure, and lime achieved a positive increase in the recorded grain yields.

4.4 Management practices and their effects on variability of N, P and K in smallholder fields

4.4.1 Summary statistics of N, P and K variables used in CART modelling

Table 4.5 indicates the realized amounts of N, P, and K after soil data analysis. From the summary statistics, it was evident that nutrient levels across farmers' fields are highly variable. This is indicated by the coefficient of variation (CV) observed for all nutrients.

Table 4.5: Summary statistics of N, P and K variables used in CART modelling

Summary statistics for soil data						
Variable	Max	Min	Mean	CV	SD	SE
K (ppm)	1170	126	438	51.05	223.6	43.85
P (ppm)	208	5.2	31.63	135.4	42.81	8.39
Total N (%)	4.1	1.2	2.97	30.35	0.9	0.18

K=Potassium, P=phosphorus, N=Nitrogen, ppm=Parts per million

The CV for nitrogen was 30.35 with a minimum score of 0.9% and a maximum score of 4%. Phosphorus had a CV of 135.4 with a minimum of 4.17 ppm and a maximum of 208ppm. Potassium had a CV of 51.05 with a minimum of 126 ppm and a maximum of 1170 ppm.

4.4.2 Summary statistics of management variables used in CART modelling

Table 4.6 indicates the summary statistics of management variables used in CART modeling. Field position (FP), fallow type (FT), cropping systems (CS) was considered predictor variables. Land conversion history (LCH), the number of seasons of fertilizer

use (NSFA) and number of seasons of manure use (NSMA) was considered as continuous variables.

Table 4.6: Summary statistics for management parameters used in CART analysis

Summary statistics for management data					
Variable	Max	Min	Mean	SD	SE
FP	0	0	0	0	0
LCH	1976	1939	1954	11	1.1
FT	0	0	0	0	0
CS	0	0	0	0	0
NSFA	5	2	4.5	1.13	0.235
NSMA	5	2	4.5	1.18	0.245

FP=Field position, LCH=Land conversion history, FT=Fallow type CS=Cropping system, NSFA=number of seasons of fertilizer use, NSMA=Number of seasons of manure use.

The maximum (latest) year when land was converted was in 1976 while the minimum year (earliest) was 1939. The maximum seasons of fertilizer use in farmers' fields were 5 and the minimum was 2. Across all the surveyed farmers, the mean seasons of fertilizer use was 4. The mean for manure use was 4.5 for all the surveyed farmers with the maximum being 5 seasons and the minimum being 2 seasons.

4.4.3 CART model on effect of management on variability of nitrogen in Kandara

The ranking indicates the importance of the predictor variables in determining the variability of N in smallholder fields in form of root competitor splits Table 4.7. The root competitor splits indicated the contribution of the predictor variable to the pruning of the initial model. Improvement indicated the contribution of the predictor variables to the development of the regression tree. In CART regression trees, the nodes falling on the right hand side (N-Right) of the tree indicate the sample from the population greatly influenced by the predictor variables. The nodes falling on the left hand side (N-Left) indicate the part of the sample from the entire population that's less influenced by the predictor variable.

Table 4.7: Root competitor splits for nitrogen showing performance of the predictor variables in model construction

Root competitor splits for nitrogen					
Rank	Competitor	Split	Improvement	N-Left	N-Right
1	NSMA	2.5	0.10	3	20
2	FP	Slope	0.09	21	2
3	LCH	1940.5	0.08	4	19
4	FT	Natural	0.08	4	19
5	CS	Mixed	0.03	18	5
6	NSFA	4.0	0.02	8	15

NSMA- Number of seasons of manure use, FP- Field position, LCH- Land conversion history, FT- Fallow type, CS- Cropping system, NSFA- Number of seasons of fertilizer use (RE= 0.5).

The results indicated NSMA predictor variable had the highest improvement (0.10) influencing variability of N in 20 (N-Right) smallholder fields. The improvement values for other predictor variables were scored in this decreasing order NSMA>FP>LCH>FT>CS>NSFA for their contribution in the development of the model. The other predictor variables that influenced N variability were, land conversion history where the N - right was 19 small holder fields, fallow type where N- right was 19 smallholder fields and fertilizer use, where N-right was 15 smallholder fields.

The optimum regression tree for nitrogen as a function of management parameters had six terminal nodes (RE: 0.5) (Figure 4.7).

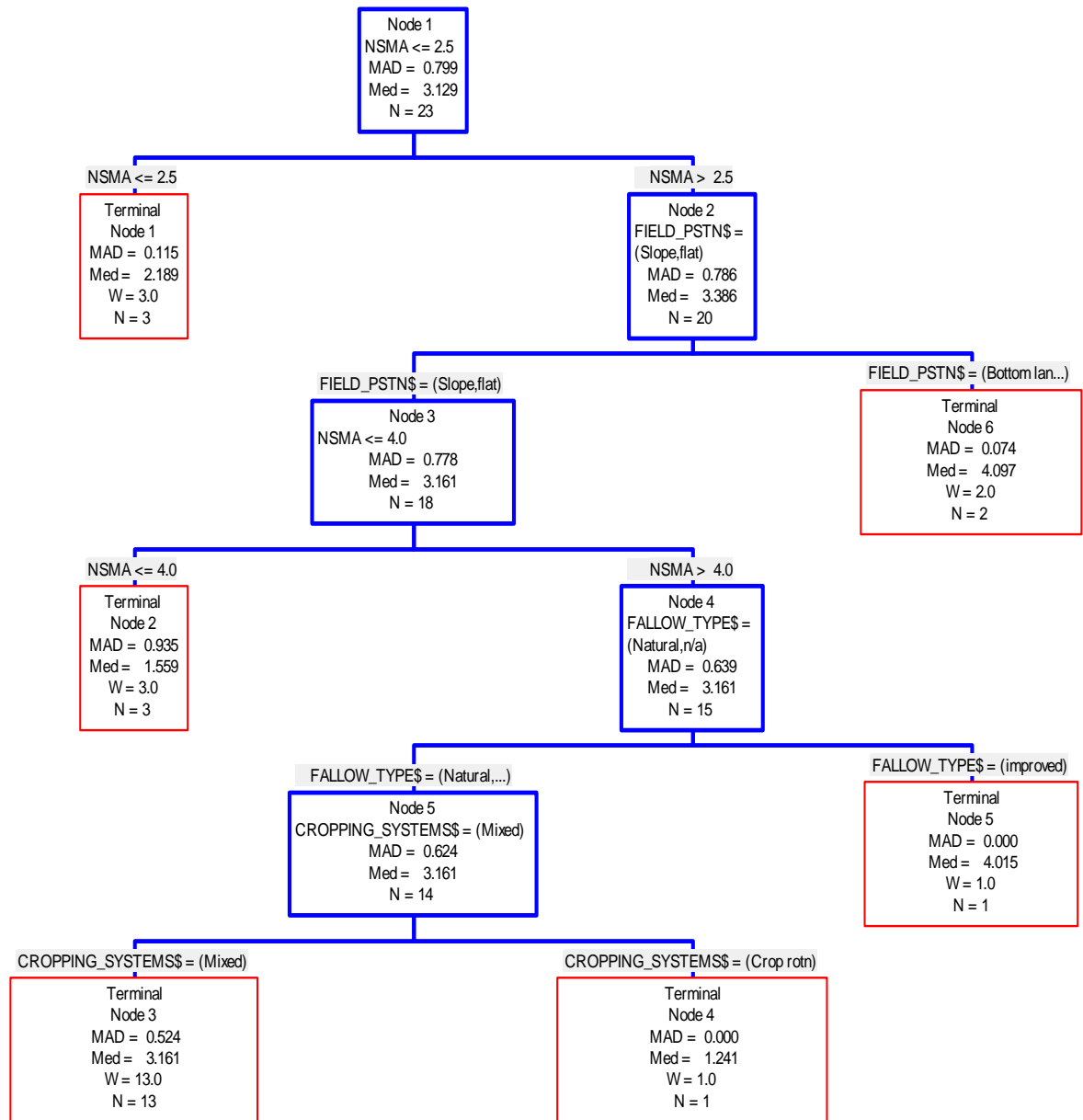


Figure 4.7. Regression tree showing the effect of management parameters on the variability of nitrogen in farmers' fields in Kandara

The number of seasons of manure use (NSMA) was the primary splitting node with average total nitrogen at 3.13% in 23 fields. In fields that had manure use ≤ 2.5 seasons of manure use in $n=3$ fields (TN1) the % nitrogen was 2.2% and 3.4% at >2.5 in $n = 20$ fields (SN2).

At splitting node 2, the fields that were bottomlands had an average of 4.1% total nitrogen; $n=2$, terminal node 6 (TN6). Further, at splitting node 3 (SN3) the average total nitrogen was 3.2% $n=18$ in the flat fields. In this node for the fields it is observed that the fields where NSMA was ≤ 4.0 average total nitrogen was 1.6% ($n=3$) at terminal node 2 (TN2). For fields where NSMA > 4.0 , the average total nitrogen was 3.2% in $n=15$ fields which is indicated at SN4. Further, SN4 is split by fallow types (FT) and NSMA. Fields that had natural fallow type had average total nitrogen of 3.2%, $n=14$ at SN5 and at TN5 the average nitrogen was 4%, although $n=1$. Cropping systems (CS) and FT were used to split SN5, where the mixed cropping system had total nitrogen 3.2%, $n=13$ at terminal node 3 (TN3) and total nitrogen achieved in crop rotation was 1.2%.

From the model, it's evident that manure use in farmers' fields determines nitrogen variability. The number of seasons of manure use were the primary splitting node in the model, implying that it is the predictor variable with the highest improvement value. Studies from various regions in the world show the importance of organic resources in improving soil fertility consequently increasing farmers' yields.

According to Giller *et al.* (2006), nitrogen is required by maize in huge amounts and its availability in the soil is greatly synergized by the amount and nature of SOM present. Indeed the low levels of N could be one of the major factors contributing to low maize yields where no external inputs are used Kihanda (1996). Further, numerous studies in SSA have shown a positive interaction between fertilizer and manure, with the benefits

of manure, increasing with decreasing soil fertility (Zingore *et al.*, 2008; Mtambanengwe and Mapfumo, 2005).

FAO (2003) indicated that high population densities have necessitated the cultivation of marginal lands that are prone to erosion hence enhancing environmental degradation through soil erosion and nutrient mining. From the model, field position was an important predictor variable affecting the availability of nitrogen as evidenced from splitting node 1 (SN1). Field position determines the extent of soil erosion, hence can be able to predict the effects of soil degradation which leads to low soil fertility whose ripple effects is depressed yields.

In Nigeria, Salako *et al.* (2007) reported 65% to 75% reduction in crop yield with 25-cm removal of topsoil when no fertilizers or manure was applied. However, productivity of eroded soils was restored more effectively by the application of manure than by use of chemical fertilizers. Similar experiments by Oyedele and Aina (2006), also conducted on Alfisols in Western Nigeria, indicated that grain yield of maize (*Zea mays*) decreased from 3.2 Mg ha⁻¹ under control to 0.1 Mg ha⁻¹ where 20 cm of topsoil rich in SOM was removed.

Nandwa (2001) indicated that increasing human population pressure has decreased the availability of arable land and it is no longer feasible to use extended fallow periods to restore soil fertility. From the model, it is evident that fallowing impacts on nitrogen variability in smallholder farmers' fields. This is shown in splitting node 4 (SN4). Fallow periods that can restore soil fertility are reduced to lengths that cannot regenerate soil fertility leading to the non-sustainability of the farming systems

(Nandwa, 2001). Further, cropping systems as indicated in splitting node 5 (SN5) contribute to the status of soil fertility.

According to Kihanda (1996), farmers who practiced mixed cropping system had legumes planted in between maize rows. Legumes are nitrogen fixers while maize is a nitrogen consumer. This mode of cropping maintains the soil in the original soil fertility state since the fixed nitrogen is eventually used by maize. Various legumes-based technologies, such as rotations of cereal crops with grain legumes, improved fallows, alley- cropping, and green manures have been advocated as viable options for providing supplementary N to cereal crops (Giller *et al.*, 1997). Within intercrops, this can result to increased grain output in maize alone, both with and without fertilizers (Snapp and Silim, 2002). Strategically targeting fertilizer use to variable soil fertility conditions, combined with recycling crop residues, manure application, and various legumes-based technologies are necessary for viable fertilizer use in smallholder farming systems in SSA (Giller *et al.*, 2006).

4.4.4 CART model on the effect of management on variability of potassium in Kandara

LCH predictor variable had the highest improvement (11.2) and influenced variability of K (N-Right) 11 smallholder fields (Table 4.8). The predictor variables were scored in the following descending order LCH>FP>NSFA>CS>NSMA.

Table 4.8: Root competitor splits for potassium showing performance of the predictor variables in model construction

Root competitor splits for potassium					
Rank	Competitor	Split	Improvement	N-Left	N-Right
1	LCH	1957.5	11.2	12	11
2	FP	Flat	7.7	1	22
3	NSFA	4.0	3.0	8	15
4	CS	Mixed	0.9	18	5
5	NSMA	2.5	0.04	3	20

NSMA- Number of seasons of manure use, FP- Field position, LCH- Land conversion history, FT- Fallow type, CS- Cropping system, NSFA- Number of seasons of fertilizer use (RE= 0.6).

The result also indicated the importance of field position on nutrient variability. The predictor variable, FP achieved an improvement of 7.7, which indicated that the levels of potassium in different farmers' fields were highly dependent on the gradient of the farmers' fields. Fertilizer application also influenced levels of potassium in farmers' fields. It achieved an improvement of 3.0, which indicated that frequency of fertilizer application played a role in determining the levels of K in the soils.

The regression tree for potassium as a function of management parameters had six terminal nodes (RE: 0.6) (Figure 4.8). LCH was used to split (SN1), where land converted into years greater or above (> 1953.5) had an average of 512 ppm of

potassium in $n = 10$, while the fields converted in ≤ 1953 achieved potassium averages of 346 ppm, $n = 13$. Further, SN2 is split into TN1 and TN2 by LCH, where land converted in years > 1957 had higher potassium averages at 583 ppm (TN2) while land converted in ≤ 1957 had potassium averages of 337 ppm (TN1).

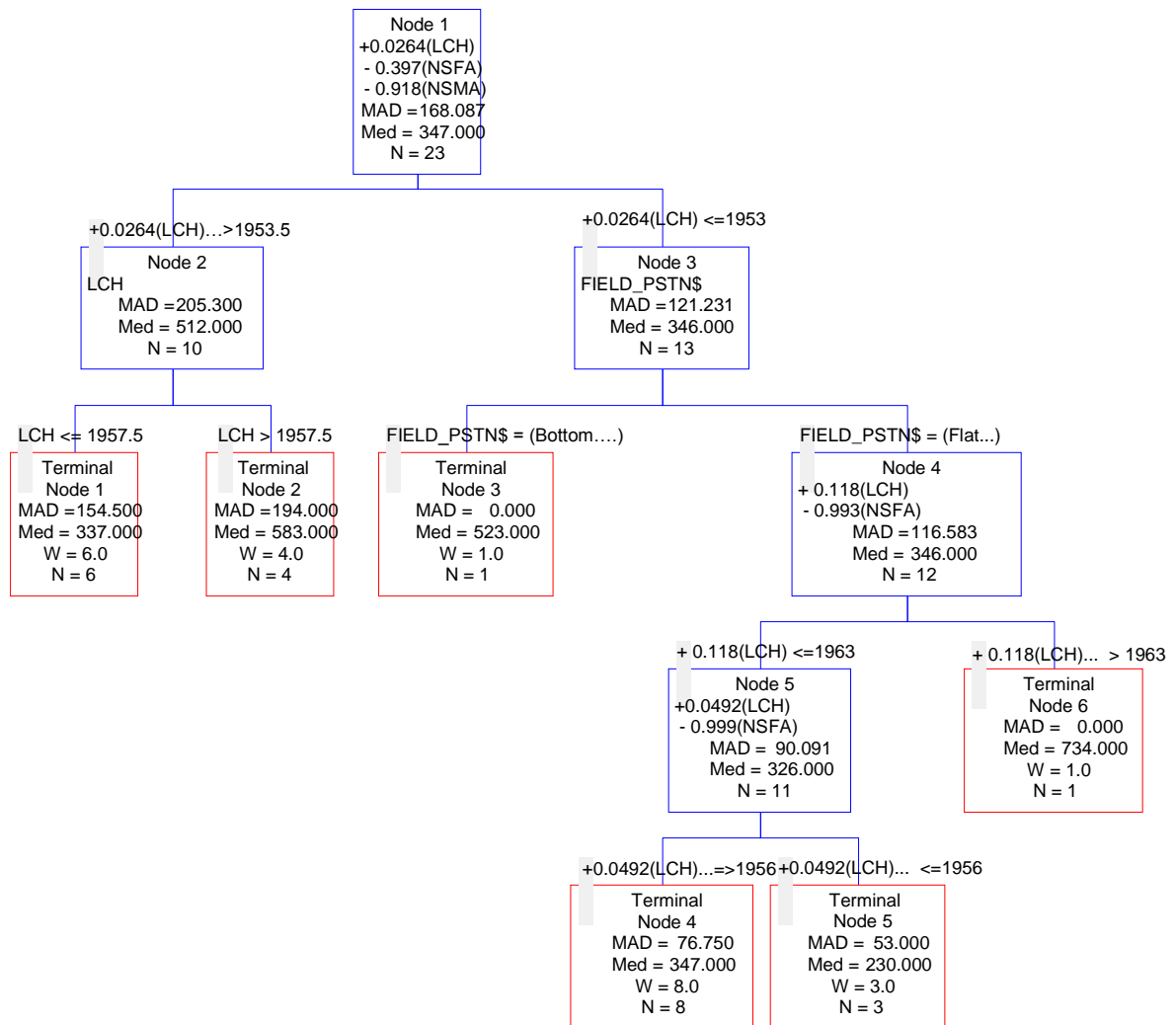


Figure 4.8: Regression tree showing the effect of management parameters on the variability of potassium in farmers' fields in Kandara

At splitting node three (SN3), average amount of potassium achieved was 346 ppm for land converted ≤ 1953 , $n = 13$ and potassium levels were 523 ppm in land converted $>$

1953 $n = 10$. The subsequent split of SN4 into SN5 indicates that potassium average in fields converted at periods ≤ 1963 , $n = 11$ was 326 ppm while those converted at periods > 1963 had a potassium average of 734 ppm, $n = 1$. Further SN5 is split by LCH and NSFA into terminal node 4 (TN4) and terminal node 5 (TN5) where in TN4 in farms converted in ≥ 1956 the average potassium was 347 ppm, $n = 8$ and in TN5 for fields converted ≤ 1956 achieved average potassium of 230 ppm.

Variability in soil fertility can occur at different scales, including field level land use, distance of the fields from the homestead, and among households (Vanlauwe *et al.*, 2002a; Tittonell *et al.*, 2005a; Tittonell *et al.*, 2005b; Tittonell *et al.*, 2006; Vanlauwe *et al.*, 2006). Decreasing soil fertility results from an imbalance between nutrient inputs and nutrient removals through harvesting, erosion, and leaching (Zingore *et al.*, 2005; Lal, 2007). This is further aggravated by land conversion history as indicated at the primary splitting node 1 which indicates the effect of nutrient mining over time. The depletion rates of specific nutrients depend on a number of factors, including management, soil type and field position and climate (Wopereis *et al.*, 2006; Tittonell *et al.*, 2007a; Zingore *et al.*, 2007) as indicated from splitting node 4 (SN4).

4.4.5 CART model on effect of management on phosphorus variability in Kandara

LCH predictor variable achieved the highest improvement (1.06) and influenced P variability (N-Right) in 19 smallholder fields (Table 4.9). The other predictor variables were scored in this diminishing order LCH>CS>NSMA>NSFA>FT>FP.

Table 4.9: Root competitor splits for phosphorus showing performance of the predictor variables in model construction

Root competitor splits for phosphorus					
Rank	Competitor	Split	Improvement	N-Left	N-Right
1	LCH	1940.5	1.06	4	19
2	CS	Mixed	1.03	18	5
3	NSMA	2.5	0.91	3	20
4	NSFA	4.0	0.77	8	15
5	FT	n/a	0.58	17	6
6	FP	Flat	0.33	11	12

NSMA- Number of seasons of manure use, FP= Field position, LCH= Land conversion history, FT= Fallow type, CS= Cropping system, NSFA= Number of seasons of fertilizer use (RE= 0.6).

The other predictor variables that influenced P variability were, cropping system, where N-right was 5 small holder fields, manure use where N- right was 20 smallholder fields, fertilizer use where N-right was 15 smallholder fields, fallow type where N-right was 6 smallholder fields and field position where the N - right was 12 farmers' fields.

The regression tree for phosphorus as a function of management parameters (RE: 0.6) (Figure 4.9) had five terminal nodes.

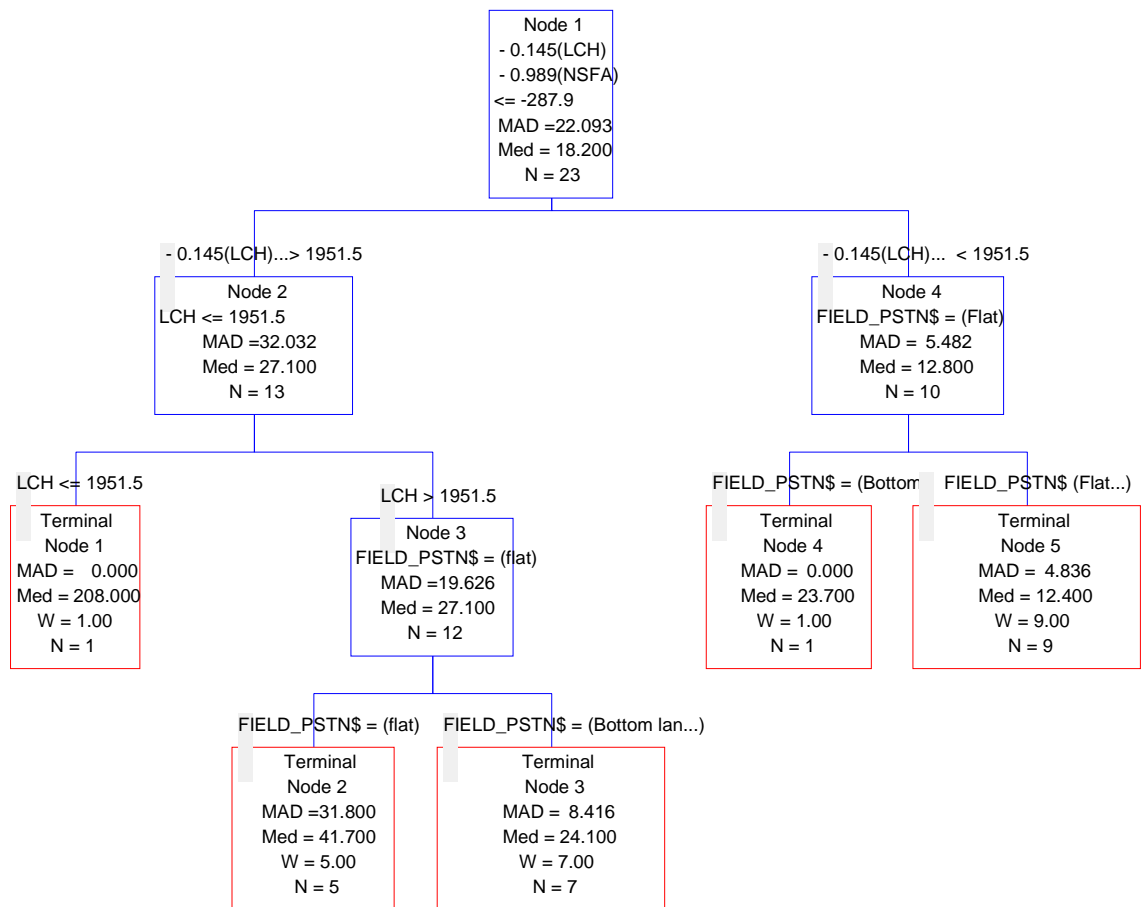


Figure 4.9: Regression tree showing effect of management parameters on variability of phosphorus in farmers' fields in Kandara

At splitting node 2 (SN2) the levels of phosphorus in $n = 13$ fields were at an average of 27.1 ppm for fields converted ≥ 1951 . At splitting node 4 (SN4), the splitting criteria was ≤ 1951 and field positions (FP). These are fields converted ≤ 1951 , the average level of phosphorus achieved was 12.8 ppm, $n=10$. At splitting node 3 (SN3) the average

phosphorus level in 12 fields was 27.1 ppm for fields converted ≥ 1951 and 20.8 ppm in terminal node 1 (TN1). At TN3, the level of average phosphorus was 41.7 ppm in flat fields, while in bottom lands it was 24.1 ppm for $n=5$ and $n=7$, respectively.

According to Giller *et al.* (2006), land conversion history influences soil fertility levels since a prolonged cropping leads nutrient mining thus exhausting soil essential nutrients, this indicated from primary splitting node 1 on the model. Escalating rates of soil nutrient mining makes nutrient losses highly variable in agricultural areas where they range from moderate to severe loss of nutrients, partly because of prolonged tilling without fallowing (Hena and Baanante, 2006). Nearly two-thirds of agricultural lands in Africa were estimated by one influential study to have degraded between 1945 and 1990, with serious degradation (involving major loss of productivity) on nearly one-fifth of agricultural land (Olderman *et al.*, 1991).

The main factors contributing to soil nutrient depletion in SSA are nutrient mining, leaching, and soil erosion (Amede, 2003; Hena and Baanante, 2006). This is due to effects of field position amongst other factors; this was shown by the appearance of field position at splitting node 3 (SN3) and splitting node 4 (SN4). One of the ways of addressing the impact of soil mining is use of inorganic fertilizers (Lungu and Dynoodt, 2008).

Fertilizers are the key to alleviating these constraints but must be integrated with other inputs and proper soil management for their economic potential to be realized (Adesina

2001). Mineral fertilizers are the only practical way to restore plant nutrients back to the severely depleted soils. However, African farmers have little access to fertilizers and cannot always afford them (Sachs, 2008). The use of inorganic fertilizers is therefore far behind recommendations (Twomlow *et al.*, 2008). Influence of fertilizer on level of phosphorus in soils appears in primary splitting node 1.

This increase in grain yield has been attributed to improved N synchrony with combined inputs through direct interactions of the organic resources (ORs) and N fertilizers (Vanlauwe *et al.*, 2002b). The ORs temporarily immobilize nutrients from mineral fertilizers and may release them in synchrony with crop nutrient uptake. Nutrient losses through leaching have been shown to decrease (Vanlauwe *et al.*, 2002a) while N mineralization of ORs is improved with the combined application of manures and nitrogenous fertilizers (Sakala *et al.*, 2001). Indirect interactions may also enhance crop growth by improving the soil environment for root growth through increased SOM, increasing the nitrogen demand, which can be met by nitrogenous fertilizers (Vanlauwe *et al.*, 2002b). The nutrient resource most readily available to smallholder farmers is cattle manure although the small nutrient contents of manures makes them poorly effective in improving crop yields (Mugwira and Murwira, 1998). One of the greatest research challenges is to develop technologies that are effective within farmer resource constraints, resource levels and acceptable risk (Snapp *et al.*, 2003).

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of Results and Conclusions

The first objective of this study was addressed by establishing omission trials in order to unravel the specific nutrients limiting maize growth and yield in Kandara. From the findings, it can be concluded that low maize yields in smallholder fields of Kandara were caused by nitrogen and phosphorus limitation. The loss from lack of N and P was at an average of 2 Mg ha⁻¹ and 1 Mg ha⁻¹, respectively during LR13 and SR13 seasons.

Management parameters affected a variety of nutrients in the soil. The importance levels of the management parameters indicated that some practices had greater impact in determining nutrient variability than others. Number of seasons of fertilizer use had the highest importance value that contributed to the variability of nitrogen. For potassium, land conversion history had the highest importance value contributing to its variability in farmers' fields. Phosphorus variability was highly influenced by land conversion history. Fallowing, fertilizer use, cropping system and field positions were important predictor variables influencing nutrient. The relative errors for the regression models were 0.5 for nitrogen, 0.6 for potassium, and 0.6 for phosphorus, which showed that the models were relatively accurate. For the farmers who had never practiced fallow nutrients were continuously mined and the soil structure interfered with for prolonged periods without allowing any break for natural recovery.

The results show that management activities in smallholder fields influence the variability of nitrogen, phosphorus, and potassium. This gives credence to objective one where nitrogen and phosphorus were established as the limiting nutrients leading to depressed yields in Kandara. The age of fields' since conversion, frequency of manure use and cropping systems were some of the practices, that farmers perform effortlessly while lacking the knowledge of the impacts caused by such practices in the long-term. If farmers were aware of the effects of these practices on the status of soil fertility, then they would adopt sustainable soil management practices. Therefore, farmers need to be trained on how to sustainably manage their fields for good crop yields.

Further, this study assessed the effect of manure, lime, and micronutrients (CaMgS) amendments together with full fertilizer treatment on maize production. From the results, it was indicated that secondary nutrients, SOM, pH, and play an important role in crop growth, and final yields. Secondary nutrients have roles in cellular mechanisms (Ca), chlorophyll components (Mg) and protein synthesis (S). Continuous cropping has led to nutrient mining and this includes primary and secondary nutrients. Replacement of these nutrients is important; just like addressing the challenges of dwindling primary nutrients.

The correction of these nutrients in smallholder fields can lead to positive changes in crop growth and improvement of the final yield. The pH levels in soils influence nutrient absorption by crops and thus directly impacting on crop growth and subsequent yields. Establishing correct pH balance in soils should be a prerequisite when developing nutrient application regimes in soils since this fundamentally affects nutrient

dynamics in soil. SOM is an important additive in soils that helps balance soil micro flora, soil moisture retention and helps improve soil structure. All these factors act harmoniously in improving soil and root environment, thus improving nutrient absorption by crops. This results in improved crop growth and improved crop yields.

5.2 Recommendations

Based on the findings of this study the following can be recommended;

- ❖ Nitrogen and phosphorus inadequacy need to be addressed in Kandara, since they are the nutrients limiting maize growth and yields.
- ❖ Trainings on good farm management need to be done, so that farmers understand the importance of having sustainable soil fertility.
- ❖ Information on precision nutrient use should be provided to smallholder farmers so that ignorant use of fertilizer that may eventually pollute soils is avoided.

5.3 Areas of further research

Based on the results from the research, the following areas of further research were identified.

- ❖ Future studies to explore the role of soil micro biota in improving soil fertility in smallholder fields.
- ❖ Future studies on the influence of water stress on nutrient dynamics in smallholder fields and the subsequent impact of actual yields.

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APPENDICES

Appendix 1: Summary of nodes from nitrogen variability model

Summary of nodes from nitrogen variability model.				
CART node	Splitting variable	<i>N</i>	Av (Med) % N	SD (MAD)
SN1	NSMA	23	3.1	0.799
TN1	≤ 2.5	3	2.2	0.115
SN2	> 2.5	20	3.4	0.786
	Field position			
SN3	Flat/slope	18	3.2	0.778
TN6	Bottom/slope	2	4.1	0.074
	NSMA			
SN4	> 4.0	15	3.2	0.64
TN2	≤ 4.0	3	1.6	0.94
	Fallow type			
SN5	Natural	14	3.2	0.6
TN5	Improved	1	4.0	0
	Cropping system			
TN3	Mixed	13	3.2	0.52
TN4	Crop rotation	1	1.2	0

CART= Classification and regression tree, SN= Splitting node, TN= Terminal node, *n*=Sampled population, Av= Average, MAD= Mean average deviation, SD= Standard deviation, Med= Median

Appendix 2: Summary of nodes from potassium variability model

Summary of nodes from potassium variability model					
CART node	Splitting variable	<i>n</i>	Av (Med) (ppm)	K	SD (MAD)
SN1	LCH	23	347		168.0
SN2	>1953.5	10	512		205.3
TN1	≤1957.5	6	337		154.5
TN2	>1957.5	4	194		538
SN3	≤ 1953	13	346		121.2
	Field position				
TN3	Bottomland/slope	1	543		0
SN4	Flat	12	346		116.6
	LCH				
SN5	≤1963	11	326		90.1
TN6	>1963	1	734		0
TN4	≥1956	8	347		76.8
TN5	≤1956	3	230		53

CART= Classification and regression tree, SN=Splitting node, TN= Terminal node, *n*= Sampled population, Av= Average, MAD= Mean average deviation, SD= Standard deviation, Med= Median

Appendix 3: Summary of nodes from phosphorus variability model in Kandara

Summary of nodes from phosphorus variability model				
CART node	Splitting variable	<i>N</i>	Av (Med) P (ppm)	SD (MAD)
SN1	LCH	23	18.2	22.1
SN2	>1951.5	13	27.1	32.0
SN4	<1951.5	10	12.8	5.5
TN1	≤1951	1	20.8	0
SN3	>1951	12	27.1	19.6
Field position				
TN2	Flat	5	41.7	31.8
TN3	Bottomland/flat	7	24.1	8.4
TN4	Flat	1	23.7	0
TN5	Bottomland/flat	9	12.4	4.8

CART=Classification and regression tree, SN=Splitting node, TN= Terminal node, *n*= Sampled population, Av= Average, MAD= Mean average deviation, SD=Standard deviation, Med= Median

Appendix 4: Management history survey form

Farmer Name	Position (upland, slope or bottomland)	Land use History (years since conversion)	Last Fallow period (year-year)	Fallow type (Improved or natural)	Cropping system

^a For the last 5 seasons, indicate in which seasons inorganic fertilizer was applied. 1= last season, 5=5 years ago. E.g. 1, 3, 4 will indicate fertilizers were applied during the immediate previous season, 3 and also 4 years ago.

^b For the last 5 seasons, indicate in which seasons Manure was applied. 1= last season, 5=5 years ago. E.g. 1,3,4 will indicate manure was applied during the immediate previous season, 3 and also 4 years ago.

Date _____ Recorded by _____

