RESPONSE OF SOYBEAN (*Glycine max* L.) TO APPLICATION OF INORGANIC FERTILIZERS, CATTLE MANURE AND LIME IN WESTERN KENYA

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DECLARATION

I declare that this thesis is my original work and has not been presented for any award of a degree in any other university.

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To my sponsors Charles Hutchings and Ruth Vincent, my friends and family. I am very grateful for your dedicated and kind support throughout my study period. May this be an encouragement to you all.

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LIST OF ABBREVIATION AND ACRONYMS

AGRA: Alliance for a Green Revolution in Africa

ANOVA: Analysis of variance

BIDCO: Business and Industrial Development Cooperation

CV: Coefficient of variation

DNA: Deoxyribonucleic acid

EC: Electrical conductivity

ERS: Economic Research Service

FAO: Food and Agriculture Organization

FAOSTAT: Food and Agriculture Organization Statistics

FURP: Fertilizer Use Recommendation Project

GOK: Government of Kenya

GTZ: German International Development Cooperation

IITA: International Institute of Tropical Agriculture

ISFM: Integrated Soil Fertility Management

LSD: Least Significant Difference

MOA: Ministry of Agriculture

RNA: Ribonucleic acid

SBP: State Bank of Parkistan

SSA: Sub-Saharan Africa

USA: United States of America

USDA: United States Department of Agriculture

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ABSTRACT

Soybean production in Kenya has remained low, partly due to soil nutrient depletion and degradation which have been considered serious threats to agricultural productivity. Studies have shown that productivity of soils in western Kenya is limited by deficiency of nutrients such as nitrogen, phosphorous and potassium a problem compounded by low organic matter and soil acidity. Responses of soybean to nitrogen and phosphorous have been studied and documented but little has been done on micronutrients, and also to establish the scale of macro and micronutrient deficiencies and soybean yield response to a combination of organic and inorganic fertilizers. Despite the major opportunities that soybean provide to human nutrition, household income and soil N budgets in Africa, their contribution has been curtailed by several factors including low priority given to proper nutrient management. This is because grain legumes, soybean included, have been promoted as crops that require no fertilizer application. The objective of the study was to evaluate the effect of inorganic fertilizer, cattle manure and lime on the growth and yield of soybean in nutrient omission trials. Field experiments were conducted in four sites (Eshirali, Masaba, Nyabeda and Eshisa) during the 2012 cropping seasons in Western Kenya to determine the effect of inorganic fertilizers, cattle manure and lime on nodulation and yield of soybean (*Glycine max* L.). The experiment was laid out in a randomized complete block design with three replicates. The treatments consisted of: 1) Control-without inoculant and fertilizer; 2) Inoculation alone; 3) NPK; 4) PK; 5) NP; 6) NK; 7) NPKSCaMgZnMo and 8) NPKSCaMgZnMo+Manure+Lime (Seeds were inoculated with rhizobia inoculant containing USDA-110 *Rhizobium* strain). Inorganic fertilizers were applied at rates of 20 kg/ha N, 30 kg/ha P, 60 kg/ha K, 23 kg/ha S, 20 kg/ha Ca, 5 kg/ha Mg, 3 kg/ha Zn, 3 kg/ha Mo, 10 tons/ha manure and 5 tons/ha lime. Soybean variety SB-132 was used in the trials during both the short and long rainy seasons. Above ground biomass, nodule number, nodule dry weight, nodule mean score, plant height, pod number, final grain yield, stover yield and 100-seed weight were determined. Analysis of variance showed significant site, treatment and site × treatment interaction effects on soybean above ground biomass, nodule mean score, number of nodules per plant, nodule dry weight, plant height, number of pods per plant, 100-grain weight, grain yield and total stover yield in both cropping seasons indicating that treatment effects were site specific. Inoculation alone significantly increased soybean nodule mean score, nodule number and nodule dry weight relative to control in both seasons. Application of NK had significantly lower values in most of the studied parameters than NPK, NP and PK applications. Overall, significantly higher values were noted in NPKSCaMgZnMo+Manure+Lime than in all the other treatments in most parameters. Eshisa site recorded significantly higher values than all other sites in all parameters except 100-grain weight and stover yield in the second season. The findings suggest that combination of inorganic fertilizers, cattle manure and lime would be a feasible option for maximizing soybean yields in western Kenya hence providing an entry point for more research on proper nutrient management to boost soybean production in the region.

CHAPTER 1

INTRODUCTION

1.1 Background information

Soybean (*Glycine max*) is the world's most important legume in terms of production and trade and has been a dominant oilseed since the 1960s (Smith and Hyser, 1987). It is a small grain creamy in colour with a few black varieties. Soybean is said to have originated from the Orient, probably in China (Synder and Kwon, 1987). In the Orient, the main products from soybean are oil and meal. About 50 countries worldwide grow soybean (Boerma and Specht, 2004). The United States of America (USA) accounted for 40 to 45% of the world's total soybean production in 2003 (Boerma and Specht, 2004). In 2008, the United States of America and Brazil were the first and second biggest producers of soybean in the world with an output of 73 million metric tons (33%) and 42 million metric tons (28%) respectively. Egypt, the largest producer of soybean in Africa, produces about 180,000 tons annually (USDA-ERS, 2009). Soybean improves soil fertility by fixing nitrogen from the atmosphere (Kasasa *et al*., 2000; Sanginga *et al*., 2003). Some varieties fix 44 to 103 kg of N/ha annually (Sanginga *et al*., 2003). Soybeans are sensitive to low pH. In acid soils, liming is essential to raise the pH to 6.0 or 6.5 for optimum yield production.

Soybean is used in the preparation of a variety of fresh, fermented and dried food products like milk, tofu, soya sauce and bean sprouts. Soybean is also processed to extract oil for various industrial purposes and food. It is found in the market as salad oil, cooking oil, margarine and shortening. Soybean is a multipurpose crop grown for human food, livestock feed, industrial purposes, and more recently, as a source of bio-energy (Myaka *et al*., 2005). Unlike most other beans that contain about 20% protein, soybean contains 40% protein (Greenberg and Hartung, 1998). Soybean products are cholesterol free, high in calcium, phosphorous and fiber, and have one of the lowest levels of saturated fat (BIDCO, 2005). About 80% of soybean produced in Kenya is consumed by the livestock industry with human consumption accounting for about 20-30%. The demand is expected to rise to about 150,000 tons per year by the year 2014 (Jagwe and Nyapendi, 2004; MOA, 2006).

Soils in Africa are typically highly variable in fertility and how they respond to application of inputs (Hossner and Juo, 1999; AGRA, 2007). Soil nutrient depletion, nutrient mining and degradation have been considered serious threats to agricultural productivity and have been identified as major causes of decreased crop yields and per capita food production in sub-Saharan Africa (Smaling *et al*., 2002; Henao and Baanante, 2006). Smallholder farmers (with land holding ranging from 0.1 to 0.2 ha) undertake soybean cultivation, which presents the farmers with alternative cash income. In Kenya, FAO (2008) estimates an average soybean yield of 800 kg ha^{-1}, which has been stagnant since 1990. In Vision 2030 (Government of Kenya, 2007), soybean has been identified as one of the crops which will contribute to the economic growth pillar. Currently, about 5000 – 7000 metric tons of soybean is produced in Kenya against an annual local demand exceeding 100, 000 metric tons (Wasike *et al*., 2009). Therefore the deficit is met through imports whose varying estimates range from 50,000 to 100,000 tons annually (Karuga and Gachanja, 2004). In 2008, Kenya spent a total of US dollars 2.754 million to import soybean and its products (FAO, 2008), an amount that is a significant drain on her scarce foreign exchange.

Productivity of soybeans in Kenya, and particularly Western province, is low (450-560 kg/ha) (Chianu *et al*., 2009). This low productivity is a problem because Kenya needs more soybeans to satisfy a growing demand for stock feed and to improve nutrition of its human population. It has been demonstrated that it is possible to obtain soybean yields of 3000 –3600 kg ha^{-1} from improved varieties and good management practices (Chianu *et al*., 2008). Integrated Soil Fertility Management (ISFM) is one of the accepted paradigms for devising and disseminating technologies that can alleviate soil fertility decline in sub-Saharan Africa (Vanlauwe *et al*., 2002). Technically, ISFM advocates for the use of mineral and organic nutrient inputs to enhance and sustain agricultural productivity.

Declining soil fertility is a fundamental impediment to agricultural growth and a major reason for slow growth in food production by smallholder farmers in sub-Saharan Africa (Sanchez *et al.*, 1997; De Groote *et al*., 2003). Poor soybean production in Western Kenya has been partly attributed to low soil fertility and acid soils. In view of this problem, there is need to identify nutrients limiting soybean production in the highly variable soil fertility conditions and determine the possible yield potential through addressing the deficiencies.

1.2 Problem statement

Productivity of soils in western Kenya is hampered by deficiency of nutrients such as N, P and K (Lijzenga, 1998; Mbakaya, 2007). Apart from widespread limitations of N and P across the widely distributed highly weathered soils in sub-Saharan Africa, low organic matter content and soil acidity also contribute to low crop yields (Mbakaya, 2007). High population growth rate in SSA and Kenya in particular has put pressure on land, therefore, most smallholder farmers are practicing continuous cropping to meet their food requirements. This leads to significant decline in soil pH and exchangeable Ca and Mg levels (Hossner and Juo, 1999). Land use intensification without adequate nutrient inputs has led to declining crop yields and increased nutrient removal and deficiencies (Bationo *et al*., 1998; de Ridder *et al*., 2004). As efforts are made to restore fertility in SSA, it is clear that both cereals and legumes respond to fertilizer N and P applications from a range of sources and rates (FURP, 1994). In Africa, soil fertility is normally tackled by the application of fertilizers containing N, P and K though in inadequate rates. There is general response of cereals to NPK fertilizer application at current recommendations; however the response remains far below the potential level especially under on-farm conditions due to nutrient deficiencies and imbalances.

Responses of soybean to N and P have been studied and documented in soybean growing areas of Kenya but little has been done to establish the scale of macro (N, P and K) and micronutrient (Zn, Mo) deficiencies. Little investment has been made in research to establish the best nutrient management strategies in soybean under variable soil conditions as a way of improving soybean production and productivity. Therefore this study seeks to assess the effect of proper nutrient management in soybean production based on on-farm trials and document nutrient induced yield gaps as per the limiting nutrients.

1.3 Justification

About 80% of soybean in Kenya is consumed by the livestock industry with human consumption accounting for about 20-30%. The demand is expected to rise to about 150, 000 tons per year over the next ten years (Jagwe and Nyapendi, 2004; MOA, 2006; Karuga and Gachanja, 2004). Considering this, there is need to increase soybean production to supply the deficit which is normally met through imports. High population growth rate has put pressure on land hence the option of increasing the area of land under soybean to boost production is not feasible. Proper plant nutrient management under intensive agriculture provides a better option to increase soybean productivity under limited land resource.

The use of micronutrients in soybean production is one of the ways to boost up productivity. For instance, zinc plays an important role in formation of chlorophyll and growth hormones and is also associated with uptake of water. Molybdenum plays a key role in the process of dinitrogen (N_2) fixation and enzyme activation. Micronutrients also maintain balanced crop physiology and play a vital role in gaseous exchange (Narimani *et al*., 2010). According to Kobraee *et al*. (2011), zinc and iron deficiency limit growth, symbiosis, nodulation, photosynthesis, dry matter production and electron transport chain in soybean. Phosphorous deficiency has also been observed to limit nodulation by legumes and P fertilizer application can overcome the deficiency (Carsky *et al*., 2001). Manure also acts as an organic source of different macro and micronutrients. Hence there is need to investigate whether we can boost soybean yield either with only macronutrients, micronutrients, manure or a combination of all. Lime application in soybean fields has been found to increase pH and decrease toxic concentrations of Al and Mn (Raij *et al*., 1977). It can also cause an increase in N, P, K and S uptake (Quaggio *et al*., 1993) and the supply of Ca and Mg (Mascarenhas *et al*., 1976). Therefore determining the response of soybean to different nutrient applications will aid in guiding the best nutrient management strategy to boost soybean production. This study seeks to assess the nutrients limiting soybean production in western Kenya based on on-farm trials and to determine soybean response to nutrient application.

1.4 Objectives

1.4.1 Broad objective

To enhance soybean production by smallholder farmers in western Kenya through improved nutrient management.

1.4.2 Specific objectives

i. To determine the influence of inorganic fertilizers, cattle manure and lime application on nodulation of soybean in selected sites of western Kenya.
ii. To determine the effect of inorganic fertilizers, cattle manure and lime on growth and yield of soybean in selected sites of western Kenya.

1.5 Hypothesis

i. Application of inorganic fertilizers, cattle manure and lime will have no effect on nodulation, growth and yield of soybean in selected sites in western Kenya.

CHAPTER 2

LITERATURE REVIEW

2.1 Botany and ecology of soybean

Soybean (*Glycine max*) is a leguminous annual plant that belongs to the family Fabaceae. It is classified as an oilseed rather than a pulse by the Food and Agriculture Organization. The pods, stems and leaves are covered with fine brown or grey hairs. The leaves are trifoliate having 3-4 leaflets per leaf, and the leaflets are 6-15 cm long and 2-7 cm broad. Leaves fall before the seeds are mature. The self-fertile flowers are borne in the axil of the leaf and are white, pink or purple in color. The fruit is a hairy pod that grows in clusters of 3-5; each pod is 3-8 cm long and usually contains 2-4 seeds (Infonet-biovision, 2012). Soybean occurs in many sizes and many hull and seed coat colors ranging from black, brown, blue, yellow, green to mottled. It grows to a height of 60-120 cm, it's well adapted to diverse environments and matures in 3-6 months depending on variety, climate and location. Altitude influences temperature that in turn affects the initiation of flowering and maturity in soybean. At very high altitudes, flowering may not occur and the crop remains vegetative. Therefore, soybean is a crop that requires warm climates and is suitable for low to medium altitudes (Ogema *et al*., 1988). It is grown in Kenya from 0 to 2200 m altitude and under rainfall regime of 300 to 1200 mm per annum. In terms of pH range, Carter and Hartwig (1963) noted that nitrogen-fixing bacteria do not function effectively under low soil pH condition of 4.2 and below and recommended a pH range of 6 to 6.5 for optimum soybean growth. Soybean grows best when planted in pure stand. It improves soil fertility by fixing nitrogen from the atmosphere (Kasasa *et al*., 2000; Sanginga *et al*., 2003). Some varieties fix 44 to 103 kg N ha^{-1} annually (Sanginga *et al*., 2003), depending on the soil environment, N and P supply (Gan *et al*., 2002; Shimamura *et al*., 2002).

2.2 Nutritional importance of soybean

Soybean is a good source of protein, lipids, and other minerals. Soybean protein products can be good substitutes for animal products because unlike some other beans, it offers a complete protein profile since it contains all the essential amino acids except methionine (Lokuruka, 2010). The approximate composition of soybean is 40% protein, 21% oil, 34% carbohydrates and 5% ash (Greenberg and Hartung, 1998; Scott and Aldrich, 1983). In accounting for utilization of soybean, 39 products have been identified ranging from livestock feeds, salad oils and baby foods to industrial adhesives, putty and a number of uses in pharmaceuticals (Smith and Huyser, 1987). Soybean is a multipurpose crop and is used as human food, livestock feed, industrial purposes, and more recently, as a source of bio-energy (Myaka *et al*., 2005). Soybeans are cholesterol-free, high in calcium, phosphorous, and fiber, and have one of the lowest levels of saturated fat (BIDCO, 2005).

2.3 Soybean production in Kenya

Kenya produces 6000-7000 metric tons of soybean which is very low even within the African context. Production data suggests that area and yield have remained almost stagnant, with little annual change (FAO, 2008). The key soybean producing regions in Kenya are Western (Bungoma and Busia counties), accounting for nearly 50% of total smallholder planted area and production in 2003, Nyanza (Rachuonyo, Homabay districts) and Central (Kirinyaga and Muranag'a counties) both of which account for 11-12% (Chianu et al., 2008). In Kenya smallholder farmers (with land holding ranging from 0.1 to 0.2 ha) almost wholly undertake soybean cultivation. Information on involvement of large-scale farms in soybean production is rather scanty (Chianu *et al*., 2008). Therefore, soybean has been identified as one such crop that has the potential to make significant contributions to healthcare, income and livelihoods of smallholder farmers (Government of Kenya, 2002; Ohiokpehai and Osborne, 2003).

Nationally, FAO (2008) data estimates an average yield of 800 kg ha^{-1} of soybean which has been stagnant since 1990. However, there is regional variability in yield. Between 1999 and 2003, soybean annual average yield ranged from 560 kg ha^{-1} (Western province) to 1100 kg ha^{-1} (Eastern province). The average yields obtained in Rift Valley and Central provinces ranged in between these figures. It has, however, been demonstrated that it is possible to obtain soybean yields of 3000 –3600 kg ha^{-1} from improved varieties and good management practices (Chianu *et al*., 2006). According to the 2003 data, the highest farm-level soybean yield (1600 kg ha^{-1}) in Western province was obtained from Butere/Mumias district. Depending on the agro-ecological conditions, the expected yields from the six different soybean varieties (out of the 300 lines evaluated) recommended from the work of GTZ SBP project (1993 - 1998) range from 0.6 to 1.9 tons per ha. Of these six varieties, a survey carried out in 1998 indicated that Nyala, Gazelle, and Duicker were the most widespread, most probably due to seed availability, rather than the choice of farmers (Kaara *et al.*, 1998).

The estimated national production, around 2000 metric tons (FAO, 2008) has been mostly stagnant across the years. This indicates the existence of scope to further increase domestic production of soybean to satisfy local demand. It is therefore surprising that farmers in Kenya, who are yet to meet domestic demand, are complaining of lack of market for soybean.

Meanwhile, demand by the human consumption market segment in Kenya is expected to rise to about 150 000 metric tons per year by 2014 (Jagwe and Nyapendi, 2004).

2.4 Constraints in soybean production

Kenya faces a number of constraints in soybean production which include biotic, abiotic and socio-economic factors. The latter include competition for cheap imports that negatively influence domestic production, low farm gate prices of soybean and unreliable markets (Kaara *et al*., 1998). Also most of the varieties currently being cultivated have limited or no ability to naturally fix high amounts of nitrogen into soils and often require artificial *Rhizobium* inoculation, a technology that is often not accessible to many smallholder farmers (Chianu *et al*., 2008). In addition, most farmers do not use fertilizers, consequently, soil fertility has continued to decline resulting in low yields and competitiveness of locally produced soybean with imports (Chianu *et al*., 2008). Poor agronomic practices (e.g., inappropriate crop husbandry methods, low use of fertilizers, poor pest management, inadequate control of weeds, low combination of organic and mineral fertilizers) among the smallholder farmers has reduced yields of soybean where low soil fertility is already a problem.

2.5 Effect of nitrogen, phosphorous and potassium on nodulation, growth and yield of soybean

Phosphorous and potassium are two essential mineral nutrients required in relatively large amounts to maintain plant growth. They play a major role in improving crop yield and quality (Raghothama, 1999; Abel *et al*., 2002). Plant height, grain yield, biomass yield and P uptake efficiency of soybean increases at high levels of P application (Sahoo and Panda, 2001; Manje *et al*., 2011). Phosphorous and potassium deficient plants often have slow growth, poor drought resistance, weak stems and are more susceptible to lodging and plant diseases (Jack and Sarah, 2001).

The application of P on soybean increases the amount of N derived from the atmosphere by the soybean-*Bradyrhizobium* symbiotic system (Chien *et al*., 1993; Sanginga *et al*., 1996). Nitrogen nutrition in soybean is ensured by dinitrogen fixation and mineral nitrogen assimilation, which is important for high vegetative growth, high productivity and high seed protein content of soybean (Ronis *et al*., 1985). Only 25 to 65% of N in soybean dry matter originates from symbiotic nitrogen fixation, the remainder comes from soil-N (Harper, 1974). Varvel and Peterson (1992) noted that soybean plants act as sinks for soil-N and effectively use N regardless of source. Therefore N fertilization could benefit soybean. Helms and Watt (1991) also found out that N fertilization of soybean increases seed protein or oil concentration. Starter N application is aimed at providing soybean with readily available soil-N during seedling development, and has been shown to increase soybean grain yield (Touchstone and Rickerl, 1986).

2.6 Effect of zinc and molybdenum on nodulation, growth and yield of soybean

Salwa *et al*. (2011) stated that micronutrients are defined as substances that are crucial for crop growth; however, they are used in lower amounts than macronutrients. For instance, zinc plays an important role in synthesizing proteins, RNA and DNA (Welch 2001; Kobraee *et al*., 2011). Studies have also shown that zinc increases plant height, number of pods per plant, biological yield, harvest index and grain yield in soybean (Khampariva, 1996). It is also essential in chlorophyll production and pollen function (Ghasemian *et al*., 2010). Molybdenum on the other hand plays a key role in the process of atmospheric nitrogen fixation and enzyme activation (Shirpurkar *et al*., 2006).

2.7 Effect of organic manure and lime on nodulation, growth and yield of soybean

Organic matter affects crop growth and yield directly by supplying nutrients and indirectly by modifying soil physical properties such as stability of aggregates and porosity that can improve the root environment and stimulate plant growth (Darwish *et al*., 1995). Incorporation of organic matter has been shown to improve soil structure and water retention capacity (Bhagat and Verma, 1991), increase infiltration rate (Acharya *et al*., 1988) and decrease bulk density (Khaleel *et al*., 1981). Studies have also shown that organic matter application can benefit N-fixation in legumes, especially in soils low in indigenous organic matter (Olayinka *et al*., 1998). Organic manure acts as source of nutrients and organic matter, increase number, biodiversity and activity of the microbial population in soil. This has an effect on physical, chemical and biological parameters of the soil (Albiach *et al*., 2000). They are also a good substrate for the growth of microorganisms and maintain a favorable nutritional balance increasing nutrient use efficiency which is good for soybean growth (Nandini *et al*., 2013; Liu *et al*., 2008). Integrated use of organic manures and inorganic fertilizers meets micronutrient needs of soybean (Joshi *et al*., 2000) enhancing its growth attributes and yield (Lourduraj, 2000).

Studies have shown an increase in soybean nodule formation upon lime application due to favorable conditions for *Bradyrhizobium* spp. proliferation (France and Day, 1980; Okpara *et al*., 2004). Liming makes phosphorous available in the soil and promotes root development, carbohydrate and nitrogen metabolism in plants (Yargodin, 1984). Application of lime in soybean has also been demonstrated to increase pH, decrease toxic concentrations of Al and Mn, increase N, P, K and S uptake and also supply Ca and Mg (Mascarenhas *et al*., 1976; Raij *et al*., 1977; Quaggio *et al*., 1993).

CHAPTER 3

MATERIALS AND METHODS

3.1 Experimental sites

The study was carried out in farmers' fields in Butere, Siaya and Khwisero districts in western Kenya. The experimental sites included: Nyabeda in Siaya County, Masaba, Eshirali and Eshisa all of them located in Kakamega county with their respective coordinates noted in Table 1. The areas are humid with average temperature of 22-24^0 C. They have evenly distributed rainfall with annual averages ranging between 1200 and 1800 mm. The areas have two cropping seasons; first season (March to July) and second season (August to December). The predominant soils are ferralsols, which are strongly weathered, consisting of red to dusky red appearance with oxic B horizons. The soils have low soil fertility due to low mineral content and low cation exchange capacity (Jaetzold *et al*., 2006). The trial was carried out during the long rains (March to July 2012) and short rains (September to December 2012, and exclusively rain fed throughout the seasons.

Table 1: Agro-ecological conditions and soil physical characteristics of the study sites in western Kenya.

Parameter	Site			
	Eshirali	Masaba	Nyabeda	Eshisa
Altitude (m.a.s.l)	1448	1335	1329	1410
Latitude	00^{0} $09^{'}$ $22.5^{''}$ N	00^{0} $12^{'}$ $0.4^{''}$ N	00^{0} $08^{'}$ $22.3^{''}$ N	00^{0} $07^{'}$ $57.4^{''}$ N
Longitude	34^{0} $35^{'}$ $09.1^{''}$ E	34^{0} $27^{'}$ $39.5^{''}$ E	34^{0} $24^{'}$ $52.7^{''}$ E	34^{0} $30^{'}$ $49.9^{''}$ E
Cropping history	Maize-bean inter crop, maize	Sugarcane	Maize	Maize-bean intercrop
Soil texture	Clay	Clay	Clay	Clay loam
Sand (%)	13.12	31.90	12.12	43.12
Silt (%)	23.95	21.39	19.61	22.28
Clay (%)	62.93	46.71	68.27	34.60
AEZ	LM 1	LM 1	LM 1	LM 1

m.a.s.l: meters above sea level; AEZ: agro-ecological zones (Jaetzold *et al*., 2006); LM: lower midland.

3.2 Experimental design, treatments and crop husbandry

The design of the experiment was a randomized complete block design with three replications. Soybean variety SB 132-Squire was used in the trial. This variety is preferred by farmers because of its resistance to rust and high oil content. The treatments comprised: control-without inoculant and fertilizers; inoculation alone with USDA-110 inoculant; NPK; PK(-N); NP(-K); NK(-P); NPKSCaMgZnMo and NPKSCaMgZnMo+manure+lime. All the treatments except the control were planted with inoculated soybean. All the treatments were applied during planting as per the application rates required to achieve attainable yield as shown in Table 2 (FURP, 1994).

Table 2: Fertilizer application rates used in the study

Nutrient	**Rate**	**Source**
N	20 kg/ha	Urea (46 % N)
P	30 kg/ha	Triple super phosphate (46 % P_2O_5)
K	60 kg/ha	Muriate of potash (60 % K_2O)
S	23 kg/ha	MEA Sympal fertilizer (4 % S) + Mg/$ZnSO_4$
Ca	20 kg/ha	MEA Sympal fertilizer (10 % CaO)
Mg	5kg/ha	MEA Sympal fertilizer (1 % MgO) + $MgSO_4$
Zn	3 kg/ha	MEA Sympal fertilizer + $ZnSO_4$
Mo	3 kg/ha	$NaMoO_4$
Manure	10 t/ha	Cattle manure (from Maseno University field station)
Lime	5 t/ha	Dolomitic lime

Land preparation in each of the four sites was done by ploughing to a depth of 15-20 cm followed by harrowing to a moderate seedbed tilth using an ox-plough; commonly used method. Plot size was 6 m by 6 m with a net plot of 9 m^2 which was used for final yield assessment. Soybean was planted at a spacing of 45 cm by 5 cm at the onset of the rainy season giving a population of 444,444 plants/ha. The seed rate used was 40 kg/acre with one seed planted per hill. Lime was broadcast in the plots of interest then ploughed into the soil before planting. Manure was applied in the furrows and mixed with soil before placing fertilizer and seed. All fertilizers were applied by banding at the time of planting i.e. 2-5 cm from the planting lines to avoid direct contact of seed with fertilizer. They were pre-weighed using a balance of 1g accuracy for each plot before going to the field.

Inoculation was done with Biofix (USDA-110) inoculant from MEA, containing *Bradyrhizobium japonicum* at the rate of 10 g/kg of seed. Gum Arabica was mixed with warm water at the ratio of 2:5 to make a sticker solution. Then 10 ml of the sticker solution was added to a jug containing 1 kg of soybean seed, the mixture was thoroughly mixed to ensure the sticker was uniformly distributed. Inoculant (10 g) was eventually added then the contents carefully mixed to minimize death of the *Bradyrhizobium* bacterium mechanically. The control experiment without inoculant was planted first to avoid contamination. The trials were kept weed free by hand weeding using hoes to reduce competition for space, moisture, nutrients and light. Weeding was done starting with the control plot, to avoid contamination with *Bradyrhizobium* bacteria.

3.3 Data collection

Information about each site was collected. This included GPS readings, land use history for the previous two seasons (Table 1) and rainfall records using portable rain gauges (Appendix 1).

Crop emergence in all treatments was assessed at 2-3 weeks after sowing in all sites and plots. The emerged plants were counted and related to the expected number of plants as a percentage.

3.3.1 Diagnosis of nutrient deficiencies

One soil sample was collected from each plot before planting and application of manure or lime from a depth of 0-20 cm using an auger, mixed to form one composite sample for each block at each site. Hence a total of three soil samples were collected from each site. Laboratory analyses were done on the samples for soil organic carbon, total N, extractable ammonium N, extractable nitrate N, extractable P, extractable K, soil pH (water), electrical conductivity and particle size distribution.

3.3.1.1: Procedure for analysis of soil chemical characteristics

Soil pH and Electroconductivity

Soil pH was measured on 2.5:1 water to soil suspension, whereby 50 ml of distilled water was added to 20 g of soil. The mixture was stirred for 10 minutes then allowed to settle for 30 minutes. It was then stirred for 2 minutes and the pH of the soil suspension measured using a glass electrode pH meter calibrated with buffers of pH 4.00 and 7.00 (Jackson, 1973). The mixture was allowed to settle for 4 hrs then transferred to a Buchner filter funnel lined with highly retentive filter paper. The conductivity of the filtrate was measured using a conductivity meter.

Total Nitrogen

Total N was determined using a Block digester followed by distillation-titration method (Okalebo *et al*., 2002). Three grams of dry soil sample was put in a digestion tube. A digestion mixture containing; 3.2 g salicylic acid in 100 ml sulphuric acid-selenium mixture was added to the digestion tube. The mixture was digested at 110^0 C for 1 hour, removed, cooled then three successive 1 ml portions of hydrogen peroxide were added. Temperatures were then raised to 330^0 C turning the solution colourless. Contents were allowed to cool and 25 ml distilled water was added, mixed well until no more sediments could dissolve. The mixture was allowed to cool then made up to 50 ml with water. The mixture was allowed to settle and a clear solution taken from the top for analysis. A 10 ml aliquot of the sample solution was transferred to the reaction chamber of the still and 10 ml of 1% NaOH added. The mixture was steam-distilled immediately into 5 ml of 1% boric acid containing four drops of the mixed indicator until it turned green.

Distillate was removed and titrated with N/140 HCl, the end point reached when indicator changed from green through grey to a definite pink. Then total N was calculated as follows:

$$\% \text{ N} = \frac{(\text{A-B}) \; 0.2 \times \text{V} \times 100}{1000 \times \text{W} \times \text{AL}}$$

Where A=Volume of the titre HCl for the blank, B= volume of the titre HCl for the sample, V= final volume of the digestion, W= weight of the sample taken and AL= aliquot of the solution taken for analysis.

Ammonium and Nitrate Nitrogen:

Mineral N was determined by steam distillation method (Bremmner and Keeney, 1965). Ten grams of refrigerated soil sample was weighed into a plastic shaking bottle, and then 100 ml of 2 M KCl extracting sample was added. The contents were shaken at 250 rpm for 1 hour then filtered through No. 42 Whatman filter paper. Five milliliters of boric acid indicator solution was added into a 50 ml conical flask. A 10 ml aliquot of the soil extract was pipetted into the distillation flask, and then 0.2 g of ignited MgO was added directly to the bulb of the distillation flask. Distillation was done up to the 30 ml mark on the receiver conical flask. Ammonium-N content in the distillate was determined by titration with 0.002 N H_2SO_4 placed in a burette. The color change at the end point was from green to a permanent faint pink. At the end point, 1 ml of 0.002 N H_2SO_4 = 28 µg NH_4-N. After distilling NH_4-N from the sample extract, 0.2 g of Devardas’s alloy was added into the bulb of the distilling flask using a dry powder funnel. Then, NO_3-N was distilled in fresh boric acid. The NO_3 was converted into NH_4 and trapped in the conical flask. Eventually, the ammonium was estimated by titration with 0.002 N H_2SO_4. The NH_4-N in the soil sample was estimated as shown below:

$$NH_4\text{-}N\ (ppm) = \frac{(A\text{-}B) \times 28 \times V \times MCF \times 1000}{W \times AL}$$

Where A=titre volume of 0.002 N H_2SO_4 for the sample; B=titre volume for the blank; V=volume of the extracting solution; MCF=moisture correction factor; W=fresh weight of the sample; AL=sample aliquot.

Available soil phosphorous:

This was determined by Olsen method (Olsen *et al*., 1954). Two and a half grams of air dried (2 mm) soil was weighed into 250 ml shaking bottle. Then 50 ml of the Olsen extracting solution (0.5 M $NaHCO_3$ pH 8.5) was added to the bottle. The mixture was shaken well for 30 minutes on a mechanical shaker. The suspension was filtered through the No. 42 Whatman paper to get a filtrate that was used for the colorimetric P measurements. The concentration of P in the sample was calculated as follows:

$$P\ (ppm) = \frac{(A\text{-}B) \times V \times F \times 1000}{1000 \times W}$$

Where A=the concentration of P in the sample; B=the concentration of P in the blank; V=volume of the extracting solution; F=dilution factor; W=weight of the sample.

Organic Carbon:

Organic carbon was determined by the sulphuric acid and aqueous potassium dichromate mixture (modified Walkley-Black method) [Nelson and Sommers, 1975]. One gram of ground (60 mesh) soil was weighed into a digester tube. Five mililiters of potassium dichromate solution and 7.5 ml conc. H_2SO_4 were added into the tube. The mixture was pre-heated at 150^0 C for 30 minutes. The digest was transferred to a 100 ml conical flask after cooling, and 0.3 ml of indicator solution was added and mixed thoroughly using a magnetic stirrer. The digest was then titrated with ferrous ammonium sulphate solution, with endpoint reaching when the colour changed from greenish to brown. The titre was recorded and also the correct mean for the two blanks. Organic carbon was calculated as follows:

$$\text{Organic carbon (\%)} = \frac{(12/4000) \times 0.2 \times (V_b - V_s) \times 100}{W}$$

Where V_b = volume in ml of 0.2 M ferrous ammonium sulphate used to titrate reagent blank solution, V_s = volume in ml of 0.2 M ferrous ammonium sulphate used to titrate sample solution, 12/4000 = Milliequivalent weight of C in grams, 0.2 = molarity of ferrous ammonium sulphate solution and W = sample weight (g)

3.3.2 Nodulation and nodule assessment

Nodulation and nodule assessment under different treatments was done at 50% pod stage. Destructive sampling was done in a row outside the net plot in an area of 0.5 m by 0.45 m. Plants from this area were counted, above ground biomass cut and below ground roots and nodules dug out to a depth of 30 cm with a ball of soil surrounding them. Nodulation was scored at a scale of 1-5 whereby; 1 (<5 nodules on top 0-5 cm of root system), 2 (5-10 nodules on the top 0-5 cm of root system), 3 (>10 nodules on the top 0-5 cm of the root system), 4 (>10 nodules on the top 0-5 cm and <5 nodules on the lower part of the root system) and 5 (>10 nodules on the top 0-5 cm and on the lower part of the root system) as developed by N2Africa. The average score of all the plants in the sampling area was recorded as nodule mean score. Soil from the roots was then carefully removed and the roots stored in a cool box. In the laboratory, the roots were washed, nodules separated from the roots and both fresh weights of nodules and roots taken. Nodules in each treatment were also counted and divided by the number of plants sampled to give the number of nodules per plant. A 10 % sample of the total number of nodules counted per treatment was used for characterisation. The nodules were cut into half and observations made for the presence of any colour. Characterization was based on the following colours: red (active), pink (active), brown (active), white (inactive), green (inactive), and black (inactive). Eventually, the roots and nodules were oven dried at 65^0 C for 24 hours, and then their respective dry weights determined.

3.3.3 Assessment of soybean yield and yield components

Data on yield and yield components included above ground biomass, number of pods per plant, total stover (haulms + husks) yield, 100-seed weight and grain yield. Above ground biomass was assessed at 50% pod stage. Destructive sampling was done early in the morning from an area of 0.5 m by 0.45 m by cutting the plants at ground level, counting them and then their fresh weights determined, then the samples stored in a cool box. In the laboratory, the samples were air dried for about two days, oven dried at 65^0 C for 24 hours or to constant weight and then dry weights taken.

At maturity, all plants in the net plot (9 m^2) were counted and harvested early in the morning. Ten representative plants were sampled and their heights measured using a 1 m ruler. Pods on each of the ten plants were counted and then averaged to determine number of pods per plant. All pods in the net plot in each treatment were harvested and their total fresh weight determined. Random sub-samples (200-300 g) of harvested pods for each treatment were taken and their weights determined. In the laboratory the sub-samples were air-dried followed by oven drying at 65^0 C for 24 hours or to constant weight. Their dry weights were determined and recorded.

Haulms in the net plot were harvested by cutting them above the ground level, all intact leaves were removed and weights recorded. Sub-samples of haulms (200-300 g) from each treatment were taken and field weight recorded. They were then oven dried at 65^0 C for 24hrs or to constant weight and dry weights recorded. Grains were separated from the pods (sub-sample), fresh weights determined then oven dried at 65^0 C for 24 hours and dry weights recorded. Both fresh and dry weights of husks were also determined from the sub-sample. Eventually, a representative sample of 100 oven dried soybean seeds from each treatment was sampled and weighed to determine 100-seed weight. Harvest index was calculated from a ratio between grain yield and total biological yield (Grain yield+Stover yield), then expressed as a percentage as shown below.

$$\text{Harvest index (\%)} = \frac{\text{Grain yield (kg/ha)}}{\text{Total biological yield (kg/ha)}} \times 100$$

3.4 Data analysis

All data collected were subjected to analysis of variance (ANOVA) using Genstat statistical package (Rothamsted Research, VSN International, 2010, 13th edition). The treatment means were compared using the least significant difference (LSD) test at 5% probability level. Correlation analysis was done using SAS edition 9.2 and regressions done using Microsoft excel 2010.

CHAPTER 4

RESULTS

4.1 Soil characterization

Sites differed significantly ($P<0.01$) in soil pH, total carbon, total nitrogen, ammonium nitrogen, nitrate nitrogen and available phosphorous (Table 3). Masaba site had significantly ($P<0.01$) lower pH than all the other sites. Eshirali, Nyabeda and Eshisa had similar pH levels. Electrical conductivity and extractable potassium levels were not significantly ($P<0.05$) different among the sites. Nyabeda site had significantly ($P<0.001$) higher total carbon than all the other sites except Eshirali. Relative to the other sites, Masaba had significantly ($P<0.001$) the highest ammonium nitrogen content. Significantly ($P<0.001$) higher nitrate nitrogen was noted in Nyabeda than in the other sites. Available phosphorous in Eshisa site was significantly ($P<0.05$) higher than in all the other sites.

4.2 Effect of inorganic fertilizers, cattle manure and lime on nodulation of soybean

Site, treatment and site × treatment interaction had significant ($P<0.01$) effects on soybean nodule mean score in both seasons (Table 4). In season 1, Eshisa site had a significantly ($P<0.01$) higher nodule mean score than all the other sites in all treatments except NPK and NPKSCaMgZnMoManureLime. No difference in nodule mean score was noted among Eshirali, Masaba and Nyabeda sites in the control plots. Eshirali had significantly ($P<0.01$) higher nodule mean score than Masaba and Nyabeda in all treatments except control. Masaba and Nyabeda were not significantly different in nodule mean score in all the treatments.

Table 3: Soil chemical characteristics of the experimental sites.

	Soil properties							
Sites	**pH H_2O**	**EC**	**Total C (%)**	**Total N (%)**	**NH_4 (ppm)**	**NO_3 (ppm)**	**K (Cmol/kg)**	**Available P (ppm)**
Eshirali	5.51b	0.20a	2.18b	0.21b	6.32b	18.29b	0.37a	7.00a
Masaba	5.16a	0.20a	1.18a	0.13a	28.51c	4.67a	1.38a	5.67a
Nyabeda	5.72b	0.20a	2.35b	0.22b	1.83a	22.83c	1.11a	5.00a
Eshisa	5.59b	0.20a	1.03a	0.15a	4.15ab	16.82b	0.47a	11.00b
Mean	5.49	0.20	1.69	0.18	10.20	15.65	0.83	7.17
$LSD_{(0.05)}$	0.27	NS	0.23	0.05	3.40	4.50	1.53	3.78
CV (%)	2.50	0	6.80	13.10	16.70	14.40	91.90	26.4
F pr.	0.01	NS	<0.001	0.008	<0.001	<0.001	0.378	0.03

LSD: Least significant difference; CV: Coefficient of variation; NS: Non-significant. Similar letters in each column shows non-significant difference to LSD test at 5% level.

In Eshirali and Masaba, NPKSCaMgZnMoManureLime had significantly (P<0.01) higher nodule mean score than all the other treatments, whereas in Eshisa, NPKSCaMgZnMo registered significantly the highest nodule mean score. Inoculation alone significantly (P<0.01) increased nodule mean score relative to control only in Eshirali and Eshisa. Treatments had no significant effect on nodule score in Nyabeda. Overall, soybean grown in Eshisa had a significantly (P<0.01) higher nodule mean score than in all the other sites. In season 2, inoculation alone significantly increased nodule mean score relative to control only in Nyabeda and Eshisa. Overall nodule mean score was significantly (P<0.01) higher in NPKSCaMgZnMoManureLime than all other treatments except NP and NPK. Masaba site had a significantly lower nodule mean score than all other sites except Nyabeda.

Site, treatment and site × treatment interaction significantly ($P<0.001$) affected soybean number of nodules per plant in both seasons (Table 5). In season 1, NPKSCaMgZnMoManureLime had significantly ($P<0.001$) higher number of nodules per plant than all other treatments in Eshirali and Masaba. Inoculation alone significantly ($P<0.001$) increased number of nodules per plant relative to control only Eshirali. No differences in nodule number between control and inoculation alone were noted in Masaba, Nyabeda and Eshisa. Nodule number in NPK, PK, NP and NK treatments were not significantly ($P<0.001$) different at Masaba and Nyabeda. Overall, soybean grown in Eshisa had significantly ($P<0.001$) higher number of nodules per plant than all sites except Eshirali. In season 2, NPKSCaMgZnMoManureLime significantly ($P<0.001$) increased number of nodules per plant relative to other treatments in Eshirali, Masaba and Eshisa. In Nyabeda, NP had significantly ($P<0.001$) higher number of nodules per plant than all other treatments. Inoculation alone significantly ($P<0.001$) increased number of soybean nodules per plant relative to control in all sites. NK treatment recorded significantly lower nodule number than NPK, PK and NP in all sites. Masaba site had significantly lower number of nodules per plant than all other sites. Overall, soybean grown with NPKSCaMgZnMoManureLime had a significantly ($P<0.001$) higher number of nodules per plant than all the other treatments.

Table 4: Nodule mean score of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa during the 2012-2013 cropping seasons.

			Season 1		
Treatment	Eshirali	Masaba	Nyabeda	Eshisa	Mean
Control	1.10	1.00	1.23	2.22	1.39
Inoculation alone	1.85	1.06	1.10	3.06	1.77
NPK	2.79	1.19	1.52	2.25	1.94
PK	1.94	1.04	1.27	3.14	1.85
NP	1.77	1.00	1.48	2.60	1.71
NK	1.49	1.22	1.21	3.13	1.76
NPKSCaMgZnMo	2.30	1.22	1.11	4.40	2.26
NPKSCaMgZnMoManureLime	3.57	3.09	1.35	3.23	2.81
Mean	2.10	1.35	1.29	3.00	1.94
			Season 2		
Control	1.70	1.00	1.00	1.70	1.35
Inoculation alone	2.20	1.43	1.90	2.50	2.01
NPK	2.87	2.50	2.43	2.53	2.58
PK	2.87	1.90	1.90	2.67	2.33
NP	2.43	1.20	3.03	3.30	2.49
NK	2.10	1.30	1.70	2.00	1.78
NPKSCaMgZnMo	3.13	1.60	1.97	3.00	2.43
NPKSCaMgZnMoManureLime	3.40	2.87	2.63	3.67	3.14
Mean	2.59	1.73	2.07	2.67	2.26
		Season 1		Season 2	
$LSD_{(0.05)}$ Site		**0.20**		**0.25**	
$LSD_{(0.05)}$ Treatment		**0.29**		**0.35**	
$LSD_{(0.05)}$ Site*Treatment		**0.58**		**0.70**	
CV%		**18.3**		**19.1**	

LSD: Least significant difference; CV: Coefficient of variation; Scale: 1-5

Table 5: Mean number of nodules per plant of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa during the 2012-2013 cropping seasons.

			Season 1		
Treatment	Eshirali	Masaba	Nyabeda	Eshisa	Mean
Control	5.41	0.20	0.00	10.93	4.14
Inoculation alone	21.02	1.59	0.00	13.08	8.92
NPK	13.11	1.46	1.67	28.38	11.15
PK	14.73	0.82	0.33	21.17	9.26
NP	8.31	2.65	0.33	19.00	7.57
NK	7.06	4.07	1.00	22.53	8.66
NPKSCaMgZnMo	20.69	1.57	1.00	25.38	12.16
NPKSCaMgZnMoManureLime	55.00	19.33	1.00	23.61	24.74
Mean	18.17	3.96	0.67	20.51	10.83
			Season 2		
Control	12.00	0.00	0.00	9.00	5.25
Inoculation alone	19.33	4.00	19.33	17.33	13.75
NPK	25.33	11.67	17.00	18.67	18.17
PK	23.67	11.33	18.00	30.33	20.83
NP	24.00	0.67	28.00	23.33	19.00
NK	15.67	4.67	8.33	16.00	11.17
NPKSCaMgZnMo	28.67	0.67	19.67	29.00	19.50
NPKSCaMgZnMoManureLime	35.00	27.67	22.00	45.33	32.50
Mean	22.96	7.58	15.92	23.62	17.52
		Season 1		Season 2	
$LSD_{(0.05)}$ Site		**1.98**		**1.27**	
$LSD_{(0.05)}$ Treatment		**2.79**		**1.79**	
$LSD_{(0.05)}$ Site*Treatment		**5.59**		**3.59**	
CV%		**31.6**		**12.5**	

LSD: Least significant difference; CV: Coefficient of variation.

Site, treatment and site × treatment interaction had significant (P<0.001) effects on soybean nodule dry weight in both seasons (Table 6). In season 1, Eshisa had significantly (P<0.001) higher mean nodule dry weight than all the other sites in all treatments except control and inoculation alone. In Masaba and Eshisa, NPKSCaMgZnMoManureLime had significantly higher nodule dry weight than all other treatments. Plots treated with NPKSCaMgZnMo in Eshisa had significantly (P<0.001) higher nodule dry than all the other treatments except NPKSCaMgZnMoManureLime. In the same site, NPK, PK and NP had significantly higher nodule dry weight than control and inoculated plots. There were no significant (P<0.001) differences in soybean nodule dry weight among all the treatments in Nyabeda. Inoculation alone did not significantly (P<0.001) increase soybean nodule dry weight relative to control in all sites. Overall, soybean grown in Eshisa had significantly (P<0.001) higher nodule dry weight than soybean grown in all the other sites. In season 2, inoculation alone significantly (P<0.001) increased nodule dry weight relative to control in Nyabeda and Eshisa. NK treatment recorded significantly (P<0.001) lower nodule dry weight than NPK, PK and NP in all sites. In Masaba and Eshisa, NPKSCaMgZnMoManureLime significantly increased nodule dry weight over NPKSCaMgZnMo. Significantly (P<0.001) higher nodule dry weight was noted in Eshisa than all the other sites except Eshirali.

Table 6: Mean nodule dry weight (g) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa during the 2012-2013 cropping seasons.

			Season 1		
Treatment	Eshirali	Masaba	Nyabeda	Eshisa	Mean
Control	0.34	0.05	0.00	0.26	0.16
Inoculation alone	0.71	0.18	0.00	0.56	0.36
NPK	0.70	0.10	0.02	1.22	0.51
PK	0.63	0.08	0.00	1.31	0.51
NP	0.37	0.15	0.08	1.15	0.44
NK	0.27	0.40	0.00	0.95	0.41
NPKSCaMgZnMo	0.61	0.25	0.02	1.84	0.68
NPKSCaMgZnMoManureLime	0.92	1.89	0.10	2.48	1.35
Mean	0.57	0.40	0.03	1.22	0.55
			Season 2		
Control	0.60	0.00	0.00	0.77	0.34
Inoculation alone	0.85	0.31	0.58	1.40	0.78
NPK	1.21	1.44	0.82	1.82	1.32
PK	1.37	1.04	0.88	1.82	1.28
NP	1.13	0.08	1.07	1.57	0.96
NK	0.52	0.21	0.23	0.75	0.43
NPKSCaMgZnMo	1.42	0.14	0.72	1.14	0.86
NPKSCaMgZnMoManureLime	1.48	1.79	0.97	1.82	1.51
Mean	1.07	0.63	0.66	1.39	0.94
		Season 1		Season 2	
$LSD_{(0.05)}$ Site		**0.15**		**0.20**	
$LSD_{(0.05)}$ Treatment		**0.22**		**0.28**	
$LSD_{(0.05)}$ Site*Treatment		**0.43**		**0.56**	
CV%		**47.9**		**36.6**	

LSD: Least significant difference; CV: Coefficient of variation.

4.3 Effect of inorganic fertilizers, cattle manure and lime on growth, yield and yield components of soybean

Soybean above-ground biomass was significantly ($P<0.001$) affected by site, treatment and site × treatment interaction in both seasons (Table 7). In season 1, NPKSCaMgZnMoManureLime had significantly ($P<0.001$) higher above-ground biomass than all the other treatments in Eshirali, Masaba and Eshisa (Table 7). Inoculation did not significantly ($P<0.001$) increase soybean above-ground biomass relative to control in all sites except Eshisa. NPK treatment had significantly higher above-ground biomass than all the other treatments except NPKSCaMgZnMo and NPKSCaMgZnMoManureLime in Eshirali and Eshisa. Overall, the highest value of above-ground biomass was noted in Eshisa which was significantly different from Masaba. In season 2, NPKSCaMgZnMoManureLime had significantly ($P<0.001$) higher above-ground biomass than all other treatments in Nyabeda and Eshisa. Similar observations were noted in Eshirali and Masaba except that NPKSCaMgZnMoManureLime did not significantly differ from NPK and NPKSCaMgZnMo in Eshirali and NPKSCaMgZnMo in Masaba. Inoculation alone significantly ($P<0.001$) increased soybean above-ground biomass relative to control in all the sites. Also, application of NP significantly ($P<0.001$) increased soybean above-ground biomass relative to control, inoculation alone, PK and NK in all sites except Eshirali where it had significantly lower above-ground dry matter than PK. Under most treatments, above-ground biomass in Nyabeda and Eshisa was significantly ($P<0.001$) higher than that of Masaba and Eshirali. Masaba site had significantly the lowest above-ground biomass in all the treatments compared to other sites.

Table 7: Mean above ground biomass (kg/ha) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa during the 2012-2013 cropping seasons.

			Season 1		
Treatment	Eshirali	Masaba	Nyabeda	Eshisa	Mean
Control	1654	1061	1318	1204	1309
Inoculation alone	1731	1019	1344	1838	1483
NPK	2214	1056	2065	2898	2058
PK	1658	1077	2020	2439	1798
NP	1864	827	2182	1914	1697
NK	1193	477	1687	2066	1356
NPKSCaMgZnMo	1984	1246	2944	2563	2184
NPKSCaMgZnMoManureLime	3553	1573	3167	3494	2947
Mean	1981	1042	2091	2302	1854
			Season 2		
Control	1110	618	1638	1307	1168
Inoculation alone	1584	1007	2269	2086	1737
NPK	2682	1518	2869	3129	2549
PK	2047	1509	2475	2502	2133
NP	1695	1849	3227	3342	2528
NK	1407	1157	1749	1958	1568
NPKSCaMgZnMo	2582	2438	3124	2415	2640
NPKSCaMgZnMoManureLime	2798	2562	3664	3964	3247
Mean	1988	1582	2627	2588	2196
		Season 1		Season 2	
$LSD_{(0.05)}$ Site		**145.4**		**106.8**	
$LSD_{(0.05)}$ Treatment		**205.6**		**151.1**	
$LSD_{(0.05)}$ Site*Treatment		**411.2**		**302.2**	
CV%		**13.6**		**8.4**	

LSD: Least significant difference; CV: Coefficient of variation

Site, treatment and site × treatment interaction had significant ($P<0.001$) effects on soybean plant height in both seasons (Table 8). In season 1, NPKSCaMgZnMoManureLime recorded a significantly ($P<0.001$) higher plant height than all other treatments in Eshirali, Masaba and Nyabeda. In Eshisa, NPKSCaMgZnMo had a significantly higher plant height than all other treatments except NPKSCaMgZnMoManureLime and NK. Eshisa site recorded significantly ($P<0.001$) higher plant height than the other sites in all the treatments except NPKSCaMgZnMoManureLime. NPK significantly ($P<0.001$) increased soybean plant height relative to all treatments except NP, NPKSCaMgZnMo and NPKSCaMgZnMoManureLime in Eshirali and Masaba. Inoculation alone significantly ($P<0.001$) increased soybean plant height relative to control only in Eshirali and Eshisa. Overall, soybean grown in Eshisa had significantly higher plant height than in Eshirali, Masaba and Nyabeda. In season 2, inoculation alone significantly increased soybean plant height relative to control only in Eshisa. On average, NPKSCaMgZnMoManureLime had significantly ($P<0.001$) higher plant height than all other treatments except NP, PK, NPK and NPKSCaMgZnMo. Overall, soybean grown in Eshisa recorded a significantly higher plant height than all other sites except Eshirali.

Site, treatment and site × treatment interaction significantly ($P<0.001$) affected number of soybean pods per plant in both seasons (Table 9). In season 1, control, inoculation alone, NP, NK and NPKSCaMgZnMoManureLime treatments had significantly ($P<0.001$) higher number of pods per plant in Eshisa than in all other sites. Application of NPKSCaMgZnMoManureLime significantly ($P<0.001$) increased the number of pods per plant across all sites. Inoculation alone significantly ($P<0.001$) increased the number of pods per plant relative to the control only in

Eshirali and Eshisa. Significant increase in the number of pods per plant was noted in NPKSCaMgZnMo relative to NPK, PK, NP and NK in Masaba, Nyabeda and Eshisa. Overall, Eshisa site had a significantly higher number of pods per plant than Eshirali, Masaba and Nyabeda (Table 9). In season 2, control, inoculation alone, NK and NPKSCaMgZnMoManureLime had significantly ($P<0.001$) higher number of pods per plant in Eshisa than in all other sites. Application of NPKSCaMgZnMoManureLime had the highest number of pods per plant in Eshirali, Masaba and Eshisa a value that was significantly ($P<0.001$) different from control, inoculation alone, NP and NK in all these sites. Significantly ($P<0.001$) lower number of pods per plant were noted in NK than in NPK, PK and NP in Eshirali, Nyabeda and Eshisa. Inoculation alone significantly increased the number of pods per plant relative to control only in Eshisa. Application of NPKSCaMgZnMoManureLime significantly ($P<0.001$) increased the number of pods per plant over NPKSCaMgZnMo only in Eshisa. Overall, Eshisa site had a significantly ($P<0.001$) higher number of pods per plant than all the other sites (Table 9).

Table 8: Mean plant height (cm) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa during the 2012-2013 cropping seasons.

			Season 1		
Treatment	Eshirali	Masaba	Nyabeda	Eshisa	Mean
Control	50.35	25.40	53.60	67.07	49.10
Inoculation alone	53.97	28.10	53.90	71.00	51.74
NPK	61.27	36.80	62.50	69.00	57.39
PK	56.53	28.20	64.50	70.27	54.87
NP	59.00	34.57	63.60	68.33	56.37
NK	56.30	26.07	61.70	71.50	53.89
NPKSCaMgZnMo	60.25	38.67	67.77	74.67	60.34
NPKSCaMgZnMoManureLime	71.90	47.50	71.90	71.80	65.81
Mean	58.71	33.16	62.43	70.45	56.19
			Season 2		
Control	49.80	44.17	49.40	56.23	49.90
Inoculation alone	52.73	44.00	51.00	64.67	53.10
NPK	71.00	56.07	60.10	69.97	64.28
PK	70.70	52.40	59.80	70.40	63.33
NP	66.77	55.43	59.17	67.20	62.14
NK	51.37	52.93	48.73	59.73	53.19
NPKSCaMgZnMo	71.50	62.43	58.77	68.43	65.28
NPKSCaMgZnMoManureLime	77.70	60.63	59.73	78.17	69.06
Mean	63.95	53.51	55.84	66.85	60.04
		Season 1		Season 2	
$LSD_{(0.05)}$ Site		**1.19**		**2.25**	
$LSD_{(0.05)}$ Treatment		**1.68**		**3.19**	
$LSD_{(0.05)}$ Site*Treatment		**3.35**		**6.38**	
CV%		**3.7**		**6.5**	

LSD: Least significant difference; CV: Coefficient of variation

Table 9: Mean number of pods per plant of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa during the 2012-2013 cropping seasons.

			Season 1		
Treatment	Eshirali	Masaba	Nyabeda	Eshisa	Mean
Control	14.33	5.20	25.00	40.33	21.22
Inoculation alone	22.33	6.30	25.00	44.67	24.58
NPK	33.00	11.45	51.33	53.33	37.28
PK	25.33	11.87	42.00	46.33	31.38
NP	23.33	10.97	45.33	56.00	33.91
NK	23.33	8.00	42.67	48.33	30.58
NPKSCaMgZnMo	27.67	11.75	55.33	58.67	38.35
NPKSCaMgZnMoManureLime	60.00	19.40	55.67	66.33	50.35
Mean	28.67	10.62	42.79	51.75	33.46
			Season 2		
Control	9.93	8.27	13.30	18.87	12.59
Inoculation alone	12.5	9.57	16.87	27.73	16.67
NPK	26.67	16.47	19.50	29.67	23.08
PK	25.23	13.10	19.00	27.27	21.15
NP	19.03	13.77	22.67	24.23	19.93
NK	13.37	13.67	21.00	25.40	18.36
NPKSCaMgZnMo	27.17	18.67	26.60	28.37	25.20
NPKSCaMgZnMoManureLime	27.30	20.77	23.37	31.13	25.64
Mean	20.15	14.28	20.29	26.58	20.33
		Season 1		Season 2	
$LSD_{(0.05)}$ Site		**1.74**		**1.36**	
$LSD_{(0.05)}$ Treatment		**2.46**		**1.93**	
$LSD_{(0.05)}$ Site*Treatment		**4.91**		**3.86**	
CV%		**9.0**		**11.6**	

LSD: Least significant difference; CV: Coefficient of variation

Site and treatment significantly ($P<0.001$) affected soybean 100-seed weight in both seasons. Significant ($P<0.001$) site × treatment interaction effects were noted in season 1, whereas in season 2, there was no significant site × treatment interaction effects on soybean 100-seed weight (Table 10). In season 1, Masaba site had significantly ($P<0.001$) higher soybean 100-seed weight than Eshirali, Nyabeda and Eshisa in all treatments. NPKSCaMgZnMoManureLime had the highest values of 100-seed weight in Eshirali, Masaba and Nyabeda whereas in Eshisa the highest value was noted in NPKSCaMgZnMo. Inoculation alone significantly ($P<0.001$) increased soybean 100-seed weight relative to control only in Masaba. In season 2, on average, NPKSCaMgZnMoManureLime had significantly ($P<0.001$) higher soybean 100-seed weight than all other treatments except NPKSCaMgZnMo. Inoculation alone significantly ($P<0.001$) increased soybean 100-seed weight relative to the control in Masaba and Nyabeda. NPK and PK treatments had significantly ($P<0.001$) higher 100-seed weight than control and inoculation alone. Soybean grown in Eshisa had a significantly ($P\leq0.05$) higher 100-seed weight than soybean grown in Eshirali and Masba.

Site, treatment and site × treatment interaction significantly ($P<0.001$) affected soybean grain yield in both seasons (Table 11). In season 1, Eshisa had significantly ($P<0.001$) higher grain yields than the other sites in all the treatments except NPKSCaMgZnMoManureLime compared to all the other sites. In Eshirali, Masaba and Nyabeda sites, NPKSCaMgZnMoManureLime had a significantly higher grain yield than all other treatments. In Eshisa, NPKSCaMgZnMo had significantly higher grain yield than all the other treatments.

Table 10: Mean 100-seed weight (g) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa during the 2012-2013 cropping seasons.

			Season 1		
Treatment	Eshirali	Masaba	Nyabeda	Eshisa	Mean
Control	10.01	16.18	9.13	10.11	11.36
Inoculation alone	9.90	17.50	9.61	10.24	11.81
NPK	10.12	17.33	9.21	10.08	11.69
PK	10.51	17.00	9.39	9.61	11.63
NP	9.53	18.33	9.87	10.11	11.96
NK	9.92	16.18	9.46	10.27	11.45
NPKSCaMgZnMo	10.58	18.00	8.76	10.82	12.04
NPKSCaMgZnMoManureLime	10.77	19.50	10.49	10.78	12.88
Mean	10.17	17.50	9.49	10.25	11.85
			Season 2		
Control	17.33	17.53	16.13	18.13	17.28
Inoculation alone	17.70	18.87	18.77	18.30	18.41
NPK	19.97	19.07	19.07	19.83	19.48
PK	18.83	20.47	19.67	20.20	19.79
NP	17.03	18.50	19.40	20.23	18.79
NK	18.03	17.80	18.23	18.40	18.12
NPKSCaMgZnMo	19.87	19.23	20.73	20.93	20.19
NPKSCaMgZnMoManureLime	20.87	20.20	21.93	20.83	20.96
Mean	18.70	18.96	19.24	19.61	19.13
		Season 1		Season 2	
$LSD_{(0.05)}$ Site		**0.38**		**0.63**	
$LSD_{(0.05)}$ Treatment		**0.54**		**0.90**	
$LSD_{(0.05)}$ Site*Treatment		**1.09**		**NS**	
CV%		**5.6**		**5.7**	

LSD: Least significant difference; NS: Non significant; CV: Coefficient of variation

Table 11: Mean grain yield (kg/ha) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa during the 2012-2013 cropping seasons.

			Season 1		
Treatment	Eshirali	Masaba	Nyabeda	Eshisa	Mean
Control	1222	43	1360	2431	1264
Inoculation alone	1235	64	2024	2526	1462
NPK	1754	162	2033	2477	1606
PK	1433	225	2142	2536	1584
NP	1712	420	2467	2768	1842
NK	1251	44	1254	3054	1401
NPKSCaMgZnMo	2102	386	2331	3785	2151
NPKSCaMgZnMoManureLime	3178	1398	3149	3295	2755
Mean	1736	343	2095	2859	1758
			Season 2		
Control	1152	850	1337	1615	1238
Inoculation alone	1518	1110	2082	2267	1744
NPK	3386	1856	2438	3252	2733
PK	2858	1608	2461	2636	2391
NP	2314	1385	3041	3072	2453
NK	1844	1398	2351	2587	2045
NPKSCaMgZnMo	3585	1800	2821	3164	2842
NPKSCaMgZnMoManureLime	4995	3041	3991	3711	3934
Mean	2706	1631	2565	2788	2423
		Season 1		Season 2	
$LSD_{(0.05)}$ Site		**76.6**		**159.7**	
$LSD_{(0.05)}$ Treatment		**108.3**		**225.9**	
$LSD_{(0.05)}$ Site*Treatment		**216.5**		**451.8**	
CV%		**7.5**		**11.4**	

LSD: Least significant difference; CV: Coefficient of variation

Inoculation alone significantly (P<0.001) increased grain yield relative to control only in Nyabeda. Application of NP had significantly (P<0.001) higher soybean grain yield than the control, inoculation alone, PK and NK treatments in Eshirali, Masaba and Nyabeda. NK treatment had significantly (P<0.001) lower grain yield than NP and PK in all the sites except Eshisa. Across the treatments, grain yield was significantly (P<0.001) different among the sites with the highest quantity noted in Eshisa followed by Eshirali, Nyabeda and Masaba in decreasing order. In season 2, NPKSCaMgZnMoManureLime treatment had a significantly higher grain yield than all other treatments across all sites. Inoculation alone significantly (P<0.001) increased soybean grain yield relative to the control in Nyabeda and Eshisa sites but not in Eshirali and Masaba. Masaba had significantly (P<0.001) the lowest grain yield across all the treatments. In Eshirali, NK had a significantly lower grain yield than NPK, PK and NP. Eshirali also had the highest grain yield in the limed plots.

Soybean stover yield was significantly (P<0.001) affected by site, treatment and site × treatment interaction (Table 12). In season 1, Eshisa site had significantly higher stover yield than all the other sites in control, inoculation alone, NP and NK plots. Masaba site had significantly (P<0.001) lower stover yield than all the other sites across all the treatments. Nyabeda's stover yield outperformed Eshirali's and Masaba's in all the treatments. In Masaba and Nyabeda, NPKSCaMgZnMoManureLime had a significantly higher stover yield than all treatments. In Eshirali, NPKSCaMgZnMoManureLime had a significantly higher stover yield than all other treatments except NPK. The NK treatment had significantly lower stover yield than most of the other treatments in all the sites except Eshisa. Inoculation alone significantly increased stover yield relative to control only in Eshisa. Mean stover yield in Eshisa was significantly (P<0.001) higher than all other sites except Nyabeda. In season 2, NPKSCaMgZnMoManureLime had significantly (P<0.001) higher stover yield than all other treatments in all the sites except Eshisa. In Eshisa, NPKSCaMgZnMoManureLime had a significantly higher stover yield than all other treatments except NPK. Inoculation alone did not significantly increase soybean stover yield relative to control in all sites. In Eshirali and Nyabeda NP significantly (P<0.001) increased stover yield relative to control, inoculation alone, NPK, PK and NK.

Site, treatment and site × treatment interaction significantly (P<0.001) affected soybean harvest index in both seasons (Table 13). In season 1, inoculation alone significantly increased harvest index relative to the control in Masaba and Nyabeda. On average, significantly (P<0.001) higher harvest index was noted in NPKSCaMgZnMoManureLime compared to other treatments. There were no significant (P<0.001) differences in harvest index among NPK, PK, NP and NK treatments. Overall, Eshisa site recorded a significantly (P<0.001) higher harvest index than all the other sites. In season 2, inoculation alone significantly (P<0.001) increased soybean harvest index relative to the control in all sites. Significantly (P<0.001) lower harvest index was noted in NP treatment than in NPK, PK and NK treatments in Eshirali and Masaba. Application of NPKSCaMgZnMoManureLime significantly (P<0.001) increased soybean harvest index over NPKSCaMgZnMo only in Masaba. Masaba site recorded significantly (P<0.001) lower harvest index than all the sites except Eshirali.

Table 12: Mean stover yield (kg/ha) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa during the 2012-2013 cropping seasons.

			Season 1		
Treatment	Eshirali	Masaba	Nyabeda	Eshisa	Mean
Control	1540	211	1737	1656	1286
Inoculation alone	1542	83	1911	2169	1426
NPK	1674	166	2010	1899	1437
PK	1375	226	2413	2155	1542
NP	1476	491	2085	2500	1638
NK	855	57	1990	2580	1371
NPKSCaMgZnMo	1543	385	2672	2873	1868
NPKSCaMgZnMoManureLime	1851	1160	3130	2661	2201
Mean	1482	347	2244	2312	1638
			Season 2		
Control	2340	1588	1993	2041	1990
Inoculation alone	2272	1410	2333	2366	2095
NPK	3301	1557	2605	3617	2770
PK	2918	1893	2532	3117	2615
NP	3770	2247	3049	2960	3006
NK	1987	1715	1796	2702	2050
NPKSCaMgZnMo	4415	2533	2570	3132	3162
NPKSCaMgZnMoManureLime	5247	3053	3655	3969	3981
Mean	3281	2000	2567	2988	2709
		Season 1		Season 2	
$LSD_{(0.05)}$ Site		**100.4**		**133.5**	
$LSD_{(0.05)}$ Treatment		**142.0**		**188.8**	
$LSD_{(0.05)}$ Site*Treatment		**284.0**		**377.6**	
CV%		**10.9**		**8.5**	

LSD: Least significant difference; CV: Coefficient of variation.

Table 13: Mean harvest index (%) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa during the 2012-2013 cropping seasons.

			Season 1		
Treatment	Eshirali	Masaba	Nyabeda	Eshisa	Mean
Control	44.26	19.24	43.91	59.47	41.72
Inoculation alone	44.48	43.44	51.36	53.80	48.27
NPK	51.16	49.60	50.13	56.60	51.87
PK	51.12	49.91	46.99	54.04	50.52
NP	53.74	46.85	54.21	52.55	51.84
NK	59.32	43.50	39.29	54.19	49.07
NPKSCaMgZnMo	57.49	50.04	47.00	56.86	52.85
NPKSCaMgZnMoManureLime	63.17	54.77	50.14	55.32	55.85
Mean	53.09	44.67	47.88	55.36	50.25
			Season 2		
Control	32.92	34.91	40.44	44.22	38.12
Inoculation alone	40.01	44.05	47.07	48.92	45.01
NPK	50.64	53.25	48.29	47.18	49.84
PK	49.29	45.91	49.27	45.81	47.57
NP	38.30	37.82	49.93	50.91	44.24
NK	48.16	44.68	56.74	48.95	49.63
NPKSCaMgZnMo	44.82	41.53	52.29	50.25	47.22
NPKSCaMgZnMoManureLime	48.75	49.64	52.16	48.32	49.72
Mean	44.11	43.97	49.52	48.07	46.42
		Season 1		Season 2	
$LSD_{(0.05)}$ Site		**1.78**		**1.60**	
$LSD_{(0.05)}$ Treatment		**2.51**		**2.26**	
$LSD_{(0.05)}$ Site*Treatment		**5.03**		**4.53**	
CV%		**6.1**		**6.0**	

LSD: Least significant difference; CV: Coefficient of variation.

4.4 Relationship among evaluated soybean parameters

There were significant positive correlations in Eshirali between grain yield and above-ground biomass (r=0.907, P<0.01), nodule number (r=0.886, P<0.01), nodule mean score (r=0.834, P<0.01), plant height (r=0.902, P<0.01), pod number (r=0.884, P<0.01), stover yield (r=0.742, P<0.01), 100-seed weight (r=0.631, P<0.01) and harvest index (r=0.683, P<0.01) (Table 14). Above-ground biomass positively correlated with nodule number (r=0.858, P<0.01), nodule mean score (r=0.832, P<0.01), plant height (r=0.868, P<0.01), pod number (r=0.896, P<0.01), stover yield (r=0.734, P<0.01), 100-seed weight (r=0.643, P<0.01) and harvest index (r=0.574, P<0.05). Number of pods per plant positively correlated with nodule number (r=0.868, P<0.01), plant height (r=0.842, P<0.01), stover yield (r=0.616, P<0.01), 100-seed weight (r=0.584, P<0.01) and harvest index (r=0.671, P<0.01). Harvest index also positively correlated with nodule number (r=0.507, P<0.05), nodule mean score (r=0.561, P<0.05) and plant height (r=0.642, P<0.01).

Table 14: Pearson correlation coefficients among evaluated parameters in soybean grown on-farm in Eshirali.

	GY	AGB	NNP	NDW	NMS	PH	NPP	SY	SDW	HI
GY	1.00									
AGB	0.907**	1.00								
NNP	0.886**	0.858**	1.00							
NDW	0.571*	0.644**	0.651*	1.00						
NMS	0.834**	0.832**	0.767**	0.721**	1.00					
PH	0.902**	0.868**	0.845**	0.579*	0.814**	1.00				
NPP	0.884**	0.896**	0.868**	0.631**	0.842**	0.943**	1.00			
SY	0.742**	0.734**	0.734**	0.557*	0.673**	0.656**	0.616**	1.00		
SDW	0.631**	0.643**	0.617*	0.424*	0.534*	0.560*	0.584*	0.433*	1.00	
HI	0.683**	0.574*	0.507*	0.273ns	0.561*	0.642**	0.671**	-0.17ns	0.459*	1.00

ns: not significant; * significant and ** highly significant at 5% probability level; GY: grain yield (kg/ha); AGB: above-ground biomass (kg/ha); NNP: number of pods per plant; NDW: nodule dry weight (g); NMS: nodule mean score; PH: plant height (cm); NPP: number of pods per plant; SY: stover yield (kg/ha); SDW: 100-seed dry weight (g) and HI: harvest index (%).

In Masaba (Table 15), significant positive correlations were noted between grain yield and above-ground biomass (r=0.626, P<0.01), nodule mean score (r=0.841, P<0.01), plant height (r=0.761, P<0.01), pod number (r=0.850, P<0.01), stover yield (r=0.877, P<0.01) and 100-seed weight (r=0.522, P<0.05). Above-ground biomass significantly correlated with nodule mean score (r=0.493, P<0.05), plant height (r=0.674, P<0.05), pod number (r=0.644, P<0.05), stover yield (r=0.660, P<0.05) and 100-seed weight (r=0.568, P<0.05). Significant positive correlations were noted between number of pods per plant and nodule number (r=0.591, P<0.05), plant height (r=0.837, P<0.01) stover yield (r=0.758, P<0.01) and harvest index (r=0.617, P<0.01).

Table 15: Pearson correlation coefficients among evaluated parameters in soybean grown on-farm in Masaba.

	GY	AGB	NNP	NDW	NMS	PH	NPP	SY	SDW	HI
GY	1.00									
AGB	0.626**	1.00								
NNP	0.740**	0.375ns	1.00							
NDW	0.768**	0.408*	0.934**	1.00						
NMS	0.841**	0.493*	0.900**	0.932**	1.00					
PH	0.761**	0.674*	0.502*	0.501*	0.626**	1.00				
NPP	0.850**	0.644*	0.591*	0.704**	0.741**	0.837**	1.00			
SY	0.877**	0.660*	0.582*	0.537*	0.621**	0.769**	0.758**	1.00		
SDW	0.552*	0.568*	0.544*	0.535*	0.556*	0.547*	0.491*	0.507*	1.00	
HI	0.582*	0.217ns	0.442*	0.532*	0.582*	0.446*	0.617**	0.223ns	0.368ns	1.00

ns: not significant; * significant and ** highly significant at 5% probability level; GY: grain yield (kg/ha); AGB: above-ground biomass (kg/ha); NNP: number of pods per plant; NDW: nodule dry weight (g); NMS: nodule mean score; PH: plant height (cm); NPP: number of pods per plant; SY: stover yield (kg/ha); SDW: 100-seed dry weight (g) and HI: harvest index (%).

In Nyabeda (Table 16), significant positive correlations were noted between grain yield and above-ground biomass (r=0.798, P<0.01), plant height (r=0.608, P<0.01), pod number (r=0.647, P<0.01), stover yield (r=0.784, P<0.01), 100-seed weight (r=0.635, P<0.05) and harvest index (r=0.618, P<0.01). Above-ground biomass positively correlated with nodule number (r=0.649, P<0.05), plant height (r=0.741, P<0.01), pod number (r=0.735, P<0.01) and stover yield (r=0.869, P<0.01). Number of pods per plant positively correlated with nodule number (r=0.664, P<0.01), plant height (r=0.664, P<0.01) and stover yield (r=0.544, P<0.05). There was also a significant positive correlation between plant height and stover yield (r=0.678, P<0.01).

Table 16: Pearson correlation coefficients among evaluated parameters in soybean grown on-farm in Nyabeda.

	GY	AGB	NNP	NDW	NMS	PH	NPP	SY	SDW	HI
GY	1.00									
AGB	0.798**	1.00								
NNP	0.455*	0.649*	1.00							
NDW	0.665**	0.646*	0.579*	1.00						
NMS	0.412*	0.419*	0.504*	0.563*	1.00					
PH	0.608**	0.741**	0.570*	0.604*	0.391ns	1.00				
NPP	0.647**	0.735**	0.664**	0.444*	0.436*	0.664**	1.00			
SY	0.784**	0.869**	0.494*	0.566*	0.366ns	0.678**	0.544*	1.00		
SDW	0.635*	0.516*	0.329ns	0.644*	0.394ns	0.421*	0.426*	0.482*	1.00	
HI	0.618**	0.200ns	-0.23ns	0.346ns	0.205ns	0.132ns	0.397ns	-0.15ns	0.373ns	1.00

ns: not significant; * significant and ** highly significant at 5% probability level; GY: grain yield (kg/ha); AGB: above-ground biomass (kg/ha); NNP: number of pods per plant; NDW: nodule dry weight (g); NMS: nodule mean score; PH: plant height (cm); NPP: number of pods per plant; SY: stover yield (kg/ha); SDW: 100-seed dry weight (g) and HI: harvest index (%).

In Eshisa (Table 17), significant positive correlations were noted between grain yield and above-ground biomass ($r=0.649$, $P<0.05$), nodule number ($r=0.590$, $P<0.05$), nodule mean score ($r=0.671$, $P<0.01$), plant height ($r=0.733$, $P<0.01$), pod number ($r=0.698$, $P<0.01$) stover yield ($r=0.878$, $P<0.01$) and 100-seed weight ($r=0.684$, $P<0.01$). Above-ground biomass positively correlated with nodule number ($r=0.761$, $P<0.01$), pod number ($r=0.795$, $P<0.01$) and stover yield ($r=0.651$, $P<0.05$). Number of pods per plant also positively correlated with nodule number ($r=0.590$, $P<0.05$), plant height ($r=0.524$, $P<0.05$), stover yield ($r=0.691$, $P<0.01$) and 100-seed weight ($r=0.625$, $P<0.05$)

Table 17: Pearson correlation coefficients among evaluated parameters in soybean grown on-farm in Eshisa.

	GY	AGB	NNP	NDW	NMS	PH	NPP	SY	SDW	HI
GY	1.00									
AGB	0.649*	1.00								
NNP	0.590*	0.761**	1.00							
NDW	0.544*	0.697**	0.561*	1.00						
NMS	0.671**	0.486*	0.472*	0.575*	1.00					
PH	0.733**	0.587*	0.581*	0.446*	0.600*	1.00				
NPP	0.698**	0.795**	0.590*	0.589*	0.380ns	0.524*	1.00			
SY	0.878**	0.651*	0.600*	0.512*	0.617*	0.716**	0.691**	1.00		
SDW	0.684**	0.413*	0.420*	0.450*	0.454*	0.627*	0.628*	0.637*	1.00	
HI	0.472*	-0.21ns	-0.17ns	-0.18ns	-0.18ns	-0.23ns	-0.23ns	-0.26ns	0.269ns	1.00

ns: not significant; * significant and ** highly significant at 5% probability level; GY: grain yield (kg/ha); AGB: above-ground biomass (kg/ha); NNP: number of pods per plant; NDW: nodule dry weight (g); NMS: nodule mean score; PH: plant height (cm); NPP: number of pods per plant; SY: stover yield (kg/ha); SDW: 100-seed dry weight (g) and HI: harvest index (%).

The grain yield, number of nodules per plant and nodule dry weight of soybean were positively correlated with soil available P and soil pH (Figure 1). A strong positive correlation was noted between soil available P with the grain yield (R^2=0.597), number of nodules per plant (R^2=0.712) and nodule dry weight (R^2= 0.509) of soybean.

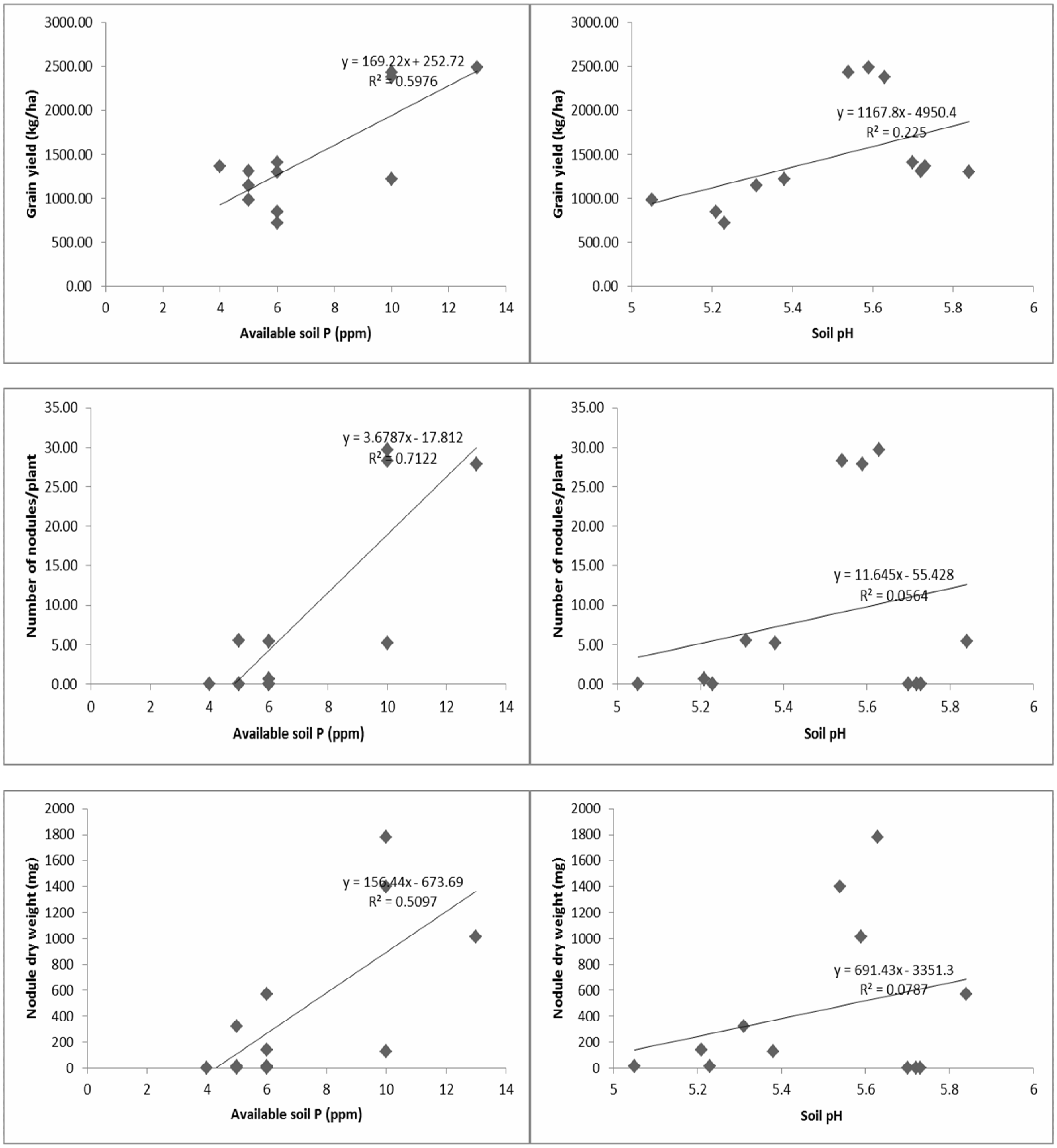

Figure 1: Relationship between soil available P vs. soybean grain yield, number of nodules plant^{-1} and nodule dry weight; soil pH vs. soybean grain yield, number of nodules plant^{-1} and nodule dry weight.

CHAPTER 5

DISCUSSION

5.1 Effect of inorganic fertilizers, cattle manure and lime on nodulation of soybean.

Inoculation alone significantly increased nodule mean score relative to control in Eshirali and Eshisa in both seasons. This may probably be due to high levels of available P (7 and 11 ppm in Eshirali and Eshisa respectively) in these sites and also favorable pH range (> 5.5 for both sites) for proliferation of nodule forming *Bradyrhizobium* bacteria. Low pH undermines the survival of rhizobia leading to formation of ineffective nodules and low rhizobial population (Sprent and Sprent, 1990). This observation agree with France and Day (1980) who reported that liming an acid soil to a pH of 5.0 increased nodulation and nitrogen fixation of *Phaseolus vulgaris* (L.) in the acid soils of Brazil. Kumaga and Eto-Bonde (2000) from pot experiments also demonstrated that nodulation and nitrogen fixation of promiscuous soybean could be increased by inoculation with effective *Bradyrhizobium* strains. Due to high level of available phosphorous, Eshisa site recorded a significantly higher nodule mean score than all the other sites. Application of phosphorous is improves root development, providing more infection sites for rhizobia, hence encouraging nodulation (Giller, 2001). Combination of fertilizer, manure and lime significantly increased nodule mean score than all the other treatments. This can be attributed to the higher number of nodules per plant noted with NPKSCaMgZnMoManureLime application.

Inoculation alone significantly increased nodule number per plant relative to control in Eshirali in season 1 and in all sites in season 2. This finding is consistent with Kumaga and Ofori (2004) who noted a significant increase in nodule number and nodule dry weight with inoculation in soybean. A significantly higher number of nodules per plant was noted in NPKSCaMgZnMoManureLime treatment than in all the other treatments in Eshirali, Masaba and Eshisa. This confirms the findings of a study by Mandal *et al*. (2009) who noted lower nodule number and nodule dry weight in plots where the crop did not receive any inorganic fertilizer or organic manure relative to plots that received NPK and NPK + manure treatments. Probably, the reason is that balanced application of organic and inorganic fertilizers favorably increased root density hence provided the infection sites for *Bradyrhizobium japonicum* (Nandini *et al*., 2013). Significantly lower number of nodules per plant was noted in Masaba site than in the other sites in both seasons. This may have been due to a significantly lower pH value (5.16) that discouraged proliferation of effective *Bradyrhizobium* bacteria (France and Day, 1980).

Nodule dry weight in Eshisa was significantly higher than in Masaba and Nyabeda in both seasons. This can be well explained by the high level of available phosphorous in this site (11 ppm). This agrees with Kumaga and Ofori (2004) who noted an increase in nodule dry weight with phosphorous application. On average, NPKSCaMgZnMoManureLime application significantly increased soybean nodule dry weight in both seasons. This could be due to increased levels of available phosphorous. Zhao *et al*. (2009) found that combination of organic and chemical fertilizers increased soil available P. Inoculation alone did not significantly increase nodule dry weight over control in all sites in season 1 but did increase significantly in Nyabeda and Eshisa in season 2.

5.2 Effect of inorganic fertilizers, cattle manure and lime on yield and yield components of soybean.

Application of NPKSCaMgZnMoManureLime recorded significantly higher above ground biomass than all the other treatments in Nyabeda, Eshisa and Eshirali. Similar results were noted in potato where maximum amounts of shoot dry matter were recorded with integrated use of fertilizer and cattle manure (Amir *et al*., 2013). Results which were also in line with Alam *et al*. (2007) which demonstrated that maximum amount of shoot dry matter could be obtained by combined application of compost and chemical fertilizers. Inoculation alone significantly increased soybean above ground biomass over control only in season 1. The results are in conformity with the findings by Tamiru *et al*. (2012) who noted a significant increase in soybean dry biomass yield in inoculated soybean compared to uninoculated control. Their findings showed that irrespective of soybean variety, inoculation of *Bradyrhizobium* strain resulted in the highest dry matter production. Masaba site recorded a significantly lower above ground biomass than all the other sites in both seasons. This could be attributed to significantly lower total nitrogen in the site (0.13 %), acidic conditions and deficiency of other essential micronutrients that could have limited the response to fertilizer (Zengeni et al., 2006; Giller, 2001). In the second season, application of NP significantly increased soybean above ground biomass relative to PK and NK. The results are in agreement with those of Xiang *et al*. (2012), Aise *et al*. (2011) and Pauline *et al*. (2010) who reported higher leaf area hence shoot dry matter in soybean under conditions of proper phosphorous application. In this study, addition of starter nitrogen in NP application significantly increased soybean above ground biomass over PK and NK.

Soybean plant height varied significantly among the treatments and in the different sites. Inoculation alone did not significantly increase soybean plant height relative to control in most sites in both seasons. This contradicts Abdul *et al*. (2012) findings in which they reported significant increase in soybean plant height in inoculated soybean relative to non-inoculated control. NPKSCaMgZnMoManureLime recorded a significantly higher soybean plant height than all the other treatments. Similarly, Mandal *et al*. (2009) reported significantly higher plant height in NPK+farmyard manure treated soybean plots than those in NPK and control. Overall, Eshisa site recorded significantly higher plant height than all the other sites probably due to a higher inherent soil fertility and a clay loam soil texture.

Application of NPKSCaMgZnMoManureLime had significantly higher number of pods per plant than all the other treatments in both seasons. The results are in agreement with Mandal *et al*. (2009) who reported significantly higher number of pods per plant in soybean plots treated with NPK+farmyard manure than in the control plots. Liu *et al*. (2008) also reported that combined application of organic and inorganic fertilizers as a total basal dressing is beneficial to the balanced release of nutrients; hence this could have probably contributed to the increase in pod number. Inoculation alone did not significantly increase number of pods per plant relative to control in Masaba, Nyabeda and Eshirali. This could probably be due to the competitive ability of native rhizobia in the sites and also emphasizes the need for fertilizer use in soybean to boost pod number. However, earlier contradictory observations by Tahir *et al*. (2009) indicated significant increase in number of pods per plant in inoculated soybean over control. Eshisa site recorded significantly higher number of pods per plant than all the other sites. This is due to a high level available phosphorous (11 ppm) in the site which is well explained by a positive correlation between grain yield and available soil phosphorous (Figure1). This is in line with the findings by Zingore and Giller (2012) who noted a strong positive correlation between yields of soybean and soil available P. High available soil P has been demonstrated to increase productivity and biological nitrogen fixation of legumes (Giller, 2001).

A significantly higher 100-seed weight was noted in NPKSCaMgZnMoManureLime than all the other treatments. This could be attributed to micronutrient and manure application as per previous studies by Kobraee *et al*. (2011) and Ghasemian *et al*. (2010) who noted a significant increase in 100-seed weight with zinc application in soybean. Zinc plays a key role in improving biological nitrogen fixation of soybean which aids in boosting seed protein and oil content (Giller, 2001; Lokuruka, 2010). In other studies, NPK+Farmyard manure application on soybean recorded significantly higher 100-seed weight than NPK and control (Mandal *et al*., 2009). Therefore, the combined application of macronutrients, micronutrients and manure could have boosted seed weight due to the supply of multiple nutrients especially from manure which could have been beneficial to the crop (Zingore et al., 2008). Inoculation alone significantly increased 100-seed weight relative to control only in Masaba in season 1 and Masaba and Nyabeda in season 2. This is in line with findings by Tamiru *et al*. (2012) who reported a significant increase in soybean 1000-seed weight upon inoculation with *Bradyrhizobium* strain. Masaba and Eshisa sites had higher 100-seed weight than all the other sites in season 1 and season 2 respectively.

Grain yield was significantly higher in NPKSCaMgZnMoManureLime than all the other treatments across all sites. This could be attributed to zinc application which according to Kobraee *et al*. (2011) enhances soybean yield by influencing the number of seeds per plant and 100-seed weight. Similarly, Heidarian *et al*. (2011) noted a significant effect of micronutrient application on number of pods per plant and grain yield of soybean. Further, Xiang *at al*. (2012) reported higher 100-seed weight and grain yield with proper phosphorous and potassium application. Alpha *et al.* (2007) found that proper phosphorous application improved shoot phosphorous uptake thereby increasing shoot dry matter, 100-seed weight, pods per plant and final grain yield of soybean. Integrated use of organic and inorganic fertilizers can enhance soybean productivity as reported by Mandal *et al*. (2009) who noted a significant increase in soybean grain yield with application of NPK+Farmyard manure. Inoculation alone significantly increased soybean grain yield relative to control in Nyabeda only in season 1 and in Nyabeda and Eshisa in season 2. This is in agreement with Tahir *et al*. (2009) who reported a significant increase in soybean seed yield by 41% over control with *Bradyrhizobium* inoculation alone. Symbiosis between soybean and *Bradyrhizobium japonicum* could be the possible explanation to the stated findings. Increased nodulation results in more nitrogen fixation that leads to increased yield components (Okereke *et al*., 2004). In season 1, NK recorded a significantly lower grain yield compared to NPK, PK and NP in Eshirali, Masaba and Nyabeda. This emphasizes the role of phosphorous in determining soybean yield components. Chiezey *et al*. (2009) suggested that the application of P stimulated leaf expansion, hence more light interception for photosynthetic activity, high assimilate accumulation and seed yield, pod yield and 100-seed weight. Overall, Masaba site recorded a significantly lower grain yield than all the other sites in both seasons.

This can be attributed to the low pH value (5.16) which according to Carver and Ownby, (1995) soils with pH <5.5 have high exchangeable aluminium and outright toxicity to most crops.

Treatment with NPKSCaMgZnMoManureLime significantly increased soybean stover yield than all the other treatments in Eshirali, Masaba and Nyabeda. This is probably due to the treatment's significant effect on above ground biomass and number of pods per plant which are major components of stover yield. In both seasons, inoculation alone did not significantly increase stover yield relative to control in all sites. Again, this is probably due to the insignificant effect of inoculation alone to soybean above ground biomass and number of pods per plant which are essential components of stover yield (Alpha *et al*., 2007). Treatment with NK recorded a significantly lower stover yield than NPK, PK and NP in most of the sites. This result once more explains the role of phosphorous, as elaborated by Tahir, *et al*. (2009) whereby application of P alone increased number of pods per plant and dry matter yield of soybean which are ultimate components of stover yield. A significantly lower stover yield was noted in Masaba site than all the other sites in both seasons. This can be attributed to low pH (<5.5) that affected crop growth.

Inoculation alone significantly increased harvest index relative to the control. This contradicts findings of a study by Tamiru *et al*. (2012) who reported that the main effects on soybean harvest index were from variety but not from rhizobial strains or their interactions. Application of NPKSCaMgZnMoManureLime significantly increased harvest index compared to other treatments. This can be attributed to its effect on pod number, 100-seed weight and grain yield.

This current finding contradicts the work of Mandal *et al*. (2009) who found no varying significant difference in soybean harvest index between NPK and NPK+Farmyad manure. There was a significantly lower harvest index in Masaba site than all the other sites. This can be attributed to the lower records of pod number, 100-seed weight and grain yield compared to the other sites.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1: CONCLUSION

This study found out that the combination of both organic and inorganic fertilizers can significantly boost soybean nitrogen fixation potential by increasing nodulation. However, inoculation alone without fertilizer application does not markedly improve soybean productivity. Inclusion of phosphorous in the fertilizer combinations is essential to maximize soybean productivity in the region. The nutrient omission trial arrangement identified nutrients limiting soybean production in the region. For instance, potassium deficiencies in Eshirali in both seasons were observed. Phosphorous was noted to be the most limiting nutrient since its omission significantly affected soybean yield and yield components.

Combination of organic and inorganic fertilizers could be a feasible option for maximizing soybean yield in western Kenya. Consistent increase in yield was observed in the treatment with NPKSCaMgZnMoManureLime, hence supply of both macro and micronutrients in an integrated approach might alleviate the problem. Also, fertilizer use in soybean production increased soybean yields tremendously in the region hence farmers should be encouraged to apply fertilizers in soybean. Response of soybean to fertilizer application is site specific; hence blanket fertilizer recommendations might not be the best option for maximizing soybean production in future.

6.2: RECOMMENDATIONS

1. Extensive trials in different areas with soybean production potential should be conducted to determine which one among cattle manure, lime and micronutrients+secondary nutrients played a major role in boosting soybean yield when combined with macronutrients NPK.

2. A similar study should be conducted on other commonly grown soybean varieties in the region in order to determine their yield response to fertilizer.

3. Long term studies should be conducted to come up with site-specific fertilizer recommendations as way of maximizing soybean productivity in the region.

4. Since factors that caused some nutrients to be limiting could not be determined, comprehensive studies should be done to establish the physical and chemical soil characteristics that occasioned this.

5. Cost benefit analysis should be done to determine economical rates and returns to investment in fertilizer use by site.

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APPENDICES

Appendix 1: Monthly rainfall (mm) at the trial sites during 2012 cropping seasons.

	Eshirali	Masaba	Nyabeda	Eshisa
Long rains				
April	211	234	225	225
May	168	195	142	229
June	204	238	242	248
July	84	63	102	151
August	145	198	113	111
Total	812	928	824	964
Short rains				
September	219	172	265	194
October	205	213	222	255
November	159	142	198	180
December	194	206	212	227
Total	777	733	897	856

Appendix 2: Analysis of variance (ANOVA) table for soil pH of Eshirali, Masaba, Nyabeda and Eshisa sites.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	0.07922	0.03961	2.15	
Site	3	0.50329	0.16776	9.10	0.012
Residual	6	0.11058	0.01843		
Total	11	0.69309			

Appendix 3: Analysis of variance (ANOVA) table for soil EC of Eshirali, Masaba, Nyabeda and Eshisa sites.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	1.4444E-34	7.2222E-35		
Site	3	0.0000E+00	0.0000E+00		
Residual	6	0.0000E+00	0.0000E+00		
Total	11	1.4444E-34			

Appendix 4: Analysis of variance (ANOVA) table for soil total C (%) of Eshirali, Masaba, Nyabeda and Eshisa sites.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	0.06792	0.03396	2.61	
Site	3	4.11390	1.37130	105.55	<.001
Residual	6	0.07795	0.01299		
Total	11	4.25977			

Appendix 5: Analysis of variance (ANOVA) table for soil total N (%) of Eshirali, Masaba, Nyabeda and Eshisa sites.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	0.0013167	0.0006583	1.18	
Site	3	0.0176250	0.0058750	10.52	0.008
Residual	6	0.0033500	0.0005583		
Total	11	0.0222917			

Appendix 6: Analysis of variance (ANOVA) table for soil NH_4 (ppm) of Eshirali, Masaba, Nyabeda and Eshisa sites.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	6.299	3.150	1.09	
Site	3	1370.699	456.900	157.86	<.001
Residual	6	17.366	2.894		
Total	11	1394.364			

Appendix 7: Analysis of variance (ANOVA) table for soil NO_3 (ppm) of Eshirali, Masaba, Nyabeda and Eshisa sites.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	3.670	1.835	0.36	
Site	3	541.158	180.386	35.63	<.001
Residual	6	30.377	5.063		
Total	11	575.205			

Appendix 8: Analysis of variance (ANOVA) table for soil extractable K (Cmol/kg) of Eshirali, Masaba, Nyabeda and Eshisa sites.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	0.9261	0.4631	0.79	
Site	3	2.1498	0.7166	1.23	0.378
Residual	6	3.5008	0.5835		
Total	11	6.5767			

Appendix 9: Analysis of variance (ANOVA) table for soil available P (ppm) of Eshirali, Masaba, Nyabeda and Eshisa sites.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	1.167	0.583	0.16	
Site	3	65.000	21.667	6.05	0.030
Residual	6	21.500	3.583		
Total	11	87.667			

Appendix 10a: Analysis of variance (ANOVA) table for nodule mean score of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 1.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	0.0578	0.0289	0.23	
Site	3	46.2958	15.4319	123.30	<.001
Treatment	7	15.4152	2.2022	17.59	<.001
Site. Treatment	21	18.5852	0.8850	7.07	<.001
Residual	62	7.7599	0.1252		
Total	95	88.1138			

Appendix 10b: Analysis of variance (ANOVA) table for nodule mean score of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 2**.**

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	0.4158	0.2079	1.12	
Site	3	14.3520	4.7840	25.68	<.001
Treatment	7	25.1366	3.5909	19.27	<.001
Site. Treatment	21	7.8472	0.3737	2.01	0.018
Residual	62	11.5508	0.1863		
Total	95	59.3024			

Appendix 11a: Analysis of variance (ANOVA) table for number of nodules per plant of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 1.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	13.11	6.56	0.56	
Site	3	7151.57	2383.86	203.49	<.001
Treatment	7	3137.48	448.21	38.26	<.001
Site. Treatment	21	3831.30	182.44	15.57	<.001
Residual	62	726.33	11.71		
Total	95	14859.79			

Appendix 11b: Analysis of variance (ANOVA) table for number of nodules per plant of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 2.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	7.146	3.573	0.74	
Site	3	4035.708	1345.236	278.46	<.001
Treatment	7	5364.458	766.351	158.63	<.001
Site. Treatment	21	1767.125	84.149	17.42	<.001
Residual	62	299.521	4.831		
Total	95	11473.958			

Appendix 12a: Analysis of variance (ANOVA) table for mean nodule dry weight (g) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 1.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	0.00433	0.00216	0.03	
Site	3	17.93030	5.97677	85.76	<.001
Treatment	7	10.47957	1.49708	21.48	<.001
Site. Treatment	21	8.80437	0.41926	6.02	<.001
Residual	62	4.32081	0.06969		
Total	95	41.53937			

Appendix 12b: Analysis of variance (ANOVA) table for mean nodule dry weight (g) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 2.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	0.1398	0.0699	0.60	
Site	3	9.5169	3.1723	27.05	<.001
Treatment	7	14.8840	2.1263	18.13	<.001
Site. Treatment	21	5.4184	0.2580	2.20	0.009
Residual	62	7.2717	0.1173		
Total	95	37.2307			

Appendix 13a: Analysis of variance (ANOVA) table for above ground biomass (kg/ha) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 1.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	204216	102108	1.61	
Site	3	22375346	7458449	117.53	<.001
Treatment	7	24674558	3524937	55.55	<.001
Site. Treatment	21	7835639	373126	5.88	<.001
Residual	62	3934367	63458		
Total	95	59024128			

Appendix 13b: Analysis of variance (ANOVA) table for above ground biomass (kg/ha) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 2.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	17460	8730	0.25	
Site	3	18224497	6074832	177.21	<.001
Treatment	7	38453092	5493299	160.25	<.001
Site. Treatment	21	5930772	282418	8.24	<.001
Residual	62	2125374	34280		
Total	95	64751195			

Appendix 14a: Analysis of variance (ANOVA) table for plant height (cm) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 1.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	15.416	7.708	1.83	
Site	3	18698.038	6232.679	1475.74	<.001
Treatment	7	2259.369	322.767	76.42	<.001
Site. Treatment	21	788.514	37.548	8.89	<.001
Residual	62	261.853	4.223		
Total	95	22023.190			

Appendix 14b: Analysis of variance (ANOVA) table for plant height (cm) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 2**.**

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	24.04	12.02	0.79	
Site	3	2926.93	975.64	63.87	<.001
Treatment	7	4079.04	582.72	38.15	<.001
Site. Treatment	21	897.09	42.72	2.80	<.001
Residual	62	947.09	15.28		
Total	95	8874.18			

Appendix 15a: Analysis of variance (ANOVA) table for number of pods per plant of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 1**.**

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	39.703	19.852	2.19	
Site	3	23193.551	7731.184	854.43	<.001
Treatment	7	6785.305	969.329	107.13	<.001
Site. Treatment	21	2183.382	103.971	11.49	<.001
Residual	62	561.000	9.048		
Total	95	32762.941			

Appendix 15b: Analysis of variance (ANOVA) table for number of pods per plant of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 2**.**

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	0.594	0.297	0.05	
Site	3	1816.812	605.604	108.58	<.001
Treatment	7	1649.896	235.699	42.26	<.001
Site. Treatment	21	525.964	25.046	4.49	<.001
Residual	62	345.799	5.577		
Total	95	4339.065			

Appendix 16a: Analysis of variance (ANOVA) table for 100-seed weight (g) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 1.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	0.1147	0.0573	0.13	
Site	3	1028.8946	342.9649	771.37	<.001
Treatment	7	19.1660	2.7380	6.16	<.001
Site. Treatment	21	19.7739	0.9416	2.12	0.012
Residual	62	27.5664	0.4446		
Total	95	1095.5155			

Appendix 16b: Analysis of variance (ANOVA) table for 100-seed weight (g) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 2.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	0.810	0.405	0.34	
Site	3	10.849	3.616	3.00	0.037
Treatment	7	121.258	17.323	14.39	<.001
Site. Treatment	21	32.546	1.550	1.29	0.219
Residual	62	74.630	1.204		
Total	95	240.094			

Appendix 17a: Analysis of variance (ANOVA) table for grain yield (kg/ha) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 1.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	9955	4978	0.28	
Site	3	79897197	26632399	1513.22	<.001
Treatment	7	20018038	2859720	162.49	<.001
Site. Treatment	21	6033144	287293	16.32	<.001
Residual	62	1091186	17600		
Total	95	107049521			

Appendix 17b: Analysis of variance (ANOVA) table for grain yield (kg/ha) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 2.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	96709	48355	0.63	
Site	3	20663802	6887934	89.88	<.001
Treatment	7	54785884	7826555	102.12	<.001
Site. Treatment	21	9492366	452017	5.90	<.001
Residual	62	4751508	76637		
Total	95	89790269			

Appendix 18a: Analysis of variance (ANOVA) table for stover yield (kg/ha) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 1.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	40651	20326	0.67	
Site	3	60084456	20028152	661.41	<.001
Treatment	7	7745734	1106533	36.54	<.001
Site. Treatment	21	4825935	229806	7.59	<.001
Residual	62	1877417	30281		
Total	95	74574193			

Appendix 18b: Analysis of variance (ANOVA) table for stover yield (kg/ha) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 2.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	26673	13336	0.25	
Site	3	22289247	7428749	138.79	<.001
Treatment	7	39026281	5575183	104.15	<.001
Site. Treatment	21	10539043	501859	9.37	<.001
Residual	62	3318985	53532		
Total	95	75200230			

Appendix 19a: Analysis of variance (ANOVA) table for harvest index (%) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 1.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	24.714	12.357	1.30	
Site	3	1702.201	567.400	59.77	<.001
Treatment	7	1456.127	208.018	21.91	<.001
Site. Treatment	21	2576.487	122.690	12.92	<.001
Residual	62	588.577	9.493		
Total	95	6348.105			

Appendix 19b: Analysis of variance (ANOVA) table for harvest index (%) of soybean grown on-farm in Eshirali, Masaba, Nyabeda and Eshisa in cropping season 2.

Source of variation	d.f.	s.s.	m.s	v.r.	F. pr.
REP stratum	2	18.688	9.344	1.21	
Site	3	568.096	189.365	24.61	<.001
Treatment	7	1324.793	189.256	24.60	<.001
Site. Treatment	21	848.039	40.383	5.25	<.001
Residual	62	477.057	7.694		
Total	95	3236.672			