EFFECTS OF PHOSPHORUS SOURCES AND STARTER NITROGEN ON SOYBEAN YIELD AND SELECTED SOIL PROPERTIES IN THARAKA NITHI AND MERU COUNTIES OF KENYA

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DECLARATION

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

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We confirm that the work reported in this thesis was carried out by the candidate under our supervision.

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DEDICATION

To my God, wife and son, my sources of motivation. To my parents for their sacrifices and exceeding support towards my education all through the years.

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ABBREVIATIONS AND ACRONYMS

AGRA SHP	-	Alliance for Green Revolution in Africa-Soil Health Program
ANOVA	-	Analysis of Variance
As	-	Arsenic
Asl	-	Above Sea level
BNF	-	Biological Nitrogen Fixation
CAN	-	Calcium Ammonium Nitrate
CEC	-	Cation Exchange Capacity
DAP	-	Di ammonium Phosphate
FAO	-	Food and Agriculture Organization
SAS	-	Statistical Analysis Software
Hg	-	Mercury
IPNI	-	International Plant Nutrition Institute
ISFM	-	Integrated Soil Fertility Management
K_2O	-	Potassium Oxide
KARI	-	Kenya Agricultural Research Institute
LM	-	Lower Midlands
LR	-	Long Rains
LSD	-	Least Significance Difference
N	-	Nitrogen
P	-	Phosphorus
PR	-	Phosphate Rock
RCBD	-	Randomized Complete Block Design
SoCo	-	Soybean and Climbing bean Commercialization Project
SOM	-	Soil Organic Matter
SR		Short Rains
TSP	-	Triple Super Phosphate
U	-	Uranium
UM	-	Upper Midlands
UNEP	-	United Nations Environmental Programme
V	-	Vanadium

ABSTRACT

Integration of legumes into farming systems is one of the Integrated Soil Fertility Management (ISFM) options for improving soil fertility. Farmers can save their cost of production by using legumes, which, in association with rhizobia, can fix atmospheric nitrogen. Soybean is an important legume compatible with the smallholder farming systems in Tharaka Nithi and Meru counties. However, low P and N, a situation prevalent in the two counties can limit its performance. The study was carried out in Kigogo in Tharaka Nithi County and Kamujine in Meru County. Sources of P, with or without starter N application were evaluated while pursuing the following objectives: (1) to determine the effects of different phosphorus sources and starter N on soybean yield and selected soil chemical properties, (2) to evaluate the effects of different phosphorus sources and starter N on nodule numbers and soybean growth parameters. Finally, the study assessed the effects of different phosphorus sources and starter N on the amount of N fixed by soybean and their economic suitability. A trial was laid out in a randomized complete block design (RCBD), having 13 treatments with four replications each on a 4.0 m by 4.5 m plot size. The P sources were Triple Super Phosphate (TSP), Minjingu rock phosphate, Mavuno fertilizer, diammonium phosphate (DAP), animal manure and fortified manure (animal manure with Minjingu fertilizer at 1:1 ratio) all providing 30 kg P ha^{-1}. Diammonium phosphate (DAP) was reference input as it has both P and N and was the farmers' choice in the study area. Data collected were soybean growth parameters, biomass and grain yields, soil chemical characteristics and soybean and fertilizer market prices. Data was analyzed using analysis of variance (ANOVA) and means separated using t-test and Least Significant Difference (LSD) ($P<0.05$). The use of Mavuno fertilizer in combination with CAN as nitrogen source significantly ($P<0.01$) improved soybean yield and significantly ($P<0.05$) enhanced BNF compared to the control and ranked higher than TSP, DAP, Minjingu and animal manure. Addition of CAN alone as starter N restricted BNF in N rich Kigogo but enhanced it in N deficient Kamujine, giving 56.32 kg $ha^{-1}yr^{-1}$. This increase was however not significant. Starter N did not enhance soybean nodulation but increased yield in combination with other P sources by 14.95% in Kamujine and 14.28% in Kigogo. The least costly source of P was DAP and therefore recommended for use in soybean production with consideration for liming to address possible reduction in soil pH. Farmers may also improve soybean yield and enhance their incomes while sustaining their soil fertility by using Mavuno fertilizer suppliments or Minjingu phosphate rock.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background to the Study

Soil fertility depletion is the most serious constraint to food production in sub-Saharan Africa (Sanchez et al., 1997; Mugwe et al., 2007a) with nitrogen (N) and phosphorus (P) being the most common deficient nutrients (Sanchez et al., 1997; Weikard and Seyhan, 2009). About 22 kg of N and 5 kg of P ha^{-1} is lost every year in African farms (Smaling et al., 1996). The problem is dire in the central highlands of Kenya which have losses as high as 126 kg N and 14 kg P ha^{-1} every year (Gitari et al., 1999) with smallholder farmers' application of commercial fertilizers to address this low fertility status remaining minimal. Several researchers have recommended Integrated Soil Fertility Management (ISFM) options for increasing soil fertility and agronomic efficiency of applied inputs (e.g. Sanginga and Woomer, 2009b; Vanlauwe et al., 2010). Use of legumes, an important component of ISFM (Sanginga and Woomer, 2009a), can reduce farmers' fertilizer costs through nitrogen fixation and improved soil physical and chemical attributes (Amede, 2003; Crews and Peoples, 2004) thereby improving farmers' profit chances (Dobereiner, 1997).

Soybean [*Glycine max* (L) Merrill.] is an important legume that can easily be integrated into farming systems and is probably among the highest N fixers, fixing up to 250 kg N ha^{-1} (Chianu et al., 2008; Tinsley, 2009). Soybean has high content of protein at between 37 - 40 % (Venter, 1999; Chianu et al., 2008) with several nutritional benefits (Fabiyi, 2006; Mc Cue and Shetty, 2007), thereby endearing the health conscious and vegetarians as a protein source. The crop's wide use is in industry with products ranging from animal feeds to vegetable oil. To satisfy the crop's huge local demand, Kenya imports most of it. In 2008 alone, Kenya spent US $2.754 million to import soybean and its products (FAO, 2008). Farmers in Tharaka Nithi and Meru counties can harness this economic opportunity by increasing soybean production.

One of the major nutrients limiting soybean production in the central highlands of Kenya is soil P deficiency (Obura et al., 2010). The soils in the central highlands of Kenya are acidic (Obura et al., 2010), fixing P, thus unavailable to crops. Continuous cultivation and cropping, prompted by small farm sizes and high populations, make P replenishing ability of the soils to be overwhelmed. Nitrogen is another nutrient with significant deficiency in the region. Nitrogen deficiency in soybean affects photosynthesis, leading to stunted growth, poor root formation and limited nodule formation (since the bacteriods will not form without the benefits of photosynthates), diminishing N fixation (George and Singleton, 1992). However, too much nitrogen hampers N fixation (Salvagiotti et al., 2008). The exact amount in which starter N is neither too much to reduce the N fixation nor too little to affect the crop's physiological requirement of nitrogen for optimum growth to necessitate fixation has not been comprehensively established.

1.2. Problem Statement and Justification of the Study

Although increased use of fertilizer has been advocated as one of strategic solution to the myriad food deficits and poverty incidences due to soil fertility decline in Africa (Larson and Frisvold, 1996), fertilizer prices continue to rise (Crew and Peoples, 2004). Incidents of poverty in central highlands of Kenya are worsening as a consequence of low yielding, increasingly smaller farms that are not rewarding farmers efforts. Low-cost nutrient inputs are therefore necessary. Given its N-fixing capability and its high economic potential, soybean is suitable for addressing the current problem of declining agricultural productivity. It is being introduced in the central highlands of Kenya for soil health improvement, nutrition and incomes.

The potential for promoting soybean is very high because Kenya's demand exceeds 100,000 MT (Wasike et al., 2009) against a local production of about 5,000 MT. However, productivity is mainly low due to high soil acidity and low P and in some instances N deficiency. Diammonium Phosphate (DAP) is the commonly used P source but it is not very suitable because of its acidifying properties. There is therefore a need for alternative P sources. Information on suitable alternative sources of P is scarce as few studies carried out targeting soybean. The purpose of study is therefore to evaluate the effect of different sources of P and starter N on soybean production in central highlands of Kenya.

1.3 Research Questions

The study sought to answer the following questions:

1. What are the effects of different phosphorus sources and starter N on soybean yield and selected soil chemical properties?
2. What are the effects of different phosphorus sources and starter N on soybean nodule numbers and growth parameters?
3. What are the effects of different phosphorus sources and starter N on amount of N fixed by soybean? Are these sources economically suitable?

1.4.1 Broad Objective

To determine effects of phosphorus sources and starter N on soil productivity in Tharaka Nithi and Meru counties

1.4.2 Specific Objectives

1. To determine the effects of different phosphorus sources on soybean yield and selected soil chemical properties
2. To evaluate the effects of different phosphorus sources and starter N on soybean nodule numbers and growth parameters
3. To assess the effects of different phosphorus sources and starter N on amount of N fixed by soybean and their economic suitability

1.5 Hypotheses

The following hypotheses guided the study:

1. Application of triple superphosphate (TSP) fertilizer significantly increases soybean yield compared to other phosphorus sources but does not improve soil pH, organic carbon, total N, available P and micronutrients levels.

2. Application of fortified manure significantly enhances soybean's nitrogen fixation ability relative to Triple Super Phosphate (TSP), Minjingu rock phosphate, Mavuno fertilizer, DAP, and animal manure.
3. Application of different P sources with starter N on soybean significantly increases nodulation and soybean yield, reducing cost of production and hence contributing to profitability.

1.6 Significance of the study

Assessment of the various P sources will inform on the most appropriate P sources for enhancing soybean yield and so guide policy makers in making appropriate policies regarding soybean and fertilizers in the region and similar areas. In the same vein, the study on the appropriateness of use of starter N in soybean production in influencing its production cost and profitability will provide informed choices for farmers on use of starter N. The outcome of this study will benefit extension agents in providing relevant options to farmers regarding soybean production. The study will also contribute to enhanced awareness on importance of soybean as a high protein-yielding legume while generating research data for further work on soybean in the study area.

1.7 Conceptual framework

Use of appropriate P sources, being agronomically efficient and economically acceptable, can promote their use by farmers and hence improve farms' soil fertility and enhance soybean production and productivity through their positive effect on soil properties (Figure 1.1). As a nitrogen-fixing crop, soybean will increase available N in the soil, which will benefit the consequent crops and so reduce the cost of production incurred to purchase required fertilizer. It is postulated that use of starter

N will enhance soybean nodulation and BNF, further reducing the need for N fertilizers and so reduce cost of production. Improved soybean yields have the benefits of reducing food insecurity, given their high nutritional content. The sale of the produce to purchase necessary food items will also indirectly improve food security. The soybean can spur employment opportunities by setting up of cottage industries for value addition of soybean and processing of soybean into products that will improve incomes. A high-income earning and well-fed farming community will be in a position to practice sustainable farming and thereby protect the environment. Use of appropriate P sources will not be damaging to the environment and may actually improve it (Figure 1.1).

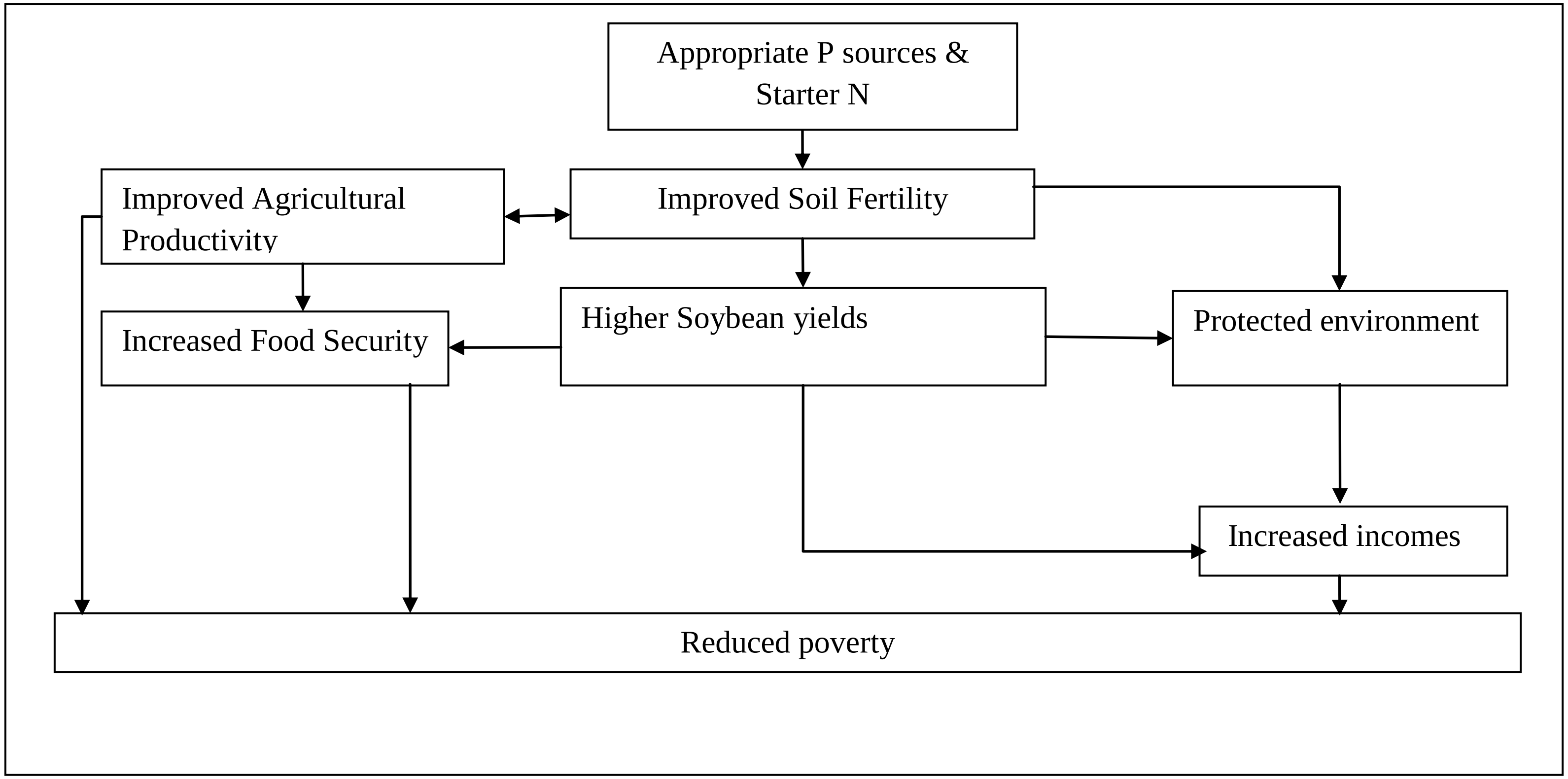

Figure 1.1: Schematic drawing depicting the conceptual framework of the study and expected impact on the society

1.8 Definition of terms

Biological nitrogen fixation: the process by which the rhizobia species of bacteria, in symbiosis with legumes, reduce the atmospheric nitrogen to plant available nitrogen. In this study, the rhizobium is *Bradyhizobium japonicum* and legume is soybean.

Sustainable agriculture: the successful management of agricultural resources to satisfy changing human needs while maintaining or enhancing the quality of the environment and conserving these resources for the future generations.

Soil fertility: the capacity of the soil to supply adequate nutrients to support plant growth, determined by physical, chemical and biological properties of the soil.

Soil characteristics: the various constituents and attributes defining the whole soil in regards to its ability to sustain crop production e.g. levels of soil pH, nutrients availability to plants, soil aeration, percentage of soil carbon e.t.c.

P sources: these are the various P-containing fertilizer inputs, either inorganic or organic as well as their combinations.

Integrated soil fertility management: the application of soil fertility management practices, and the knowledge to adapt these to local conditions, which optimize fertiliser and organic resource use efficiency and crop productivity. These practices necessarily include appropriate fertiliser and organic input management in combination with the utilization of improved germplasm.

1.9 Limitations of the study

The study did not address the long-term effects of P sources on soil characteristics e.g. pH, soil carbon and the dynamics of the various nutrients because of the short study period. Though mentioned briefly as possible determinants of farmers' use of various P sources, the study did not delve much on aspects regarding accessibility and availability of the P sources.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Overview

Africa is unable to feed her increasing population (Dyson, 1999; Muchena et al., 2005). Declining nutrients status of her soils is a major reason for this sorry state (Omotayo and Chukwuka, 2009).This has been brought about by nutrient mining through crop harvests, residue removal (Mugendi et al., 2003) and soil erosion (Zobisch et al., 1995; Muchena et al., 2005). Lack of or inadequate nutrient replenishment has exercebated the situation (Wallace and Knauzenberger, 1997; Mugendi et al., 2010). To meet her food security challenge, Africa has to incorporate nutrient replenishment in her farming systems (Tilman et al., 2002).

Many studies have shown that central highlands of Kenya have negative nutrient balance (Gitari et al., 1999; Maingi et al., 2006; Mugendi et al., 2010). To address this, several studies recommend the use of legumes for soil improvement (e.g Dobereiner, 1997; Crews and Peoples, 2004; Albareda et al, 2009), incorporation of organic inputs (Place et al., 2003), increased use of mineral fertilizer (Tilman et al., 2002) and integrated soil fertility management (ISFM) (Sanginga and Woomer, 2009a, b; Chianu et al., 2011) as possible solutions. Use of commercial fertilizers to address low fertility status in smallholder farmers remains minimal due to high fertilizer prices (Crew and Peoples, 2004; Sanginga and Woomer, 2009a, b), low commodity prices that do not recoup costs and weather variability that compound risks of crop loss (Duflo et al., 2008; Chianu et al., 2011). Poor techniques of fertilizer use have also discouraged wide adoption, with farmers unable to experience the expected returns to fertilizer use (Chianu et al., 2011).

As a technology in ISFM, legume incorporation is touted as especially viable in smallholder farming sytems (Sanginga and Woomer, 2009a). Legumes have capacity to fix atmospheric N through biological nitrogen fixation (BNF), a vital process that can avail N_2 into plant tissues through symbiotic relationship between legumes and *Rhizobium spp* (Kessel and Hertley, 2000; Albaredaet al., 2009; Sanginga and Woomer, 2009a). Legumes also increase soil aggregation, improve soil pH, increase Cation Exchange Capacity (CEC) and enhance soil microbial populations (Cruz et al., 1997; Onweremadu et al., 2011). Legumes are also a critical source of protein in many households, providing oil as well as fodder and are increasingly being industrially used as biofuels (Chianu et al., 2008; Tinsley, 2009; Mabapa et al., 2010) and therefore desirable for their multifunctional role.

As a legume, soybean generally has a high N fixation capacity compared to other legumes (Unicovich & Pate, 2000; Chianu et al., 2008), with superior protein content (Venter, 1999; Agwu et al., 2009) several health benefits (Fabayi, 2006; McCue and Shetty, 2007; Jooyandeh, 2011) and high potential market value (Chianu et al., 2008; Tinsley, 2009). With these attributes, Tinsley (2009) has recommended the need to enhance soybean production by small-scale farmers in Kenya. For soybean to effectively contribute in soil nutrition improvement, it is necessary to address the effectiveness of the rhizobia- host plant symbiosis (Sanginga et al., 2000), ability of the plant to accumulate N, the amount of soil N (Salvagiotti et al., 2008) and the environment constraints to N fixation (Tahir et al., 2009).

2.2 Factors affecting soybean BNF and yield

The type of cultivar, the soil nutrients and the environmental conditions such as moisture, temperature and aeration influences nitrogen fixation potential (Keyser and Li, 1992; Dakora and Keya, 1997; Zahran, 1999). Abiotic factors affecting BNF include; salinity, unfavorable soil pH, nutrient deficiency, mineral toxicity and topography (Keyser and Li, 1992; Belnap, 2001). High acidity hinders availability of necessary nutrients like P, Mo, and Zinc, which are vital for nodulation and BNF. Optimum nodulation take place in near neutral conditions (Pedersen et al., 2010) while very acidic conditions reduce rhizobia population as well as affect N fixation and fixation of P, harming rhizobia and reducing other micronutrients like molybdenum and Fe (Cruz et al., 1997; Zahran, 1999). Biotic factors affecting nitrogen fixation include; nodule competition,weeds, stage of growth of the host plant, rhizobium type, diseases and pests such as cyst nematodes, ants, and *phytophthora sojae* among others (Silva and Uchida, 2000; Rahman et al., 2010).

Number and size of nodules correlate to N fixation levels (Peoples et al., 2002). Soybean nodulates depending on variety, the immediate environment of the root such as presence or absence of moisture and at what levels, temperature of the soil and the presence or absence of competing infecting rhizobia (Fatima et al., 2007; Youn et al., 2008). Nodulation depends on nitrogen levels, too much of nitrogen will reduce nodulation (Salvagiotti et al., 2008). However, soil N should be adequate for there to be photosynthesis that will provide energy to initiate nodulation and onset of BNF (Belnap, 2001). The effective amount of N in soil may depend on the type of legume crop, the variety of the crop and the stage of the crop (Albareda et al., 2009). Nodulation also depends on the nutrients available in the soil; soybean nodulates with high presence of P, Mo, Boron, which are involved in nodule formation and bacteriods need them in the fixation of N (Nieuwenhuis and Niewelink, 2002).

Soybean is very sensitive to acidity, having optimum yields at moderate pH levels of 6.1 -6.5 (Pedersen et al., 2010). Liming improves the pH of the soil, which enhances soybean yield. Phosphorus deficiency is the most limiting in Soybean growth and yield with crop requiring 20-25 kg ha^{-1} to be sufficient (Vance et al., 2003). Phosphorus is necessary for photosynthesis and chlorophyll formation for Ribonucleic acids (Vance et al., 2003). Phosphorus is also very important for energy transfer and a number of life process reactions (IPNI, 1999; Mokwunye and Bationo, 2002) in the plant as well as seed formation (Kamanga et al., 2010). Energy transfer is necessary to provide rhizobium with photosynthates, for nodule formation and for fueling N fixation (Tinsley, 2009) which provide the crop with fixed N for its further vegetative growth (Gan et al., 2002).

The most critical stages for soybean are the vegetative stage 3 and reproductive stage 4 which are pod formation, grain filling and flowering, respectively (Finke et al., 1982). At these stages, any deficiencies in nutrients or biotic or abiotic constraints will reduce subsequent yield. The main biotic factors affecting soybean include pests and diseases (Rahman et al., 2010). Main soybean diseases are the Phytophthora root rot, charcoal root rot, Sudden death root rot, Asian leaf rust and bean mosaic (Hartman et al., 2011).

2.3 Phosphorus and its role in soybean growth and yield

Phosphorus is essential for energy transfer to root nodules for N fixation, enhances root growth and is important in nodulation and increase rhizobia density in the soil surrounding the roots (IPNI, 1999; Kamanga et al., 2010). Phosphorus is vital for synthesis of ribonucleic acids, seed formation, early maturity, nodule formation and development as well as energy mechanisms in legumes (Vance et al., 2003; Tahir et al., 2009). Phosphorus is also necessary for formation of chlorophyll and photosynthetic activity itself. Studies have shown that P helps in efficient uptake of N and plant's ability to withstand moisture stress (Barker and Pilbeam, 2007; Zheng et al., 2010). Phosphorus is also very vital for root formation, efficient nitrogen fixation (Carsky et al., 2002; Vance et al., 2003; Tahir et al., 2009) and yield (IPNI, 1999; Kamanga et al., 2010). It is required in large quantities by legumes for supply of energy to the roots for fixation of N (George and Singleton, 1992; Tinsley, 2009). It is therefore necessary to apply P in soils sown with legumes for increased soybean yields (Sanginga and Woomer, 2009a).

Unlike the nitrogen which is abundant in the atmosphere and can be reduced to plant available forms, phosphorus sources are non-renewable and are being depleted faster (Cordell et al., 2009; Vaccari, 2009; Weikard and Seyhan, 2009; Crasswell et al., 2010; UNEP, 2011) and commercial ones are expensive (Okalebo et al., 2007;

Sanginga and Woomer, 2009a). Researchers have estimated that the current consumption rate will exhaust the world's phosphorus sources in 50 to 100 years (Cordell et al., 2009; Vaccari, 2009). This situation is pertinent in the developing world especially in Africa, which is the largest exporter of P raw materials but a scant user of P sources in her agricultural systems (FAO, 2006; Cordell et al., 2009).

The ability of the sources of P to supply the P depends on their effectiveness in delivering P in available forms for plant uptake (Schachtman et al., 1998). Sources that reduce soil physical conditions favorable for rhizobia reduce the chances of both nodulation and N fixation. Sources that increase acidity reduce N fixation while those that buffer or increase soil pH increases BNF (Barker and Pilbeam, 2007; Richardson et al., 2009).

Studies on the P nutrient have previously received little attention than has N on soil fertility improvement, especially on the viewpoint of local P sources (Nziguheba et al., 2002; Cordell et al., 2009). However, with increased acknowledgement of the depleting finite sources of P and the consequences of inadequate P nutrient in agricultural systems to the increasing populations, several researchers have identified various approaches of overcoming the looming P crisis (Cordell et al., 2009; Vaccari, 2009). In Africa generally and Kenya in particular, some of the solutions suggested such as P recycling from waste water (Vaccari, 2009) have impractical considerations to her agricultural systems and so homegrown approaches pertinent to local situations have to be sought (Obaga et al., 2000; Okalebo et al., 2007; UNEP, 2011).

2.4 Phosphorous Sources

Phosphorus is the most limiting nutrient in legume production in Africa (Sanchez, 2002). Available P sources are expensive for many small-scale farmers necessitating the need to identify local sources available for farmers' use (Cordell et al., 2009; Kamanga et al., 2010). Approaches recommended in addressing P deficiency include efficient use of the available resources (Van Vuuren et al., 2010), use of rock phosphate (Bationo et al., 1992), recycling of the wastewater containing phosphates (Vaccari, 2009) and organic phosphorus sources (Van Vuuren et al., 2010) as well as recovery of the resource after use (Cordell et al., 2009). Weikard and Seyhan (2009) observed that there is hardly any notable recovery from wastewater treatment in Africa compared to developed countries and so the most appropriate strategy is recycling organic sources containing P. The effectiveness of P sources depends on their solubility, existing soil conditions such as soil pH and presence of sesquioxides that may fix P (Mokwunye and Bationo, 2002). For bean growth and yields, Adulaju et al. (2009) recommended a rate of 30 kg ha^{-1} in low P soils. There are various sources of P available for its replenishment in soils and they include the following:

2.4.1 Phosphate rock (PR)

Phosphate rock (PR) is any naturally occurring geological material containing one or more phosphate minerals suitable for commercial use (Van Straaten, 2002) and includes unprocessed phosphate ore as well as the concentrated phosphate products. Phosphate rock is cheaper than other sources (Okalebo et al., 2007; Kolawale and Tian, 2007; Sanginga and Woomer, 2009a). There are high amounts of PR reserves in neighboring countries of Tanzania and Uganda that are cheaper than other imported mineral fertilizers such as DAP and TSP (Okalebo et al., 2007; Sanginga and Woomer, 2009b). A major constraint to PR is that phosphorus in PR is not readily available to plants. Factors affecting release of P from PR are; chemical and physical properties of soil, nature of climate and plant characteristics (Maene, 2001; Mokwunye and Bationo, 2002).

Another limitation to PR use is that phosphate rock application rates are high due to lower solubility, reduced P content and its bulkiness (Sanginga and Woomer, 2009a; Weikard and Seyhan, 2009; UNEP, 2011). However, one time large application of PR has positive residual effects on crop yields during several consecutive cropping seasons, which justifies use of PR to improve soil's P status (Buresh et al., 1997; Sanginga and Woomer, 2009a). Sedimentary phosphates commonly have a higher specific surface area than igneous fluor-apatites (Van Straaten, 2002). In general, the PRs with the highest specific surface areas also have the highest citrate solubility. One way to increase the surface area is by grinding, which creates fresh surfaces that improve solubility.

The main factors affecting PR use include the following:

2.4.1.1 Soil factors

These include pH, CEC, Ca concentration, P concentration, P sorption capacity and organic matter content of the soil. The following equation summarizes soil factors affecting P availability: $Ca_{10}\ (PO_4)6F_2 + 12H^+ = 10\ Ca^{2+} + 6H_2P0_4^- + 2F$ (Van Straaten, 2002). Dissolution of apatites is dependent on the neutralizing reaction between proton (H^+) ion concentrations and the apatites in PRs. Increasing the H^+ ion concentrations (protonation/acidulation) in the soil drives the reaction from left to right. Acid soils and acid generating processes, as well as inorganic and organic acids, all contribute to enhanced PR dissolution at low pH. The conditions of low pH, low exchangeable Ca and low P concentrations are common in many tropical, weathered soils (Carsky et al., 2002). Acid soils are more conducive to PR dissolution than calcium rich alkaline soils (FAO, 2004).

Decreasing the activity of Ca^{2+} or the P-species, enhances apatite dissolution (Van Straaten, 2002). To enhance the P concentration in soils, a useful way to pull the dissolution reaction from left to right is decreasing calcium ion concentrations in the soil solution (Barker and Pilbeam, 2007). Soil P-sorption capacities effect the dissolution of PR (Nekesa et al., 2005). High P-sorbing soils such as oxisols and ultisols enhance the dissolution of PRs by reducing the P concentration in the immediate surroundings of the PR (Barker and Pilbeam, 2007; Olibone and Roselem, 2010). Slow release P-desorption from these soils might become important in the long term. Volcanic soils with the principal mineral allophane on the other hand are ultimate sinks of P with very low release rates (Van Straaten, 2002).

Directly applied, finely ground, low reactivity PRs are more effective on soils with low P-sorption capacity than on volcanic soils (andisols) with high P-sorption capacity compared to TSP (Van Straaten 2002). Closely related to the Ca status of soils is the soil cation exchange capacity (CEC), which in turn relates to soil texture (Tisdale et al., 1993). Sandy soils with low CEC, for example, do not provide substantial Ca-sinks (FAO, 2004) hence slow their dissolution and the agronomic effectiveness (Sahrawat et al., 2001). The influence of organic matter on the dissolution of PR is related to the formation of Ca and organic matter complexes (Van Straaten, 2002). Reducing Ca activity in the solution (Ca-sink) increases the phosphate rock dissolution. Hence, the higher the organic matter content in the soil the better the dissolution of the PR (Waigwa et al., 2003).

2.4.1.2 Crop factors

Crops vary in their ability to use P from PR sources mainly because the mobilizing capacity of P from various PRs varies with crop species. The best-known plants with relatively high P-mobilizing capacities include Buckwheat *(Fagopyrum esculentum)*, White sweet clover *(Melilotus albus)*, kale (*Brassica oleracea acephala*), or rape *(Brassica napus)*, White Lupins *(Lupinus albus)*, Cabbage *(Brassica oleracea capitata)* and Pigeon pea *(Cajanus cajan)* and other legumes and Crucifae family (Van Straaten, 2002; FAO, 2004). These plants enhance P solubilization from inorganic P sources by the excretion of organic acids from their roots. For example, the roots of the leguminous pigeon pea *(Cajanus cajan)* release piscidic acid that can complex iron to enhance the availability of ironbound phosphorus (Van Straaten 2002). Subsequent crops or intercropped sorghum for example can thus benefit from the increased availability of phosphorus. Other plants, like buckwheat *(Fagopyrum esculentum)* can enhance P uptake through high uptake of Ca. By lowering the concentration of Ca ions, the dissolution of apatite is enhanced (Van Straaten, 2002).

Acidification of the rhizosphere will also result in an increase in the rate of dissolution of apatite in the PR. P-deficient rapeseed plants *(Brassica napus)* acidify parts of their rhizosphere by exuding malic and citric acids (FAO, 2004) and can thus access the P pool of poorly soluble PR sources. The dissolution and uptake mechanisms include root exudation of various other acids and the formation of extensive fine root hairs, as well as uptake through mycorrhizae (Vanlauwe et al., 2000).

2.4.1.3 Management factors

Management practices, such as method of placement, timing of application and lime application can influence the effectiveness of PR or water-soluble P-fertilizer (Sahrawat et al., 2001; Van Straaten, 20002). The placement of PR in soils influences the rate of P release from PR, for example, broadcasting and incorporating the PR in the soil increases the effectiveness of PR whereas, banding of PR is less effective (Sahrawat et al., 2001; FAO, 2004). In addition, timing the application of PRs is important for their effective use.

Liming is a management option to increase pH and reduce exchangeable Al^{3+} concentration, especially for crops that are sensitive to Al^{3+} (Nekesa et al., 2005). However, when increasing the pH through liming, the PR dissolution decreases due to increased Ca^{2+} concentration (the common ion effect) (Van Straaten, 2002). Increasing the soil pH through liming reduces the aluminum toxicity to plant roots and decreases the supply of H+ ions (Nekesa et al., 2005). This can decrease the dissolution of PR in calcareous soils, through the common ion effect. In such scenario, applying the PR well in advance of the application of liming materials ensures that P is applied before being affected by the common ion effect by addition of liming materials, as long as the P-sorption capacity of the soil is not high

(Saharawat et al., 2001). When lime application rates are high, PR dissolution reduces (Van Straaten, 2002).

Decomposing organic matter generally produces organic acids that can enhance PR dissolution (Sahrawat et al., 2001). Microorganisms in the compost pile require P nutrition for growth thereby converting inorganic P into the organic form of P (Leu, 2009). This organic P pool converts to plant available P on their death and decomposition (Vance et al., 2003). Calcium chelation by organic functional groups or anions supplied during composting can also contribute to PR dissolution (Upjohn et al., 2005).

There are however, concerns on direct application of phosphate rocks. Most PRs contain heavy metals and toxic elements such as As, Cd, Cr, Hg, V and U, which may pose potential health and environmental risks (Smil, 2000; FAO, 2004). Phosphate rocks, like all mineral sources, are non-renewable and with increased mining and the high demand for phosphate fertilizers to sustain food production for the increased world population, their supply is dwindling (Vaccari, 2009).

Ten million tons of Minjingu phosphate (having 20% P_2O_5) is currently being processed for direct application in farms (SEAMIC, 2008). The Minjingu PR production commenced in 1983 (Maene, 2001). Minjingu phosphate hyper-phosphate fertilizer contains 13% P and 3% neutral Ammonium Citrate (NAC) soluble P (Jama and Van Straaten, 2006). Minjingu is considered a viable option as P sources and extensive research has been done on P Minjingu in western Kenya

(Nekesa et al., 2005; Jama and Van Straaten, 2006). Direct application of Minjingu Phosphate requires P deficient acidic soils and the other factors described above. MPR has relative agronomic effectiveness of 70-75% and so suitable for direct application in P deficient soils. Its estimated cost is 24-50% less than of TSP (Jama and Van Straaten, 2006). Minjingu Phosphate rock is the only deposit in East Africa with sufficient quantities and reactivity with potential for direct application (Jama and Van Straaten, 2006).

2.4.2 Manures

Manure is considered a renewable alternative source of P, currently providing about 15 million tons of P per year to farming systems globally (Cordell et al., 2009). Manure fixes sesquioxides reducing fixation of P (Diels et al., 2002). It delivers P over a long time though the amount of P in it is low (Diels et al., 2002; Sanginga and Woomer, 2009a). The higher the level of organic matter, the more the P reserves for long-term supply (Gitari and Friesen, 2001; Sharma et al., 2002). Manure increases SOM in soils (Karami et al., 2012) and has soil physical improvement attributes like soil moisture retention and chelating effect which buffer soil pH (Mucheru-Muna et al., 2003; Kowale and Tian, 2007) and lowers soil temperature (Adeyemo and Agele, 2010). Manure also increases soil carbon (Karami et al., 2012), accounting to more than 80% of C input in soils and increase soil microorganisms some of which are beneficial in reducing nematodes (Wachira et al., 2011).

Use of manure alone for soil replenishment is limited by the high quantity required (Mugwe et al., 2007b) and its low quality (Muchena et al., 2005) and so the need to fortify it (Kowale and Tian, 2007). The promise of increased CEC and SOM by addition of organic material is not guaranteed especially in the tropics and in some soil types (Diels et al., 2002).

The rate of microorganism breakdown is not usually sustainable to warrant increased CEC and SOM addition. Use of manure as a substitute for rock phosphate as P source has been suggested by various researchers (e.g. Weil, 2000; Weikard and Seyhan, 2009) and is seen to contribute to maintaining agricultural productivity over a long term span (Omotayo and Chukwuka, 2009), being considered as a recycling of P in the farming system (Cordell et al., 2009).

Other than provision of P, manure is also a good source of N. Using N from the organic sources depends in part on the mineralization rate of the organic source. High C:N ratio of different manures may slow N mineralization as seen in Heitholt et al. (2007) study using dairy manure compost. Use of organic materials is not necessarily a soil nutrient improving endeavor since their quality and availability is a serious constraint although it is a cheaper source (Place et al., 2003; Vanlauwe and Giller, 2006).

Organic materials are land and labor intensive, a major limitation in sourcing and utilizing them. The organic materials also contain a serious threat to the health of the overall farm as they may harbor pests and diseases negating their potential benefits (Vanlauwe and Giller, 2006). Manure could increase the vigor and aggressiveness of existing weeds and introduce noxious weeds to a farm especially if imported into the farm.

2.4.3 Mavuno fertilizer

Mavuno fertilizer is relatively new in the Kenyan market. Mass production of Mavuno fertilizer started in 2004 (World Bank, 2006; African Alliance Securities Research, 2007). It is a blend of DAP, gypsum and dolomite produced by Athi River Mining Cement Company and is the only locally produced fertilizer in Kenya (African Alliance Securities Research, 2007). Also containing micronutrients, it makes a good compound fertilizer for crop growth and production (World Bank, 2006), an observation shared by farmers assessing Embu demonstration plots including Mavuno in Eastern Kenya (Mutsotso et al., 2011) enhancing their adoption.

Coming in various packages from 50 kilograms to one kilogram (World Bank, 2006), Mavuno has calcium oxide (10%) which reduces soil acidity and enhance nodulation (Waluyo et al., 2004). It also has other micronutrients such as magnesium (MgO, 4%), sulfur (SO_4, 4%) Boron, Zn, Mo, and copper all of which are very vital in N fixation and soybean growth thus outperforming other established fertilizers (World Bank, 2006; Okoth and Siameto, 2011). Mavuno has the grade of 10% N-11% P - 10% K_2O together with over five micronutrients and thus a good blend for soils depleted of micronutrients. It is also comparably cheaper than the available commercial fertilizers by up to 15% (World Bank, 2006). The availability of the microelements improves plant performance. In a study on selected soil fertility management interventions to suppress *Fusarium spp*. in maize bean intercrop, Okoth and Siamento (2011) reported Mavuno fertilizer as having the highest yield and most effective in suppressing root colonization by *Fusarium spp.*

Mavuno fertilizer is not widely available in spite of demand (Blackie and Albright, 2005) as was the case with Embu farmers adopting the use of Mavuno fertilizer after a demonstration (Mutsotso et al., 2011). However, its sales are increasing (Blackie and Albright, 2005) with partnership with state owned National Cereal and Produce Board (NCPB) as its distribution agent in Kenya (African Alliance Securities Research, 2007).

2.4.4 Diammonium Phosphate (DAP)

Diammonium Phosphate (DAP) is the most widely available and used fertilizer in the Kenyan market (Yamano and Arai, 2010; Mutsotso et al., 2011; Sheahan, 2011). Continuous use of Diammonium Phosphate (DAP) increases soil acidity affecting negatively the soil properties (Vlek et al., 1997; Crews and Peoples, 2004; Nekesa et al., 2005). As soil pH reduces, the nodule formation and N fixation also reduces (Barker and Pilbeam, 2007). Though DAP avails both P and N, which are essential for soybean growth, the N in it volatilizes quickly or is lost through leaching or erosion and may not last through the whole growing period (Vlek et al., 1997).

Kenyan farmers have traditionally top-dressed with CAN (Calcium Ammonium Nitrate). The CAN is expensive, especially during the planting season, draining farmers' resources and discouraging farmers' efforts of replenishing their soils. Yet due to its availability and thus popularity to farmers, it is often the first choice for those who use commercial fertilizers (Sheahan, 2011, unpublished). Long term use of DAP has damaging environmental effects, polluting ground water, causing eutrophication and increasing greenhouse gases (Olfs et al., 2005) though these repercussions have been said to not be relevant in Sub Saharan context given the small amount of the fertilizer used (Vanlauwe et al., 2006).

Nitrogen is the most limiting soil nutrient for most crops in Africa being lost though volatilization, erosion, leaching and crop harvesting (Olfs et al., 2005). Crops take in Nitrogen in large amounts, reducing their growth and productivity when inadequate (Oz, 2008). Legumes fix their own nitrogen through their association with the rhizobia. For the fixation to happen, the soils have to have low nitrogen status, as the process of fixation is a high energy- utilizing endeavor to the crop, which would rather utilize existing N in the soil than from N fixation.

2.4.5 Triple Super Phosphate (TSP)

Triple Super Phosphate (TSP), a derivative of phosphate rock prepared by reacting the apatite with concentrated phosphoric acid, has a high P analysis (containing 46% P_2O_5). The P in TSP is readily available for plant use due to its high solubility than other sources (Sahrawat et al., 2001). However, it is very expensive making its use for small-scale farmers limited (Mutsotso et al., 2011). Its high solubility makes it easily fixed by clays and thus unavailable. During erosion, this P resource easily drains in solution (Richardson et al., 2009). In Kenya, it is also not widely available as a source of P comparable to DAP.

The world market of TSP paints a gloomy picture over its sustainable availability in the future given the dwindling reserves of its main source, PR (Cordell et al., 2009, Craswell et al., 2010). Production of TSP also requires a significant supply of energy and so contributes to CO_2 emission through use of fossil fuel in the excavation process and transportion to the processing sites, processing rock phosphate and preparation of phosphoric acid, which is a key raw material of TSP production (Cordell et al., 2009).

2.4.6 Fortified Manure

Despite the benefits of manure, its quality and quantity is not sufficient to replenish the depleted nutrients in the soils (Place et al., 2003). For efficient nutrient utilization, inorganic fertilizers must be incorporated with organic ones while considering other strategies like soil conservation, conservation agriculture, and good agronomic practices (Vanlauwe et al., 2002; Place et al., 2003). However, because inorganic fertilizers are expensive, use of the promising PR-manure mix need to be tried (Sanginga and Woomer, $2009_{a,b}$). Phosphate rock is effective if reacted with organic acid (Van Straaten, 2006). The release rate of P from PR is enhanced with addition of manure to Minjingu rock phosphate as has been reviewed earlier.

The combination also increases the rhizosphere microbial population, which further breaks down the PR and enhance favorable conditions for root uptake of other minerals. Any organic source of P that has an analysis of less than 2.0 g kg^{-1} will induce P immobilization with ferralsols fixing P for those sources with content less than 3.0 g kg^{-1} (Leu, 2009). Phosphorus content of organic residues on its own is insufficient to predict release pattern and ensuing effects on P availability (Nzinguheba et al., 2002). Use of Minjingu had limited population of *Fusarium spp*. in a study in Embu and Taita districts of Kenya (Okoth and Siamento, 2011).

2.5 The role of Starter Nitrogen in BNF

The amount of N affects N fixation, too much N reduces N fixation while too low N or none will reduce the fixation (Tinsley, 2009). When the crop demand for N is lower than the available soil N, BNF drastically reduces but when crop demand is higher than the soil can provide, the BNF is enhanced and maximized (George and Singleton, 1992). BNF however, hardly meets plant requirements during early vegetative growth therefore the need for initial N (George and Singleton, 1992; Schmitt et al., 2001). Studies indicate that using N fertilizers at planting greatly reduce nematodes population by increasing nematode destroying fungi (Wachira et al., 2011) thus improving the vigor and growth of soybean (Melakeberhan, 2007).

The role of starter N on leguminous crops is inconclusive with various authors giving conflicting conclusions regarding it (Finke et al., 1982; Barker and Sawyer, 2005). It is still not clear to what extent the starter N can increase the N fixation efficiency (Finke et al., 1982; Mendes et al., 2003) and the yield of soybean (Gan et al., 2002) or if it is indeed necessary (Barker and Sawyer, 2005). When thought necessary, the amount used for soybean crop has been varied, ranging from 25 kg/ha to 50 kg/ha (Yinbo et al., 1997; Kubota et al., 2008; Albareda et al., 2009). Heitholt et al. (2007) recommend more study on soil fertility interaction with soybean growth. They also recommend further studies on N balance and testing of the starter N on different environments to understand its response on soybean yield.

The amount of starter N applied on soybean differs. Farmers in USA, for example, apply 5-12 kg ha^{-1} while those in Brazil apply 8 kg ha^{-1} (Melakeberhan, 2007). Use of starter N enhances N balance by increasing initial photosynthesis (Oz, 2008), increasing CO_2 assimilation and thereby enhancing BNF. The BNF adds N to plant, which later becomes available in the soil if incorporated. Nitrogen fixation is expensive for plants thus the need to apply N especially for young plants which have to apportion much of their photosynthates to roots and nodules (Barker and Sawyer, 2005).

Heitholt et al. (2007) reported no response to application of various treatment rates of starter N from mineral fertilizer and animal manure. Results of Heitholt et al. (2007) further suggested that the use of mineral fertilizer starter nitrogen has different response than use of organic source of starter nitrogen. In that study, there was no response to application of dairy manure compost (DMC) while mineral fertilizer had some response.

Researchers have used CAN and Urea interchangeably as sources of N (Bationo et al., 1992). However, CAN is more neutral than urea in soil acidification and is widely available and used by farmers than urea. The CAN is also cheaper than urea in the Kenyan market (Yamano and Arai, 2010). Urea on the other hand is not easily leached as CAN and can provide N over a longer period than CAN. The mechanisms of utilization of N from urea by crops are also more complicated than CAN. Urea has to be converted to NH^{4+} through enzymatic reaction of urease a reaction that requires energy.

2.6 Management factors affecting nodulation and BNF

The management factors affecting nodulation and BNF include the cultural practices that will provide conditions necessary or those limiting both the abiotic and abiotic factors. They include inoculation of effective rhizobia (Fatima et al., 2007) which enhances the nodulation chances due to large populations of bacteria available to infect root hairs, tillage, which increase aeration and thus improve the effectiveness of bacteriods as well as necessitate root uptake of nutrients for photosynthesis, and application of pesticides. Marenco et al. (1993) showed that application of pesticides had effect on BNF depending on the type and amount applied. In their study, Marenco et al. (1993) showed that application of Trifluralin increased the number and weight of nodules while application of Chlorimuron reduced both the number and weight of the nodules. Increased use of Trifluralin, however reduced the two parameters. The same study showed that, use of Clomazone did not affect weight of nodules but increased their numbers (indicating increased BNF) while high dosage of all the herbicides reduced the BNF fixation.

2.7 Soybean use and Economics of production

Soybean has wide industrial use, which is of economic value in spurning cottage and industrial functions. For example, soybean oil finds wider application in the manufacture of soaps, glycerine, printing inks, greases, lubricants, water proofing materials, oilcloth, linoleum, putty, resins, insecticides and disinfectants (Tao, 1994;

Endres, 2001). Soya lecithin is an important product of oil industry used in food industries, cosmetics, pharmaceuticals, paint and plastic industries and in detergents (Tao, 1994). The crop is widely used in the production of antibiotics and adhesives (Endres, 2001). Soybean importance is widely felt in the feed production and vegetable oil industry where its value worldwide is in the tune of US $200 billion per year (FAO, 2012).

Production of soybean in Kenya has been hampered by its farm-gate price, fetching around Ksh. 50 (0.60 US$) per kg compared to Ksh 80 (0.93 US$) per kg for common beans (Tinsley, 2009). For a farmer to benefit there is need for value addition. By adding value to soybean, prices have been shown to increase to Ksh. 150 (US$ 1.8) per kg when converted to soybean products (Vandeplas et al., 2010). In addition, processing and trading of the crop is providing many employment opportunities, spurning a cottage industry in the rural areas (Tinsley, 2009; Rakasi, 2011).

Summary of the literature review and identified gaps

The literature reviewed has shown that soybean has huge economic, nutritional and industrial opportunities for Kenya, providing an impetus for increased production in regions of the country that have a high potential for its production. The central highlands of Kenya, where this study concentrates on, are some of the high potential areas for soybean production in the country. The main limitation in soybean production in the study area is soil fertility decline of which P limitation is the most critical due to the P fixing nature of the soils in the study area. Use of phosphate rock is a possible alternative P source but its effectiveness is limited by factors such as mineralogy and chemistry of PR, reactivity/solubility of PR, grain size and surface area. Other factors include chemical and physical status of the soil especially pH, moisture holding capacity, P and Ca status, and P-fixing capacity of the soil, type of crops and their nutrient requirements, management practices including method and time of application, and liming.

Few studies have assessed the locally available P sources in regard to their contribution to soil characteristics while addressing their cost effectiveness to soybean production in central highlands of Kenya. This study therefore bridges this literature gap by assessing both mineral and organic P sources' contributions to soil chemical characteristics and soybean yield while estimating their effect on soybean biological N fixation. The study goes further to identify the least costly P sources in soybean production in view of recommending them to farmers in the study area and similar areas. The study also tries to assess the relevance of using starter N for improved biological fixation and higher soybean yields in the study area.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Study Sites

The study was conducted at Kigogo Primary School (00^0 23' 08.6''S, 37^0 38' 0.3" E) in Magumoni Division, Meru South district, Tharaka Nithi county and Kamujine site (00^0 06'19.4"N, 037^0 54' 49.7''E) in Mikinduri Division, Tigania East district, Meru County, in the Central Highlands of Kenya (Figure 3.1), respectively. Magumoni Division is in Upper Midland 2 and 3 (UM 2 -UM 3) agro ecological zones having an altitude of about 1432 m a.s.l with annual temperature of about 20^0 C and annual rainfall of 1200-1500 mm (Jaetzold et al., 2006). The rainfall is bimodal with two seasons; long rains (LR) in March through to June and Short Rains (SR) from October through to January. Over 65% of the rains occur in the LR season (Jaetzold et al., 2006).The soils of Kigogo site are humic Nitisols (Jaetzold et al., 2006). Farmer practice small-scale mixed farming with main cash crops being coffee, tea and horticultural crops. Food crops grown include maize (*Zea mays*), banana (*Musa spp*. L. e.g. *paradisiaca*.) and Irish potatoes (*Solanum tuberosum*).

Mikinduri Division is in Lower Midlands 3 (LM 3) and Upper Midland 3 (UM 3) agro ecological zone with average rainfall of 1175 mm yr^{-1} (Jaetzold et al., 2006) having an altitude 1231 m a.s.l. Agriculture practice is mixed farming with main cash crops being *Catha edulis* (Khat) and horticultural crops. Food crops grown include maize, banana and Irish potato. Farmer also practice livestock production with goat and cattle rearing being key. Soils in Mikinduri are eutric Nitisols with humic Cambisols (Jaetzold et al., 2006).

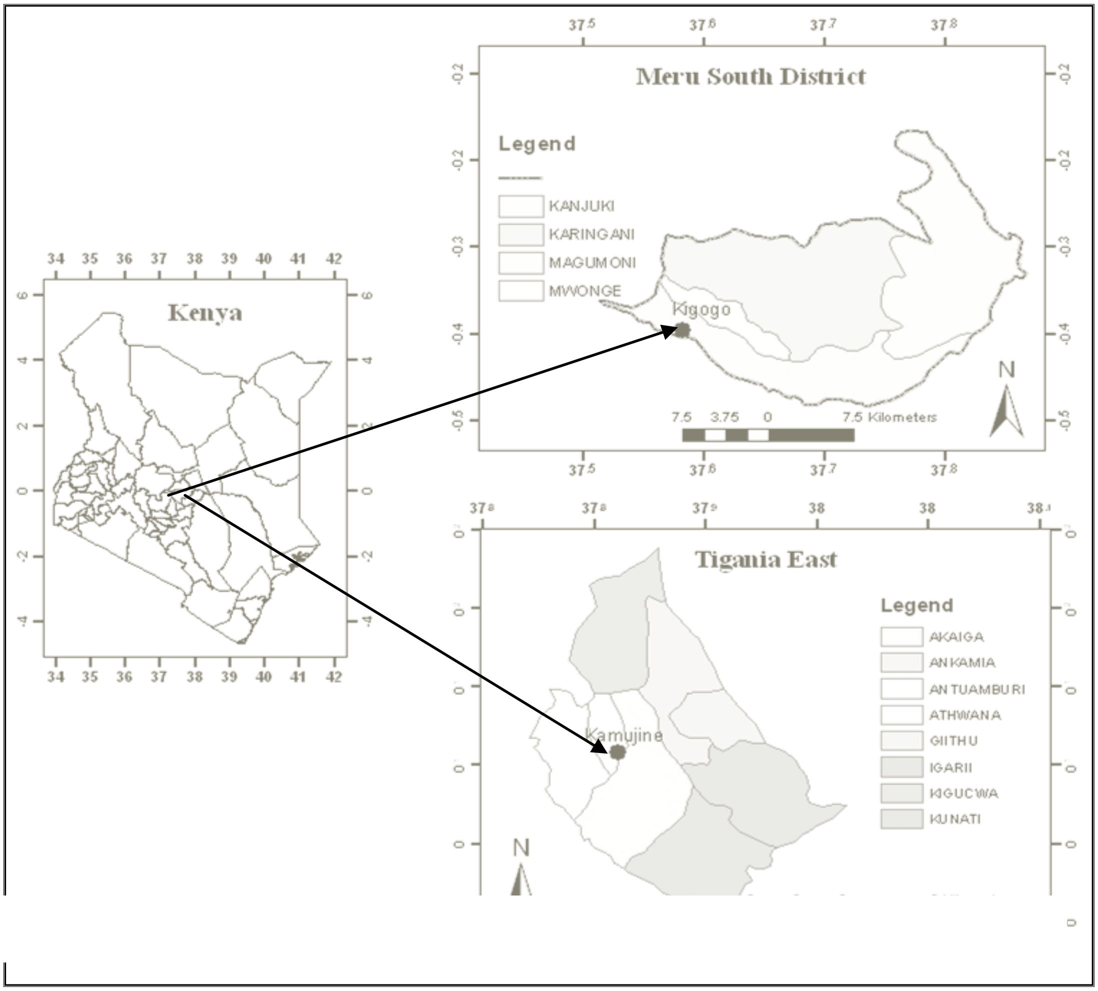

Figure 3.1: Map of the research study area

During soybean growth, the long rains season (March 2011-September 2011) and short rains season (October 2011-Feb 2012) in Kigogo recorded 635 mm and 639 mm of rainfall, respectively (Figure 3.2). In Kamujine site, LR and SR seasons had 866.62 mm and 785.35 mm of rainfall, respectively for soybean growth (Figure 3.2)

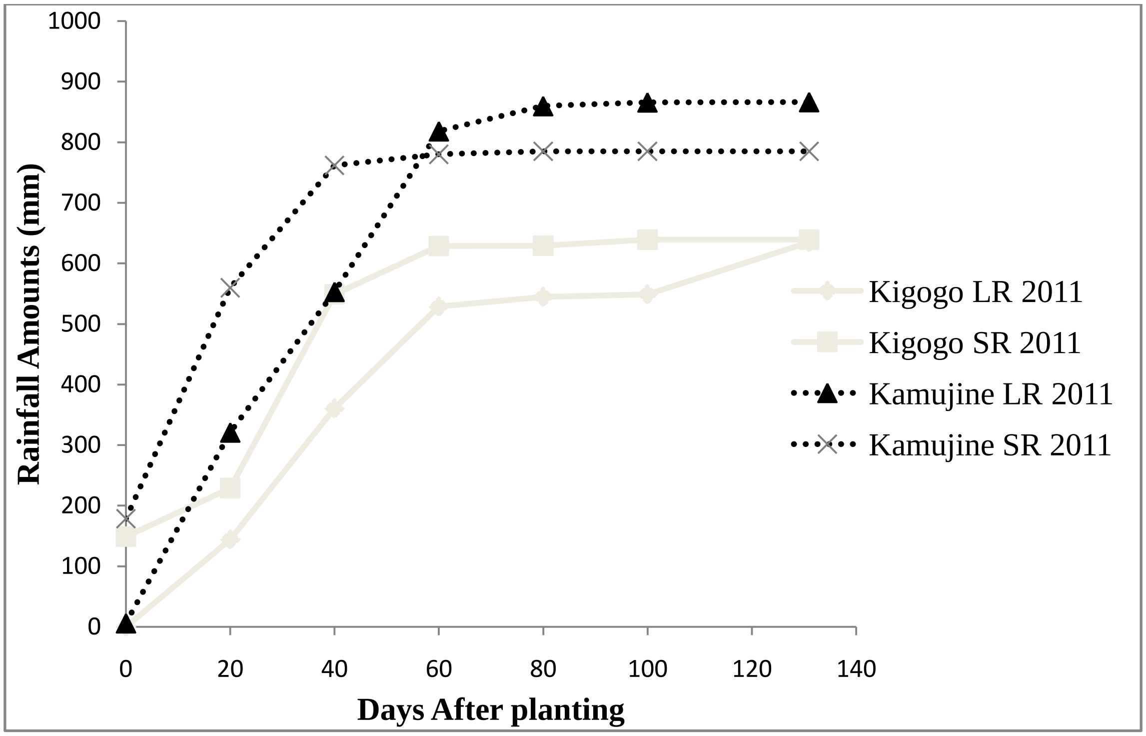

Figure 3.2: Rainfall distribution over the experiment period in Kamujine and Kigogo sites

3.2 Study Design

The experiment was arranged in randomized complete block design. Treatments were replicated four times in plots measuring 4.0 m x 4.5 m, with a net plot area of 10.5 m^2. The treatments were a combination of P sources with or without starter nitrogen totaling to 13 treatments, including control. Sources of P were Minjingu phosphate rock, Mavuno basal fertilizer, TSP, DAP fertilizer, manure only and fortified manure (manure + Minjingu phosphate fertilizer) each providing 30 kg ha^{-1}. The manure used was a mixture of goat and cattle manure. Calcium Ammonium Nitrate (CAN) was the source of starter nitrogen. With DAP as a P source containing a substantial amounts of N (18%), it did not receive starter N. For this study, the amount of 10 kg per ha was identified to be adequate as a starter N to effectively meet the requirement of the soybean crop at its initial stages before BNF can commence. This amount was chosen following leads by Chen et al. (1992) and Starling et al. (1998) and the studies of Albareda et al. (2009) who had used 50 kg per ha and found that this amount reduced biological nitrogen fixation. On the other hand, Anon (2004) in Melekeberhan (2007) found that farmers in Brazil applied 8 kg ha^{-1} with crops improving BNF fixation.

Charcoal-based culture of *Bradyhizobium japonicum* USDA 110C, licensed by University of Nairobi and produced by MEA Ltd branded BIOFIX®, was inoculated in soybean seeds in all the treatments. The soybean variety used was Gazelle, being a popular variety in the study area. It was also easily accessible and available, being a better variety for growing a sole crop (Wandahwa et al., 2006). The spacing was 50 cm and 5cm for inter- and intra- row repectively, giving a population of 360 plants per plot that translated to total plant population of 400,000 plants per hectare. To increase the chances of germination, two seeds per 5 cm were drilled and later thinned or replanted where there was good and poor germination respectively. The plots were gapped two weeks after planting to maintain the required plant population. Weeding was done twice, first after two weeks and second at six weeks after planting. Spraying of pesticide was done as per occurrence of pest while maintaining economic threshold for pesticide application.

3.2.1 Sampling and Laboratory analyses methods

Soils were sampled at 0-20 cm depth using Elderman auger. Six sub-samples per plot were taken across the plot using a diagonal pattern. They were mixed to give a composite sample per plot and were analyzed following the methods described by Ryan et al. (2001). These included; soil texture by hydrometer method; pH water (1:1, soil: water) using pH meter; Cation Exchange Capacity (CEC) by NH_4 acetate leaching; Total N by Kjeldahl method; P by Mehlich 3 method; K by flame photometer and organic carbon determination by Walkley and Black method (1934).

A destructive systematic random sampling of soybean was carried out for determination of dry matter and N concentration in plant tissues and for assessing nodulation. Six plants per plot were selected by considering only second to ninth row in each plot, avoiding first and tenth row while also leaving alternate row and picking one plant per row every 50 cm. The reference crop was a soybean isoline variety EAI 3600 sourced from TSBF-CIAT Maseno. Soybean isoline was chosen as a reference crop as it best simulates the physiological requirements of soybean test crop and so useful for estimating soil nitrogen used in the test crop as compared to other reference crops. Plant materials were oven dried at 60 ^{0}C for 48 hours and ground to pass through 1.0.mm sieve. Materials were subjected to Kjedahl digestion with concentrated sulphuric acid to determine total N as described by Okalebo et al. (2002). Nitrogen uptake by the soybean crop was determined by multiplying the dry matter yields (kg) with the nitrogen concentration (%).

3.2.2 Data collection

Objective 1: To determine the effects of different sources of phosphorus on yield of soybean and selected chemical properties of soil

Variables measured included; Dates for all operations (sampling, tillage, fertilizer applications, planting, weeding, and harvesting) as well as physiological stages such as germination rate and podding rate were collected. Other variables collected included total biomass at harvest (Mg/ha), grain yield (Mg/ha) and final plant population (plants/m^2). Soil samples were collected before start and at end of experiment as described above and taken to laboratory for soil analysis.

Objective 2: To evaluate the effects of different sources of phosphorus and starter N on number of nodules and growth parameters of soybean

Variables measured included the number of nodules per plant and nodule coloration. Data was collected from six plants 50 days after planting in a selection described earlier. Plants were carefully uprooted after wetting the root zone just enough to avoid water saturation while ensuring no nodule is sloughed off during the uprooting. The nodules were cut into halfs and their interior nodule colors used to identify BNF activity. The colors were either white, black, green, brown, pink or red; the first three indicated the nodules were inactive while the later three showed BNF was taking place in them. Soybean growth parameters were collected two weeks after assessing nodulation and data collected was leaf numbers, pod numbers and plant height in six plants per plot randomly selected as described earlier. Number of leaves and pods were counted for each of the individual plants while their heights were measured using a ruler.

Objective 3: To assess the effects of different sources of phosphorus and starter N on amount of N fixed by soybean and their economic suitability

Nitrogen estimation was done using N- difference method (Herridge et al., 1990; Unicovich and Pate, 2000) at 50% flowering stage by having collected plant samples analyzed for total nitrogen at reproductive stage 1 together with a non-nodulating isoline soybean grown at same site. Total nitrogen differences between treated soybean and Isoline soybean was attributed to atmospheric nitrogen fixed by the rhizobia. Nitrogen difference method is the cheapest of all the available BNF measurement methods (Peoples et al., 2002) being used in many studies for estimating BNF (e.g, Isreal and Button, 1997; Israel and Mikkelsen, 2001; Dashti et al., 2008).

To assess the profitability of the various P sources, value-cost analysis (VCR) was performed and rated against the benchmark of VCR ≥2 for acceptable profitability (Heerink, 2005). The VCR of the different treatments was based on the 2011 and 2012 market values. Value-Cost ratio is defined as the sales value of the extra yield produced by using fertilizer divided by the cost of that fertilizer. Normally, a VCR of at least two is considered necessary, although a VCR of this level is risky if there is a danger of drought, disease or crop prices falling. In that scenario, a higher VCR of four is considered enough to mitigate the risks. It is given by the following formula:

$$\textbf{VCR=}\left(\frac{\text{Product Price(Kg)}}{\text{Fertilizer Price(Kg Nutrient)}}\right)\textbf{*Fertilizer Response Rate i.e.}\left(\frac{\text{Kg Yield}}{\text{Kg Nutrient}}\right)$$

In calculating VCR, data regarding market prices of the P sources, the prevailing market price of soybean and yields of soybean from various P sources in kg/ha was collected. Calculation of VCR used a conservative soybean price of Ksh. 60 (US$ 0.645), which was the market price of soybean in the region at the time of study.

3.2.3 Harvesting of Soybean

Soybean grain and biomass were harvested at maturity from a net plot of 10.5 m^2 demarcated by leaving out soybean within 0.5 m of each side of the length of the plot as well as first and last rows of soybean of a plot’s width. The soybean was harvested on plot-by-plot basis as to have all soybean in a net plot packed in a labeled gunny bag for weighing and threshing. The threshed soybean was winnowed and then packed in tared paper bags for further weighing to determine the grain weight. Moisture content of the grains was determined using a moisture meter immediately after weighing. Biomass weight was derived by calculating the difference between total biomass and grain weights, respectively. Their weights were standardized to 12% moisture content.

3.3 Data analyses

The data on selected soil chemical properties, soybean nodulation, number of leaves, pod number, plant height, grain yield and biomass, and N at physiological maturity were subjected to analysis of variance (ANOVA) using PROC GLM in SAS Version 9.1 statistical Software for Windows (SAS Institute, 2009). Significantly different means were separated using Least Significant difference test (L.S.D) and t-test at P = 0.05.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 Overview

This chapter has three sections. Section 1 presents and discusses results of the effects of treatments on soybean yield and selected soil chemical properties at Kamujine and Kigogo sites. Section 2 presents and discusses results of effects of treatments on soybean nodule numbers and growth parameters. Finally, section 3 presents and discusses the effects of the treatments on amount of N fixed by soybean and their economic suitability based on their value-cost ratios.

4.2 Objective 1: To determine the effects of different sources of phosphorus on soybean yield and selected soil chemical properties

4.2.1 Effect of phosphorus sources on grain yield

Crop maturity in LR 2011 in Kigogo site took approximately 124 days against 116 days in Kamujine whereas in SR 2011 it took 131 days and 108 days in Kigogo and Kamujine, respectively. There were significant differences (p=0.0085) in yields among treatments (Table 4.1). Application of P increased yields irrespective of P source. Grain yields in Kamujine ranged from 0.54 Mg ha^{-1} (control) in SR 2011 to1.96 Mg ha^{-1} (CAN-Mavuno) in LR 2011 season (Table 4.1). In Kigogo, the yields ranged from 0.56 Mg ha^{-1} (manure) to 1.20 Mg ha^{-1} (Mavuno) (Table 4.1).

Table 4.1: Grain yield (Mg ha^{-1}) at Kamujine and Kigogo sites during the LR 2011 and SR 2011 seasons

Treatments	**Average grain Yield (Mg ha^{-1})**			
	LR 2011		**SR 2011**	
	Kamujine	**Kigogo**	**Kamujine**	**Kigogo**
CAN_Manure	1.18bc	1.01ab	1.24abc	0.94ab
TSP	1.10bc	0.96ab	0.86cd	0.61de
CAN_TSP	1.14bc	1.0ab	0.96bcd	0.79bcd
CAN	0.97bc	0.88ab	0.93bcd	0.82ab
Manure	1.27abc	1.16ab	1.22abc	0.56e
CAN_Fortified	1.33abc	0.95ab	1.46a	0.84ab
CAN_Mavuno	1.96a	1.12ab	1.07abc	0.90ab
Minjingu	1.05bc	0.92ab	1.16abc	0.80bcd
Fortified	1.20bc	0.99ab	1.18abc	0.78bcd
CAN_Minjingu	1.45ab	1.13ab	1.11abc	1.08a
Control_N0_P0	0.71c	0.70b	0.54d	0.69cde
DAP	1.21bc	0.71b	1.34ab	0.69cde
Mavuno	1.11bc	1.20a	1.04abc	0.90ab
LSD (α=0.05)	**0.704**	**0.473**	**0.447**	**0.1987**

Means with the same letter down the column are not significantly different.

During the LR 2011 in Kamujine, CAN-Mavuno treatment had significantly ($p<0.001$) higher grain yields than other treatments except from animal manure, CAN-fortified and CAN-Minjingu treatments. Grain yield from CAN-Minjingu and CAN mavuno treatments were significantly ($p<0.001$) higher than the control. Grain yield from Mavuno treatment at Kigogo site was significantly ($p<0.001$) higher than those from DAP and control. During the SR 2011 season CAN-Manure treatment in Kamujine gave significantly ($p<0.001$) higher yield than control. Grain yield from CAN-fortified manure treatment was significantly ($p<0.001$) higher than those from TSP, CAN-TSP, CAN and control treatments (Table 4.1). At Kigogo site, manure treatment gave significantly ($p<0.001$) less soybean grains than all other treatments except DAP, TSP and control. Yield from CAN-Minjingu in the same site was significantly ($p<0.001$) higher than all the other treatments except CAN-manure, CAN, CAN-fortified manure and CAN-Manure treatments.Yields in LR 2011 season were significantly ($p<0.001$) higher than those during SR 2011. Grain yields in Kamujine were significantly higher ($p<0.05$) than those in Kigogo in both seasons.

Mavuno fertilizer having more micronutrients than other fertilizers may explain the superior performance of CAN-Mavuno. World Bank (2006) reported Mavuno to contain over 10 micronutrients. The three treatments, CAN-Mavuno, CAN-Minjingu and manure may have improved soil pH enhancing availability of fixed nutrients (Maene 2001; Vance et al., 2003) while still supplying multiple nutrients (Okoth and Siameto, 2010). A significantly higher yield in CAN-Minjingu than control may have been because of CAN-Minjingu's liming effect (Reyes, 2008; Okalebo et al., 2007, Weil, 2000) and nutrient supply (Weil, 2000; Rotaru, 2010). Micronutrients in Mavuno such as molybdenum, Cu and Zinc, may have contributed to the better grain yield compared to DAP that does not have such (World Bank, 2006). Given high initial soil N in Kigogo compared to Kamujine, the results of Mavuno in Kigogo were similar to CAN-Mavuno yield in Kamujine, with CAN in Kamujine taking a similar role as soil N in Kigogo. Therefore, Mavuno was superior in both sites. Manure may have contributed in providing favorable environment for rhizobial multiplication, liming effect, micronutrients provision for plant uptake and increased soil physical properties, which improved soybean uptake of these nutrients (Mutsotso et al., 2011). The manure may have also acted as buffer for nutrients uptake for entire growing period compared to TSP, CAN-TSP, CAN and control treatments (Waluyo et al., 2004). Using manure also alleviates Al^{3+} toxicity thereby improving availability of nutrients like P (Vance et al, 2003; Okoth and Siameto, 2010).

4.2.2 Effect of phosphorus sources on biomass yield

During LR 2011 at Kamujine site, CAN-fortified had the highest biomass yield being significantly ($p<0.001$) higher than TSP, CAN-TSP and control treatments (Table 4.2). Biomass yield in CAN-manure treatment was significantly higher ($p<0.001$) than those in TSP, CAN-TSP and control (Table 4.2). Biomass yield from CAN-Mavuno treatment in Kogogo was significantly higher ($p<0.01$) than those from CAN, manure, Minjingu PR and control. Biomass yield from DAP treatment was significantly higher ($p<0.001$) than in control, Minjingu PR, CAN and manure (Table 4.2).

During the SR 2011, DAP in Kamujine had significantly ($p<0.001$) higher biomass yield than manure. Biomass yield from CAN-fortified manure in Kigogo was significantly ($p<0.001$) higher when compared to those from CAN-TSP, CAN, manure, Minjingu PR, CAN-Minjingu and Mavuno treatments, respectively. Kamujine had higher biomass yields compared to Kigogo with LR 2011 performance in biomass yield being significantly ($p<0.001$) better than the SR 2011, a trend similar to that seen for the grain yields.

Table 4.2: Treatment effects on biomass yield (Mg ha^{-1}) at Kamujine and Kigogo sites in both LR 2011 and SR2011 seasons

Treatments	**Average biomass Yield (Mg ha^{-1})**			
	LR 2011		SR 2011	
	Kamujine	Kigogo	Kamujine	Kigogo
CAN_Manure	4.36a	1.94abcd	2.26ab	2.34abc
TSP	2.36c	2.17abc	2.90ab	2.74ab
CAN_TSP	2.86bc	2.00abcd	2.60ab	1.06bc
CAN	3.10abc	1.60cd	2.70ab	1.28bc
Manure	4.12ab	1.68bcd	1.74b	0.56c
CAN_Fortified	4.55a	1.88abcd	1.85ab	3.40a
CAN_Mavuno	4.12ab	2.69a	2.84ab	2.16abc
Minjingu	3.23abc	1.21cd	2.18ab	1.18bc
Fortified	3.60abc	1.80abcd	2.53ab	1.79abc
CAN_Minjingu	3.70abc	2.16abc	1.88ab	0.95bc
Control_N0_P0	2.56c	1.15d	2.28ab	1.83abc
DAP	4.15ab	2.72a	2.94a	2.75ab
Mavuno	3.81abc	2.59ab	1.98ab	0.83bc
LSD (α=0.05)	**1.47**	**0.98**	**1.18**	**1.96**

Means with the same letter down the column are not significantly different.

The better performance of CAN-mavuno against CAN, Minjingu PR and control may be attributed to its contribution of other nutrients other than N, which is contained in CAN-Mavuno (World Bank, 2006) and the slow release of P in the Minjingu PR and manure. Rock phosphate is a slow releaser of P and Ca (Vlek et al., 1997, Schachtman et al., 1998). Biomass increases exponentially at vegetative stages where plants require optimum availability of P and N (Barker and Pilbeam, 2007). These nutrients may not have been availed at the appropriate time for biomass accumulation. Together with DAP treatment CAN- Mavuno could have delivered P faster for the crop than manure and Minjingu PR. Minjingu lacked N and manure may have had its slow release.

The superior yield in CAN- fortified manure compared to TSP, CAN TSP and control may be due to liming effect of Minjingu PR and manure in the treatment making P available for biomass formation (Okalebo et al, 2007; Okoth and Siameto, 2011). The TSP and CAN-TSP treatments had available P, which may have been fixed and so unavailable for biomass growth. Manure, may have had a buffering effect on P and micronutrients ensuring biomass growth. Given the relatively low amount of soil N in Kamujine, provision of DAP ensured higher vegetative growth and thus higher biomass accumulation. It may be noted that DAP had a higher N content than CAN at 18% compared to the 10% in CAN.

In the SR 2011, DAP performed better than manure probably because of its high content of available N and P in the DAP for maximum vegetative growth than was in slow releasing manure. Crops under CAN-fortified manure treatment could have had nutrients available throughout the growing season and less susceptible to erosion compared to Minjingu PR, CAN-Minjingu combination and Mavuno which lack organic matter (Karami et al., 2012). Manure alone may have provided requisite N for soybean vegetative growth slowly as compared to with CAN-fortified manure, which may have delivered its N faster because of the starter N (Gentile et al, 2011).

4.2.3 Effect of Starter nitrogen on soybean grain and biomass yield

During LR 2011 season in both sites, there were no significant differences in grain yields in treatments with starter N than those without (Table 4.3).

Table 4.3 Soybean grain yield performance with and without N source at Kamujine and Kigogo sites during LR 2011 season

Treatments	Kamujine Grain Yield (Mg ha-1)			Kigogo Grain Yield (Mg ha-1)		
	With N source	Without N source	**p Value**	With N source	Without N source	**p Value**
Control	0.97	0.71	0.10	0.88	0.70	0.39
Fortified	1.33	1.20	0.72	0.95	0.99	0.89
Manure	1.18	1.27	0.83	1.01	1.16	0.28
Mavuno	1.96	1.11	0.09	1.12	1.20	0.79
Minjingu	1.45	1.05	0.27	1.13	0.92	0.49
TSP	1.14	1.10	0.91	1.00	0.96	0.74

During the SR 2011 season, CAN had significantly (p=0.01) higher grain yield than control in Kamujine with CAN-Minjingu having significantly (p=0.01) higher yield than Minjingu in Kigogo (Table 4.4).

Table 4.4 Soybean grain yield performance with and without N source at Kamujine and Kigogo sites during SR 2011 season

Treatments	Kamujine Grain Yield (Mg ha-1)			Kigogo Grain Yield(Mg ha-1)		
	With N source	Without N source	**p Value**	With N source	Without N source	**p Value**
Control	0.93	0.54	0.01	0.82	0.69	0.06
Fortified	1.46	1.18	0.13	0.84	0.78	0.46
Manure	1.24	1.22	0.97	0.94	0.56	0.07
Mavuno	1.07	1.04	0.91	0.90	0.90	0.91
Minjingu	1.11	1.16	0.83	1.08	0.80	0.01
TSP	0.96	0.86	0.70	0.79	0.61	0.30

Results during LR 2011 season as shown in Table 4.3 agree with those of Wood et al. (1993) and Albareda et al. (2009) that did not find any significant grain yield with starter N use. In LR season, the baseline soil N may have been sufficient for grain production in both sites (Table 4.7). During SR 2011 season however, the significant differences in grain yields from control compared to CAN treatment in Kamujine and CAN-Minjingu compared to Minjingu alone can be attributed to depleted soil N, having been utilized by LR 2011 crop. Both control and Minjingu treatments may therefore have required external N source for grain production.

In Kamujine, CAN had significantly (p=0.02) higher biomass yield than control while CAN-TSP also had significantly (p=0.03) higher biomass yield than TSP alone (Table 4.5). In Kigogo, CAN-Manure and CAN-Minjingu had significantly (p=0.04, p=0.03) higher biomass yield than Manure and Minjingu respectively.

Table 4 5 Soybean biomass yield performance with and without N source at Kamujine and Kigogo sites during the LR season

Treatments	**Kamujine Biomass Yield(Mg ha-1)**			**Kigogo Biomass Yield (Mg ha-1)**		
	With N source	Without N source	**p Value**	With N source	Without N source	**p Value**
Control	3.10	2.56	0.02	1.60	1.15	0.72
Fortified	4.55	3.60	0.06	1.88	1.80	0.58
Manure	4.36	4.12	0.08	1.94	1.68	0.04
Mavuno	4.12	3.81	0.13	2.69	2.59	0.91
Minjingu	3.70	3.23	0.70	2.16	1.21	0.03
TSP	2.86	2.36	0.03	2.00	2.17	0.06

During SR 2011 season in Kamujine (Table 4.6), biomass yield from CAN- Minjingu, CAN-Mavuno and CAN-TSP were the only treatments that were not significantly different with starter N than without at p=0.09, 0.31 and 0.42 respectively. In Kigogo however, all the treatments with starter N were significantly different from those without (Table 4.6).

Table 4.6 Soybean biomass yield performance with and without N source at Kamujine and Kigogo sites during the SR season

Treatments	Kamujine Biomass Yield(Mg ha-1)			Kigogo Biomass Yield(Mg ha-1)		
	With N source	Without N source	**p Value**	With N source	Without N source	**p Value**
Control	2.70	2.28	0.03	1.28	1.83	0.03
Fortified	1.85	2.53	0.02	3.40	1.79	0.03
Manure	2.26	1.74	0.03	2.34	0.56	0.01
Mavuno	2.84	1.98	0.31	2.16	0.83	0.03
Minjingu	1.88	2.18	0.09	0.95	1.18	0.03
TSP	2.60	2.90	0.42	1.06	2.74	0.02

During the LR 2011 season, starter N in Control and TSP in Kamujine and manure and Minjingu PR in Kigogo may have significantly contributed to higher biomass yield due to higher demand for N by the crop for vegetative growth given the treatments had little or no N in them and so N had to be supplimented. However, Control in Kigogo may have had sufficient residual soil N for vegetative growth. Manure may have had a time lag before N mineralization thus poor vegetative growth (Richardson et al., 2009). Additional N from starter N in manure could have readily supplied N to soybean other than quickening N mineralization by improving C:N ratio for microbial breakdown (Omotayo and Chukwa, 2009; Opala, 2011).

During SR 2011 season however, the significant increase in biomass yields in all treatments with starter N in Kigogo may have been due to exhausted soil N that was replenished by an external source. These reasons explain Kamujine results as well except for Minjingu, TSP and Mavuno where addition of starter N had insignificant increase in biomass yield. It seems that the most limiting nutrient required by soybean crop from TSP treatment was probably P, which may have been fixed on soil colloids limiting further vegetative growth. Further application of N source may not have had any effect on biomass accumulation. Minjingu may not have sufficiently provided plant available P, limiting crop's vegetative growth (Richardson et al., 2009). Given the factors described in chapter two, Minjingu PR may not have adequately supplied P such that it may have been the most limiting nutrient and improved N supply may not have had significant effect on soybean biomass yield.

4.2.4 Effect of different sources of phosphorus on chemical properties of soil

There were differences in initial soil characteristics between the two study sites. Kigogo had higher Organic C%, N%, P, K, Ca, Mn, and Zinc levels than kamujine (Table 4.7). Kamujine however had higher levels of Mg, Cu, Fe and Na than Kigogo (Table 4.7).

Table4 7 Summary of Soil Characteristics in Kamujine and Kigogo at the beginning LR 2011 and the end of the experiment in SR 2011

Soil Characteristics	**Kamujine**		**Kigogo**	
	Baseline	SR 2011End	Baseline	SR 2011End
Soil pH	5.34	5.51	5.48	5.27
Org. C%	1.52	1.75	2.06	2.23
Total N%	0.17	0.18	0.23	0.22
P ppm	32.88	28.75	47.00	50.06
K Cmol$_c$ kg^{-1}	0.24	0.32	0.52	0.45
Ca Cmol$_c$ kg^{-1}	4.41	5.15	5.59	5.05
Mg Cmol$_c$ kg^{-1}	6.01	3.39	2.41	2.55
MnCmol$_c$ kg^{-1}	0.57	0.54	0.63	0.59
Cu Cmol$_c$ kg^{-1}	10.87	8.01	2.92	3.70
Fe Cmol$_c$ kg^{-1}	74.87	59.04	20.62	36.53
Zinc Cmol$_c$ kg^{-1}	9.95	8.89	15.24	13.31
Na Cmol$_c$ kg^{-1}	0.37	0.30	0.34	0.23

Changes in soil pH, organic C and macronutrients

There were no significant differences among treatments on soil pH changes in Kamujine (Table 4.8). However, all the treatments had positive soil pH changes. In absolute terms, CAN-Minjingu and fortified manure had higher improvement in soil pH than the other treatments. In Kigogo, all the treatments registered decreased pH levels except in CAN-

Minjingu, which maintained initial pH levels. The CAN-Minjingu treatment had better effect on pH compared to control. The level of organic C reduced in all the treatments in Kamujine (Table 4.8). However, CAN-Minjingu treatment had the least decrease in organic C and was significantly ($p<0.01$) higher than control. In Kigogo, all treatments had a positive effect on organic C except for control and TSP. Both TSP and control treatments had significant ($p<0.001$) decrease in organic C compared to Mavuno. In Kamujine, soils under CAN-Mavuno had significantly ($p<0.01$) higher total N than under DAP (Table 4.8). In absolute terms, control, DAP, fortified manure and manure in Kamujine depleted the total N while in Kigogo, CAN-Minjingu significantly ($p<0.001$) improved total N levels in soils compared to TSP. In absolute terms, CAN-Minjingu and CAN-fortified treatments were the only fertilizers that improved total N levels in Kigogo soils.

Table 4.8: Changes in selected soil chemical properties and nutrients at Kamujine and Kigogo sites at the end of the experiment (SR 2011)

Treatment	**Soil pH**		**Total N $Cmol_c.Kg^{-1}$**		**Organic C%**		**P ppm**		**K $Cmol_c.Kg^{-1}$**		**Ca $Cmol_c.Kg^{-1}$**	
	Kam	Kig	Kam	Kig	Kam	Kig	Kam	Kig	Kam	Kig	Kam	Kig
CAN	0.2a	-0.2ab	-0.01ab	-0.01ab	-0.2ab	0.2ab	-7.3bc	11.8a	0.0cd	0.1ab	0.1ab	-1.5ab
CAN_Fortified	0.2a	-0.3ab	0.01ab	0.003ab	-0.3ab	0.2ab	7.0a	13.5a	0.0bcd	-0.1abc	-0.1abc	-1ab
CAN_Manure	0.2a	-0.3ab	0.01ab	-0.003ab	-0.3ab	0.4ab	-6.0bc	4.8ab	0.2ab	-0.1abc	-0.1abc	-0.6ab
CAN_Mavuno	0.1a	-0.2ab	0.03a	-0.025ab	-0.2ab	0.1ab	1.0ab	1.5ab	0.1abcd	-0.1abc	-0.1abc	-0.7ab
CAN_Minjingu	0.3a	0.0a	0.01ab	0.01a	0.0a	0.4ab	-4.3abc	12.3a	0.2a	0.2a	0.2a	0.8a
CAN_TSP	0.2a	-0.2ab	0.03ab	-0.01ab	-0.2ab	0.1ab	-12.8c	9.8ab	0.1abcd	-0.1abc	-0.1abc	-0.8ab
Control	0.2a	-0.3b	-0.01ab	-0.04ab	-0.3b	-0.1b	-8.5bc	-20.8b	0.0cd	-0.3bc	-0.3bc	-2.2b
DAP	0.2a	-0.1ab	-0.01b	-0.02ab	-0.1ab	0.1ab	-3abc	-0.8ab	0.1abc	-0.2abc	-0.2abc	-1.3ab
Fortified	0.3a	-0.1ab	-0.003ab	-0.01ab	-0.1ab	0.0ab	-3.3abc	7.5ab	0.1abcd	0.2a	0.2a	0.1ab
Manure	0.1a	-0.3ab	-0.003ab	-0.01ab	-0.3ab	0.2ab	-2.5abc	-1.3ab	0.1bcd	0.0ab	0.0ab	-0.2ab
Mavuno	0.2a	-0.3ab	0ab	-0.01ab	-0.3ab	0.6a	-4.8bc	11.8a	0.0cd	0.0abc	0.0abc	-0.2ab
Minjingu	0.1a	-0.2ab	0.003ab	-0.03ab	-0.2ab	0.2ab	-3.8abc	-9.8ab	-0.1d	-0.1abc	-0.1abc	1.0a
TSP	0.1a	-0.3ab	0.01ab	-0.04b	-0.3ab	-0.1b	-8.3bc	-9.8ab	0.1abcd	-0.5c	-0.4c	-0.8ab
LSD	0.21	0.29	0.04	0.05	0.40	0.57	11.41	36.39	0.17	0.48	1.81	2.92

NB/ Results presented at one decimal place where appropriate, Kam denotes Kamujine while Kig denotes Kigogo site respectively. Means with the same letter down the column are not significantly different.

Only CAN-Mavuno and CAN-fortified manure improved available P levels in Kamujine (Table 4.8). Available P levels reduced most (36%) in soils under CAN-TSP. Significant ($p<0.001$) improvement in the P levels was in CAN-fortified compared to CAN, CAN-manure and CAN-TSP, TSP and control. In Kigogo, only control, DAP, Manure, Minjingu PR and TSP reduced P levels. In absolute terms, CAN-Fortified treatment had the highest available P increase (28%) while control had the highest decrease (30%). There was significant ($p<0.001$) increase in available P for CAN, CAN- fortified manure, CAN-Minjingu PR and Mavuno treatments compared to control. In Kamujine, soils under CAN-Minjingu treatment had significantly ($p<0.001$) higher K improvement than CAN, CAN-fortified manure, control, manure, Mavuno and Minjingu PR treatments (Table 4.8). In Kigogo, CAN-Minjingu PR treatments had significantly ($p<0.001$) higher K changes compared to Control and TSP-treated soils. Manure and fortified manure treatments also showed a significant ($p=0.001$) improvement of K levels than TSP.

In Kamujine, there were significantly higher Ca changes in CAN-Minjingu treatment compared to TSP (Table 4.8). In Kigogo, only CAN-Minjingu PR, fortified manure and Minjingu PR treatments improved Ca levels. However, the change was not significant except for CAN-Minjingu, which had significantly higher levels compared to control.

All treatments showing significant increase levels in soil Ca contained Minjingu, which has dolomite (Reyes, 2008) that may have improved soil Ca levels. All treatments in Kamujine reduced Mg levels (Table 4.9). The TSP treatment had the least amount of change in Mg and had significantly less decrease than under CAN-TSP and CAN-

Manure. In Kigogo, only DAP, TSP and control gave a decrease in soil Mg levels. Soils that had been applied CAN-Minjingu combination had the most increase in Mg having a significantly higher Mg levels than those under control and TSP with a change of 0.7 Mg $Cmol_c Kg^{-1}$.

The improvement in soil pH in Kamujine, though not statistically significant, may have been due to application of P sources and planting of soybean, which is a heavy user of Fe and absorbed NH_3^+ ions, a situation that may have necessitated chemical dynamics, which improved base saturation, which in turn improved CEC (Tisdale, 1993). The organic P sources may have bound Fe^{2+} and Al^{3+} ions and therefore slightly improved soil pH (Karami et al., 2012; Nyongesa et al., 2009). The increase in soil pH with CAN-Minjingu and fortified manure agree with results of Nekesa at al. (2005) where Minjingu PR increased pH to more than 5.5 from pH 5.01. The change could be due to the treatments' liming effect. The two resources contain dolomite (World Bank, 2006), a liming material, while manure may have compounded Al^{3+} and hence reducing acidity (FAO, 2004; Nyongesa et al., 2009).

The higher total N in CAN-mavuno compared to DAP could have been due to addition of CAN, which may have improved total N than DAP. Mavuno fertilizer itself is a blend of imported DAP with locally made granule comprising dolomitic limestone, gypsum, Muriate of Potash and micronutrients (World Bank, 2006). The CAN-Mavuno also had considerable N fixation (Table 4.13), which may have eased crop's uptake of soil's Total N during its growth.

Organic matter is a very important soil chemical characteristic in soil productivity (Vlek et al., 1997). Organic C correlates with organic matter. Reduction in organic C reflects the decrease in organic matter and therefore depletion of soil N reserves (Karami et al., 2012). Reduction in soil organic matter may be due to their mineralization. Organic C is important in sustaining soil microbes as it provides energy nessesary for various activities. The general decline in soil organic C was expected due to climate in the tropics that encompasses high temperature and humidity, factors that encourage high decomposition (Six et al., 2002). Higher organic C levels in Kigogo compared to Kamujine mirror temperature differences between sites and the general soil N differences in the two sites both before and after experiment. Soybean production in Kamujine seems to have depleted organic C while replenishing it in Kigogo except for TSP and control both of which had among the poorest yields. Microbes may have mineralized the soil N in Kamujine hence reducing organic C except for CAN-Minjingu, which may have enhanced net microbial immobilization of organic C with adequate nutrition, and available N from CAN compared to control (Gentile et al. 2011). In Kigogo, The decrease in organic C in TSP and control in Kigogo may be attributed to N deficiency, which necessitated microbial use of N utilizing organic C in the processs. Kamujine is hotter than Kigogo hence higher mineralization.

The increase in available P in soils under CAN-Mavuno and CAN-fortified may have been due to N source. Increased microbial activity due to N source may have eventually availed P on their death after having immobilized it on breakdown of the treatments. Soil colloids may have fixed P in CAN TSP given that the treatment has easily soluble P. The high depletion of available P in control may have been due to crop uptake to meet high requirement for P in nodulation, BNF, crop growth, reproduction, and yield production (Vance et al., 2003). The increase in available P from CAN may have been due to good suppy of N source by CAN for microbial breakdown of available organic C in kigogo soils. The Microorganisms may have mobilized fixed P in soil colloids through either their enzymes or acidification for their utilization becoming available after their death (Vance et al., 2003). Similarly, microorganisms, rendering the P available after their death, may have utilized fortified manure, CAN-Minjingu PR and Mavuno, all for their growth and reproduction.

Calcium and Mg compete with K^+ ions. Higher changes in K were observed in many of the treatments also thought to contain high levels of Ca and Mg, such as Minjingu, manures and Mavuno. Tisdale et al. (1993) have explained that presence of high levels of NO^{3-} trigger organic anion synthesis within the plant coupled with corresponding accumulation of inorganic cations such as Ca, Mg, and K with some H_2CO^{3-} being released from the roots to maintain electroneutrality in the plant and soil solution. This may have taken place in Kamujine. In Kigogo, the significant increase in Mg in CAN-Minjingu treatment compared to control and TSP may have been from the treatment given that it contains Mg.

Changes in soil micronutrients

In Kamujine, Minjingu PR had the highest increase in Mn levels being significantly higher than in TSP and manure (Table 4.9). In Kigogo, soils under CAN-Fortified and CAN-TSP combinations had significantly more Mn than those under DAP treatment. In

Kamujine, only fortified manure gave higher levels of Cu after experiment (Table 4.9) and was significantly higher than CAN-Minjingu PR ($p<0.001$), which had the highest decrease in Cu levels (42%). In Kigogo, soils under DAP treatment had the most improvement in Cu levels being significantly higher than all other treatments (9.51 ppm). In Kamujine, only CAN-TSP and TSP treatments gave higher Fe levels. Mavuno treatment had the greatest decrease in Fe levels (Table 4.9). There levels of Fe were significantly higher in soils under CAN compared to those under manure. Interestingly, in Kigogo all treatments had improved soil Fe levels with no significant difference among them. The highest increase was in DAP.

Table 4.9: Changes in Mg and selected micronutrients at Kamujine and Kigogo sites at the end of the experiment (SR2011)

	Mg $Cmol_c.Kg^{-1}$		Mn $Cmol_c$ Kg^{-1}		Cu ppm		Fe ppm		Zinc ppm		Na $Cmol_c$ Kg^{-1}	
	Kam	Kig	Kam	Kig	Kam	Kig	Kam	Kig	Kam	Kig	Kam	Kig
CAN	-2.4abc	0.1ab	0.03ab	0.01ab	-3.5ab	-0.13b	-19.35ab	5.38a	-1.655a	-3.3ab	0.04ab	-0.1ab
CAN_Fortified	-2.1ab	0.4ab	0.1ab	0.1a	-2.9ab	0.61b	-10.1ab	15.53a	-0.628a	0.3ab	0.05ab	-0.1ab
CAN_Manure	-3.4bc	0.6a	0.1ab	-0.1ab	-3.1ab	-0.108b	-20.15ab	21.85a	-1.727a	11.9a	0.1a	-0.1ab
CAN_Mavuno	-2.4ab	0.4ab	-0.01ab	0.01ab	-2.1ab	0.315b	-7.6ab	14.53a	1.218a	0.8ab	0.003b	-0.1ab
CAN_Minjingu	-2.3ab	0.7a	-0.1abc	-0.15ab	-5.3b	0.098b	-27.93ab	6.88a	-2.815a	-4.3ab	0.1a	0.02a
CAN_TSP	-3.6c	0ab	-0.06abc	0.1a	-1.5ab	0.11b	8.67a	14.05a	0.878a	-4.3ab	0.07ab	-0.1ab
Control	-2.5abc	-0.3bc	-0.01ab	-0.17ab	-1.3ab	0.313b	-18.6ab	10.6a	0.41a	-2.9ab	-0.01b	-0.2b
DAP	-2.5abc	-0.1abc	0.023ab	-0.24b	-3.4ab	9.508a	-18.5ab	28.15a	-2.093a	-1.9ab	0.12a	-0.1ab
Fortified	-2.4ab	0.4ab	-0.013ab	0.05ab	0.3a	0.59b	-5.05ab	16.05a	-0.142a	-0.8ab	0.05ab	0.01a
Manure	-2.4abc	0.3ab	-0.3c	0.1ab	-3.0ab	0.29b	-32.71b	9.23a	-2.915a	-1.6ab	0.05ab	-0.04ab
Mavuno	-2.6abc	0.1ab	-0.05abc	-0.1ab	-4.1ab	-0.017b	-28.3ab	21.25a	-3.683a	-2.7ab	0.05ab	-0.1ab
Minjingu	-3.2abc	0.1ab	0.2a	-0.2ab	-4.0ab	-0.113b	-23.85ab	18.5a	-1.487a	-12.6b	0.005b	-0.2ab
TSP	-2.0a	-0.8c	-0.2bc	-0.03ab	-2.2ab	-1.693b	3.97ab	18.85a	-0.432a	-5.2ab	0.06ab	-0.3b
LSD	1.259	0.763	0.275	0.335	4.816	8.128	39.074	23.197	5.053	17.444	0.105	0.236

NB/ Results presented at one decimal place where possible, Kam denotes Kamujine while Kig denotes Kigogo sites respectively. Means with the same letter along the column are not significantly different

In Kamujine, only CAN-Mavuno, CAN-TSP and control treatments increased zinc levels (Table 4.9). The highest increase was in CAN-Mavuno.In Kigogo, only CAN-fortified manure, CAN-manure and CAN-Mavuno gave higher Zinc levels after experiment. The highest increase was in CAN-Manure, which was significant only to that from Minjingu PR. There was improvement in Na levels in Kamujine soils except for control treatment. However, these increases were not statistically significant except for soils under DAP and CAN-manure whose changes in Na levels were significantly higher than Minjingu ($p<0.001$). In Kigogo, except for CAN-Minjingu PR and fortified manure all other treatments gave lower Na levels than before the experiment. The two treatments had a significant increase in Na levels than TSP and control. Overal, all the sites decreased their Na levels (Table 4.9).

The significantly higher Mn levels in Minjingu PR and CAN-fortified can be attributed to the Ca levels in the two treatments which Tisdale et al., 1993 note replace Mn freeing the element which is converted to unavailable forms. The authors also note that Mn deficiency is the most common in soybean. The higher levels in CAN-TSP could have been due to lower uptake of the Mn considering the high yield in DAP treatment compared to CAN-TSP. The high levels of Cu in fortified manure may be attributed to Cu chelation and complexing by the manure (Tisdale et al., 1993). The $NH4^{+}$ after dissolution from DAP may have exchanged with Cu ions from the soil colloids, being stronger than Cu in the lysoric substitution. Iron levels were elevated in Kigogo given acidity increase in Kigogo after the experiment compared to Kamujine. Increased acidity increases Fe concentrations. Tisdale et al. (1993) note that for every unit decrease in pH, Fe^{3+} decreases 1,000-fold while Fe^{2+} decreases 100-fold. With soybean under CAN-Mavuno having high fixation and active nodule numbers, the crop might have used high amount of Fe. A key element in nitrogen fixation, Fe deficiency can limit BNF in legumes (Barker and Pilbeam, 2007; Gohari and Niyaki, 2010). Given that in Kigogo, BNF performance was lower and acidity higher than in Kamujine, the high levels of Fe were expected.

The high Zn amount in soils under CAN-Manure CAN-fortified manure, CAN Mavuno in Kigogo may also be due to Zinc chalation and complexing by these treatments making Zn available later in solution (Tisdale, 1993). Generally, there was trend in Zinc decrease in soils at both Kigogo and Kamujine sites where soybean crop had better nodule numbers, BNF and yields. This can be attributed to the demand of this element by the crop for the said functions. Soybean is also a heavy consumer of zinc with high accumulation in seed (Tisdale et al., 1993; Tinsley, 2009; Kobraee et al., 2011). The significant increase of Zinc in soils under CAN-manure, CAN-Mavuno and Minjingu PR may also be attributed to fertilizer supply from these fertilizers and their liming effect (Karami et al., 2012; El Magd et al., 2006).

The high levels of Na in DAP and CAN-Manure may be a case of ion substitution. NH4+ ion is stronger for cation adsorption in lyotropic series than Na^+, which was in the two treatments that may have substituted Na from soil colloids (Tisdale et al., 1993). There may have been a faster breakdown of CAN-Manure releasing $NH4^+$ due to lower C:N ratio (Omotayo and Chukwa, 2009). Kigogo may have had more $NH4^+$ at the exchange sites given it had higher soil N levels. Kigogo is steeper than Kamujine, which is more or less flat. The increase in Na in Kamujine can be attributed to its terrain, which is flat and may be an issue of higher water table and poor drainage than that in Kigogo and the temperature differentials that evaporated soil water in kamujine faster than in Kigogo. Kamujine had everage temperatures of 23 ^{0}C compared to kigogo with evarage of 20 ^{0}C. The increase in Na levels in CAN-manure and fortified manure and DAP could have been due to NH_3^+ ions exchange with the Na^+ on the exchange sites thus increasing it in the soil.increase of Na in CAN-Minjingu could be that the fertilizer contains Na ions that increased Na levels in the soil (Tisdale et al., 1993).

4.3 Objective 2: To evaluate the effects of different sources of phosphorus and starter N on number of nodules and growth parameters of soybean

4.3 1 Effect of phosphorus sources and starter N on soybean nodulation

During the LR 2011, control treatment in Kamujine gave significantly ($p<0.001$) more nodules compared to the other treatments (Table 4.10). There were no significant differences in nodule production among treatments in Kigogo during the LR 2011 season (Table 4.10). During the SR 2011, CAN-manure at Kamujine had significantly ($p<0.001$) higher number of nodules than CAN-Mavuno, Mavuno and CAN-fortified manure whereas CAN-Mavuno treatment had significantly ($p<0.001$) more nodules than CAN-Fortified (Table 4.10).

In Kigogo during the SR 2011 season, CAN-Mavuno treatment had significantly ($p<0.001$) more nodules than CAN-Minjingu treatment (which did not have any nodules), CAN-TSP, DAP, fortified manure, manure, Mavuno, Minjingu PR, CAN and

CAN-fortified manure. It was however not significantly different from CAN-manure, control and TSP treatments (Table 4.10).

Table 4.10: Treatment effects on the number of nodules in the soybean plants at Kamujine and Kigogo during the LR 2011 and the SR 2011

Treatment	**Kamujine**		**Kigogo**	
	LR 2011	SR 2011	LR 2011	SR 2011
CAN	0b	47.25abc	0.25a	8b
CAN-Fortified	8b	25.25c	0.75a	6.75b
CAN-Manure	1.25b	90a	0.25a	13ab
CAN-Mavuno	1.75b	67.75b	0.25a	25.5a
CAN-Minjingu	1.25b	69.25abc	0a	0b
CAN-TSP	3.5b	64abc	0a	4.7b
Control	25a	53.5abc	0.25a	13.75ab
DAP	0.5b	52.25abc	0a	7.75b
Fortified	1b	72.0ab	0.5a	11.25b
Manure	3b	88.0a	0a	2.5b
Mavuno	1.5b	34.25bc	0.5a	2.5b
Minjingu	2.5b	61.25abc	0a	1.75b
TSP	0.5b	65.5abc	0.25a	12.75ab
LSD	**10.523**	**44.942**	**0.8078**	**14.192**

NB: Means with the same letter along the column are not significantly different at α=0.05

Control treatment had more active nodules than all treatments in Kamujine probably due to the poor soil N status of Kamujine (Table 4.7) which provided suitable conditions for nodulation for plants to benefit from BNF. These findings agree with many studies that identify poor soil N status as critical condition for nodulation and BNF to take place (e.g. Ray et al., 2006; Salvagiotti et al., 2008). As for Kigogo, its sufficient soil N status compared to Kamujine (Table 4.7), may have suppressed nodulation process. In SR 2011, the higher nodulation of CAN-manure treatment compared to CAN-Mavuno, Mavuno and CAN-fortified manure may be due to higher microbial activity in CAN-manure, suitable for for nodulation. Compared to CAN-fortified, CAN-Mavuno may have provided sufficient P and micronutrients to ensure active nodulation.

Just like in Kamujine, the active nodulation under CAN-Mavuno may have been due to sufficient micrutrients, P and K delivery while slowly releasing N just like it may have occurred in CAN-Manure (Vlek et al., 1997). Control and TSP not having N, may have deprived soybean the initial N nutrition for development of nodule (George and Singleton, 1992).

4.3.2 Effect of phosphorus sources and starter N on soybean growth parameters

There was no significant difference among treatments on the number of pods in Kamujine in LR 2011 (Table 4.11). However, CAN-Mavuno had the highest number of pods with 34 pods per plant and produced significantly ($p<0.01$) more leaves than CAN-fortified manure, CAN-Manure, control and TSP treatments. Soybean plants in the CAN-fortified manure treatment were significantly ($p<0.01$) taller than in Minjingu PR, TSP and control. During the SR 2011, plants in CAN treatment had significantly ($p<0.01$) more pods per plant than those in CAN-fortified manure (Table 4.4). There was no significant difference among treatments on the number of leaves per plant. However, plants in the TSP treatment were significantly ($p<0.01$) taller compared to those in control.

Table 4.11: Treatment effects on soybean number of pods, leaves and plant height in Kamujine during the LR2011 and SR2011 seasons

Treatment	Number of Pods Plant^{-1}		Number of Leaves Plant^{-1}		Plant Height (cm)	
	LR2011	**SR2011**	**LR2011**	**SR2011**	**LR2011**	**SR2011**
CAN	22.67a	38.29a	28.79abcd	52.67a	43.83abc	43.88abc
CAN_Fortified	29.63a	18.04b	33abcd	37.75a	53.33a	34.83a
CAN_Manure	22.33a	27.42ab	28.13bcd	44.33a	50.67ab	44.54ab
CAN_Mavuno	34.08a	22.96ab	38.63a	39.88a	51.96ab	44.33abc
CAN_Minjingu	26.83a	28.79ab	33.5abcd	45.5a	45.08abc	38abc
CAN_TSP	30.33a	22.33a	36.13abcd	40.25a	47.33abc	37.29abc
Control	22.25a	24.88ab	25.88d	40.46a	39.17c	37.08bc
DAP	32.88a	30ab	35.38abcd	47.46a	49.13ab	40.17abc
Fortified	27.54a	29.75ab	31.38abcd	50.42a	46.25abc	41.88abc
Manure	27.58a	30.46ab	31.63abcd	41.79a	52.67ab	39.46abc
Mavuno	28.83a	32.63ab	36.88abc	49.63a	52.13abc	39.75abc
Minjingu	24.67a	25.42ab	28.79abcd	43.25a	43.75bc	39.54abc
TSP	23.08a	31.29ab	26.25cd	44.67a	39.42c	46.58a
LSD	12.43	16	10.16	20.65	9.52	9.26

NB: Means with the same letter along the column are not significantly different

In Kigogo site, treatments did not show any significant difference on the number of pods (Table 4.12). However, CAN-Mavuno and control had the highest number of pods in LR and SR seasons, respectively. Minjingu PR and control gave the highest number of leaves during LR and SR seasons, respectively. Both control and CAN-Minjingu had significantly ($p<0.001$) more leaves than manure in SR 2011. In the same season, CAN-Fortified had significantly ($p<0.001$) taller plants than manure and Minjingu, respectively. Mavuno and CAN-Fortified had the tallest plants in LR and SR seasons, respectively.

The good performance of CAN-Mavuno on number of leaves in Kamujine may have been due to the sufficient N, P and K as well as the micronutrients provided by the treatment to plants for leaves development. The treatment may have released these nutrients faster than CAN-Manure that needs to be broken down by microorganisms. Triple Superphosphate (TSP) did not provide any additional N therefore limiting plant vegetative growth and leaves development, given the already insufficient N levels in the site (Table 4.7). Control treatment had insufficient soil N to support vegetative growth and leaves development. The significance increase of leaves in plants under CAN-Fortified manure compared to Minjingu PR, TSP and control may have been due to the starter N in it, which may have played a role in both mineralization of the fertilizer and faster release of P and N (Vlek et al., 1997). As mentioned earlier, the site already had insufficient soil N and addition of CAN may have ensured plant growth and development of leaf and pods. Taller plants under TSP compared to control reflected the importance of P in plant growth.

Table 4.12: Treatment effect on number of pods, number of leaves and plant height at Kigogo site during the LR 2011 and SR2011 seasons

Treatments	**Number of pods plant^{-1}**		**Number of leaves plant^{-1}**		**Plant height (cm)**	
	LR2011	**SR2011**	**LR2011**	**SR2011**	**LR2011**	**SR2011**
CAN	17.08a	20.79a	21.96a	29.38ab	30.79a	32.42abc
CAN_Fortified	16.17a	23.33a	23.42a	33.46ab	30.38a	38.92a
CAN_Manure	18a	17.83a	24.04a	26.38ab	33.04a	36.04ab
CAN_Mavuno	22.80a	19a	26.71a	29.80ab	36.33a	34.42abc
CAN_Minjingu	18.33a	22.29a	24.04a	35.38a	35.08a	34.92ab
CAN_TSP	16.04a	12.54a	23.13a	24.04ab	31.29a	32.04abc
Control	18.67a	24.5a	24.13a	34.71a	30.79a	34.92ab
DAP	18.54a	21.04a	25a	28.71ab	32.83a	38.08ab
Fortified	20.75a	17.88a	25.29a	27.13ab	32.5a	36.75ab
Manure	19.54a	11.83a	24.42a	19.38b	34.46a	26.17c
Mavuno	16.88a	16.92a	21.46a	29.63ab	36.68a	31.20abc
Minjingu	18.63a	16.08a	26.96ab	26.96ab	31.25a	28.75bc
TSP	19.13a	17.21a	26a	26.75ab	36.33a	35.38ab
LSD	**8.86**	**12.96**	**5.85**	**12.79**	**6.96**	**8.45**

NB: Means with the same letter along the column are not significantly different

The available soil N in Kigogo may have ensured pods development across the treatments. The fewer numbers of leaves in manure may have been due to microbial immobilization of available soil N for manure breakdown, becoming unavailable for plant uptake. The shorter plants in manure and Minjingu treatments compared to CAN-Fortified manure indicates the synergistic effect of the two fertilizers if combined with CAN in releasing P and N for plant growth. Studies have shown that lowering of C:N ratio enhances microbial breakdown of organic fertilizers which facilitates release of minerals for plant uptake (e.g. Vlek et al., 1997, Omotayo and Chukwa , 2009).

4.4 To assess the effects of different sources of phosphorus and starter N on amount of N fixed by soybean and their economic suitability

Generally, starter N did not enhance BNF but reduced it in P sources containing adequate amounts of N (Table 4.13). In Kamujine, a site that was N deficient (Table 4.7), starter N alone or in combination with either manure, Mavuno, Minjingu or TSP enhanced BNF compared with the P sources without. However, in combination with fortified manure starter N reduced BNF. In Kigogo where there was sufficient soil N (Table 4.7), addition of starter N reduced and even inhibited BNF altogether in some treatments. No BNF activity was recorded in CAN treatment, whereas for manure and Mavuno, addition of starter N reduced N fixation. However, starter N with Minjingu and fortified manure improved biological nitrogen fixation. The results in Kigogo agree with several studies that found out use of starter N reduced BNF (Yinbo et al., 1997; Mendes et al., 2003; Salvagiotti et al., 2008). In Kamujine however, starter N enhanced BNF except for fortified manure, which may have had together with N sufficiently provided N through out the soybean growth period thereby limiting BNF.

4.4.1 Effect of Phosphorus sources and starter N on biological nitrogen fixation

Soybean plants under CAN-fortified manure did not fix any N in both sites across the two seasons while those under Fortified manure treatment did not fix N in Kigogo in either LR 2011 or SR 2011 (Table 4.13). Plants under CAN-Mavuno and Mavuno fertilizer treatments gave better results, consistently fixing more than 10 kg N ha^{-1} yr^{-1} in all the sites and seasons. Soybean plants under mavuno fertilizer treatment fixed at least 15 kg ha^{-1} N yr^{-1} across the sites and seasons. The highest N fixation was recorded at Kamujine by soybean under DAP, fixing 111.75 Kg N ha^{-1} yr^{-1} followed by those under CAN-Mavuno. The performance of the two treatments was however, not significantly different.

During LR 2011 in Kamujine (Table 4.13), plants under CAN-Mavuno treatment fixed the highest amount of N (58.3 kg N ha^{-1}) while in SR 2011, those under DAP treatements fixed the highest N (66.93 kg N ha^{-1}). During LR 2011 season in Kigogo, plants under Mavuno-treatment fixed the highest N (28 kg N ha^{-1}) although this was not significantly different among other treatments. During the SR 2011 season, there was no significant difference among treatments on amount of N fixed although plants under Mavuno fixed the highest (43.87 kg N ha^{-1}).

Table 4.13: Estimated amount of Nitrogen fixed ($Kg.ha^{-1}$) in Kamujine and Kigogo during LR 2011 and SR 2011 seasons

	Kamujine			Kigogo		
	N fixed Kg ha^{-1}		Total N fixed	N fixed Kg ha^{-1}		Total N fixed
	LR 2011	SR 2011	Kg ha^{-1} yr^{-1}	LR 2011	SR 2011	Kg ha^{-1} yr^{-1}
CAN	29.44ab	26.88ab	56.32abc	0	0	0
CAN_Fortified	-4.49b	-3.83b	-8.32c	-3.95a	-3.05a	-7a
CAN_Manure	21.46ab	39.52ab	60.98abc	3.46a	6.83a	10.28a
CAN_Mavuno	58.3a	45.08ab	103.38ab	14.61a	10.46a	25.07a
CAN_Minjingu	6.2b	6.73b	12.93abc	19.08a	15.03a	34.11a
CAN_TSP	14.9ab	24.29ab	39.18abc	7.34a	9.02a	16.37a
Control	14.17ab	20.02ab	34.19abc	8.24a	4.44a	12.68a
DAP	44.82ab	66.93a	111.75a	5.52a	5.33a	10.85a
Fortified	30.99ab	41.17ab	72.16abc	-7.11a	-2.95a	-10.85a
Manure	16.9ab	15.96ab	32.86abc	20.06a	12.35a	32.41a
Mavuno	36.94ab	23.66ab	60.6abc	28.28a	15.58a	43.87a
Minjingu	3.17a	3.9b	7.07bc	1.84a	1.05a	2.88a
TSP	12.12ab	7.48b	19.6abc	21.15a	19.44a	40.6a
LSD	**49.93**	**52.46**	**99.48**	**37.36**	**30.76**	**66.56**

NB: The negative sign indicates the soil N used by the crop more than the extracted N by the soybean isoline. Means with the same letter along the column are not significantly different

Fortified manure and CAN-Fortified manure, both having manure and Mingingu PR, may have released P and N slowly especially at the start of nodulation stage therefore starving the crop of the two vital nutrients necessary for nodulation and nodule development (Tahir et al., 2009). Mavuno treatment may have contributed to a higher N fixation by providing the necessary nutrients for BNF (World Bank, 2006). Other than N and P, Mavuno fertilizer contains Ca, Mg, Mo, S, Cu, Fe and Zinc which are all essential for soybean nodulation and BNF (World Bank, 2006). Mavuno may have also enhanced nodulation and thereby BNF due to its promotion of microbial population (Okoth and Siameto, 2011). In Kamujine, the high fixation from DAP treatment can be attributed to fast release of P and N in amounts adequate both for soybean growth and nodule development and nitrogen fixation. In the site, the micronutrient status may have been sufficient for BNF with the most limiting nutrients being N and P (Table 4.9). In SR 2011, the initial heavy rain in Kigogo and later moisture stress may have limited nodulation and BNF (Keyser and Li, 1992; Arrest-Igor et al., 2011).

4.4.2 Economic analysis of the P sources to determine their suitability using VCR

Table 4.14 and 4.15 show the price attributes of various treatments in the study in the LR 2011 and SR 2011 respectively. Considering the price of P source per kg, TSP was the most expensive [Ksh. 455.10 (US $ 5.06)] with the least costly being manure [Ksh. 4.00 (US $ 0.043)]. In terms of cost per kg of P, manure however is a bulky and poor quality fertilizer, costing Ksh. 972.80 (US $ 10.46). The most costly source was CAN-Manure treatment with the least being DAP at Ksh.1583.31 (US $ 17.02) and Ksh. 273.06 (US $ 2.94) per kg of P, respectively.

As a P source, TSP was the most expensive probably because of factors mainly related to market dynamics such as its international prices, international PR and hydrochloric acid supply, demand from major markets, transportation costs both in the high seas and inland, taxes and or lack of subsidies e.t.c. (Heerick, 2005; Cordell et. al., 2009; Vaccari, 2009; UNEP, 2011). Such costs are passed on to consumers (Beert, 2005). For this reason and due to its single nutrient supply, the fertilizer demand is low with few quantities ordered. The low orders in turn exercerbate its price. This is where DAP becomes a popular fertilizer for Kenyan farmers (Mutsotso et al., 2011). It is cheaper than TSP yet with nearly equal amounts of P per kg. In addition, it also contains almost 18% N. The fertilizer has consistently improved yields making farmers demand more of it. Traders order more knowing their stocks will sell thereby increasing its availability and due to competition and economies of scale, it becomes cheaper (Chianu et al., 2011).

Table 4.14: Costs of various fertilizers and their corresponding soybean yields at Kamujine and Kigogo sites during the LR 2011 season

Treatment	**Fert. used ha^{-1} (Kg)**	**Kamujine Yield (Kg)**	**Kigogo Yield (Kg)**	**Fert. Price**	**Unit (Kg)**	**Cost of $fert.ha^{-1}$ (Ksh.)**	**Fert. Price Kg^{-1}**	**Price of P Kg^{-1}**	**P used Ha^{-1}**
CAN	38.46i	973.3bc	883.8ab	2800	50	2153.76k	56.00c	0k	0
CAN_Fortified	3810.96c	1332.4abc	951.8ab	9600	1100	33272.38b	8.73f	1109.08b	30
CAN_Manure	7334.46a	1184.7bc	1010.4ab	6800	1050	47509.07a	6.48g	1583.64a	30
CAN_Mavuno	267.46e	1957.0a	1123.5ab	5400	100	14523.84f	54.00d	484.13f	30
CAN_Minjingu	267.46e	1451.7ab	1130.3ab	5600	100	15061.76e	56.00c	502.06e	30
CAN_TSP	190.16g	1142.2bc	1046.0ab	7300	100	13991.18g	73.00b	466.37g	30
Control	0j	714.9c	723.9b	0	0	0	0.00i	0k	0
DAP	151.7h	1210.0bc	706.3b	2700	50	8272.80j	54.00d	275.76j	30
Fortified	3772.5d	1199.5bc	994.1ab	6800	1050	24441.14d	6.48g	814.70d	30
Manure	7296b	1269.4abc	1156.0ab	4000	1000	29190.00c	4.00h	973.00c	30
Mavuno	249f	1108.2bc	1123.5ab	2600	50	13026.00i	52.00e	434.20i	30
Minjingu	249f	1054.8bc	922.5ab	2800	50	14028.00g	56.00c	467.60g	30
TSP	151.7h	1098bc	961.3ab	4500	50	13788.00h	90.00a	459.60h	30
LSD	0.31	703.94	473.06	-	-	58.76	0	1.96	-

N/B: 1 US$= Ksh. 93 (March 2011). Means with the same letter along the column are not significantly different

Table 4.15 Costs of various fertilizers and their corresponding soybean yields at Kamujine and Kigogo sites during the SR 2011

Treatment	Fert. used ha^{-1} (Kg)	Kamujine Yield (Kg)	Kigogo Yield (Kg)	Fert. Price	Unit (Kg)	Cost of $fert.ha^{-1}$ (Ksh.)	Fert. Price Kg^{-1}	Price of P Kg^{-1}	P used Ha^{-1}
CAN	38.46i	927.4bcd	816.5bc	2800	50	2153.76k	56.00c	0k	0
CAN_Fortified	3810.96c	1456.3a	837.0bc	9600	1100	33272.38b	8.73f	1109.08b	30
CAN_Manure	7334.46a	1235.6abc	938.6ab	6800	1050	47509.07a	6.48g	1583.64a	30
CAN_Mavuno	267.46e	1072.6abc	895.5ab	5400	100	14523.84f	54.00d	484.13f	30
CAN_Minjingu	267.46e	1106.6bcd	1084.5a	5600	100	15061.76e	56.00c	502.06e	30
CAN_TSP	190.16g	955.9bcd	7922.0bcd	7300	100	13991.18g	73.00b	466.37g	30
Control	0j	542.5d	689.2cde	0	0	0	0.00i	0k	0
DAP	151.7h	1340.1ab	689.0cde	2700	50	8272.80j	54.00d	275.76j	30
Fortified	3772.5d	1179.1abc	782.8bcd	6800	1050	24441.14d	6.48g	814.70d	30
Manure	7296b	1224.9abc	558.9e	4000	1000	29190.00c	4.00h	973.00c	30
Mavuno	249f	1038.7abc	902.3ab	2600	50	13026.00i	52.00e	434.20i	30
Minjingu	249f	1160.8abc	796.9bcd	2800	50	14028.00g	56.00c	467.60g	30
TSP	151.7h	857.9cd	612.0de	4500	50	13788.00h	90.00a	459.60h	30
LSD	0.31	446.86	204.13	-	-	58.76	0	1.96	-

N/B: 1 US$= Ksh. 93 (March 2011). Means with the same letter along the column are not significantly different

Manure was the cheapest P source because of its availability in farming sytems as a by-product of mixed farming. However, it has low quality, requiring large quantities for sufficient supply to meet crop nutrient requirements (Mugwe et al., 2007b). In Kigogo, manure was among the least responsive fertilizers (Table 4.16). Its use also increases cost of production, as more labour is required to apply it compared to other fertilizers (Place et al., 2003). When combined with CAN, it became the most expensive given CAN did not sufficiently improve yield to warrant its additional cost.

Table 4.16 shows response rates of various treatments to the yields of soybean in Kamujine and Kigogo. In Kamujine, during the LR 2011, CAN-Mavuno had significantly ($p<0.001$) higher response rates than all treatments expect CAN-fortified manure, CAN-Minjingu and manure while CAN fortified was significantly ($p<0.001$) more responsive than CAN-TSP (31.86) and TSP (28.59) during the SR 2011. In Kigogo, during the LR 2011, mavuno had a significantly ($p<0.001$) higher response rate than DAP. In SR 2011, CAN Minjingu was significantly ($p<0.001$) more responsive than all treatments except CAN-manure, CAN-Mavuno and Mavuno treatments. Treatments had higher response rates in Kamujine than in Kigogo.

Table 4.16: Fertilizer response and VCR at Kamujine and Kigogo sites during the experimental period

Treatment	**Kamujine**				**Kigogo**			
	Fert. Response Rate		**VCR**		**Fert. Response Rate**		**VCR**	
	LR 2011	**SR 2011**	**LR 2011**	**SR 2011**	**LR 2011**	**SR 2011**	**LR 2011**	**SR 2011**
CAN_Fortified	44.41ab	48.54a	2.40efg	2.63de	31.73ab	27.90bc	1.72c	1.51ef
CAN_Manure	39.49b	41.19abc	1.50fg	1.56ef	33.68ab	31.29ab	1.28cd	1.19f
CAN_Mavuno	65.26a	35.76abc	8.08ab	4.43bc	37.45ab	29.85ab	4.65a	3.70bc
CAN_Minjingu	48.39ab	36.89abc	5.78bc	4.41bc	37.68ab	36.15a	4.50	4.32ab
CAN_TSP	38.07b	31.86bc	4.90cde	4.10bcd	34.87ab	26.40bcd	4.49a	3.40c
Control	0c	0d	0g	0f	0c	0f	0d	0g
DAP	40.53b	44.67ab	8.78a	9.71a	23.54b	22.97cde	5.12a	5.00a
Fortified	39.98b	39.30abc	2.95def	2.90cde	31.14ab	26.09bcd	2.44bc	1.92e
Manure	42.31ab	40.83abc	2.61defg	2.52de	38.53ab	18.63e	2.38bc	1.15f
Mavuno	36.94b	34.62abc	5.1cd	4.78b	39.89a	30.08ab	5.51a	4.16b
Minjingu	35.16b	38.69abc	4.51cde	5.00b	30.75ab	26.56bcd	3.94ab	3.41c
TSP	36.62b	28.60c	4.77cde	3.73bcd	32.04ab	20.40de	4.18a	2.66d
LSD	**23.17**	**14.55**	**2.70**	**1.70**	**15.05**	**6.63**	**1.69**	**0.72**

NB: Means with the same letter along the column are not significantly different

The most profitable P source in Kamujine site was DAP (Table 4.16). Its value-cost ratio of 9.71 in SR 2011 was more than 2.43 times the recommended threshold value of 4.0 VCR considered profitable in risk prone African farming systems (Heerink, 2005). Given the minimum recommended VCR of two for returns to cost of input, CAN-Manure combination was seen to be unprofitable having VCR of 1.50 and 1.56 in LR 2011 and SR 2011, respectively. In Kigogo site, only DAP, CAN-Minjingu PR and Mavuno met the high threshold of 4.0 VCR. Considering the lower threshold of two, CAN-fortified, CAN-manure in both seasons, and fortified manure and manure in SR 2011 were not profitable in this site.

The high response rate of CAN-Minjingu in Kigogo may have been due to the site's low P and micronutrients levels (Table 4.7) whose supply made crops respond well to it. Crops responded poorly to manure because of its low P levels and possible slow release rates of both the P and micronutrient levels (Vlek et al., 1997). The better response in Kamujine compared to Kigogo may be due to initial poor nutrient status in Kamujine than in Kigogo (Table 4.7). Being also cheaper and higher yielding, and with high amounts of N and P, in a site where both are deficient, DAP had among the highest response rates and making it the most profitable fertilizer in Kamujine. Manure on the other hand may have had low profitability potential due to its low reponse rate, its high cost per kg of P and its rather low yields compared to other treatments. Addition of CAN in manure compounded its cost factor. Kigogo site may have have responded better with P than with starter N because it already had sufficient soil N but poor in P, and micronutrients (Cu, Mg and Fe). Soybean requires these nutrients in large amounts and so their faster uptake by DAP (P), CAN-Minjingu PR and Mavuno (N, P, K and micronutrients) made them profitable in that site. With increased availability of P and micronutrients, crops may have demanded more N and so fertilizers that also included N ensured adequate nutrient supply to crops.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Use of TSP as a source of P did not have advantage over other sources of P. Its use had among the least benefits in increasing BNF and yields and contributing to improved soil chemical characteristics. Economic benefits of TSP were also among the least. The use of CAN-fortified manure fertilizer combination had soybean having poor yields and not fixing N compared to other sources. The cost of CAN-fortified manure treatment was also prohibitive. Use of DAP fertilizer was considered the most economically suitable. It was cheap, had good yields, nodulated well and fixed more nitrogen than most of the other fertilizers. This was the case in all the sites. However, DAP increased acidity although not significantly higher than other P sources. Minjingu PR is a possible alternative in soybean production in acidic areas, considering, it is cheap and performed well, especially at Kigogo site which was more acidic than Kamujine. Organic sources of P (i.e. manure, CAN-Manure combination, fortified manure, Can-fortified) had poor economic returns than the inorganic types (Mavuno, CAN-Mavuno, TSP, DAP).

Application of starter N did not significantly improve yields. Use of starter N in combination with other organic fertilizers depressed yields and reduced economic benefits of these fertilizers in Kigogo. Nonetheless, use of starter N in sources in soils with little or no N was beneficial in some cases. For example, Minjingu PR and Mavuno yielded more when in combination with starter N. Starter N did not significantly increase BNF in any of the sites, actually decreasing it at Kigogo site. In conclusion, performance of all indicators in Kamujine was better than in Kigogo, implying that

Kamujine is a better site for soybean production than Kigogo site. Starter N is not suitable in areas with sufficient soil N and is not economically viable. The most suitable P source in the study area is DAP save for its acidifying nature.

5.2 Recommendations

Based on the study results, continued use of DAP as a source of P in soybean production in the region is recommended. However, liming and supplimenting with organic amendments such as manure can offset its long-term harmful effects of increasing soil acidity. Use of Minjingu fertilizer in such areas is also viable given it is a cheaper source of liming material that does not compromise soybean yield. Use of CAN-Mavuno is another suitable alternative to DAP given its effects on soybean BNF, nodulation and yield. Use of starter N in soybean production is not recommended unless in areas very poor in soil N.

Further study on long-term effects of organic fertilizers i.e. manure, CAN-manure combination, fortified manure and CAN-fortified manure combination regarding their long-term economic implication and soil characteristics improvement need to be done considering residual effect of the fertilizers on consequent crops. The short period of the study may not have reflected their true economic and agronomic value that may accrue later. Further studies should be done in areas with different agroecological zones and soils to compare treatment effects. The study recommends use of organic fertilizers especially given their contribution to soil organic carbon.

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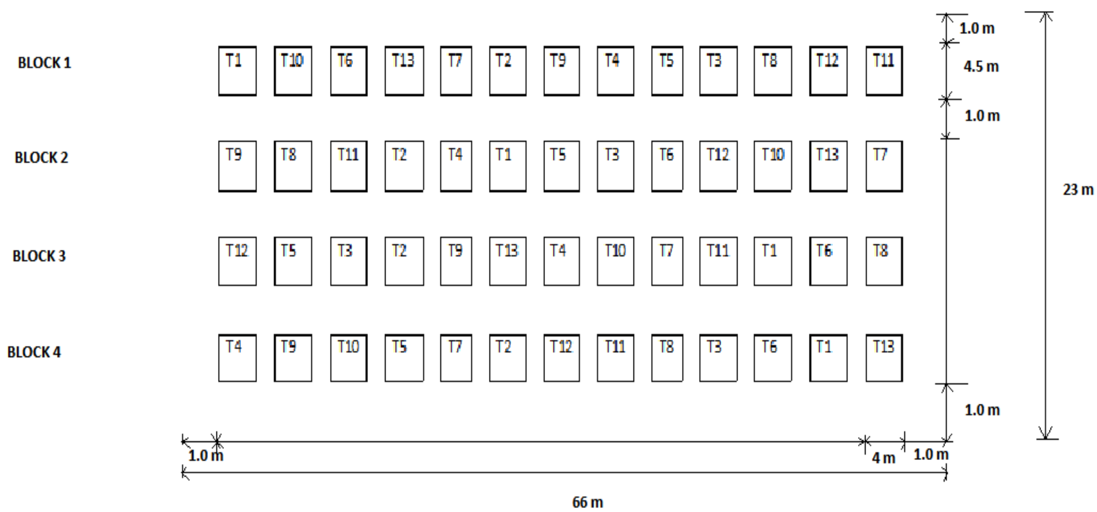
APPENDICES

APPENDIX I: EXPERIMENT PROTOCOL

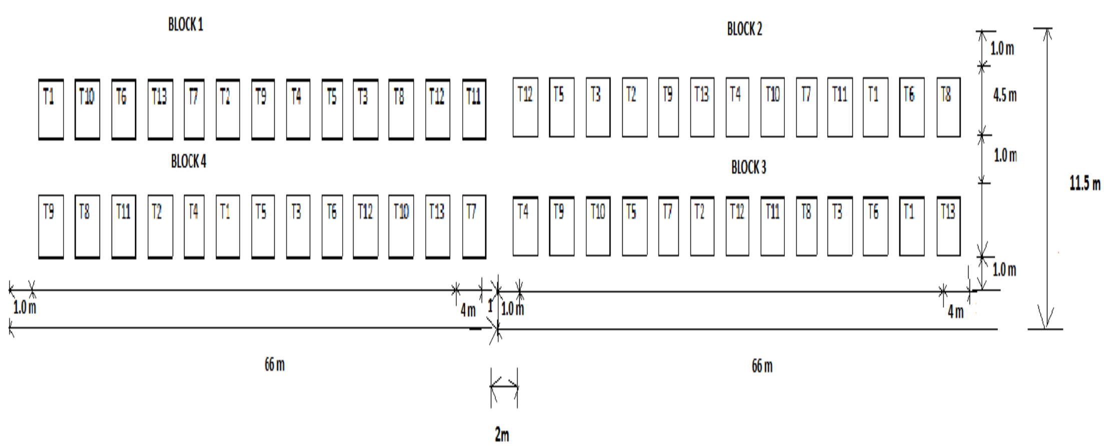
<u>Farm Layout for the experimental plots and various phosphorus sources on soya beans</u>

The following is the combinations of various P source treatments with or without Nitrogen source on soya bean.

The following is an outlook of the randomized plots in the four blocks.



Appendix 1: Sketch of plots at Kamujine site



Appendix 2: Sketch of plots at Kigogo site

KEY:

T1: Control (No Nitrogen source, No Phosphorus source)

T2: Minjingu Phosphorus fertilizer only

T3: Mavuno legume fertilizer only

T4: Triple Super Phosphate fertilizer (TSP) only

T5: DAP fertilizer only

T6: Manure only

T7: Fortified Manure (manure + Minjingu phosphate fertilizer)

T8: CAN

T9: CAN, Minjingu Phosphorus fertilizer

T10: CAN, Mavuno legume fertilizer

T11: CAN, Triple Super Phosphate fertilizer

T12: CAN, manure

T13: CAN, fortified manure (Manure + Minjingu PR)

Treatment 5, DAP already has N and P sources and will be the main control on treatments. Treatment 13 is a combination of CAN and 1:1 ratio of animal manure and Minjingu fertilizer.

Appendix 3: Table 1 Plot details

	Measurement specification					
Row length	No. of Rows	Inter rows Spacing	Intra row size	Plot size	Net plot size	**N**o. of the plots
4.5 m	6	50 cm	5cm	$18m^2$	$10.5\ m^2$	52

NB: There will be 53^{rd} plot for the isoline variety in season two in each site. The trial will be done at Kigogo and Kamujine in Meru south and Tigania Districts respectively. The trial will use a completely randomized blocked design replicated four times.

Methods:

1. Identify a suitable plot and mark the boundaries
2. Collect and record the site characteristics and history of the plot
3. Get the land prepared using normal land preparation procedure applicable at the location while recording the details of all operations
4. Divide the area into Four blocks(4) each measuring about 4.5 m x 66 m
5. Mark 13 plots of 4 m x 4.5 m within each block (see figure), separating adjacent plots by 100 cm pathway and number them
6. Collect a composite soil sample from each of the plots by recovering two soil samples from each plot to a depth of 20 cm. The samples will be used for characterizing the soil for soil fertility. Collect about 500 g.
7. Number the plots and prepare a map of field layout of plots
8. Assign treatments randomly using the above layout, entering treatment labels into the farm layout plans of the plots
9. The amount of fertilizer to be added will vary depending on the type of fertilizer as given in the table below. The required quantities will be weighed and be kept ready in advanced. This fertilizer will be applied at the time of sowing. Fertilizer will be applied uniformly where they are to be applied in particular plots.

Appendix 4: Fertilizer measurements per plot

Fertilizer	Fertilizer to be used/ha	P amount (g) required per m^2@ 30 kg /ha	Fertilizer amount (g) required for plot of 4.5 m x 4 m@ 30 kg P/ha
DAP 18-46-0	151.7 kg	6.5 g	273 g
TSP 19.78% P	151.7 kg	6.5 g	273 g
Mavuno 12% P	249 kg	5.4 g	448.5 g
Minjingu 12% P	249 kg	5.4 g	448.5 g
Manure 0.41% P	7296 kg	730 g	13.13 kg
Fortified manure (50:50 ratio)manure:Minjingu	3648 kg manure 124.5 kg Minjingu	361 g manure 12.46 g	6.5 kg manure, 224.25 g Minjngu
CAN 26% N	38.462 kg	-	69.2 g

N/B: CAN will be the source of N. The Decision on the amount of Manure to be used will be measured depend on the results of the manure analysis. The manure should give the required amount of P and N.

Inoculate *Rhizobium japonicum* using the standard procedures as indicated below;

1. Add 30 g gum arabic to 300 ml of clean lukewarm water in a soda bottle and shake well to dissolve
2. Fill container with 15 kg of soya beans
3. Pour the gum Arabic into the container with soya beans and mix until all the seeds are well mixed
4. Mix the *Rhizobium japonicum* innoculum contents into the mixture and mix thoroughly until all the seeds are uniformly covered with the inoculants. Protect the innoculant from direct sunlight.
5. Plant the inoculated seeds as soon as possible in a well prepared moist bed.

Measurements

Site characteristics: Latitude,altitude, soil type (texture) and depth (m), slope (%), slope length

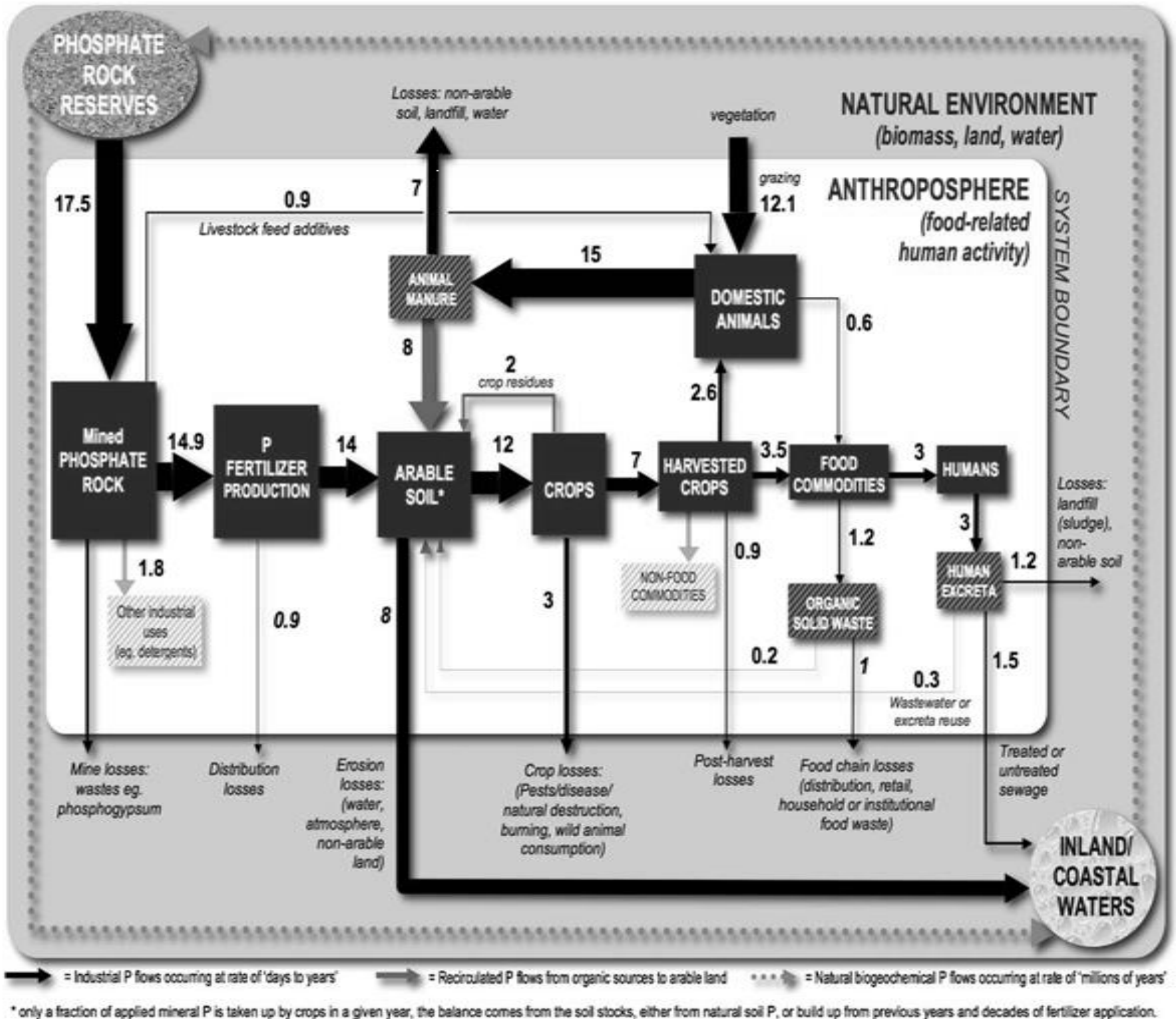
Climate: Daily rainfall (mm).

Crop phenology: Cultivar name, average duration to flowering and maturity, date of 50% flowering, nodulation rate and number of nodules, % N, % P plant analysis

Crop growth: Total biomass at harvest (Kg/ha), Grain yield (Kg/ha), final plant population (plants/m^2) The seeds will be drilled at a row spacing of 50 cm. and there after thinned to 10 cm between plants after 2 weeks of planting . This will have enabled the plantings to be able to withstand any shock during gapping and thinning.

Management: Date for all operations (sowing, harvest, weeding, tillage, fertilizer applications) and samplings and population at planting (Plants/$m^{2)}$

Soil N and P: Sampled soils will be analyzed for Available N, Phosphorus and exchangeable bases. Analysis on pH, %C, Available P and N and Total P and N will be done.



Appendix 5: Key Phosphorus flows in the global food production system in Million Tons per year

Animal manure and P fertilizer are important in availing P into the soil for crop production. Source; Cordell at al., 2009.

Appendix 6: Percentage of N and P in sampled plants applied with various treatments in Kamujine and Kigogo sites in SR 2011

Treatment	**Nitrogen %**		**Phosphorus %**	
	Kamujine	Kigogo	Kamujine	Kigogo
CAN	2.45	1.75	0.15	0.12
CAN_Fortified	1.63	1.63	0.19	0.16
CAN_Manure	2.57	1.87	0.17	0.13
CAN_Mavuno	2.45	2.10	0.17	0.20
CAN_Minjingu	1.87	2.22	0.18	0.18
CAN_TSP	2.33	1.98	0.19	0.15
Control	2.22	1.98	0.18	0.15
DAP	2.92	1.98	0.16	0.15
Fortified	2.45	1.63	0.17	0.16
Isoline	1.75	1.75	0.16	0.17
Manure	1.98	2.33	0.17	0.19
Mavuno	2.33	2.33	0.19	0.13
Minjingu	1.87	1.75	0.18	0.16
TSP	1.98	2.33	0.17	0.14
LSD	**1.01**	**0.94**	**0.04**	**0.07**

APPENDIX II: SOIL PROPERTIES OF THE VARIOUS TREATMENTS OVER THE SEASONS

Appendix 7: Soil pH and major macronutrients before and after experiment period at Kamujine

	pH		Org C%		Total N %		P ppm		K Cmolc kg-1		Ca Cmolc kg-1	
Kamujine	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011
CAN_Manure	5.42	5.59	1.50	1.72	0.17	0.18	33.00	27.00	0.21	0.39	4.10	5.40
TSP	5.42	5.49	1.63	1.85	0.18	0.18	39.25	31.00	0.21	0.28	4.00	4.90
CAN_TSP	5.40	5.52	1.49	1.77	0.16	0.18	39.50	26.75	0.18	0.27	4.55	4.90
CAN	5.38	5.53	1.27	1.64	0.17	0.17	34.75	27.50	0.27	0.28	4.53	4.80
Manure	5.35	5.46	1.50	1.69	0.17	0.17	31.00	28.5	0.27	0.32	4.50	5.30
CAN_Fortified	5.35	5.55	1.46	1.70	0.17	0.18	29.50	36.5	0.26	0.30	4.25	5.55
CAN_Mavuno	5.33	5.41	1.53	1.87	0.16	0.19	27.75	28.75	0.17	0.26	3.95	4.80
Minjingu	5.33	5.47	1.60	1.82	0.18	0.19	31.75	28.00	0.30	0.26	4.85	5.45
Fortified	5.31	5.57	1.63	1.59	0.18	0.17	32.25	29.00	0.22	0.29	4.50	4.53
CAN_Minjingu	5.27	5.54	1.60	1.90	0.19	0.19	31.00	26.75	0.30	0.52	4.65	5.80
Control_N0_P0	5.26	5.44	1.54	1.72	0.18	0.18	33.75	25.25	0.22	0.20	4.13	4.45
DAP	5.30	5.49	1.56	1.73	0.18	0.17	31.75	28.75	0.22	0.35	4.38	5.10
Mavuno	5.32	5.55	1.51	1.74	0.18	0.18	32.25	27.50	0.26	0.28	4.68	5.35
LSD	0.02	0.15	0.43	0.39	0.05	0.03	9.70	8.67	0.18	0.23	1.03	1.84

Appendix 8: Soil micronutrients before and after experiment period at Kamujine

	Mg Cmolc kg-1		Mn Cmolc kg-1		Cu ppm		Fe ppm		Zn ppm		Na Cmolc kg-1	
Kamujine	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011
CAN_Manure	6.74	3.39	0.44	0.49	11.39	8.34	78.45	58.3	9.90	8.173	0.23	0.36
TSP	5.68	3.67	0.67	0.48	11.95	9.72	75.03	79.00	10.93	10.50	0.22	0.26
CAN_TSP	6.86	3.22	0.64	0.58	9.63	8.12	56.40	65.08	7.45	8.33	0.22	0.29
CAN	5.89	3.50	0.50	0.53	10.46	6.99	83.90	64.55	9.51	7.86	0.27	0.31
Manure	5.93	3.51	0.79	0.47	10.80	7.87	81.28	48.56	11.17	8.25	0.25	0.30
CAN_Fortified	5.79	3.67	0.44	0.51	11.15	8.25	79.13	69.03	9.36	8.74	0.24	0.29
CAN_Mavuno	6.00	3.65	0.58	0.57	11.20	9.14	75.65	68.05	9.75	10.97	0.24	0.25
Minjingu	6.01	2.81	0.52	0.67	12.30	8.33	79.90	56.05	10.98	9.49	0.28	0.28
Fortified	5.77	3.42	0.52	0.51	8.50	8.76	70.48	65.43	9.08	8.93	0.23	0.28
CAN_Minjingu	5.90	3.65	0.69	0.63	12.55	7.27	73.85	45.93	10.79	7.98	0.27	0.39
Control_N0_P0	5.78	3.25	0.64	0.64	8.38	7.11	74.70	56.10	8.32	8.73	0.27	0.26
DAP	5.84	3.35	0.48	0.50	11.13	7.77	69.18	50.68	10.44	8.34	0.22	0.34
Mavuno	5.94	3.34	0.49	0.44	11.88	7.76	75.35	47.05	11.67	7.99	0.25	0.30
LSD	1.11	0.65	0.29	0.15	3.28	3.50	24.42	36.94	3.16	4.78	2.03	0.31

Appendix 9: Soil Characteristics and major macronutrients before and after experiment period at Kigogo

	pH		Org C%		Total N %		P ppm		K Cmolc Kg-1		Ca Cmolc Kg-1	
Kigogo	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011
CAN_Manure	5.51	5.26	1.82	2.17	0.22	0.22	45.00	49.75	0.55	0.44	5.15	4.60
TSP	5.57	5.31	2.69	2.56	0.28	0.24	55.25	45.50	0.94	0.45	6.42	5.70
CAN_TSP	5.49	5.27	1.97	2.12	0.23	0.22	45.25	55.00	0.52	0.44	5.40	4.65
CAN	5.39	5.15	1.77	1.94	0.21	0.20	38.50	50.25	0.43	0.49	5.85	4.40
Manure	5.59	5.33	2.02	2.24	0.23	0.22	50.50	49.25	0.51	0.55	5.70	5.55
CAN_Fortified	5.53	5.26	2.21	2.30	0.23	0.24	45.50	59.00	0.51	0.44	6.25	5.25
CAN_Mavuno	5.50	5.32	2.12	2.21	0.24	0.21	51.25	52.75	0.47	0.40	6.15	5.45
Minjingu	5.45	5.25	1.98	2.14	0.24	0.21	54.50	44.75	0.44	0.33	3.71	4.70
Fortified	5.42	5.30	1.97	2.01	0.22	0.21	35.50	43.00	0.24	0.43	4.85	4.95
CAN_Minjingu	5.29	5.28	1.88	2.31	0.21	0.22	34.25	46.50	0.28	0.52	4.50	5.30
Control_N0_P0	5.66	5.34	2.50	2.43	0.27	0.23	70.75	50.00	0.90	0.59	8.05	5.85
DAP	5.32	5.20	1.90	2.02	0.23	0.21	45.00	44.25	0.46	0.28	5.30	4.05
Mavuno	5.52	5.26	1.93	2.52	0.23	0.22	39.75	51.50	0.49	0.48	5.35	5.15
LSD	0.27	0.25	0.52	0.55	0.05	0.04	30.66	15.95	0.44	0.38	2.72	2.11

Appendix 10: Soil Characteristics and major micronutrients before and after experiment period at Kigogo

	Mg Cmolc kg-1		Mn Cmolc kg-1		Cu ppm		Fe ppm		Zn ppm		Na Cmolc kg-1	
Kigogo	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011	Baseline	SR 2011
CAN_Manure	2.14	2.73	0.73	0.59	3.12	3.01	20.30	42.15	12.48	24.37	0.36	0.21
TSP	3.45	2.65	0.62	0.60	4.82	3.13	16.63	35.48	17.90	12.75	0.52	0.26
CAN_TSP	2.43	2.43	0.56	0.67	2.71	2.82	19.50	33.55	15.03	10.77	0.33	0.22
CAN	2.25	2.30	0.55	0.55	2.73	2.60	27.23	32.60	12.14	8.85	0.32	0.25
Manure	2.29	2.60	0.49	0.57	2.52	2.81	20.05	29.28	14.83	13.28	0.33	0.29
CAN_Fortified	2.26	2.67	0.55	0.66	2.23	2.83	17.20	32.73	13.59	13.93	0.33	0.24
CAN_Mavuno	2.30	2.67	0.61	0.62	2.54	2.86	20.35	34.88	13.71	14.53	0.35	0.24
Minjingu	2.27	2.37	0.78	0.59	3.06	2.95	22.95	41.45	24.40	11.81	0.35	0.20
Fortified	2.20	2.61	0.47	0.52	2.36	2.95	18.00	34.05	11.35	10.58	0.22	0.23
CAN_Minjingu	1.92	2.61	0.75	0.61	3.24	3.34	23.53	29.03	16.85	12.58	0.26	0.28
Control_N0_P0	3.10	2.75	0.73	0.56	2.44	2.76	18.43	30.40	16.90	14.05	0.50	0.26
DAP	2.21	2.15	0.74	0.51	3.14	12.65	22.43	50.58	13.97	12.12	0.31	0.18
Mavuno	2.58	2.72	0.66	0.60	3.08	3.06	21.48	42.73	15.05	12.37	0.33	0.24
LSD	0.75	0.87	0.27	0.19	1.98	8.64	9.17	22.84	13.19	12.54	0.20	0.16