GEOSPATIAL ANALYSIS OF LEGUME PRODUCTION CONSTRAINTS AND OPPORTUNITIES IN SMALLHOLDER SYSTEMS IN NANDI COUNTY

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Geospatial analysis of legume production constraints and opportunities in smallholder systems in Nandi County

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DECLARATION

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

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DEDICATION

This work is dedicated to my parents, Mr. Moses K. Mutai, and Mrs. Norah C. Mutai, for their endless encouragement and moral support during my studies. To relevant researchers and farmers, may this thesis shed light on the many challenges you face with respect to variability and unpredictability of your work environments.

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LIST OF ACRONYMS

BCMV	Bean common mosaic virus
BF	Bean fly
CBB	Common bacterial blight
csv	comma delimited
ESRI	Environmental Systems Research Institute
FAO	Food and Agriculture Organization
GIS	Geographical Information System
GPS	Global positioning systems
LR	Leaf rust
MASL	Meters above sea level
QGIS	Quantum GIS (SOFTWARE)
RR	Root rot
RS	Resistant Starch
RV	Rosette Virus
SBB	Soybean blight
SSA	sub-Saharan Africa

ABSTRACT

The productivity of grain legumes (*Phaseolus vulgaris, Arachis hypogaea L.,Glycine max L., and Llablab purpureus* L.) is low in smallholder systems in sub-Saharan Africa (SSA). Low soil fertility, high pest and disease pressure, and high heterogeneity of biophysical and socioeconomic contexts, makes it hard to find a suitable legume specie to grow in the smallholder systems of western Kenya. These constraints have resulted in low productivity, leading to food and nutritional insecurity, and low household income. It is therefore necessary to apply geospatial technologies to visualize the distribution of the production constraints and opportunities, as well as show how they interact to influence legume productivity. This study assessed selected biophysical factors influencing productivity of bean, groundnut, soybean and lablab, the most important food legumes in the region, and established their spatial and temporal distribution in the smallholder systems of Nandi County, western Kenya. Experiments were set up in 66 farms during the short rains 2016, and the long rains 2017 growing seasons at Kapkerer, Kiptaruswo, and Koibem sites in Nandi County, western Kenya. Composite soil samples were taken from each of the farms for the determination of pH, organic carbon, texture, and micro-nutrients. Daily rainfall, temperature, incidences and severity of pests and diseases, and legume grain yield were scored at each farm. Results showed large spatial and temporal variations in the distribution of pests and diseases, creating possible hotspots that significantly decreased legume productivity. Rainfall was negatively correlated with pests and diseases, especially BF (r=-0.35**), BCMV (r=-0.31**) and RV (r=-0.16), while a positive correlation was observed between rainfall and RR (r=0.12*). The impact of pests and diseases on legume productivity exhibited a temporal variation. Of the soil factors assessed, pH, Fe, Mn, Mg, and Ca had the largest effect on legume productivity. The results of this study indicate that knowledge of the spatial and temporal distribution of legume production constraints, and their impact on legume productivity is critical for informed technology testing and dissemination of production options that match biophysical contexts to improve legume productivity in the heterogeneous smallholder systems. In general, this study can inform national policy formulation and the necessary reform of agricultural technology dissemination services to improve smallholder productivity.

CHAPTER ONE

INTRODUCTION

1.1 Background

Legume productivity is low in smallholder systems in sub-Saharan Africa (SSA) due to numerous constraints, including low soil fertility, high incidences of pests and diseases, and low capacity of farmers to purchase production inputs, particularly inorganic fertilizers and certified seed. Variability in climatic conditions (e.g. rainfall and temperature), prevalence of pests and diseases and different socio-economic circumstances of farmers are additional factors that must be taken into account in the formulation of appropriate legume production options (Ojiem *et al.,* 2006). Generally, most western Kenya smallholders are suffering food and nutritional insecurity which could be contributed to by these challenges (Waithaka *et al.,* 2007). Western Kenya is characterized by four agro-ecological zones (low midland 1 (LM1), low midland 2 (LM2), lower midland 3 (LM3) and upper midland 3 (UM3), three of which are exhibited in Nandi County. A majority of the households in western Kenya are largely subsistence, with 7 people per household depending on 0.6 ha of land (Marenya & Barrett, 2007). Due to insufficient use of fertilizers, yields of maize and legumes, which are the staple foods are often very low.

Importance of legumes in smallholder systems

Legume species (common bean, groundnut, lablab, soybean, green grams, etc.) are known for their huge contribution to human, animal, and soil health. They are a major source of proteins, energy, minerals and vitamins, particularly in SSA where pulses takes the place of animal products (Taylor *et al.*, 2005). Beans and other legumes are grown primarily by smallholder, resource-poor farmers and provides essential dietary protein, fiber and income for at least 100 million people in Africa (Kimani *et al.*, 2001). Common bean (*Phaseolus vulgaris* L.) is an important grain legume in sub-Saharan Africa (SSA), especially in Eastern, Central and Southern Africa, where its consumption per capita exceeds 50 kg a year and perhaps the highest in the world, particularly in western Kenya (Ojiem, 2017; Ochieng et al., 2019). Bean is highly valued in parts of Africa and the America for its provision of up to 15% of total daily calories and 36% of total daily protein (Schmutz *et al.,* 2014). Like bean, groundnut (*Arachis hypogaea* L.) is a popular legume known for its provision of carbohydrates, micronutrients, and energy in the tropics. It is an important legume providing protein with higher essential amino acids compared with other grain legumes (Ijarotimi and Esho, 2009). The developing countries of Africa and Asia accounts for up to 95 % of groundnut production. Production, marketing, and trade of groundnut in the SSA create foreign exchange, income, and employment (Ntare et al., 2005; Ntare et al., 2007; Janila et al., 2013).

Soybean on the other hand, is one of the world's major crops which has been grown for nearly 5000 years due to its commercial, agronomic and nutritive value (Date, 2013). The legume offers huge potential benefits to smallholder production systems, as well as diets and income (Lubungu *et al.,* 2013a). Soybean's high protein content of 40 % (Agada, 2015), high potential for profitability and, several possibilities of incorporating the crop into the daily diets of household has brought about the belief that the crop possesses huge prospects of reducing malnutrition among the poor, who constitute the highest proportion of the population (Batiano, 2011). Lablab is an important legume that is being cultivated throughout the tropics. It is an annual short-lived perennial vine, which is believed to have originated from Africa (Koile, 2014). Lablab is a source of protein for both humans and livestock (Madzonga and Mogotsi, 2014), and is known to enhance soil fertility through nitrogen fixation (Nyambati *et al.,* 2006). Similar to other legumes, lablab is high in protein, having high crude protein in the leaves and foliage as well as minerals (calcium, phosphorus) and vitamins (A and D complex). The productivity of these legumes is low in much of SSA (Ojiem *et al.,* 2006), leading to food and nutritional insecurity.

Constraints to legume productivity

Numerous factors constrain legume productivity, especially in the highlands of East Africa and much of western Kenya, where smallholders face a myriad of challenges raising land productivity. The major constraints to legume productivity include land scarcity, low soil fertility, prevalence of pests and diseases, and variability in climatic conditions (e.g. rainfall and temperature). Western Kenya region is generally characterized by wet and humid climatic conditions and because of this, high incidences of a range of fungal, bacterial and viral legume diseases are often observed (Medvecky et al., 2007; Chirchir et al., 2010; Simon et al., 2018). Similarly, damage by insect pests constitute a major constrain to legume productivity (Medvecky et al., 2007). Low soil fertility is generally accepted to be an important constraint to crop productivity in many parts of SSA (Kandji et al., 2001). In Nandi County in particular, widespread soil degradation and nutrient depletion, and inadequate use of inorganic fertilizers have been identified as the major causes of declining food production in smallholder farms (Ochieng et al., 2019).

Important soil-related legume production constraints in western Kenya and most of the tropical legume production regions include nitrogen and phosphorous deficiencies, and aluminum and manganese toxicities in acid soils (Smithson and Sanchez, 2001). Biological nitrogen fixation rates and tolerance to P deficiency are low especially in common bean in comparison to other legumes (Broughton *et al.,* 2003). Soil acidity and P deficiency, which combine to adversely affect root nodulation, survival of rhizobia and biological nitrogen fixation, seriously lower legume yields.

Analyzing legume production constraints

The complex variability in biophysical factors such as, soil fertility, rainfall, altitude and pests and diseases in smallholder systems presents challenges in identifying the major constraints to increased legume production. Geospatial data plays an important role in decision-making in agricultural activities, particularly in response to the impacts and vulnerability of agricultural production to variability (Ayanlade *et al.,* 2013). A good understanding of the spatial and temporal distribution of productivity limiting factors is necessary to establish the spread of constraints then recommend specific species to specific production environments. Spatial analysis can be used to guide where to test and disseminate agricultural production technologies. Although a systematic sampling of study sites can be done to ensure coverage of diverse range of testing environments, without spatial analysis it is possible to miss areas where a cultivar might produce high yields (Hyman *et al.,* 2013). Utilization of geospatial analysis in sub-Saharan Africa has lagged behind because of limited development of geospatial data infrastructure to enhance agricultural practices, especially agricultural risk management in this age of climate change (Ayanlade *et al.*, 2013). Where such data is available, the scale is often too large to allow application in local level e.g. specific smallholder situations like Nandi County. This study assesed the major biophysical factors influencing legume productivity in smallholder farms in Nandi County, then did geospatial analysis to show distribution of these factors to facilitate matching legume production options to contexts to improve productivity.

1.2 Problem statement

Grain legumes are important sources of protein, energy and household income for resource poor smallholder farmers in sub-Saharan Africa. However, their wide scale adoption has remained low amongst smallholder farmers in spite of years of active promotion (Brand, 2011). In Nandi County, adoption of grain legumes is constrained by a high degree of heterogeneity in biophysical and socio-economic factors, which make it hard predict performance of desired legumes. These include incidences of pests and diseases, low or excessive rainfall, low soil fertility, land scarcity, lack of access to production inputs, e.g. certified seed, fertilizers and pesticides. Due to this heterogeneity in the smallholder biophysical and socio-economic environments, legume production technologies developed do not fit and function as desired. This study sought to develop mechanisms for matching legume production options to their appropriate biophysical and socio-economic contexts by conducting spatial analysis of legume production constraints and opportunities in Nandi County smallholder systems. Doing this will make it possible to visualize production constraints and opportunities in the target smallholder systems. This will in turn allow targeted testing of legume production technologies against the identified constraints, and scaling out the identified promising technologies in their appropriate biophysical and socio-economic contexts. This will lead to smallholder farmers receiving appropriate legume production technologies, leading to improved legume productivity, enhanced food and nutritional security, and household income.

1.3 General objective

To assess the distribution of grain legume production constraints and opportunities in smallholder systems of Nandi County to guide scaling out of the available production options to improve productivity

1.4 Specific objectives

1. To assess the characteristics of biophysical factors constraining legume production in smallholder systems of Nandi County
2. To evaluate the possibility of utilizing geospatial maps as framework for scaling out targeted legume technologies

1.5 Research Questions

1. Can the biophysical constraints and opportunities of legume production (pests and diseases, rainfall, temperature, altitude, and soil properties) be identified and assessed by mapping their spatial and temporal distributions in the smallholder systems of Nandi County?
2. Can maps of the spatial and temporal distribution of pests and diseases, rainfall, temperature, altitude, and soil properties be used as framework for matching legumes to appropriate contexts and facilitating scaling out targeted technologies?

1.6 Justification

Maps allow us to gain perspective of our surroundings. They bring out patterns by reducing the complexity of the environment of interest. Many site-specific farming systems utilize GIS and several related technologies (global positioning system, receivers, continuous yield sensors, remote sensing instruments) to collect spatially referenced data, perform spatial analysis and decision making, and apply variable rate treatment (Raju, 2018). Although several studies have been carried out on application of GIS and remote sensing for agricultural and rural development in other parts of the world, little research has been done in sub-Saharan Africa in terms of developing geospatial data infrastructure to enhance agricultural practices especially agricultural risk management in this age of climate change (Ayanlade *et al.,* 2013). Consequently, there is need to explore the visualization capacity of Geographical Information Systems (GIS) which can assist in capturing the broader spatial contexts of smallholder systems. This will in turn augment the efforts of combating food insecurity in the sub-Saharan Africa, provide researchers with framework for predicting legume technology recommendation domains, and improve legume productivity by recommending appropriate legume species and varieties to farmers.

1.7 Scope

This study is limited to smallholder farming systems in Nandi County and similar regions, where land has become limited, and therefore continuously cultivated over several years. Consequently, the results and recommendation given can only be applied in the areas covered in this study, and those falling within agro-ecological zones and situations similar to Nandi County.

1.8 Limitation

Being a Masters research (most Masters Sponsorship including this one covers only 1 year of research), this study was done for two seasons only. However, there is need to run the study for more seasons to observe more trends and enrich insights and recommendations drawn from this study.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Legume species (common bean, groundnut, lablab, soybean, etc.) are uniquely suited to provide nutrient-enriched grains and vegetables, provide income, as well as enhance soil productivity for the resource-limited farmers (Graham & Vance, 2003). Fodder legumes are beneficial as animal feed, soil nutrients enrichment, cover crops, as well as soil erosion control. These legumes have a positive impact on soil structure and composition, i.e. improving water holding capacity, aggregate stability, and increasing organic matter content (Kahnt, 2008; Kautz *et al.,* 2010). Fodder legumes can fix atmospheric N_2 and therefore reduce the requirement for N-fertilizers (Sinclair & Vadez, 2012), which has adverse effects on environment when used in excess. Further, grain legumes have the unique capacity to recover phosphorus from the soil that is in forms unavailable to other crops (Sinclair & Vadez, 2012), in addition to having pests/weed/diseases control effect when intercropped with cereals, reducing the requirement for pesticides (Papendiek et al., 2016). The demand for grain legumes is increasing worldwide due to their use directly as human food, feed for animals, as well as industrial uses (Sinclair & Vadez, 2012).

Grain legumes play an important role in the sustainability of agricultural systems and in food protein supply in developing countries (Tharanathan & Mahadevamma, 2003). They are highly nutritious, especially in the dietary pattern of low-income groups of people in sub-Saharan Africa. Grain legumes are next to maize in order of importance of food crops in Kenya (Muthomi *et al.*, 2007). They are a major source of proteins of high biological value, energy, minerals and vitamins for many people in Africa where main diets consist mostly of starchy staples and minimal animal protein (Taylor *et al.,* 2005). Among the grain legumes, common bean (*Phaseolus vulgaris* L.) forms an important food and cash crop in Africa, particularly in the eastern parts of Africa (van Loon et al., 2018). It is a popular crop among small scale farmers mainly for subsistence and marketing of the surplus (Katungi *et al.,* 2010), and is grown for its green leaves, green pods, and immature and/or dry seeds. Grain legumes are normally consumed after processing, which not only improves palatability of foods but also increases the bioavailability of nutrients, by inactivating trypsin and growth inhibitors and haemagglutinins (Zia-ur-Rehman & Salariya, 2005). Starch, the major biopolymeric constituent of legumes, upon processing gets partially modified into resistant starch.

Grain legumes do not bring about only improvements in terms of environmental sustainability, but also generates significant profit increase in the smallholder systems (Tshering, 2002; Ngwira et al., 2012). Common bean is known to provide substantial health and income opportunities, a popular crop among small scale farmers mainly for subsistence and marketing of the surplus (Katungi *et al.*, 2010). The dry seeds of common bean are the ultimate economic part of the bean plant. They are valued throughout the developing countries because they have good nutritional properties, an extended storage life, and can be easily stored and prepared for eating (Zia-ur-Rehman & Salariya, 2005). 1Furthermore, a growing number of authors argue that legume production could increase farmers' profits by increasing income stability and reducing production costs because of lower pesticide demand (Malézieux *et al.*, 2009; Peeters *et al.*, 2006). Tshering (2002) assessed costs and patterns of inputs and labour use and profitability of bean production for farmers growing traditional and improved bean varieties in Honduras, and concluded that modern varieties of legumes have higher productivity compared to the traditional varieties. Along with these benefits, cereal crop yields and grain quality are improved by the preceding legume crop (Gooding *et al.*, 2007, Grzebisz *et al.*, 2002; Hejcman *et al.*, 2012) with yield benefits of 10%–20% for the succeeding crop (Freyer, 2003; Kirkegaard *et al.*, 2008). This is an additional economic benefit the farmers.

2.2 Theoretical review

2.2.1 Constraints to grain legumes production

Legumes offer an important means of improving food security and the sustainability of maize-based cropping systems, but there are many challenges, including limited seed access, low soil phosphorus status and limited area devoted to growing legumes (Kandji et al., 2001). Although farmers are interested in expanding areas devoted to legume production, there are barriers to wider adoption and scaling up. Nutrient deficiencies are a major factor limiting productivity on smallholder farms in sub-Saharan Africa (SSA), as soils are widely infertile and farmers have limited access to amendments such as inorganic fertilizers and manure (Okalebo *et al.,* 2006).

Socio-economic challenges include: limited and uncertain market access (Sibhatu et al., 2015); unstable and highly variable prices for legume inputs across locations and time (Jonas et al., 2011); limited farmer access to seeds of improved legume genotypes (Snapp & Silim, 2002); and insufficient attention by researchers to the multi-functionality of legumes. Improved legume seed is expensive and hence not affordable for many smallholder farmers. Moreover, surveys indicate that labour requirements, seed access and appropriate genotypes are barriers to legume intensification (Kamanga *et al.,* 2014). Snapp and Silim (2002) reported that biological properties of legumes also pose challenges to farmer adoption of legumes, some of them include: the moderate yield of legumes compared to cereals and tubers; the high labour requirement associated with a crop of initially slow growth habit; and relatively few large seeds are produced per plant, necessitating the use of large amounts of seed (on a weight basis) per land area, which substantially increases establishment costs compared to cereals.

Legume production is also faced by a range of field pests as well as their susceptibility to post-harvest weevil damage. Damage by insect pests is considered the limiting factor of bean production in East Africa (Medvecky et al., 2006). The main field pests are aphids, bean flies and pollen beetle, which suck the legume sap and feeds on the plant’s floral parts, resulting in low rate of podding and consequently, low yield (Broughton et al., 2003). Pre-harvest infestation of pests is very serious because it multiplies dramatically, and damage continues in storage reaching a level of 80% in 6-8 months (Sapunaru et al., 2006).

Diseases of legumes cannot be overemphasized. RR, BCMV, and CBB are major diseases constraining legume production in western Kenya (Ojiem *et al.*, 2006). HB reduces yields of legumes in smallholder systems (Agrios & George, 2005). Legume diseases lead to low yields, and low adoption of legumes by farmers (Farrow et al., 2016). Low yields of legumes are also associated with declining soil fertility due to continuous cropping without soil replenishment (Ojiem *et al.,* 2006) and reduced N2-fixation due poor plant growth which rhizobia rely on for carbon (Udvardi & Poole, 2013). This becomes more severe as farmers expand into marginal lands in response to population pressure.

2.2.2 Prior studies on legumes

As much as legumes face a number of challenges, there exists opportunities for their production. Bean is a crop that is adapted to many niches, both in agronomic and consumer preference terms (Broughton *et al.,* 2003). Legumes are beneficial crops which can be grown solely, or grown intercropped with cereals. Maize and legume intercrops are common in SSA, and lead to increased productivity of maize (FAO, 2011). Legume growth and rhizobial nodulation are highly dependent on adequate moisture and aeration (Farrow et al., 2016). Temperature gradients can also influence legume production, but across tropical Africa the climate is generally sufficiently warm for most legume species.

The growth habits and other characteristics of legumes vary by species and variety (Rao *et al.,* 2000). Mhango (2012) determined that some of the characteristics can be complementary, depending on the species and management practices; for example, differences in growth habits allow intercropping of maize with pigeon pea, fish bean or climbing bean. Similarly, upright groundnut varieties or soybean can be intercropped with pigeon pea. Intercropping, if carefully designed and managed, can help to increase resource-use efficiency (Hauggard *et al.,* 2008).

2.2.3 Biophysical and socio-economic heterogeneity

Smallholder systems in Nandi County are not only unproductive but are also characterized by high level of heterogeneity in biophysical and socio-economic aspects (Ojiem *et al.,* 2006). The systems are heterogeneous with respect to rainfall, temperature, soil fertility, pests and diseases, land and labor availability, income, market availability, and farmer preferences. Rainfall is a particularly important factor in annual legume biomass production and N inputs (Mhango *et al.,* 2012). In one study, biomass production in cowpea (V. unguiculata) was found to be 34% higher in high rainfall areas (900mm annual precipitation) than in low rainfall sites (450mm annual precipitation) (Kayinamura *et al.*, 2003). Generally, insufficient rainfall limits legume growth; however, excess moisture and extreme rainfall events are becoming major problems for African crop production (Akinnifesi *et al.*, 2011).

Soil factors, including both biological and geochemical properties, exert a major influence on legume performance (Giller, 2011). Phosphorus for example, affects root growth and development, nodulation and the N fixation process (Hoa *et al.,* 2002; Jemo *et al.,* 2006). Additionally, Mhango (2012) noted that deficiencies of soil N and inorganic P are some of the most widespread constraints to legume development and yield potential in Africa.

Socio-economic factors also influence legume productivity. Access to capital by smallholder farmers is an important legume adoption factor. Firstly, capital affects the available labour in a household and the ability of the household to manage the environment in which they grow legumes. Secondly, capital affects access to inputs, such as improved legume seeds, inoculant and fertilizers (Jonas et al., 2011). Land availability and land tenure systems also affect legume production. When farm sizes are small, legume production may suffer because maize, which is the main cereal, is given higher priority (Adamtey et al., 2016). On the other hand, where farmers have access to sufficient land, legume production may be possible but there may be less incentive to invest in soil fertility improvement through the use of legumes (Jonas et al., 2011).

Access to markets is an important incentive for production of grain legumes, especially the ones that are not used as traditional food. Three components to marketing often mentioned in literature are: the demand for legume products and the existence of a market, functioning linkages among market actors (Farrow, 2014), and marketing of grain legumes by individual or groups of producers (Jonas et al., 2011; Farrow et al., 2016).

2.3 Overview of GIS

Geographical information systems are a special class of information systems that keeps track of not only events, activities and things, but also where these events, activities and things happen or exist (Longeley *et al.*, 2006). Geographic location is an important attribute of activities, strategies, and plans. GIS integrates hardware, software, and data for capturing, managing, analyzing, and displaying all forms of geographically referenced information (Mendas & Delali, 2012). Maps produced using GIS allow us to understand our surroundings, and enable us to see the trends of occurring things by reducing the complexity of the environment (Yousefi & Razdari, 2015). Virtually any data that can be spatially referenced can be shown on maps and various kinds of data can be represented on a simple map (Yousefi & Razdari, 2015). This would give us the chance to analyze the interaction between the different kinds of data and reach at a better conclusion than we would have done it otherwise (Osamu and Noriko, 2009).

2.3.1 Prior studies utilizing GIS

In this era of climate change, Geographic Information Systems (GIS) and Remote Sensing (RS) techniques are starting to gain popularity, especially in agricultural management to forecast and sustain emergencies and natural disasters that influence agricultural productivity (Ayanlade *et al.*, 2013). Yousefi and Radzari (2015) reported the use of GPS and GIS for mapping pest infestations and using the maps to communicate the information to field managers to apply correct chemicals in areas where they are needed. In the urban planning, forestry, climate science, military use, emergency management, public health, epidemiology, etc., GIS has been used to establish trends within spatially referenced data, make detailed location based analysis, and keep track of events on an area over extended period of time to see how things are changing with time.

Often times, we have to make decisions that require the knowledge about our environment. Our environment is so complex that sometimes we make decisions with incomplete information. Yet GIS enables us to build a model of the complex environment in a much simpler and easier way for us to understand the environment and make decisions about it (Mendas & Delali, 2012). Visually depicted data is far easier to understand than just the raw data itself. In addition to that, GIS makes the interaction between various factors that the data represents to be easily recognized. For example, in planning to set new legume technologies in new areas one might need to understand the biophysical and socio-economic characteristics of that area first.

In farming, environmental factors such as weather conditions and soil types vary from location to location. By taking this information along with other farming data such as cultivation records and location based differences in yield and quality and using GIS technology to link it to locations on the farm, the information is made easier to manage and it also becomes possible to bring together and represent visually the many different factors that influence productivity.

There are numerous other uses for GIS technology in agriculture. Examples include taking note of past production when establishing new cropping plans in order to maintain a crop rotation regime, collating data on the total planting area for each crop, on-site reviewing of rice production adjustments, displaying the age of farmers and whether or not they have someone to take over from them on a map to determine the situation in each village, and estimation of land area on sloping land. As remote sensing technologies that use satellite images can be used to estimate differences in parameters such as crop growth and yield, this information can be used for various different purposes such as using it as a basis for soil management practices in the following year. By using GPS (global positioning system) to obtain the position of agricultural machinery in real-time, the information can also be used to support equipment allocation planning including identifying where to move agricultural machinery to next.

2.3.2 Matching of options to appropriate contexts

Due to the heterogeneous nature of the smallholder systems, there is need for fully understanding the biophysical contexts in which the legume production technologies are being applied. This would allow the identification and promotion of best-fit technologies for a given context and ensure more effective targeting of the technologies in the multiple biophysical and socio-economic contexts of smallholder farmers. Sumberg (2005) proposes a general framework for analysis of adoption of agricultural innovations (Technologies) which emphasizes a three way interaction between the user (farmer), the innovation and the context. In this framework, the context is defined as external to a project and not modifiable, so factors involving the context are deemed prerequisites for adoption. Examples of contexts for legume production can be incidences of pests and diseases, rainfall regimes, soil fertility status (biophysical), and land availability, access to markets, labor availability, access to credit (socio-economic), etc.

Sumberg considers that only factors which are an interaction between the innovation and the user are modifiable by organizations implementing development and research activities. Sumberg assumes a predominantly technological innovation and we can see that the boundaries of the context change according to the type of innovation being promoted or tested. Ric Coe (https://www.youtube.com/watch?v=NNy0dj_gElE) also presents the concepts of options by context interactions, showing how best options can be fitted in right contexts, giving examples of the standard "genotype by environment" interactions that plant breeders use.

2.3.4 Geospatial analysis

There is a high level of heterogeneity in smallholder systems in western Kenya (Ojiem *et al.,* 2006). New grain legume species bred for disease tolerance and high productivity are being introduced in Nandi County, with an expectation of them being quickly adopted but since they do not function as desired, adoption has remained low. To capture the broader spatial and social contexts of these systems, there is need to explore the visualization capacity of Geographical Information Systems (GIS). GIS through spatial analysis allows visualization of constraints, their specific distribution, and their interactions. Large landscapes can be characterized on the basis of digital spatial data and observations made on patterns and trends not visible with other tools (Sahraoui et al., 2018). Chirowodza *et al.* (2009) also added that the visualization capacity of information management tools such as

Geographical Information Systems (GIS) can assist researchers in capturing the broader spatial and social contexts of communities. Biophysical factors like soil properties, rainfall, temperature, and landscape of a place cannot be controlled, but can be better understood and managed with GIS applications. GIS has been proven to significantly help in effective identification and distribution of diseases, soil properties, as well as yield estimation (Razdari & Reza Yousefi, 2015). Many site-specific farming systems utilize GIS and several related technologies (global positioning system, receivers, continuous yield sensors, remote sensing instruments) to collect spatially referenced data, perform spatial analysis and decision making, and apply variable rate treatment (Zhang et al., 2015). The benefit of GIS technology is that it provides for the rapid integration of data from a variety of sources, with the added benefit of computer graphics display (Zenilman *et al.,* 2002). Global positioning systems (GPS) and remote sensing are advanced technologies offering numerous advantages at scales ranging from the farm field to the entire globe because they can be used to: generate and synthesize new information cheaply and quickly; document data sources and methods of integration; provide diagnostics for error detection and accuracy assessments; provide input data for a variety of crop yield and non-point source pollution models; and prepare maps and tables that meet specific needs (Mendas & Delali, 2012; Zhang et al., 2015; Sahraoui et al., 2018). Once GPS coordinates of a place have and information on biophysical factors of interest collected, GIS in-built mathematical calculations can be used to interpolate/extrapolate (predict unknown) values for any geographic point data that was not studied and form a continuous raster.

2.4 Summary

The ability of GIS to analyze and visualize agricultural environments and work-flows has proved to be very beneficial to those involved in the farming industry. From mobile GIS in the field to the scientific analysis of production data at the farm manager's office, GIS is playing an increasing role in agriculture production throughout the world by helping farmers increase production, reduce costs, and manage their land more efficiently. While natural inputs in farming cannot be controlled, they can be better understood and managed with GIS applications such as crop yield estimates, soil amendment analyses, and constraints identification and remediation.

2.5 Research gaps

Geospatial data plays an important role in decision-making in agricultural activities, particularly in response to the impacts and vulnerability of agricultural production to climate change and variability (Ayanlade *et al.,* 2013). As much as spatial analysis can be used in a number of ways including guidance of where to test and disseminate agricultural production technologies, and scaling out of promising technologies, little is being done in Kenya and most parts of SSA. Utilization of geospatial analysis in SSA has lagged behind because of limited development of geospatial data infrastructure to enhance agricultural practices, especially agricultural risk management in this age of climate change (Ayanlade *et al.,* 2013). Where such data is available, the scale is often too large to allow application in specific smallholder situations like western Kenya. Therefore, most GIS use is in national level and not location level. Efforts to enhance soil fertility and reduce pest and disease damage in order to increase grain legume productivity in the smallholder systems of western Kenya has been in place for many years, but many technologies being introduced are not working as desired. There is need to apply GIS tools to assist in capturing the broader spatial and social contexts of smallholder systems. This will in turn enhance the efforts of increasing grain legume productivity, as well as providing researchers with framework for use while scaling out promising legume options to new locations, and reduce food insecurity.

CHAPTER THREE

METHODOLOGY

3.1 Study area

The study was carried out at three sites (Kapkerer, Kiptaruswo and Koibem) in Nandi County, western Kenya. Nandi County is highly heterogeneous and these locations represent a range of environmental conditions in terms in terms of precipitation, temperature, and elevation (Table 3.1). Precipitation in Nandi is bimodal, with the long rains (LR) starting from March to July, and short rains (SR) from September to December.

Table 3.1: Location and characteristics of study sites

Site	GPS coordinates	Mean annual rainfall (mm)	Average annual Temperature	Altitude (m)
Kapkerer	0.02˚N, 34.78˚ E	1000- 1800	21 °C	1400- 1700
Kiptaruswo	0.04˚N, 34.56˚ E	1500- 2200	17 °C	1500- 2200
Koibem	0.15˚N, 34.97˚ E	1500- 2000	17 °C	1500- 2100

Smallholder farmers in Nandi County generally practice mixed farming, with crops and livestock coexisting in most farms. A sizable number of farmers are also involved in farming of cash crops (mainly tea) to supplement household income. Farmers in this region typically cultivate smaller plots of land, with maize and beans being the most common crops. Soils are dominated by Acrisols in Nandi County and typically have low inherent fertility and low pH (Ojiem, 2017; Medvecky & Ketterings, 2009).

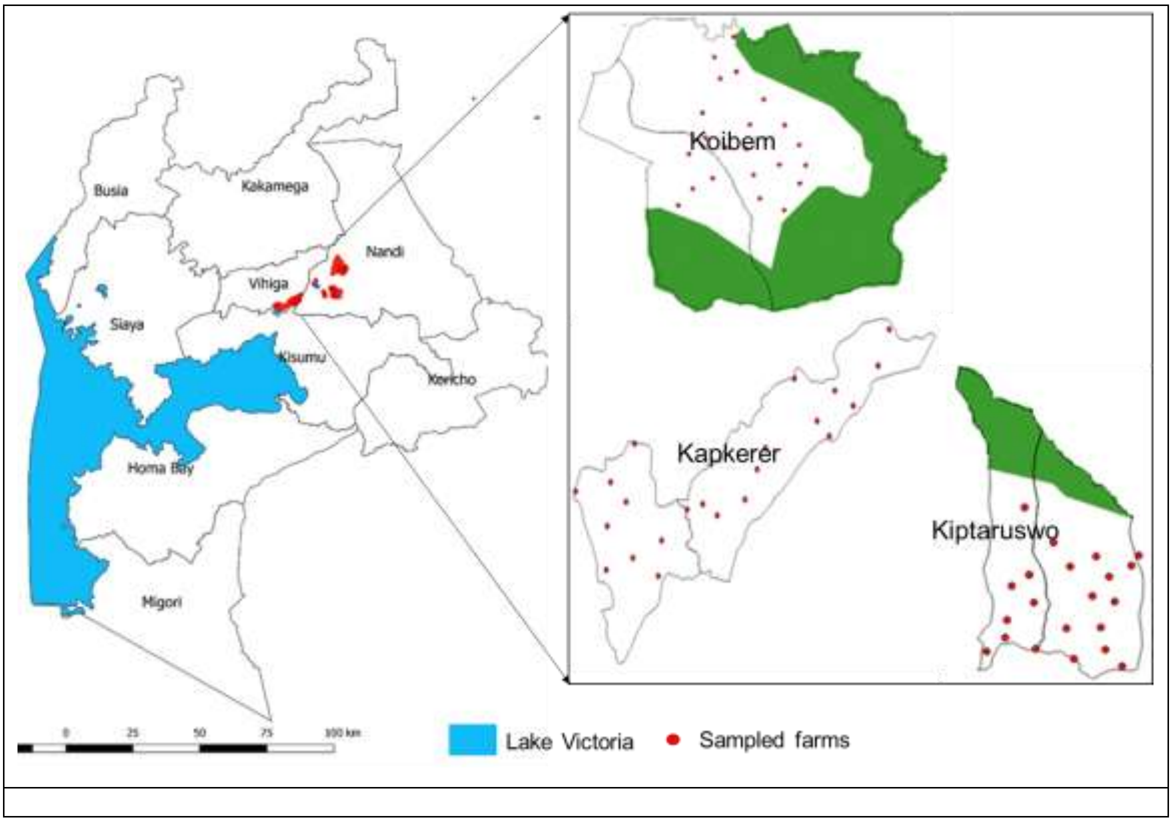


Figure 3.1: Map of the study area, showing the three study locations: Kapkerer, Kiptaruswo, and Koibem in Nandi County, western Kenya

3.2 Research design

Spatial experimental design was used in this study. However, Randomized Complete Block Design (RCBD) was employed, where similar experimental units were repeated in 66 farms to account for farm variations. In each farm, a field of $49m^2$ was marked out. The field was then divided into four plots measuring $9m^2$ each, to which the four legumes (bean, groundnut, soybean and lablab) were assigned at random.

3.3 Population

The study targeted smallholder farmers in Nandi County, western Kenya. Purposive random selection of farms was applied in sampling, where only farms from areas practicing cultivation of maize and bean were picked. Farmers growing cash crops (e.g. Tea) were left out of the study, since it is not their normal practice to grow legumes.

3.4 Sampling frame

A total of 66 farms were sampled for this study, 22 in each of the three study sites. A systematic sampling procedure was applied to ensure even spatial distribution of data points, taking into consideration the heterogeneity of observations. This procedure involved random selection of 22 farms from each site at a sampling interval of one km. The sampling interval of one km was determined by dividing the total area under agricultural use in each site (approximately 22 km^2) by 22 farms. Systematic sampling eliminated the phenomenon of clustered selection of farms.

3.5 Sample and sampling technique

Since the objective of the study was to map the distribution of legume production constraints and opportunities, even distribution of data points was essential. Therefore, spatial (considering heterogeneity and dependency of observations) and systematic sampling was applied to achieve an even distribution of data points within each study site (Figure 3.1). The sampling interval was approximately 1 km.

3.6 Materials

Table 3.2: Materials used in this study for collecting GPS coordinates, and rainfall and temperature for two seasons (short rains 2016 and long rains 2017) in Nandi County

Materials	Functions
Garmin e-Trex 20 GPS unit	For recording GPS coordinates and altitude of all the selected farms
Rain gauges	For recoding daily rainfall
Thermometers	For recording daily temperature

3.7 Data collection procedure

Establishing trials and data collection

Four grain legumes (common bean, soybean, lablab, and groundnut) were planted in un-replicated experimental plots in each of the farms to assess the variation between farms. The plots were established at the beginning of the short rain season in September 2016. Spacing was at the recommended spacing of 50 cm inter-row and 10 cm intra-row. Fertilizer Triple Super Phosphate (TSP) was applied at 30 kg P ha^{-1} in planting holes. Weeding was done twice, first weeding 21 days after planting (DAP) and the second one 42 DAP. The trial was repeated in the same farms but different plots during the long rains season-March to July 2017. Prior to planting, composite soil samples (0 to 20 cm) were taken from the trial plots in each of the 66 farms for determination of soil factors important for legume growth. Soil pH, organic carbon, exchangeable calcium, magnesium and potassium, and soil texture were determined at the Kenya Agricultural & Livestock Research Organization laboratory based in Nairobi, Kenya. In addition, soil concentrations of important micro-nutrients (Fe, Zn, Mb, and Mn) were analyzed by Ethylenediamine-tetraacetic acid (EDTA) extraction and measurements using Atomic Absorption Spectrometer (AAS).

Climatic data (rainfall and temperature) was collected every growing season using a set of rain gauges and thermometers that were installed at strategic locations to provide even coverage of the entire study site. Placement of these weather data collection tools was done taking into consideration the topography, nearness to the forest, and the position of farms on the hills. Daily rainfall was recorded at each of the locations. Morning, mid-day and evening temperatures were recorded at each location using the installed thermometers. Morning temperature was recorded at 9 am, mid-day temperature at noon, while evening temperature was recorded at 6 pm. From these three readings, an average daily temperature was calculated for each location.

Emergence of legume plants was assessed 10-14 days after planting (DAP) by counting the number of plants that had emerged and expressing this as a percentage of the seeds that were planted in each plot. The percentage emergence was calculated on the basis of viable seeds (germination assessment was done in the laboratory before planting). Pest and disease damage was assessed and scored based on symptoms that were observed at various stages during the growing season. Plant fatality due to RR and BF were recorded cumulatively at 14, 21 and 28 DAP and percent plants dying determined based on emerged plants. Bean common mosaic virus (BCMV), angular leaf spot (ALS), common bacterial blight (CBB), anthracnose, soya bean blight (SBB), leaf rust (LR), Rosette virus (RV) and halo blight (HB) was scored as they appeared on a scale of 1-5, where 1 represents least diseased and 5 represents most diseased. The scoring was based on CIAT bean program standard evaluation scale (CIAT, 1992). In addition to scores, plant samples were taken to University of Nairobi plant pathology laboratory for isolation of pathogens and culturing to facilitate positive identification of the fungal, bacterial and viral diseases, whose symptoms were observed during the growing season. This was used to validate the disease-related mortalities reported. Damage by aphids was also scored on a scale of 1-5, as explained above. Legume plots were harvested at the end of each growing season, pods removed and threshed for determination of grain yield. Grain moisture content was measured using an electronic moisture meter, grain weighed and grain yield expressed in t ha^{-1} at 13% moisture content.

3.8 Data Processing and analysis.

Grain yield data was subjected to visual evaluation of generating boxplots using Stata software, to assess the variability of legume performance between and within sites, over the long and short rain seasons. Statistical analysis was conducted by assessing factors that directly influence legume productivity, and those whose influence is indirect. Figure 3.2 gives the conceptual framework that guided the analysis. Correlation analysis was conducted to determine how the soil quality parameters, pests and diseases, and rainfall relate with legume grain yield, and with each other. This was followed by development of visual correlation diagrams to show the relationship between grain yield and rainfall, elevation, soil pH, root rot, and bean fly. A second correlation diagram was constructed to show the relationship between rainfall and percentage of plants dying due to RR and BF. The diagrams were made using R statistical package version 3.4.0. Data was then subjected to ANOVA to identify the variables with significant influence on legume grain yield. The variables that were included in the ANOVA models were selected based on the output of correlation analysis to avoid multi-collinearity. The ANOVA output informed the regression analysis which was conducted to determine the variables with significant contribution to legume grain yield. Linear mixed model (fixed and random effects) was fitted using both forward and backward selection of variables to get the model best fitting the data. The ANOVA and regression analyses were conducted on data combined over seasons and sites.

Spatial analysis was conducted to establish the spatial and temporal distribution of the key factors affecting legume productivity in the three study sites. Variables which showed correlation with grain yield and had significant effect on grain yield, according to the regression analyses, were selected for spatial analysis. Quantum GIS (QGIS) version 2.8.2 was used to analyze and map the spatial information of selected variables from the above analyses. GIS overlay maps showing the interaction of BF, RR, and BCMV with grain yield were done for each study site for both the long and the short rains growing seasons. Inverse Distance Weighting (IDW) interpolation method was used in the development of the maps. Variogram models were fitted in R using the gstat libraries to analyze the spatial relationship between data points.

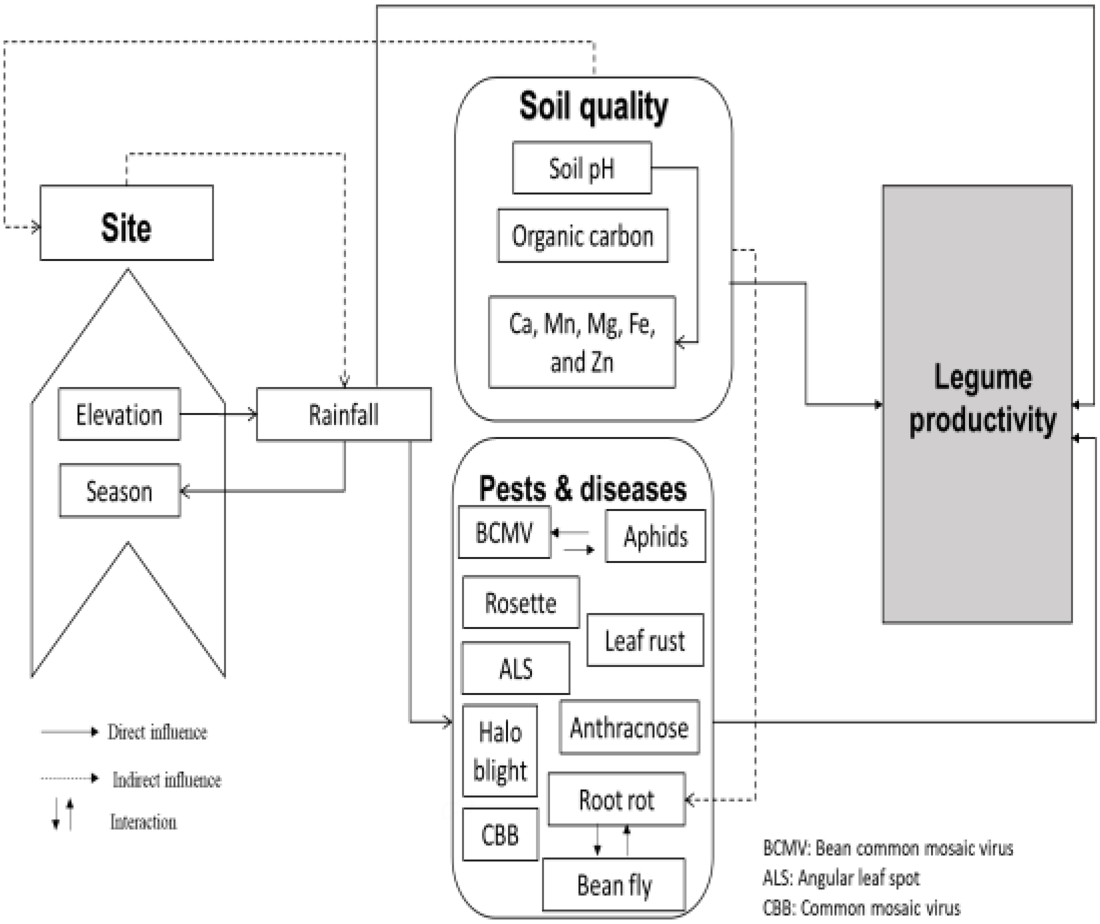


Figure 3.2: Conceptual framework for assessment of factors influencing legume productivity, and data analysis

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Environmental factors influencing grain yield

The variations in grain yield as determined by correlation and regression are partly attributable to rainfall, elevation, incidences of pests and diseases, and micro-nutrient deficiencies, especially Fe. Negative correlation was observed between a number of pests and diseases, and the grain yield of the four legumes.

4.1.1 Rainfall distribution

Rainfall was variable between the study sites both during the short rains 2016 and the long rains 2017 growing seasons (Figure 4.1). At Kapkerer, monthly rainfall was much below the long term average during the short rains 2016 growing season (Figure 4.1a). During the subsequent growing season (long rains 2017), the monthly rainfall was much higher than the previous season, and closely mirrored the long term average. The higher rainfall received at Kapkerer during the long rains growing season resulted in increased grain yield performance of bean, soybean, and groundnut, and reduced grain yield of lablab. At Kiptaruswo site however, the short rains season 2016 started with fairly good rainfall amounts, which was followed by a sharp decline during the month of November (Figure 4.1b). This sharp decline in rainfall occurred during flowering stage, and the relatively poor legume grain yield observed during this season is partly due to poor podding and grain filling as a result of this drought. Rainfall was adequate during the long rains growing season resulting in much higher grain yield performance compared to the short rains growing season. Similar to Kiptaruswo, rainfall declined sharply between November and December during the short rains 2016 growing season at Koibem (Figure 4.1c). This coincided with the podding and grain filling growth stages when moisture availability is critical. Bean, groundnut and soybean grain yield performance was therefore relatively lower during the short rains season 2016 than the long rains season 2017 (Figure 3), when soil moisture was adequate, while lablab grain yield was relatively higher during the short rains growing season.

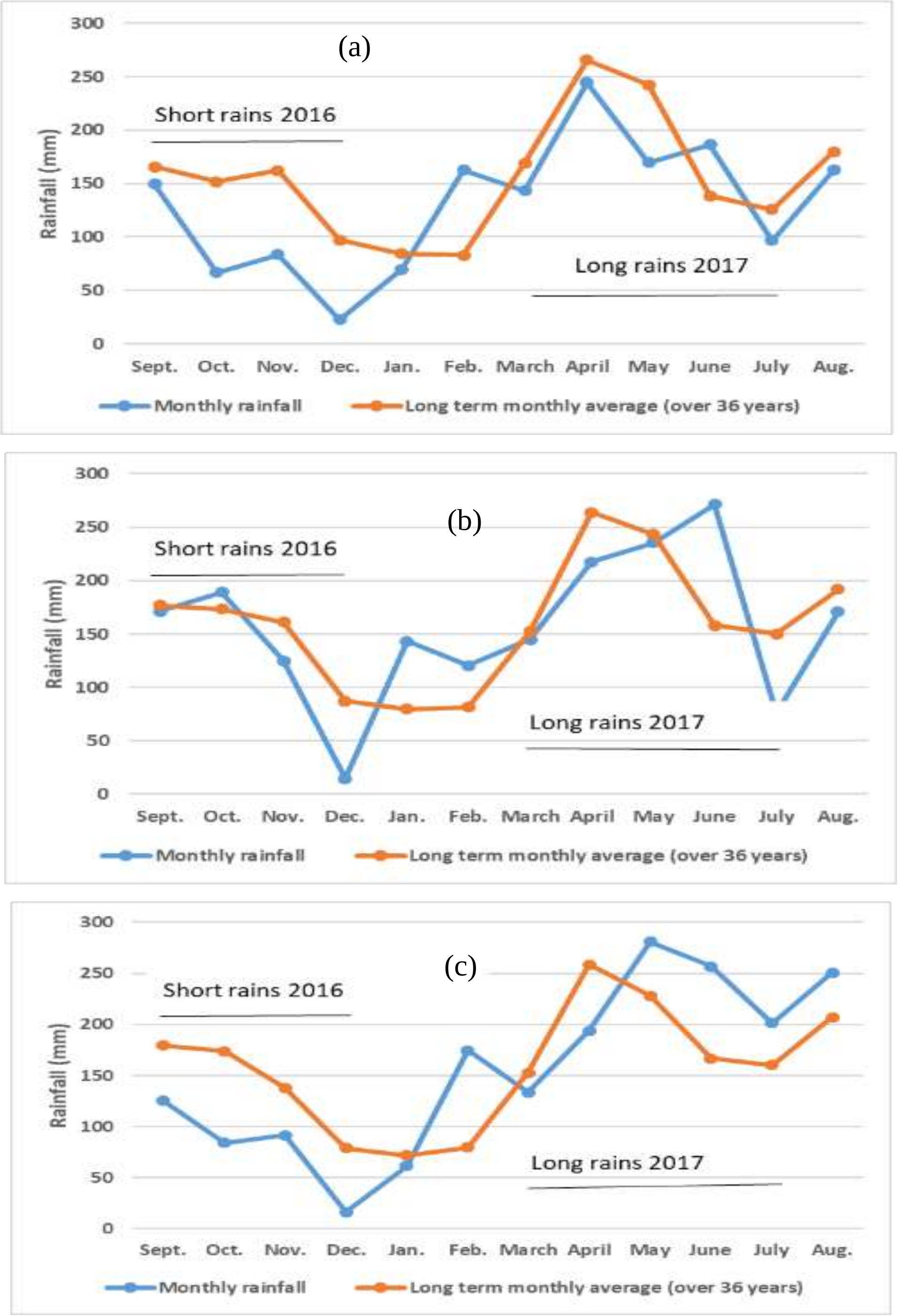


Figure 4.1: Rainfall distribution during the short rains 2016 and the long rains 2017 growing seasons at Kapkerer (a), Kiptaruswo (b) and Koibem (c) sites.

4.1.2 Elevation

Significant variation in altitude was recorded both within and between the study sites. Farms that were sampled at Kapkerer were at the lowest altitude (1350–1680 masl), while those sampled at Kiptaruswo and Koibem were at about 1700-1980 masl (Figure 4.2). Altitude has indirect effect on legume grain yield since it modifies factors such as rainfall and temperature, which directly influence pests and diseases. In addition, altitude affects days to maturity and rates of evapotranspiration (Wortmann *et al.,* 1988), thus influencing legume grain yield. Legumes are grown in a wide range of agro-ecological zones in Kenya, with altitudes up to 3000 masl (Broughton et al., 2003), and the yields realized in these different agro-ecological conditions vary.

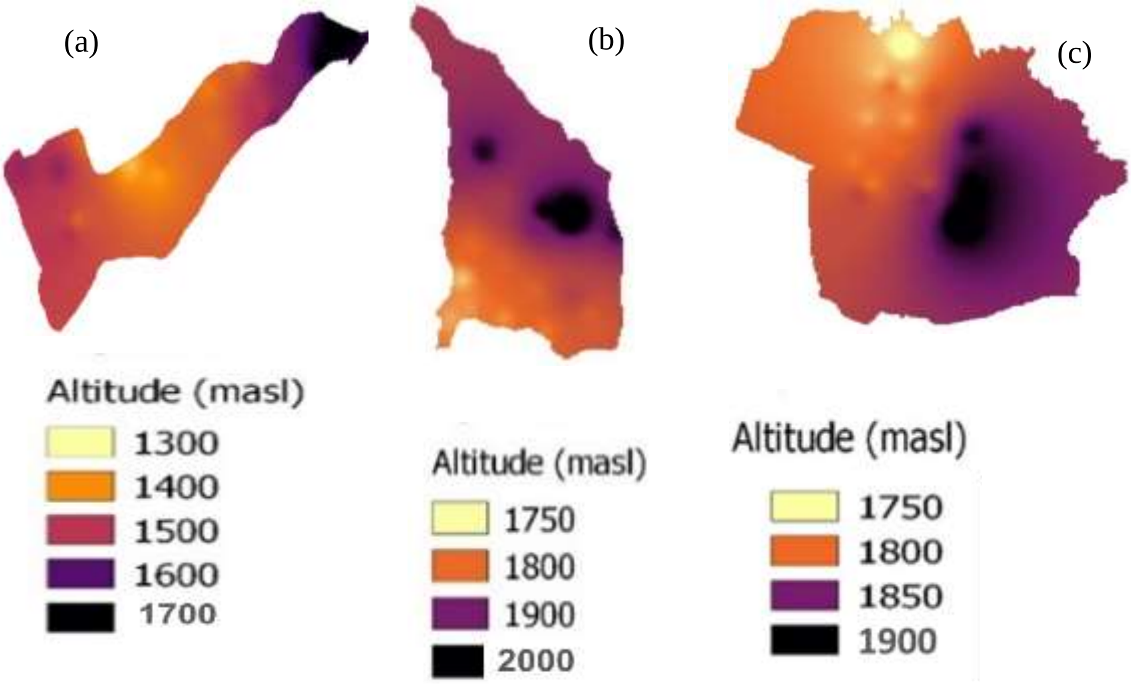
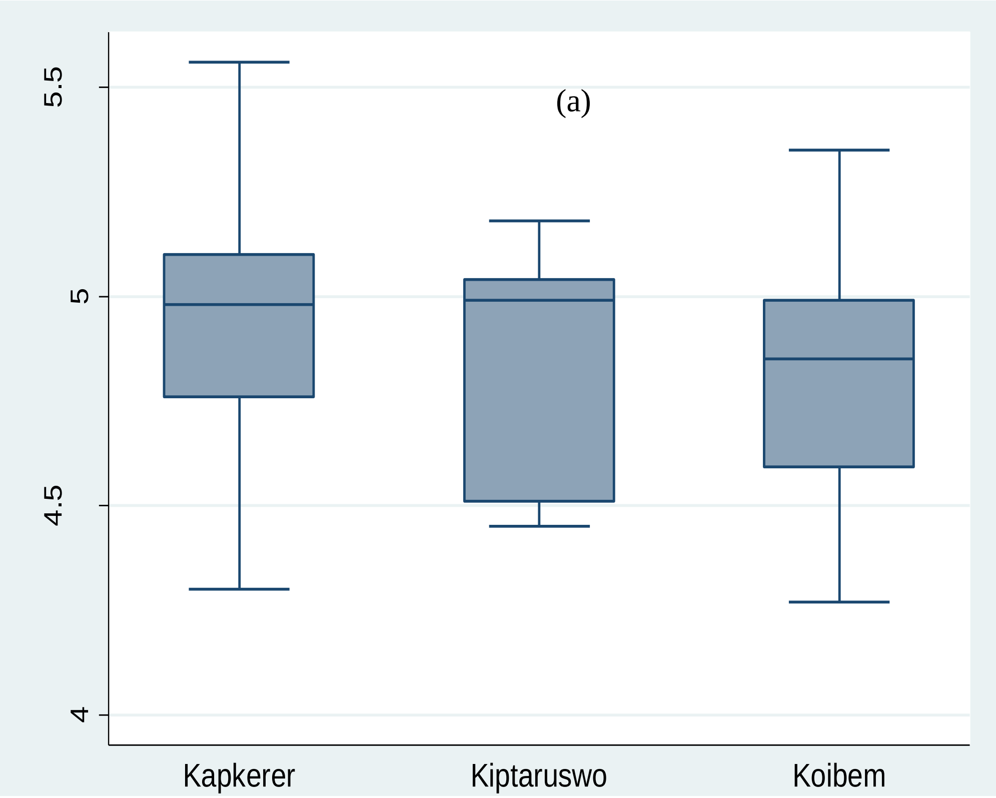


Figure 4.2: The range in altitude at Kapkerer (a), Kiptaruswo (b), and Koibem (c) sites, Nandi County.

4.1.3 Soil properties

A variety of soil quality factors influence the productivity of legumes, and indeed, the vulnerability and resilience of cropping systems (Smaling & Dixon, 2006). These factors include soil pH, organic C content, available P and N, and a number of micro-nutrients. Variations were observed in soil pH, organic carbon, iron, and manganese contents within and between study sites (Figure 4.3). Across the sites, pH ranged from 4.2 to 5.5, with 75% of the observations falling between 4.2 and 5.1 (Figure 4.3a), which is strongly acidic and likely to inhibit legume root growth (Yang *et al.*, 2012). Organic C is an important indicator of soil health. However, levels of organic C were lowest at Kapkerer, ranging from 0.8% to 2.9%, and highest at Koibem, ranging from 2.9% to 5.8% (Figure 4.3b), with most of the observations falling above 3%, which is considered adequate for maintaining good soil health. Iron and manganese contents were also variable within and between study sites (Figs. 4.3c and d). Generally, greater variability was observed in iron and manganese at Kapkerer, relative to Kiptaruswo and Koibem sites (Figs. 4.3c and d).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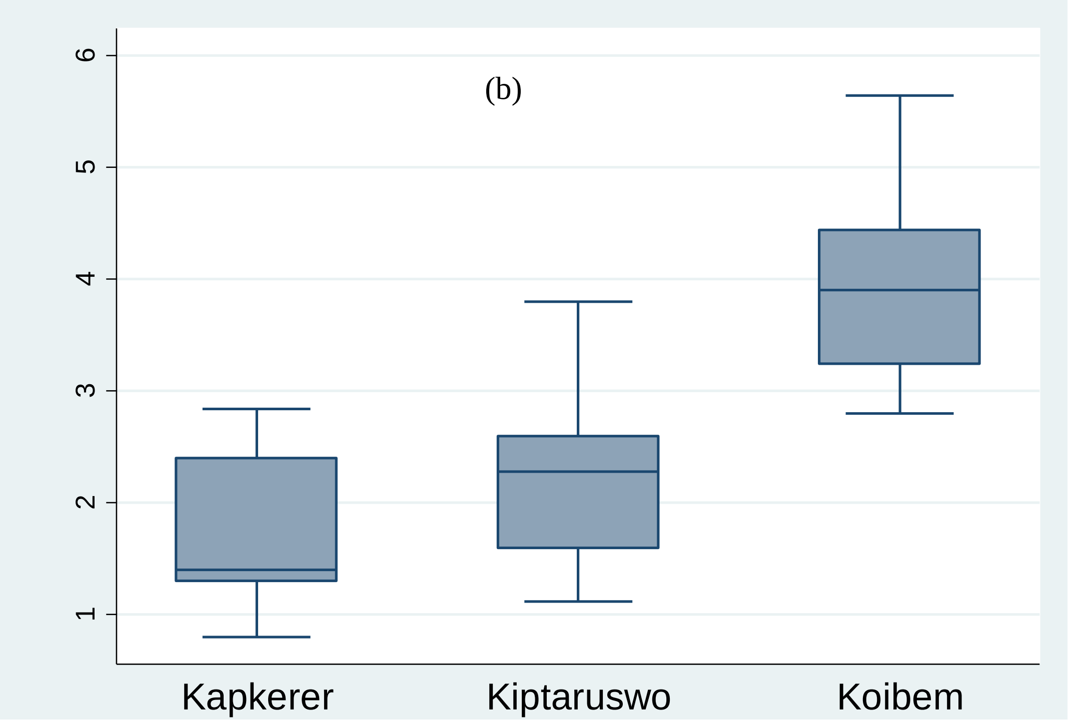
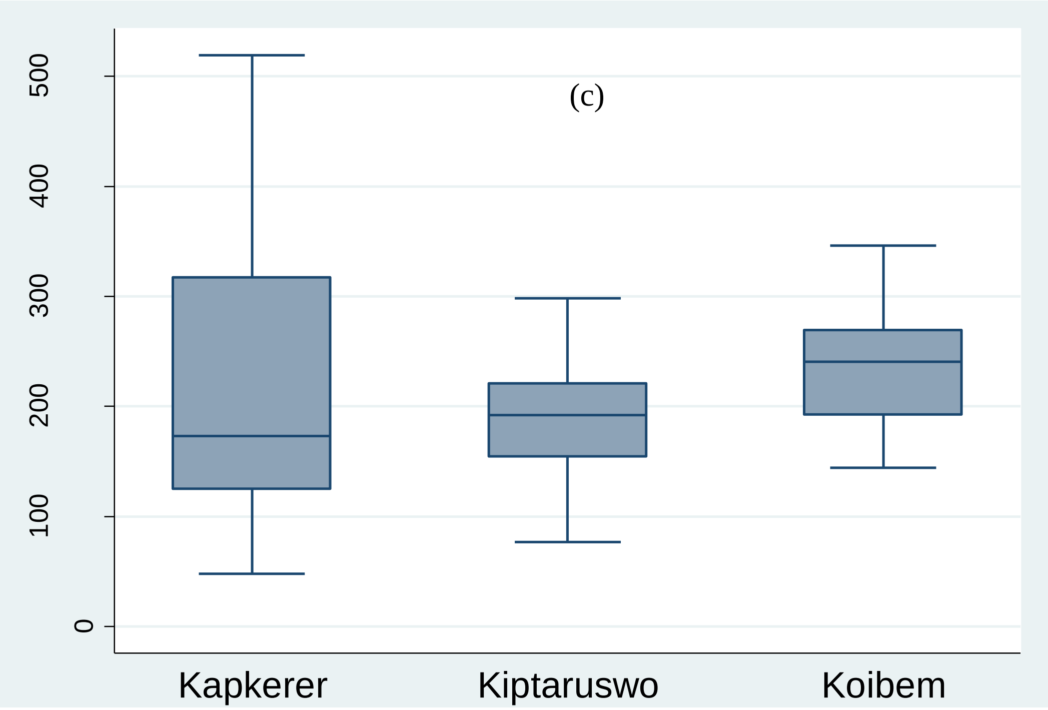
5
4.5
4
(a)
Kapkerer
Kiptaruswo
Koibem


6
5
4
3
2
1
(b)
Kapkerer
Kiptaruswo
Koibem


(c)
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Kapkerer
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Koibem

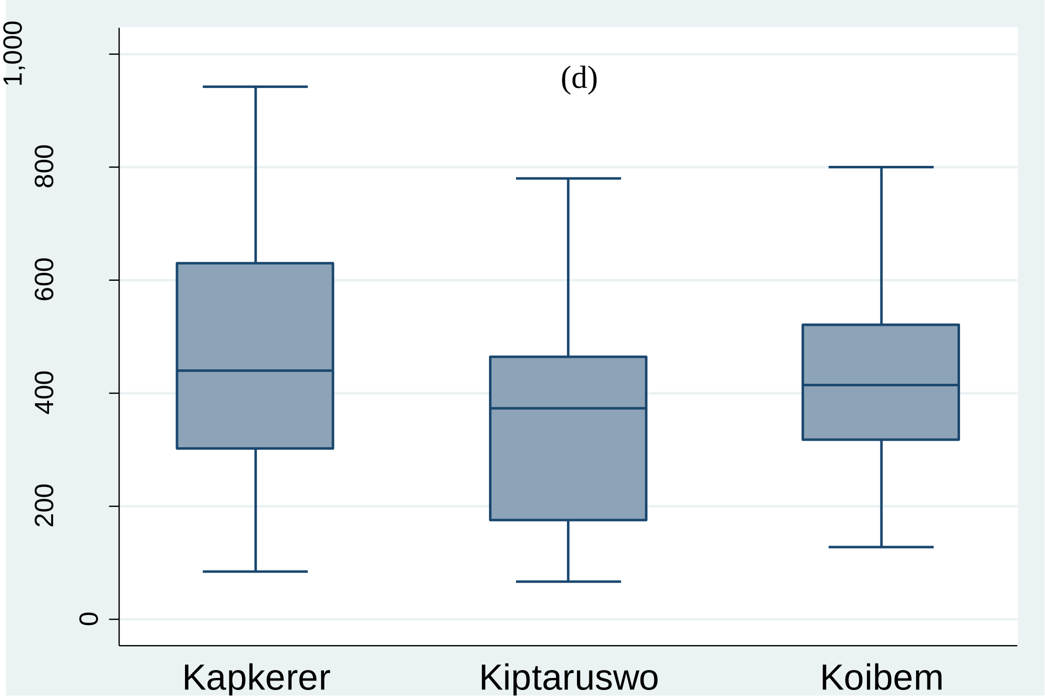
(d)
0
200
400
600
800
1,000
Kapkerer
Kiptaruswo
Koibem

Figure 4.3: Variations in soil pH (a), organic carbon (b), and levels of selected micronutrients: Iron (c) and Manganese (d) in the soil at Kapkerer, Kiptaruswo and Koibem.

4.2 Bean

4.2.1 Bean grain yield

Bean grain yield varied with site and season (Figure 4.4). During the short rains season in 2016, the range in grain yield at Kapkerer was 0.00 to 0.98 t ha^{-1}, with 75% of the observations falling between 0.00 and 0.18 t ha^{-1}. At Kiptaruswo, the range was 0 to 0.58 t ha^{-1} with 75% of the observations falling between 0 and 0.40 t ha^{-1}, whereas at Koibem, the range was 0 to 2.84 t ha^{-1}, with 75% of the observations falling between 0 and 1.5 t ha^{-1}. Similarly, during the long rains season 2017, Kapkerer had the lowest grain yield performance, ranging from 0.00 to 1.20 t ha^{-1} with 75% of the observations falling between 0 and 0.59 t ha^{-1}. Kiptaruswo had a highest grain yield range of 0 to 2.21 t ha^{-1}, with 75% of the observations falling between 0 and 1.08 t ha^{-1}. The grain yield range at Koibem was 0.31 to 2.15 t ha^{-1}, with 75% of the observations falling between 0.31 and 1.35 t ha^{-1}. The observed yields of bean at Kiptaruswo and Koibem sites compare favorably with national mean yields of 0.5t/ha. However, the yields at Kapkerer are far below the national mean yields as well as the mean yield eastern Africa highlands (Katungi *et al.*, 2010), which include Kenya, Uganda, Tanzania, Burundi and Rwanda.

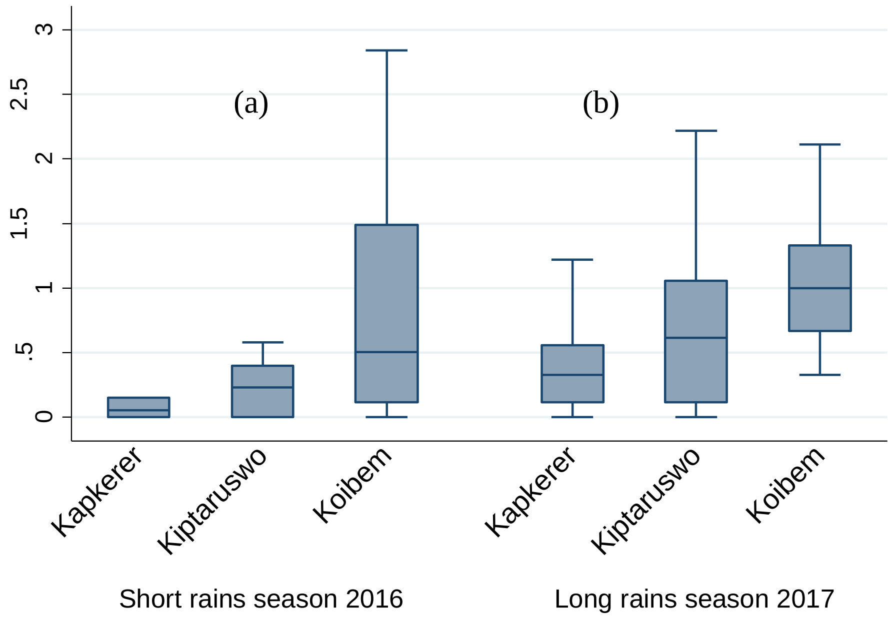

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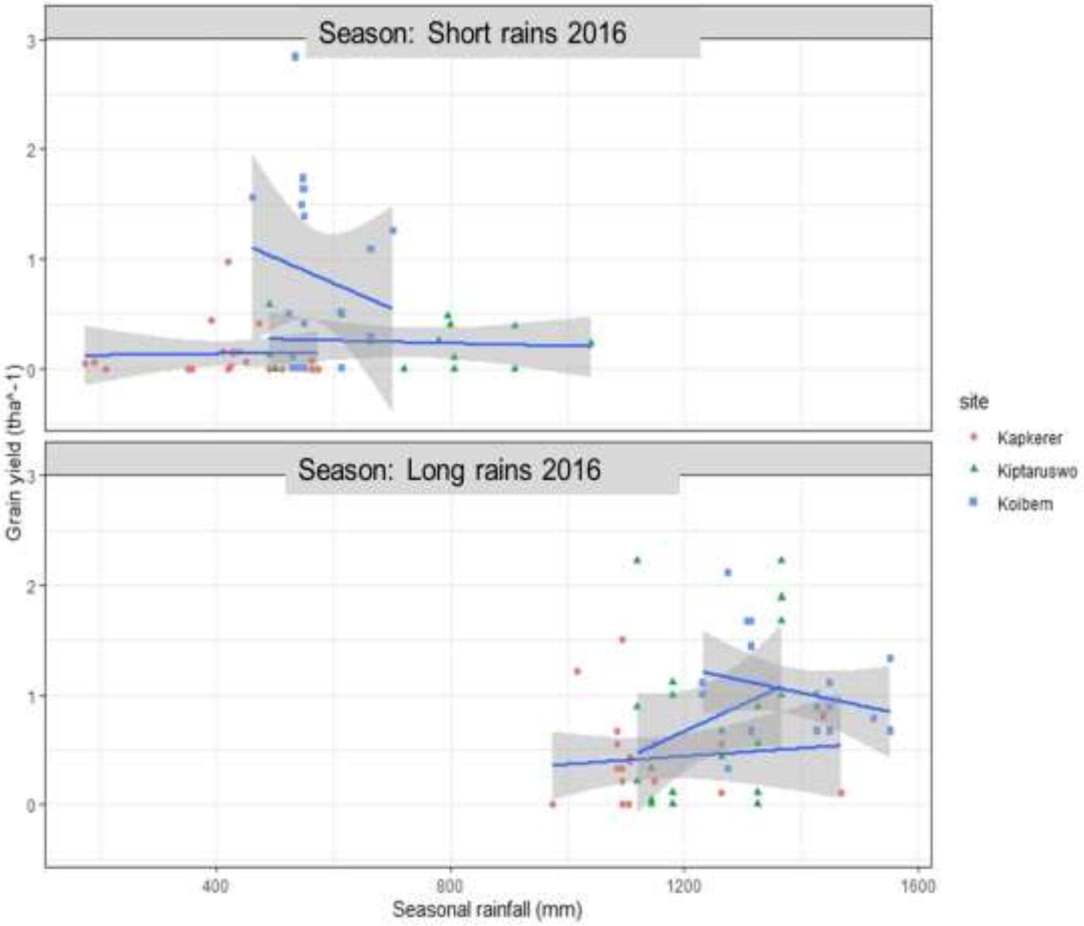
Figure 4.4: Bean grain yield performance at Kapkerer, Kiptaruswo and Koibem sites in Nandi County: (a) short rains 2016, and (b) long rains 2017

4.2.2 Effect of rainfall on grain yield

There was variation in rainfall both within and between seasons (Figure 4.5). During the short rains 2016 growing season when seasonal rainfall was low, bean grain yield was correspondingly low and no clear relationship observed between bean grain yield and rainfall. Insect pests and viral outbreaks tend to increase during dry seasons (Katsaruware-Chapoto *et al.*, 2017), hence contributing to low bean productivity. This was also observed in our study during the short rains 2016 growing season. Aphids, BCMV, and bean fly infestations were higher during the season. Conversely, during the long rains 2017 growing season when seasonal rainfall was high, grain was also high.

Successful bean production requires between 200 to 400 mm of rain during the growing season (Broughton *et al.*, 2003), and the distribution over the growing season is an important consideration. In addition, climate change is an emerging challenge that is likely to negatively influence bean productivity especially in the predominantly rain fed smallholder production systems of SSA.



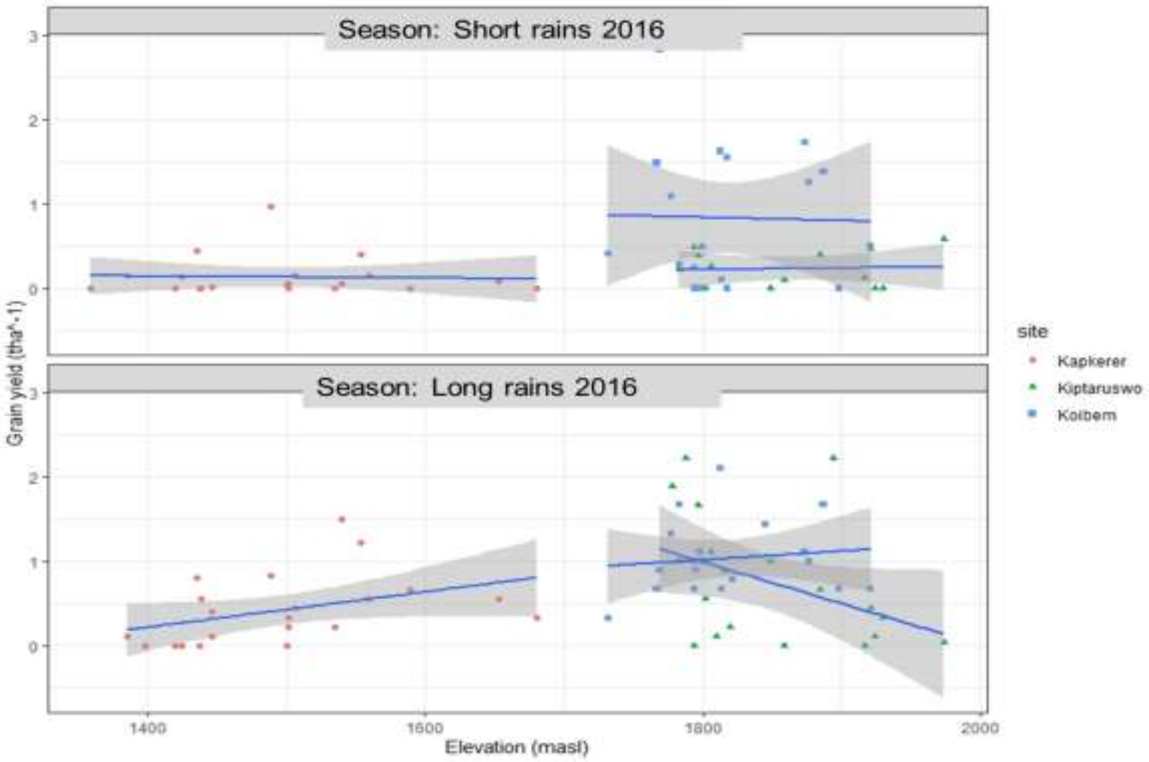


Figure 4.5: Correlation between bean grain yield performance and seasonal rainfall, and elevation at Kapkerer, Kiptaruswo and Koibem during the short rains 2016 and the long rains 2017 growing

4.2.3 Pests and diseases

Bean fly and aphids were the only pests of bean observed in this study. However, only bean fly had a significant correlation with grain yield (r= -0.278**). Bean diseases observed were root rot, BCMV, ALS, anthracnose, and CBB. Nevertheless, root rot and BCMV were the ones that had major effect on grain yield. Root rot was more severe during the long rains season across the sites, while BCMV was generally more prominent during the short rains season at Kapkerer and Kiptaruswo. Incidences of ALS, anthracnose and CBB were relatively minor across the sites and seasons.

Bean fly, also known as bean stem maggot, is the most important field pest of beans in smallholder systems in Africa. In Kenya, it causes grain yield losses of between 30% and 100 % (Mwanauta *et al.*, 2015). A negative relationship was observed between bean fly and bean grain yield across the sites during the short rains and the long rains growing seasons (Figure 4.6a). Greater damage by bean fly was observed during the short rains season than the long rains season, especially at Kapkerer. Bean fly damage was negatively correlated with seasonal rainfall (Figure 4.6b). During the short rains season, when seasonal rainfall was up to 900 mm, plant death per plot ranged from 0-70%, compared to plant death rate of about 0-8% during the long rains season when seasonal rainfall was up to 1580 mm

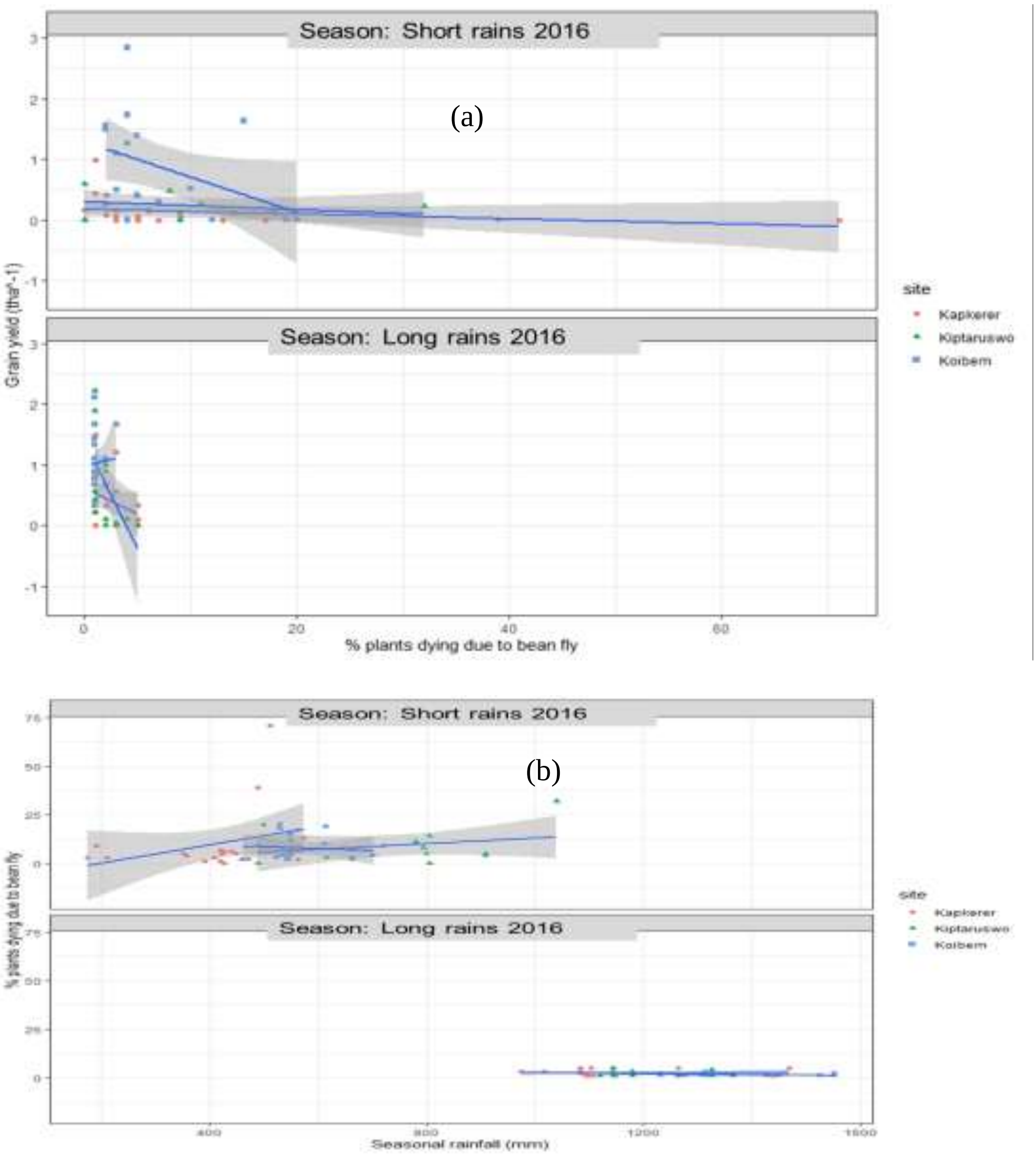
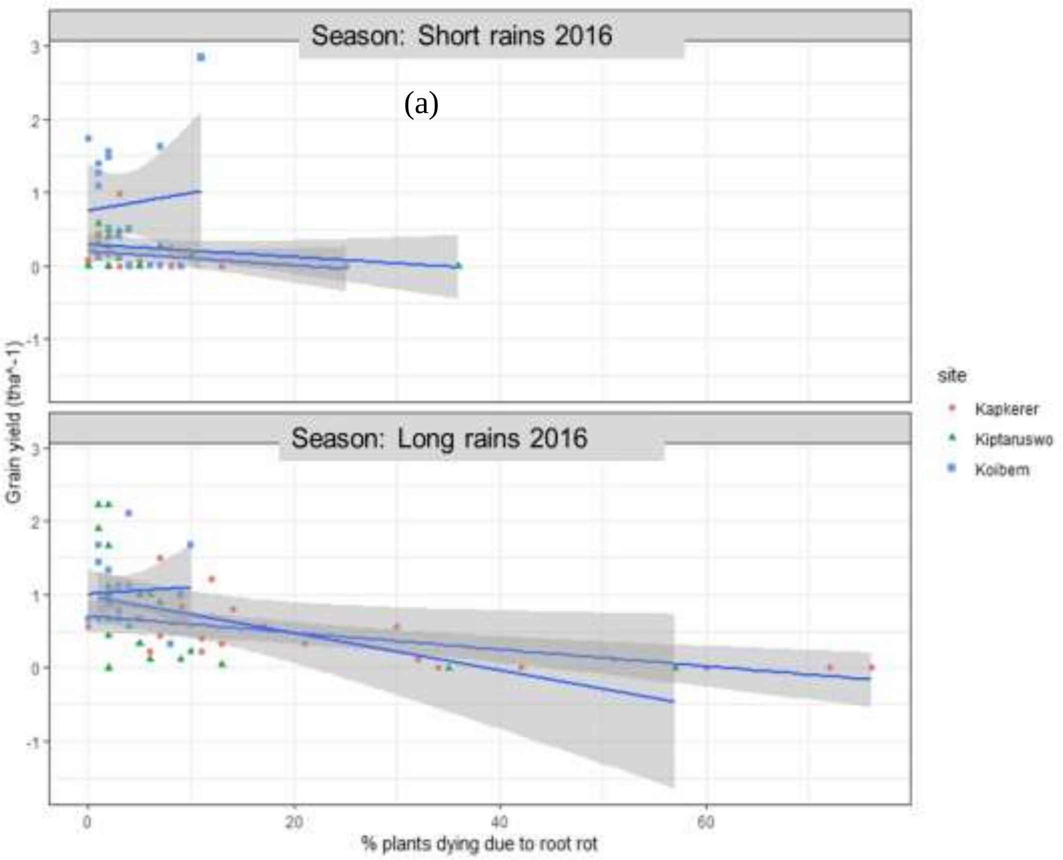


Figure 4.6: Correlation between grain yield and bean fly (a), and bean fly and rainfall (b), at the three study sites during the short rains 2016 and the long rains 2017 growing seasons

Incidences of root rot were observed at all the sites during the short and the long rains growing seasons. However, severity varied within and between sites, causing grain yield losses (Figure 4.7a). Damage by root rot was more severe during the long rains than the short rains, and Kapkerer and Kiptaruswo were more affected than Koibem. Root rot was also correlated with seasonal rainfall (r=0.100*) (Figure 4.7b). The relatively lower seasonal rainfall observed during the short rains 2016 growing season was associated with lower rate of root rot damage. During the long rains 2017 growing season, when higher rainfall was received, a higher rate of root rot damage was observed. Root rot severity tends to be more in smallholder farms where soils have been degraded, coupled with low soil pH, low K, and continuous bean cultivation (Kimani *et al.*, 2001).



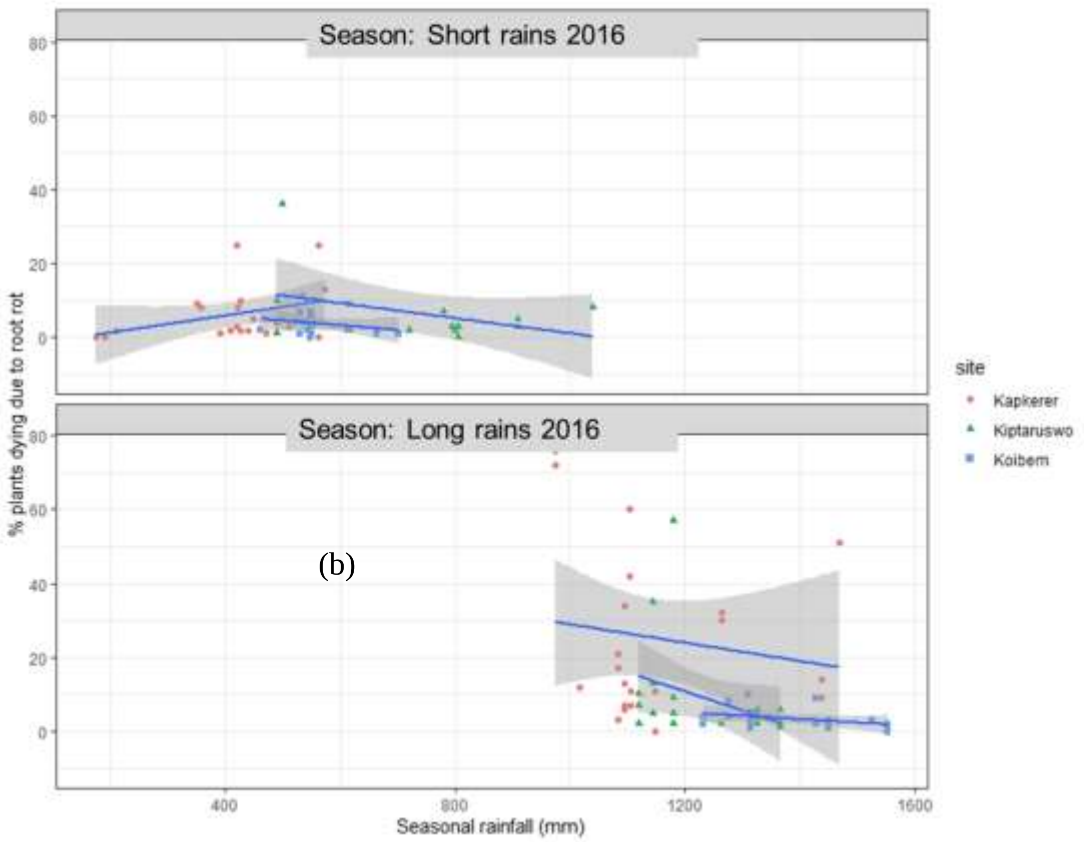


Figure 4.7: Correlation between grain yield and root rot (a), and root rot and rainfall (b), at the three study sites during the short rains 2016 and the long rains 2017 growing seasons

4.2.4 Bean multivariate analysis

The outputs of linear mixed effect regression show that several factors had significant influence on the productivity of beans (Table 4.1). Season had the greatest influence on bean productivity, accounting for an increase in bean grain yield by 0.35 t ha^{-1} moving from short rains season 2016 to long rains season 2017. The analysis also show that BCMV and root rot had significant negative influence on bean productivity. A decrease in grain yield by 0.14 t ha^{-1} was observed for every unit increase in the score of BCMV. Relative to BCMV, the influence of root rot on bean grain yield was relatively minor, a reduction of 0.018 t ha^{-1} for every one percent increase in plant mortality. Iron and manganese also had significant influence on bean productivity, with grain yield increase of 0.003 tha^{-1} for every unit increase of iron and reduction of grain yield by 0.0002 tha^{-1} for every unit increase in exchangeable manganese. Abundance of iron in soil is important for rhizobia growth and development in soil, which in turn lead to nodulation and increased legume productivity (Domingues et al., 2016).

Table 4.1: Regression analysis output showing major factors having significant influence on bean productivity in smallholder systems, Nandi County

	Estimate	Std. Error	df	t value	Pr(>|t|)
(Intercept)	0.3339	0.2639	100	1.265	0.208629
Season	0.3510	0.0983	54	3.572	0.000752 ***
BCMV	-0.1363	0.0674	97	-2.022	0.045921 *
Root rot	-0.0184	0.0052	99	-3.531	0.000629 ***
Iron (Fe)	0.0034	0.0008	80	4.021	0.000129 ***
Manganese (Mn)	-0.0002	0.0001	56	-4.146	0.000115 ***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

4.2.5 Geospatial analysis

Bean fly

Bean fly had a variable spatial and temporal distribution (Figure 4.8). During the short rains season 2016 at Kapkerer, bean mortality rates of 0-10% and 11-25% (% of plants dying per hectare) covered about 90% of the area of the study site (Figure 4.8a). However, high mortality rate of > 50% covered only about 4% of the site. These areas recording >50% of plants dying can be regarded as possible bean fly hotspots. Since this study was conducted for two growing seasons only, it is not possible to confirm the hotspots as more temporal data would be required for this confirmation. However, further analysis conducted by fitting variogram model indicated high correlation between farms close to each other hence the high mortality rates can be generalized for a cluster of farms in a particular location.

In the long rains 2017 season (Figure 4.8b), bean mortality distribution was more variable. Higher mortality rates of between 26-50% and > 50% were observed in about 60% of the site, and the possible hotspot observed at 34.74828˚ E, -0.01257˚ S in the previous season shifted to 34.77384˚ E, -0.00544˚ S and increased six fold in size. In addition, a new possible hotspot emerged at 34.82195˚ E, 0.02752˚ N. Mortality was generally correlated with grain yield. Overall, bean fly hotspots were associated with low bean grain yield.

Similar to Kapkerer, bean mortality due to bean fly showed a spatial and temporal distribution at Kiptaruswo. However, there was generally more mortality at Kiptaruswo (Figs. 4.8c and d) compared to Kapkerer. The low mortality rates of 0-10% and 11-25% were recorded in only about 25% of the study site during the short rains season (Figure 4.8c), while possible hotspots, observed at 34.93352˚ E, 0.03358˚ N and 34.95442˚ E, 0.04653˚ N increased in coverage to about 10%. Mortality slightly reduced during the long rains 2017 season (Figure 4.8d), although possible hotspots still covered about 10% of the site, but were observed in different locations. One was at 34.94136˚ E, 0.04225˚ N, and the other at 34.96209˚ E, 0.05202˚ N.

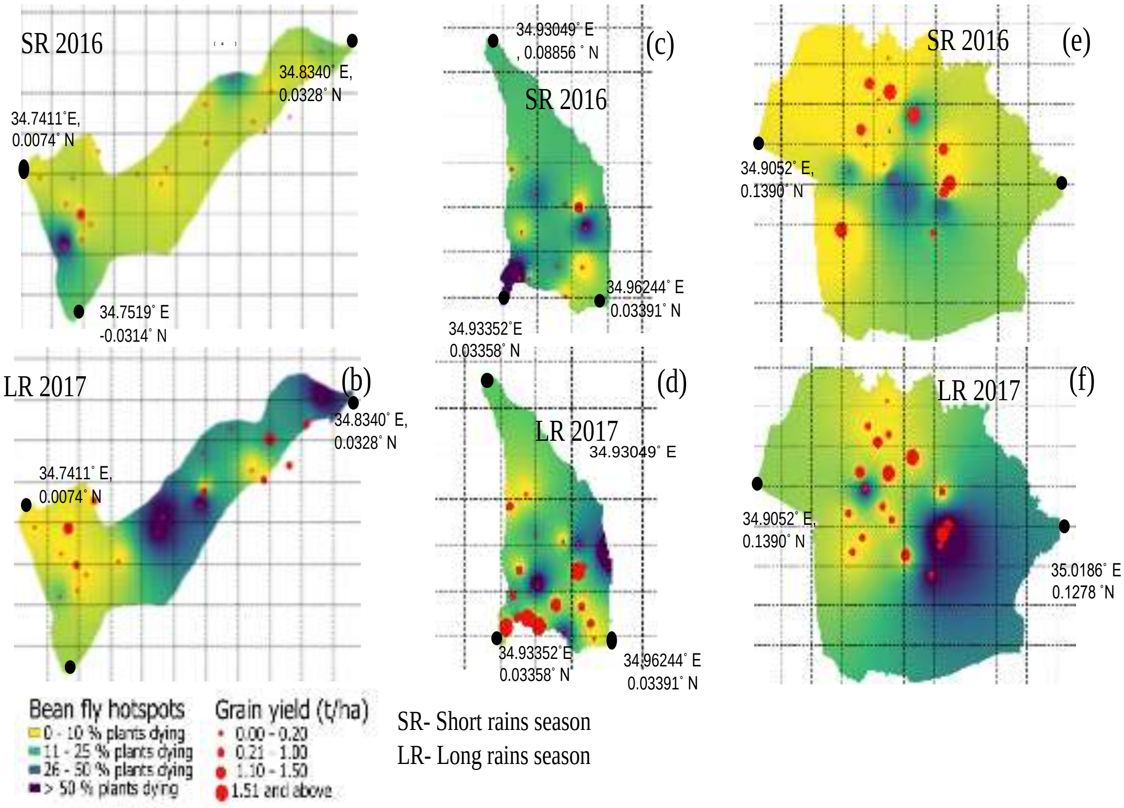


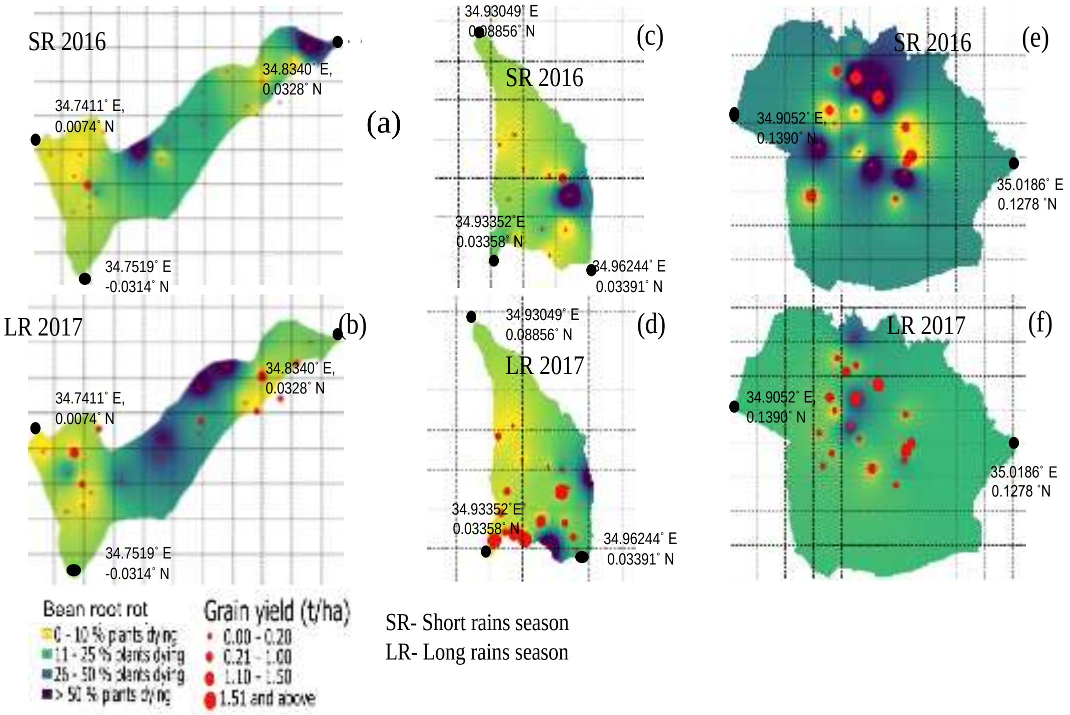
Figure 4.8: The distribution of bean mortality due to bean fly at Kapkerer (a,b), Kiptaruswo (c,d), and Koibem (e,f) during the short rains 2016 and the long rains 2017 growing seasons

Bean fly pressure was much lower at Koibem than Kapkerer and Kiptaruswo during the short rains season 2016, with about 90% of the site recording a mortality rate of 25% and below (Figure 10d). The highest mortality recorded was 26-50% at 34.9606˚ E, 0.1228˚ N and 34.9741˚ E, 0.1191˚ N, and covered about 3% of the study site. Similar to observations at Kiptaruswo and Kapkerer, bean grain yield at Koibem generally decreased with increasing mortality rating. During the long rains season 2017, bean mortality significantly increased (Figure 4.8e). About 25% of the site suffered a mortality rate of at least 50%, with possible hotspots (>50% mortality) having an area coverage of about 5%.

Bean root rot

Similar to bean fly, bean mortality due to root rot had a variable spatial and temporal distribution (Figure 4.9). Generally, a close association between bean fly and root rot was observed (r= 0.382**) at Kapkerer and Kiptaruswo, but not at Koibem. Similar relationships have been reported, where pests damage plant tissue and becomes an entry point for fungal pathogens like root rot (Broughton et al., 2003). Similarly, a close correlation between root rot mortality and bean grain yield was observed at Kapkerer and Kiptaruswo, especially during the long rains season. No clear relationship was observed at Koibem. The lower mortality rates of 0-10% and 11-25% were recorded in about 50% of the area of Kapkerer site in the short rains season 2016 (Figure 4.9a). However, possible root rot hotspots (mortality rate of > 50%) were recorded in an area of about 4% of the site, at 34.76951˚ E, 0.00351˚ N and 34.82579˚ E, 0.03141˚ N. Mortality increased considerably during the long rains season, with about 30% of the area of the site recording up to 25% of bean plants dying per hectare (Figure 11b). similarly, area under possible hotspots increased substantially. There were slight to big changes in the location of these possible hotspots. One that was at 34.76951˚ E, 0.00351˚ N shifted slightly to 34.7745˚ E, 0.00356˚ N, and nearly doubled in size. A new possible hotspot was observed at 34.79121˚ E, 0.01920˚ N, which covered nearly 4% of the site.

Root rot mortality at Kiptaruswo was slightly lower compared to Kapkerer both during the short and the long rains seasons. About 90% of the study site recorded mortality rates of up to 25% during the short rains season (Figure 4.9c). A single small possible root rot hotspot (> 50% mortality) was observed at 34.95909˚ E, 0.04984˚ N. Overall, bean root rot mortality during the long rains season followed a similar distribution to that of the short rains season. Mortality rates of up to 25% covered about 90% of the area of the site (Figure 4.9d). Possible hotspots were however recorded in two locations, at 34.96209˚ E, 0.05202˚ N and 34.95062˚ E, 0.03667˚ N.



SR- Short rains season
LR- Long rains season

Figure 4.9: The distribution of bean mortality due to root rot at Kapkerer (a, b), Kiptaruswo (c, d), and Koibem (e, f) during the short rains 2016 and the long rains 2017 growing seasons

There was relatively more root rot mortality at Koibem compared to Kapkerer and Kiptaruswo, with a slightly different spatial and temporal distribution (Figure 4.9). While there were several possible root rot hotspots (at 34.9602˚ E, 0.1506˚ N; 34.9732˚ E, 0.1187˚ N; 34.9603˚ E, 0.1218˚ N; and 34.9387˚ E, 0.1290˚ N) during the short rains season (Figure 4.9d), none was observed during the long rains season (Figure 4.9e).

Bean common mosaic virus (BCMV)

The distribution of BCMV varied spatially and temporally across the study sites (Figure 4.10). Generally, the disease covered most of the land area of each site, with the exception of a few scattered spots where no visible symptoms of disease were observed. Only a slight difference in the distribution of the disease was observed at Kapkerer between the short and the long rains seasons (Figs. 4.10a and b). Generally, there were no major changes in the location of BCMV hotspots (50 % plant stand showing foliar damage) at Kapkerer, with the exception of the north-east tip of the site, which was a major hotspot during the second season. Similar to Kapkerer, there were only minor changes in the distribution of BCMV at Kiptaruswo between the short rains (Figure 4.10c) and the long rains (Figure 4.10d) growing seasons. Most of the area of the site showed at least 25 % plant stand damage during the two seasons, with hotspots appearing at 34.95916˚ E, 0.04831˚ N, and 34.94341˚ E, 0.05677˚ N during the short rains and the long rains seasons, respectively. Grain yield was correlated with disease rating during the long rains season. Grain yield was generally higher where foliar damage by BCMV was lower. The distribution of BCMV at Koibem followed a slightly different pattern than the other two sites. Serious damage was concentrated in the north-east corner of Koibem during the short rains season (Figure 4.10e), while during the long rains season (Figure 4.10f) the total area showing serious damage had shrank considerably and was located towards the center of the site.

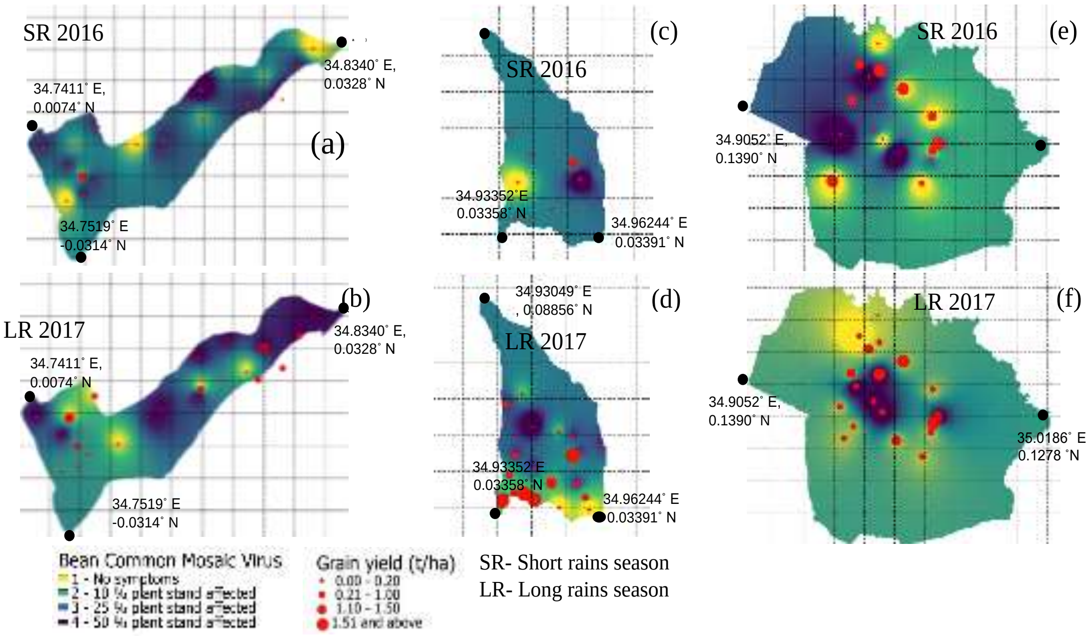


Figure 4.10: The distribution of BCMV hotspots in Kapkerer (a, b), Kiptaruswo (c, d), and Koibem (e, f) during the short rains 2016 and long rains 2017 growing seasons

4.3 Groundnut

4.3.1. Groundnut grain yield

Groundnut grain yield varied with site and season (Figure 4.11). Kapkerer recorded the highest groundnut grain yield performance during the short rains season 2016, which was contrary to bean grain performance (Figure 4.11).The grain yield performance of Kiptaruswo was the lowest. The range in grain yield at Kapkerer was 0 to 0.99 t ha^{-1}, with 75% of the observations falling between 0.0 and 0.65 t ha^{-1}. At Kiptaruswo, the range was 0 to 0.3 t ha^{-1} with 75% of the observations falling between 0 and 0.09 t ha^{-1}, whereas at Koibem, the range was 0 to 0.90 t ha^{-1}, with 75% of the observations falling between 0 and 0.40 t ha^{-1}. Similarly, during the long rains season 2017, Kapkerer had the best but also the most variable grain yield performance, ranging from 0.20 to 3.50 t ha^{-1} with 75% of the observations falling between 0.20 and 2.10 t ha^{-1} (Figure 4.11). The range in grain yield at Kiptaruswo was 0 to 0.80 t ha^{-1}, with 75% of the observations falling between 0 and 0.60 t ha^{-1}, while at Koibem the range was 0 to 1.00 t ha^{-1}, with 75% of the observations falling between 0 and 0.60 t ha^{-1}. According to recent statistics on groundnut productivity in SSA, the average groundnut yield recorded in the year 2006 was 0.98 t ha^{-1} (Asekenye *et al.,* 2016), which compares fairly well with the mean grain yield observed at Kapkerer, but much higher than the mean yield observed at Kiptaruswo and Koibem.

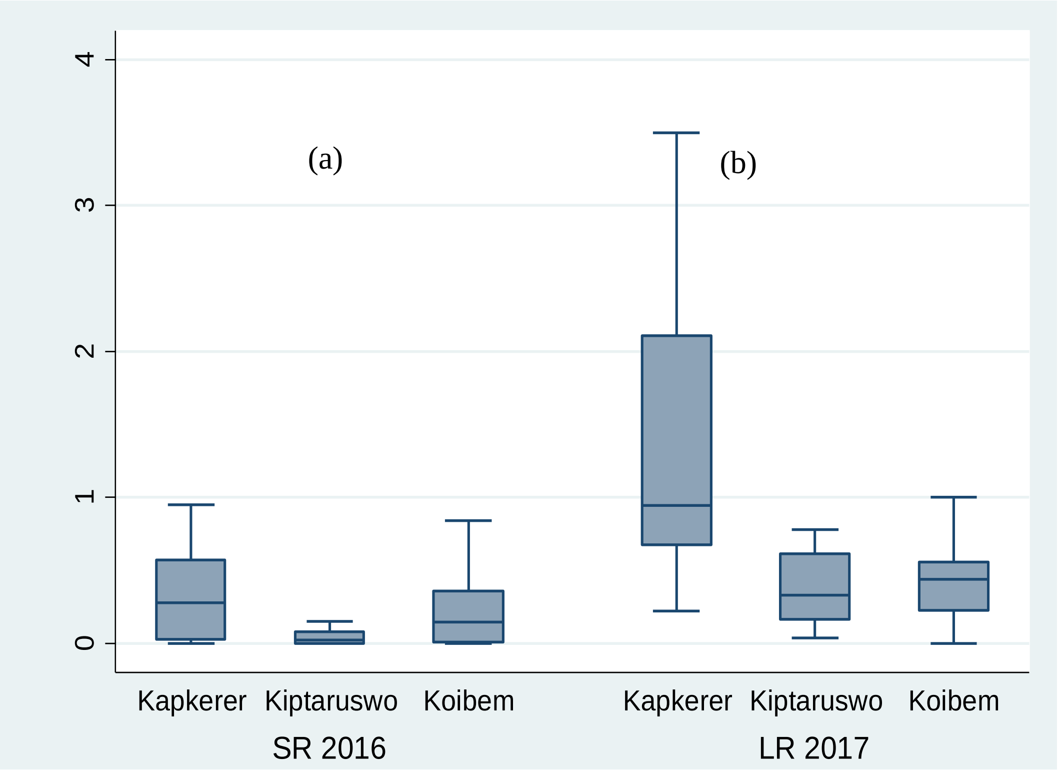


Figure 4.11: Groundnut grain yield performance at Kapkerer, Kiptaruswo and Koibem sites in Nandi County: (a) short rains 2016, and (b) long rains 2017.

4.3.2 Effect of rainfall on grain yield

Groundnut grain yield was significantly correlated with rainfall (r = 0.280**). Generally, groundnut productivity was low during the short rains 2016 growing season when rainfall was low, and high during the long rains 2017 growing season when rainfall was relatively high (Figure 4.12). Consistent with these results, Reddy *et al.*, (2003) established that groundnut productivity in most of the regions of Asia and Africa is constrained by low rainfall and prolonged dry spells experienced during the crop growth period. Between 500 and 1200 mm of rainfall is necessary for groundnut production. However, dry weather is required for ripening and harvesting (Dwivedi *et al.*, 2003).

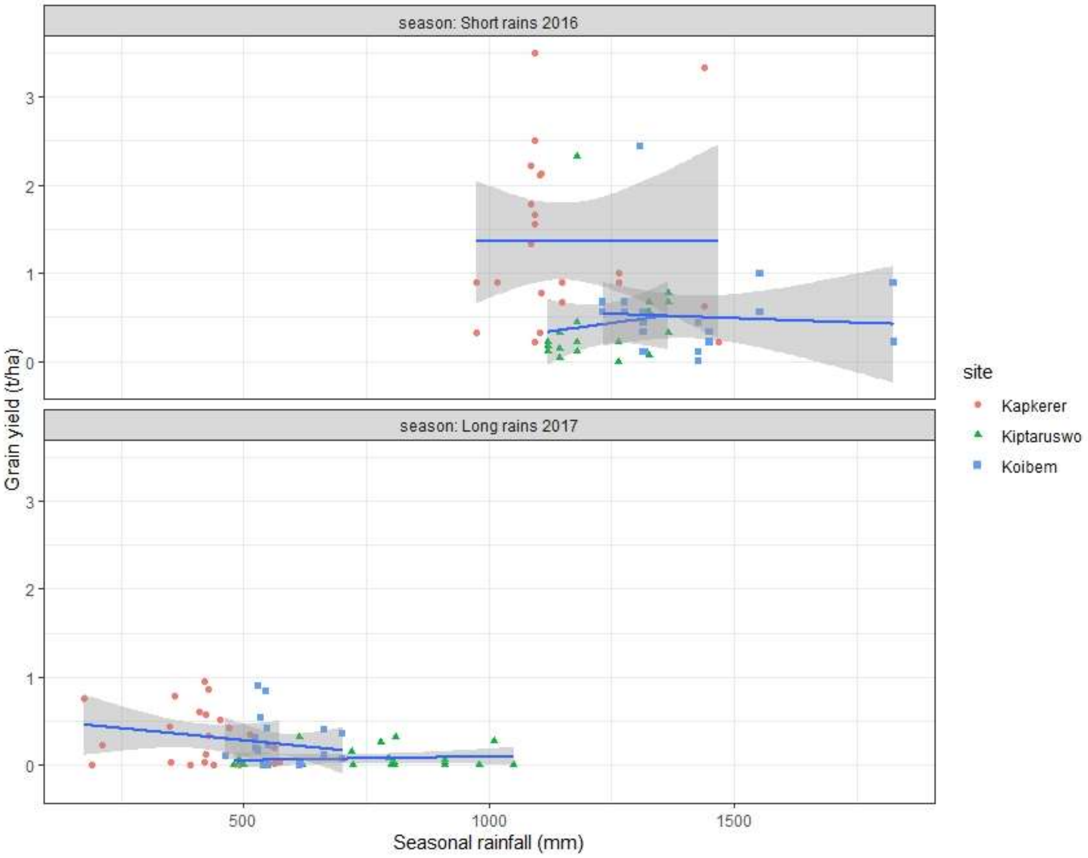


Figure 4.12: Relationship between groundnut grain yield performance and seasonal rainfall at Kapkerer, Kiptaruswo and Koibem during the short rains 2016 and the long rains 2017 growing seasons

4.3.3 Effect of altitude on grain yield

Groundnut grain yield was significantly correlated with altitude (r= -0.362****). Relatively higher productivity was observed at Kapkerer, which is a lower altitude site, compared to Kiptaruswo and Koibem sites (Figure 4.13). Kiptaruswo and Koibem sites (high altitude) received higher amounts of rainfall, over 1200 mm. This high altitude sites receives excessive rainfall which would have negative impact on groundnut grain yield, especially since high rainfall is experienced towards the end of the two growing seasons, the critical period for groundnut ripening

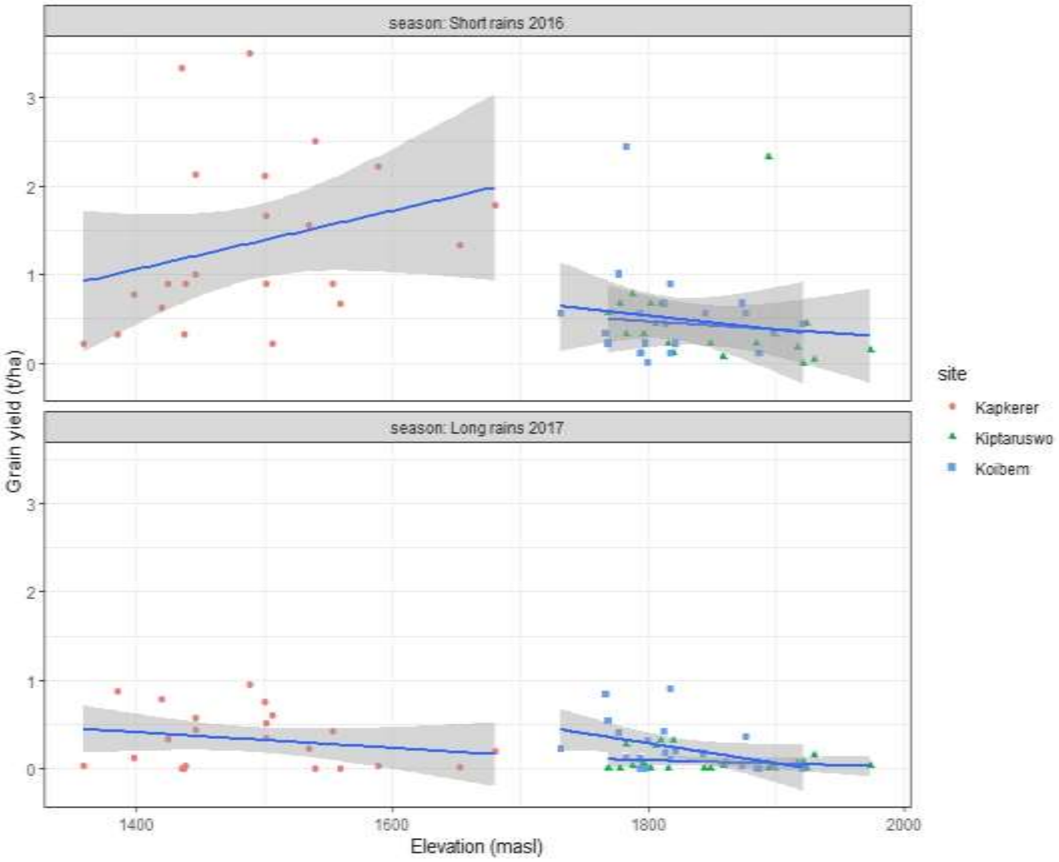


Figure 4.13: Relationship between groundnut grain yield performance and elevation at Kapkerer, Kiptaruswo and Koibem during the short rains 2016 and the long rains 2017 growing seasons

4.3.4 Multivariate analysis

The results from regression analysis indicate that season, leaf spot, rosette, elevation, Mg, Fe, and Mn are important factors affecting groundnut productivity (Table 4.2). The model fitted (gy= 1.82315 + 0.556^{season} – $0.14169^{rosette}$ – $0.14562^{leaf\ spot}$ - $0.00134^{elevation}$ - 0.00076^{Mg} + 0.00143^{Fe} + 0.00042^{Mn}) was highly significant (p-value: 3.067e-13). Season had the greatest impact on groundnut productivity, accounting for an increase in groundnut grain yield of 0.556 t ha^{-1} moving from the short rains 2016 to the long rains 2017 growing seasons. The analysis also confirms that rosette virus and leaf spot were the most important diseases of groundnut the production systems covered in this study. A decrease in grain yield of 0.142 t ha^{-1} and 0.146 t ha^{-1} were observed for every unit increase in the score of rosette and leaf spot, respectively. Iron also had a significant influence on groundnut productivity, accounting for an increase of grain yield of 0.001 t ha^{-1} for every 1ppm increase. Magnesium and manganese had the least contribution to groundnut productivity.

Table 4.2: Regression analysis output showing major factors having significant influence on groundnut productivity in smallholder systems, Nandi County.

Variables	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**
Intercept	1.82315	0.5132277	3.552	0.000545 ***
Season	0.49837	0.0925854	5.383	3.65e-07 ***
Rosette	-0.14169	0.0568137	-2.494	0.013982 *
Leaf spot	-0.14561	0.0794750	-1.832	0.069373.
Elevation	-0.00134	0.0002639	-5.080	1.39e-06 ***
Mg	-0.00075	0.0004405	-1.722	0.087679.
Fe	0.00143	0.0006903	2.076	0.040048 *
Mn	0.0004224	0.0002663	1.586	0.115299

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’

Multiple R-squared: 0.4486, p-value: 3.067e-13

4.3.5 Geospatial analysis of rosette virus

Rosette virus distribution varied both spatially and temporally across the study sites. A significant negative correlation was obtained between rosette and groundnut grain yield (r= -0.271**). This negative correlation is also depicted in the relationship between the geospatial distributions of rosette and groundnut grain yield (Figure 4.14). Generally, high scores of rosette were observed during the short rains 2016, compared to the long rains 2017 growing seasons. During the short rains season 2016, higher rates of rosette virus were observed at Kapkerer site, with about 20% of the area of the site indicating >50% plants stand affected by the virus (possible rosette hotspots) (Figure 4.14a). However, no rosette symptoms were observed in about 10% of the area of Kapkerer during this season. Contrary to the short rains season 2016, no possible rosette hotspots were observed in the long rains season 2017 at Kapkerer. Most area (90%) of Kapkerer had score rates of 10 and 25% plants stand affected. The possible hotspots observed at 34.77384˚ E, -0.00544˚ S and 34.81954˚ E, 0.02650˚ N during the short rains season 2016 were not observed in the long rains season 2017. Similar to Kapkerer, rosette pressure was more during the short rains season at Kiptaruswo, compared to the long rains season. About 20% of the area of the study site had possible rosette hotspots (Figure 4.14c), that reduced grain yield significantly. Most of the Kiptaruswo site showed 10 and 25% plant stand damage during the short rains season. The distribution of rosette virus followed a different pattern in the long rains season 2017 (Figure 4.14d), with only two possible hotspots at 34.94084˚ E, 0.06627˚ N, and 34.96192˚ E, 0.05186˚ N. However, area showing no symptoms, and 10 % plant stand damage increased substantially compared to the previous season.

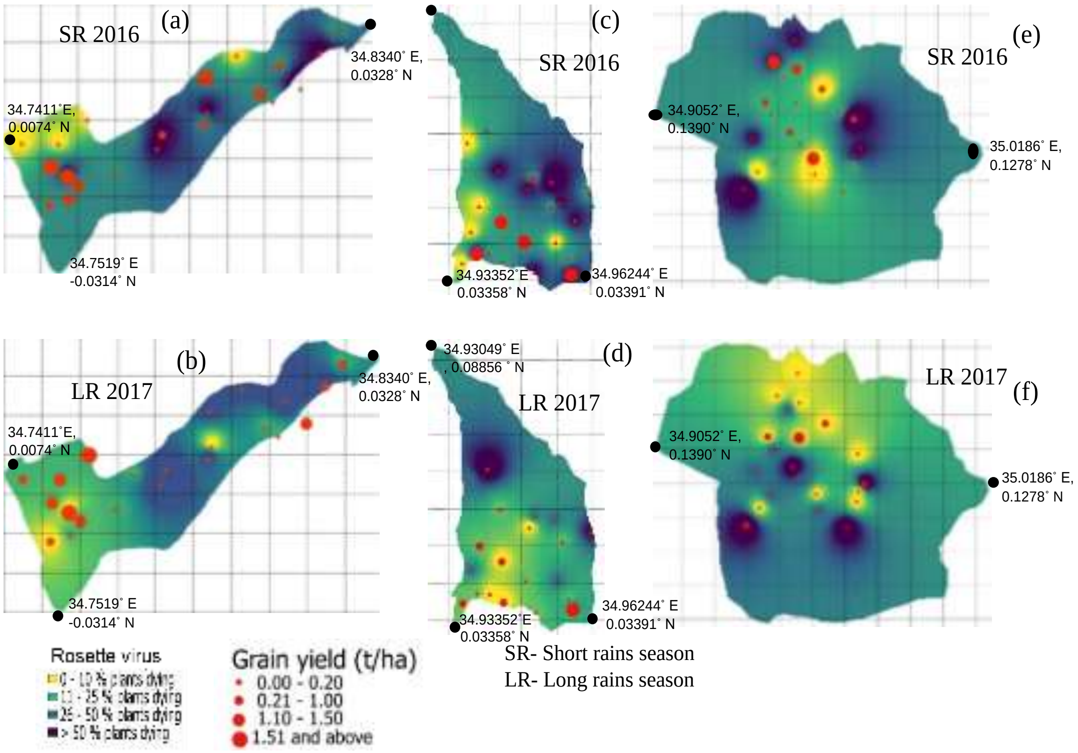


Figure 4.14: The distribution of rosette hotspots in Kapkerer (a, b), Kiptaruswo (c, d), and Koibem (e,f) during the short rains 2016 and long rains 2017 growing seasons

Rosette damage at Koibem site showed more possible hotspots than Kapkerer and Kiptaruswo. About 5% of the area of the site showed no symptoms of rosette virus, about 80% showed 10 and 25% of plants stand damage, and roughly, 10% showed possible rosette hotspots distributed across the site (Figure 4.14e). During the long rains season 2017, possible hotspots were observed in new locations, except for one at 34.9348˚ E, 0.1118˚ N (Figure 4.14f). Overall, rosette pressure was higher in the short rains season, when rainfall recorded was low, which is consistent with the findings by Mugisa *et al.,* 2015, who reported higher t rosette incidence and severity under low rainfall conditions.

4.4 Soybean

4.4.1 Soybean rain yield

Soybean productivity varied both within and between sites, and across seasons (Figure 4.15). Similar to bean and groundnut, the highest soybean grain yield was recorded during the long rains season 2017. However, soybean grain yield across sites followed a different pattern from that of bean. During the short rains 2016 growing season, Kapkerer site recorded the highest soybean grain yield of between 0 and 1.2 tha^{-1}, with 75% of farms harvesting between 0 and 0.65 tha^{-1}. Kiptaruswo and Koibem sites on the other hand recorded lower soybean grain yield of between 0 and 0.95 tha^{-1}, and between 0 and 0.9 tha^{-1}, respectively. 75% of farms at Kiptaruswo and Koibem had relatively same amount of soybean grain yield ranging from 0 to 0.5 tha^{-1}. During the long rains season 2017, Kapkerer still had the highest grain yield ranging from 0.45 to 3 tha^{-1}, with 75% of the observations falling between 0.45 and 2.2 tha^{-1}. The grain yield range at Kiptaruswo ranged from 0.1 to 2.6 tha^{-1}, with 75% of the observation ranging from 0 to 1.6 tha^{-1}. Koibem had a lowest soybean grain yield of between 0.1 and 1.5 t ha^{-1}, with 75% of farms recording a range of 0.1 to 0.8

tha^{-1}. Productivity of soybean in SSA is at an average of 2 t ha^{-1} (Sinclair *et al.*, 2013), implying that even Kapkerer site that performed best in this study, (mean productivity of 0.54 t ha^{-1} and 1.44 t ha^{-1} during the short rains 2016 and the long rains 2017 growing season, respectively) was not good enough.

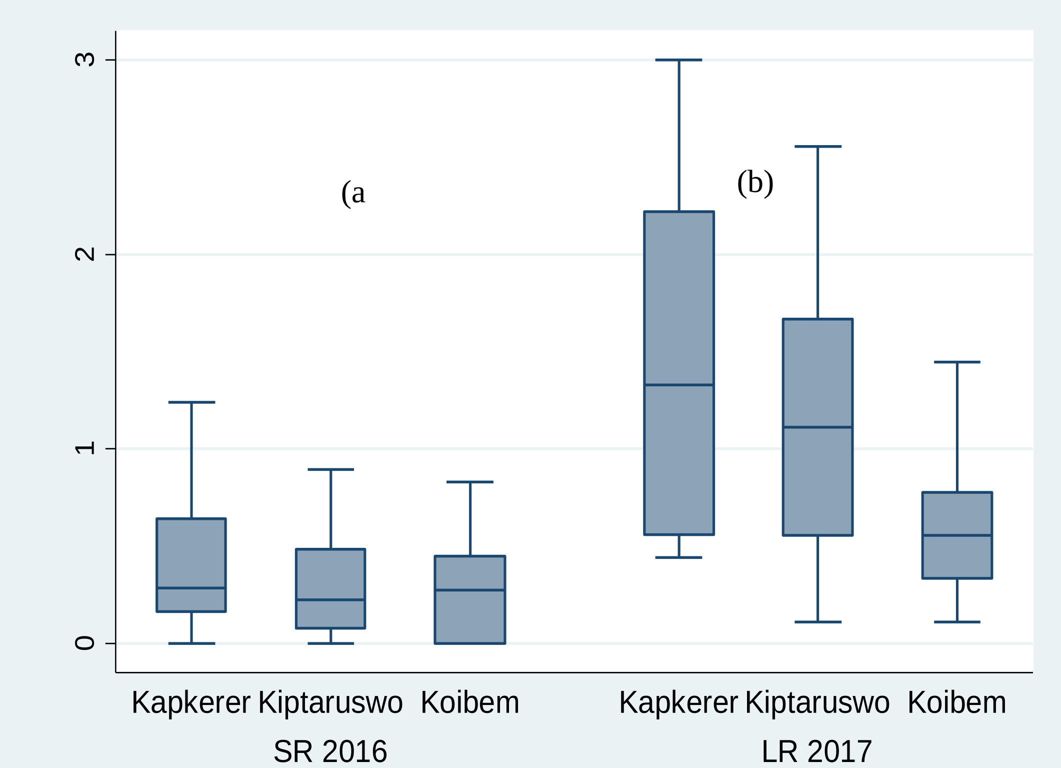


Figure 4.15: Soybean grain yield performance at Kapkerer, Kiptaruswo and Koibem sites in Nandi County: (a) short rains 2016, and (b) long rains 2017

4.4.2 Effect of rainfall on grain yield

Soybean grain yield was significantly correlated with rainfall (r = 0.283**). During the short rains 2016 growing season when seasonal rainfall was low, bean grain yield was correspondingly low. Rainfall of between 400 and 1200mm in a growing season is ideal for soybean production. High soybean productivity was however observed when the rainfall amounts increased in 2017 (Figure 4.16). Furthermore, the relationship observed between soybean grain yield and rainfall varied across sites. While Kapkerer presented consistent increase in grain yield with increasing rainfall, Kiptaruswo and Koibem exhibited unclear patterns. Reduction of soybean grain yield with rainfall increase in some farms at Kiptaruswo and Koibem was observed. This can be attributed to the hailstones that accompany heavy rains in these sites, shredding leaves and instigating abortion.

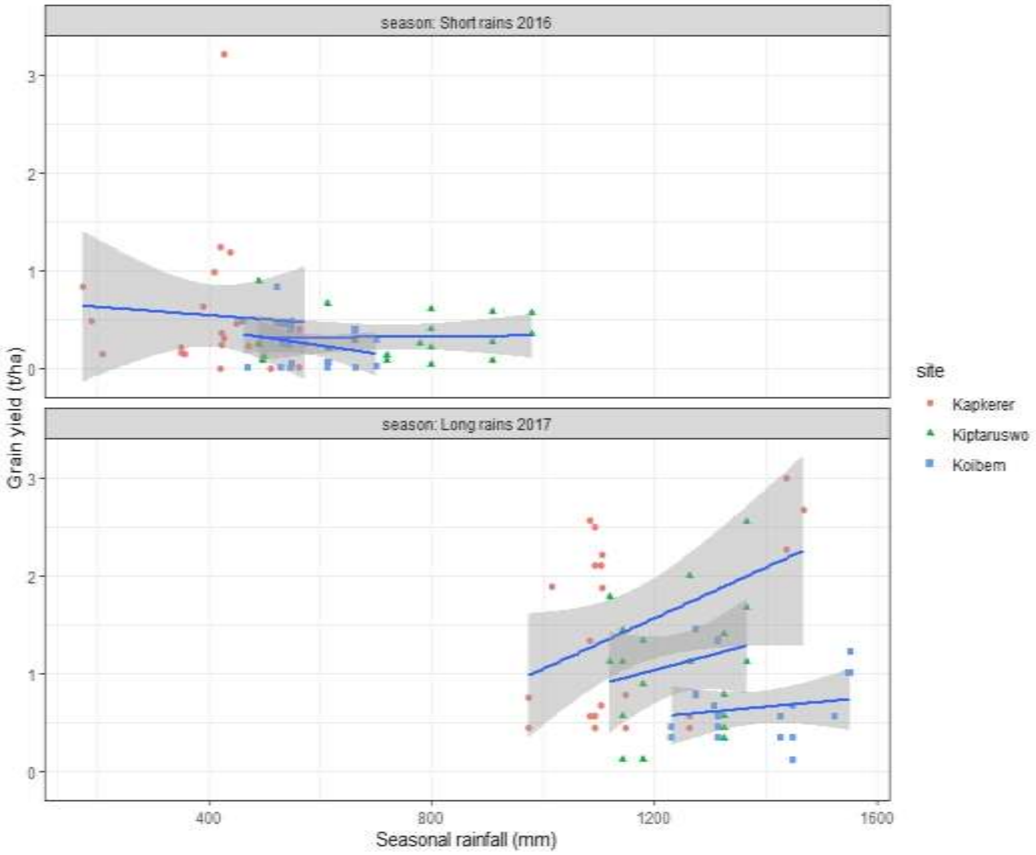


Figure 4.16: Relationship between soybean grain yield performance and seasonal rainfall at Kapkerer, Kiptaruswo and Koibem during the short rains 2016 and the long rains 2017 growing seasons

4.4.3 Effect of altitude on grain yield

Soybean grain yield was negatively correlated with altitude (r= -0.114*). Relatively higher productivity was observed at Kapkerer, which is a lower altitude site, compared to Kiptaruswo and Koibem sites, which are in higher altitudes (Figure 4.17). Urgessa (2015) reported that soybean can be grown from 0-2000 masl, depending on the variety. However, Ogema *et al.,* (1988) established that soybean growth and development (especially during initiation of flowering and maturity stages) is affected by altitude, and is a crop suitable for low to medium altitudes, classified with warm climates. At high altitudes, temperatures are low inhibiting flowering and the crop remains vegetative (Ogema *et al.*, 1988).

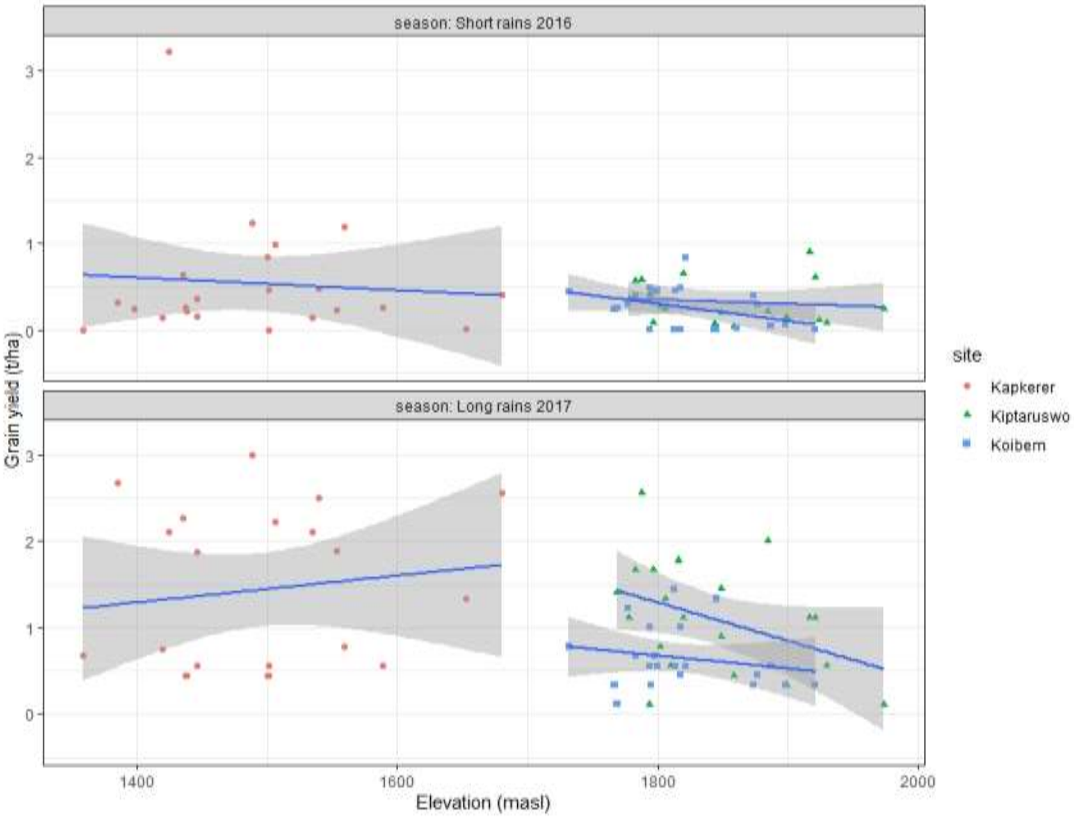


Figure 4.17: Relationship between soybean grain yield performance and elevation at Kapkerer, Kiptaruswo and Koibem during the short rains 2016 and the long rains 2017 growing seasons

4.4.4 Multivariate analysis

The results from regression analysis indicate that season, elevation, pH and Mn are important factors affecting soybean productivity (Table 4.3). Season had the greatest impact on soybean productivity, accounting for an increase in soybean productivity of 0.705 t ha^{-1} moving from the short rains 2016 to the long rains 2017 growing seasons. Results from this analysis also shows that altitude is an important factor influencing soybean grain yield. A reduction of soybean grain yield of 0.232 t ha^{-1} was observed for every rise in altitude by 100 masl. Among the soil parameters analyzed, soil pH and manganese levels appeared to be the most important soil qualities in soybean production. An increase in soybean grain yield of 0.03 t ha^{-1} was observed with every unit increase in pH. Aluminum toxicity occur in low pH soils, significantly affecting root growth and plant vigor, especially in legumes (Yang *et al.,* 2012). Manganese also had a significant influence on soybean productivity, accounting for an increase of grain yield of 0.0006 t ha^{-1} for every 1Ppm increase. The model fitted (gy= $0.518 + 0.705^{season} - 0.232^{elevation} + 0.030^{pH} + 0.0006^{Mn}$) was highly significant (p-value: 1.249e-14).

Table 4.3: Regression analysis output showing major factors having significant influence on soybean productivity in smallholder systems, Nandi County.

Variables	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**
Intercept	0.51791	0.15527	3.336	0.00113 **
Season	0.70497	0.09233	4.959	1.05e-12 ***
Elevation	-0.23231	0.05563	-4.175	5.64e-05 ***
pH	0.03012	0.00645	3.021	0.00247**
Mn	0.00060	0.00020	3.001	0.00327 **

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’

Soybean diseases observed were soybean blight (SBB) and Leaf rust (LR). Nevertheless, these diseases were relatively minor across the sites and seasons, hence no need to show their spatial distributions.

4.5 Lablab

4.5.1 Lablab grain yield

Lablab grain yield varied with site and season (Figure 4.18). During the short rains season 2016, the range in grain yield at Kapkerer was 0 to 1.05 t ha^{-1}, with 75% of the observations ranging from 0 to 0.46 t ha^{-1}. At Kiptaruswo, the range was 0 to 1.75 t ha^{-1} during the short rains 2016, with 75% of the observations ranging from 0 to 0.76 t ha^{-1}, whereas at Koibem, the range was 0 to 1.94 t ha^{-1}, with 75% of the observations falling between 0 and 1.35 t ha^{-1}. The grain yields attained in the short rains season 2016 were very low compared to 2.5 to 3 t ha^{-1} average productivity in eastern Africa, reported by Karanja, 2016. During the long rains season 2017, no lablab grain yield was harvested at Kapkerer and Koibem because the crop grew vegetative throughout the season. Poor grain yields are expected in wetter conditions because lablab becomes a vegetative climber, leading to poor seed set (Karanja, 2016). Grain yield was however harvested in a few farms at Kiptaruswo site, especially where organic carbon levels were low.

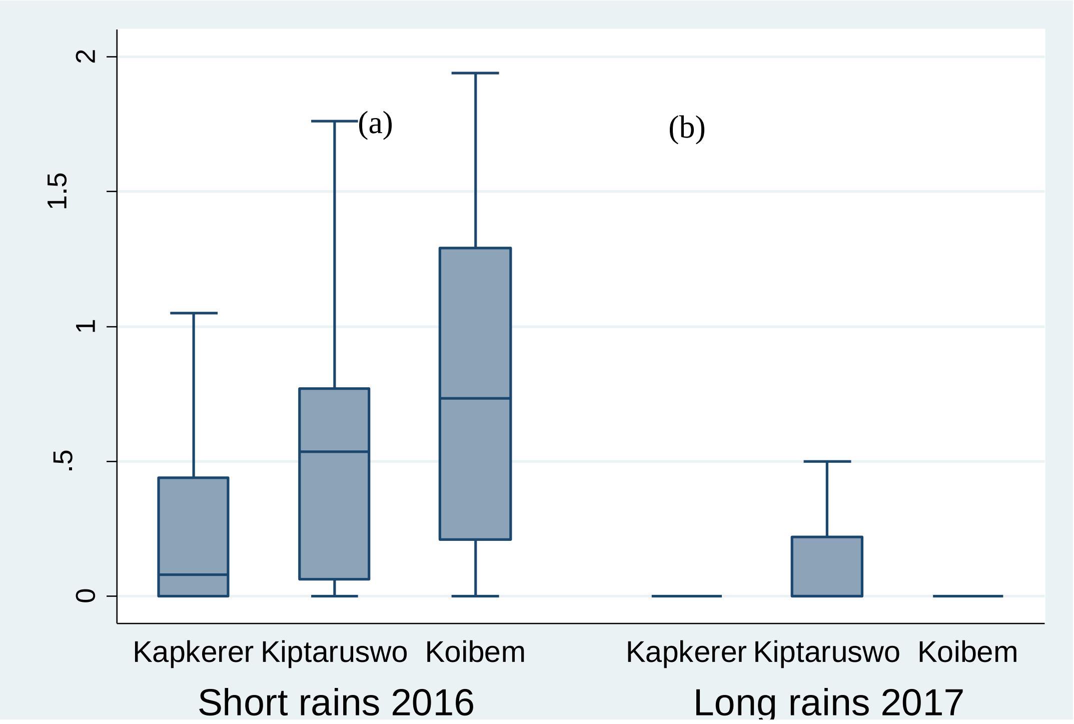


Figure 4.18: Lablab grain yield performance at Kapkerer, Kiptaruswo and Koibem sites in Nandi County: (a) short rains 2016, and (b) long rains 2017

4.5.2 Effect of rainfall on lablab grain yield

A significant negative correlation was observed between rainfall and lablab grain yield (r= -0.353***). During the short rains season 2016 when rainfall amounts were low, lablab grain yield was high (Figure 4.19), which was contrary to the observations made in the relationship between rainfall and bean (Figure 4.19a), groundnut (Figure 4.12) and soybean (Figure 4.16) grain yields. The high rainfall amounts received during the long rains season 2017 stimulated vegetative growth of lablab at Kapkerer and Koibem, substantially limiting flowering and pod formation. Lablab is a legume recommended for cultivation in dry parts because of its tolerance to low soil moisture (Kankwatsa & Muzira, 2018). Lablab is a drought tolerant crop and grows well in dry lands with limited rainfall. However, low rainfall (650mm) is good for seed production because of its taproot that can extract water from two m below the soil surface (Heuzé *et al.*, 2016), and high rainfall (2500-3000 mm) suited for forage production (Cook *et al.*, 2005).

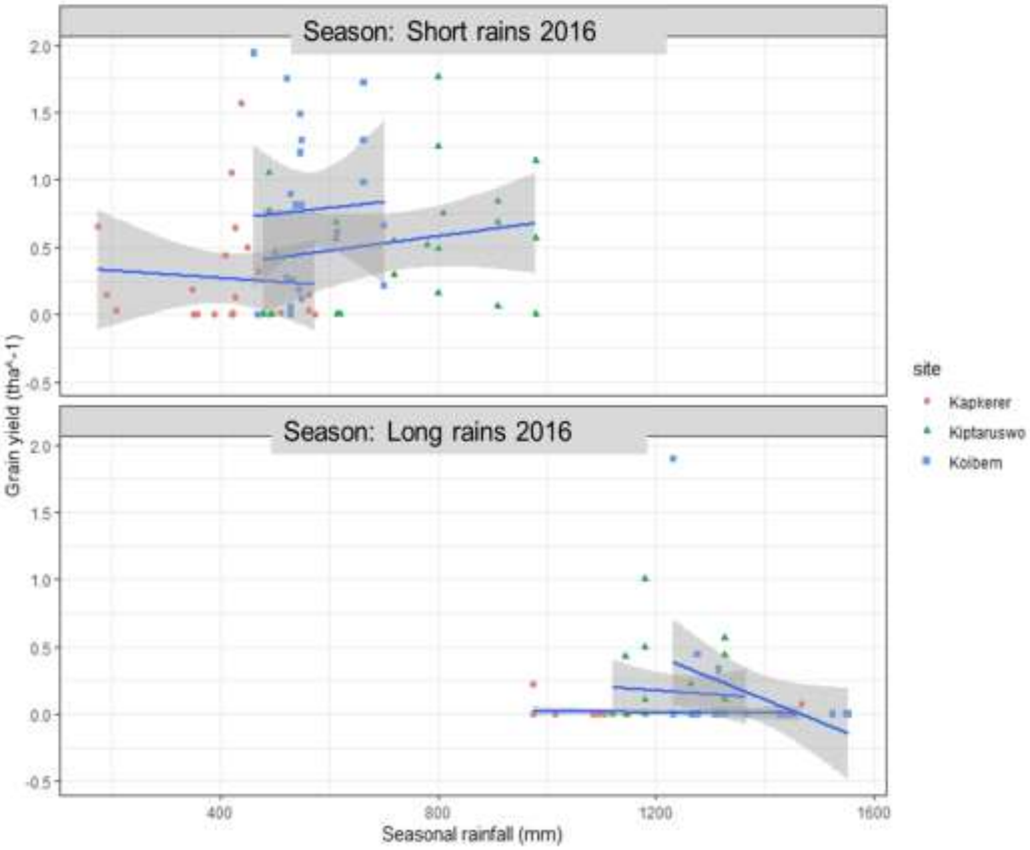


Figure 4.19: Relationship between lablab grain yield performance and seasonal rainfall at Kapkerer, Kiptaruswo and Koibem during the short rains 2016 and the long rains 2017 growing seasons

4.5.3 Effect of altitude on grain yield

There was no clear relationship between lablab grain yield and altitude (Figure 4.20). Higher lablab grain yield was observed at Koibem and Kiptaruswo, whose altitude ranges between 1700 and 2000 masl. This is contrary to Karanja's (2016) report that the crop becomes a vegetative climber when grown in cooler high elevations of more than 1800 masl. The high lablab grain yields observed in high altitudes during the short rains season 2016 can be supported by the fact that the season was not typical (prolonged drought was experienced). Moreover, Koile *et al.,* (2014) reported that soil organic matter enhances lablab growth and development. Soil organic C was generally high at Koibem and Kiptaruswo sites (high altitude), compared to Kapkerer (low altitude) (Figure 4.3b) hence lablab grain yield could have been constrained by poorer soils at Kapkerer, which is a consequence of continuous cultivation over many years.

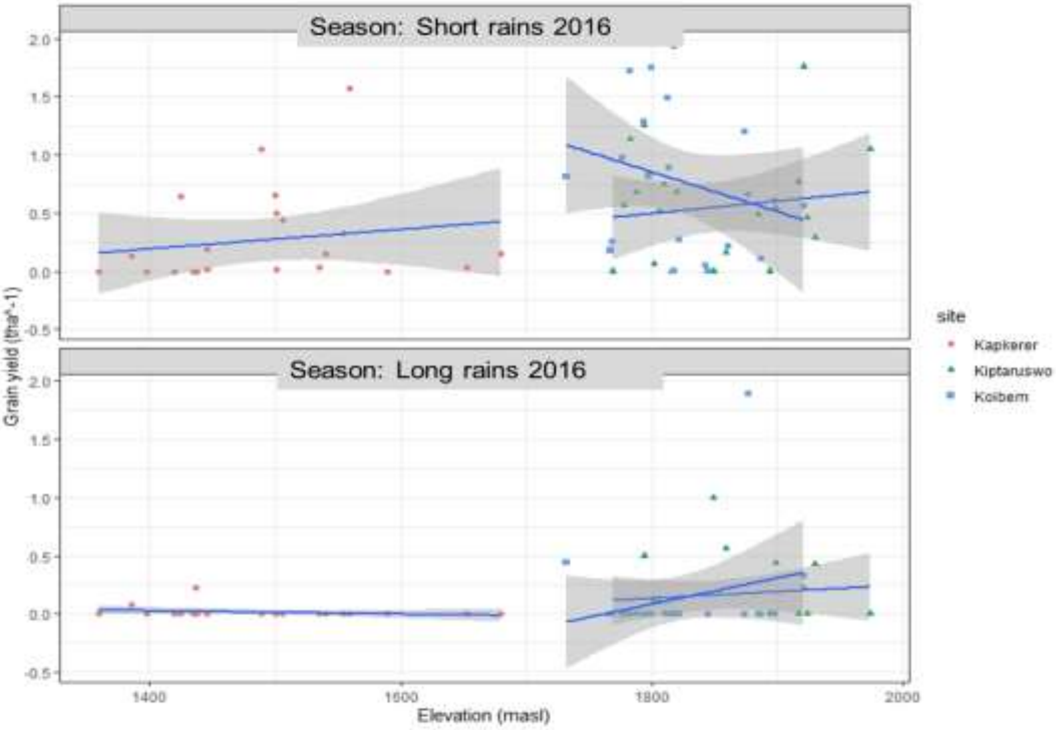


Figure 4.20: Relationship between lablab grain yield performance and elevation at Kapkerer, Kiptaruswo and Koibem during the short rains 2016 and the long rains 2017 growing seasons

4.5.4 Multivariate analysis

The results of regression analysis indicate that season, halo blight (HB), elevation, and calcium (Ca) are important factors affecting lablab productivity (Table 4.4). The model fitted (gy= 0.8556 + 0.3731^{season} – 0.0921^{HB} + $0.0006^{\text{Elevation}}$ + 0.00013^{Ca}) was highly significant (p-value: 2.213e-10). Season had the greatest impact on lablab productivity, accounting for an increase in lablab grain yield of 0.373 t ha^{-1} moving from the long rains 2017 to the short rains 2016 growing seasons. HB appeared to be the most important disease of lablab in the smallholder systems of Nandi County. A decrease in grain yield of 0.092 t ha^{-1} was observed for every unit increase in the score of HB. Elevation also had a significant influence on groundnut productivity, accounting for an increase in grain yield of 0.001 t ha^{-1} for every 100 m rise in altitude. Calcium had a positive but the least contribution to lablab productivity.

Table 4.4: Regression analysis output showing major factors having significant influence on lablab productivity in smallholder systems, Nandi County.

	Estimate	**Std. Error**	**t value**	**Pr(>|t|)**
Intercept	0.8556	3.683e-01	2.323	0.02177 *
Season	0.3731	7.350e-02	5.077	1.36e-06 ***
Halo blight	-0.0921	3.434e-02	-2.682	0.00831 **
Elevation	0.0006	2.034e-04	2.987	0.00339 **
Calcium	0.00013	7.093e-05	1.874	0.06324.

4.5.5 Geospatial analysis of halo blight (HB)

Similar to bean and groundnut diseases, HB had a variable spatial and temporal distribution (Figure 4.21). A significant negative correlation was observed between lablab grain yield and HB (r= – 0.355). Generally, more HB pressure was observed at Kapkerer and Kiptaruswo sites during both the short rains 2016 and the long rains 2017 seasons, compared to Koibem. The lower scores of no symptoms, and approximately 2% of leaf surface area covered by round lesions were recorded in about 85% of the area of Kapkerer site in the short rains season 2016 (Figure 4.21a). However, possible HB hotspots (score of 4) were recorded in an area of about 15% of the site, at 5 locations. HB severity increased considerably during the long rains season, with the area covered by scores of no symptoms, and approximately 2% of leaf surface area covered by round lesions being recorded in only about 50% of the area of the site, while the rest of the site was covered by possible hotspots (Figure 4.21b). There were slight to big changes in the location of these possible hotspots, with a new large one being observed at 34.82195˚ E, 0.02752˚ N.

Contrary to Kapkerer, HB pressure was higher at Kiptaruswo site during the short rains season 2016. About 80% of the study site recorded a score of approximately 50% of leaf surface area covered by round lesions during the short rains season (Figure 4.21c). Possible HB hotspots were recorded in about 15% of the area of the site, with the 2 major ones being observed at 34.9389˚ E, 0.04976˚ N and 34.9579˚ E, 0.03897˚ N. HB followed a different pattern during the long rains season 2017 at Kiptaruswo. Most of the area of the site (about 60%) was covered by scores of no symptoms, and approximately 2% of leaf surface area covered by round lesions (Figure 4.21d). Furthermore, possible HB hotspots covered smaller areas at different locations (34.93705˚ E, 0.06272˚ N; 34.93777˚ E, 0.04440˚ N; and 34.96218˚ E, 0.05186˚ N).

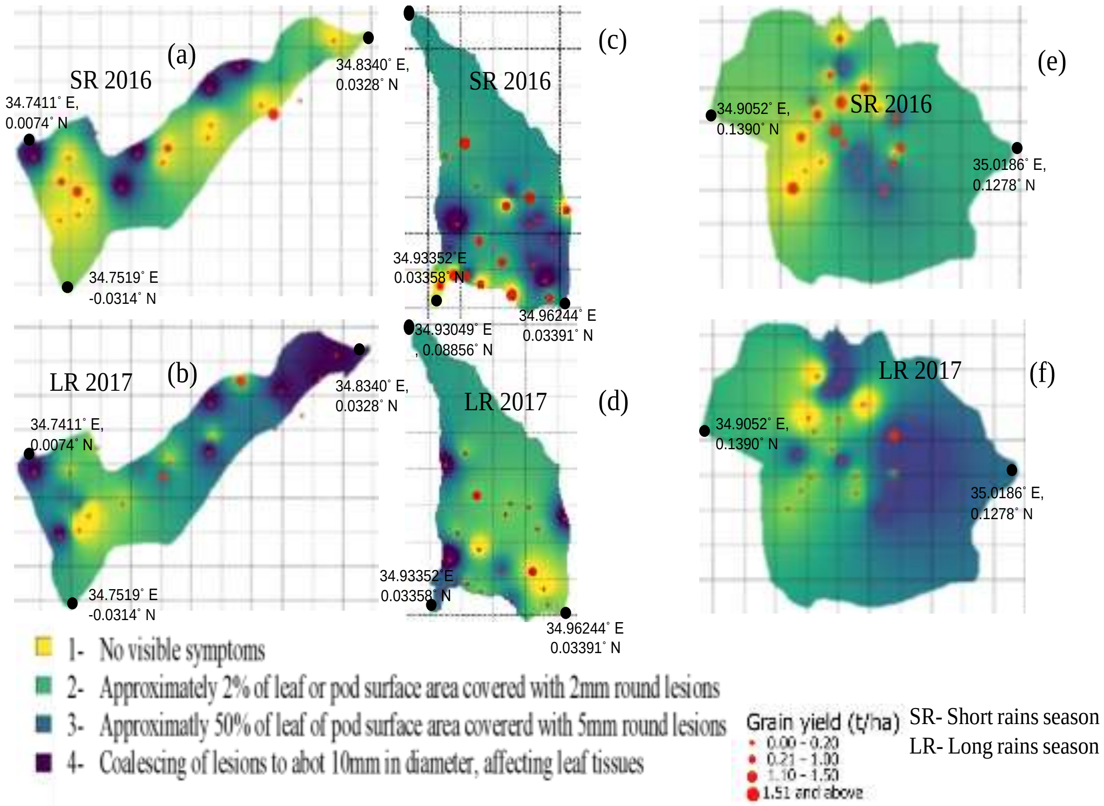


Figure 4.21: The distribution of halo-blight in Kapkerer (a, b), Kiptaruswo (c, d), and Koibem (e, f) during the short rains 2016 and long rains 2017 growing seasons. The red dots represent grain yield in each farm.

The distribution of HB at Koibem followed a slightly similar pattern to that of Kapkerer, although the diseases pressure was generally low. During the short rains season 2016, HB pressure was quite low at Koibem (Figure 4.21d), and no possible hotspots were observed. About 95% of the area of the site was covered by scores of no symptoms, and approximately 2% of leaf surface area covered by round lesions, with the remaining 5% being covered by a score of approximately 50% of leaf surface area covered by round lesions. During the long rains season 2017 however, the area of the site being covered by a score of approximately 50% of leaf surface area covered by round lesions increased substantially to about 20%. About 10% of the area of Koibem recorded no symptoms of HB disease (Figure 4.21e). No possible HB hotspots was recorded at Koibem both during the short rains 2016 and the long rains 2017 growing seasons.

CHAPTER FIVE

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

This section summarizes the results, conclusions, and recommendations drawn from a study that was conducted to explore distribution of legume production constraints in small holder systems of Nandi County. It highlights key findings on biophysical factors constraining legume productivity and how they vary spatially and temporally, as well as how information can be utilized.

Grain legumes (bean, groundnut, soybean and lablab) are important food crops for improving livelihoods in the smallholder systems of sub-Saharan Africa. The utilization of these grain legumes is vital in smallholder systems, where other sources of protein may not be affordable. Apart from curbing food insecurity and malnutrition, legumes are also known for their ability to improve soil fertility, provide fodder, and generate income for smallholder farmers. However, the productivity of these legumes has remained low due to various constraints that are so variable in time and space. In this research, the distribution of these biophysical (pests and diseases, rainfall, soil qualities, elevation) constraints were established both spatially and temporally, and the impact on legume productivity determined. In doing this, there is a better chance of addressing them in a more sustainable manner and with greater impact.

Results from this study showed spatial and temporal variations in the distribution of pests and diseases, creating possible hotspots that significantly decreased legume productivity. Rainfall was positively correlated with bean, groundnut, and soybean grain yields, hence rainfall is an opportunity to these legumes. Lablab grain yield however reduced with increase in rainfall amounts, making rainfall a constraint. Furthermore, rainfall was negatively correlated with pests and diseases, especially BF, BCMV and RV, while a positive correlation was observed between rainfall and

RR. The impact of pests and diseases on legume productivity exhibited a temporal variation. While BF and RV caused more damage and yield reduction during the short rains season, damage and yield reduction by RR was more pronounced during the long rains season. Effect of soil factors assessed varied with legume species. Mn and Fe had the greatest effect on bean, Mn, Fe and Mg on groundnut, pH and Mn on soybean, productivity. Calcium was the only soil factor that showed significant influence on lablab productivity. The results of this study indicate that knowledge of the spatial and temporal distribution of legume production constraints, and their impacts on legume productivity is critical for informed technology testing, and dissemination of production options that match biophysical contexts to improve legume productivity in the heterogeneous smallholder systems.

5.2 Conclusions and Recommendations

This study demonstrates that large spatial and temporal variations exist in the distribution of important biophysical factors that constrain the productivity of legumes in smallholder systems in Nandi County. Legume productivity varies in relation to the spatial and temporal distribution of these constraints. The results indicate that bean fly, root rot, bean common mosaic virus, rosette virus, and halo blight are among the most important pests and diseases whose variable spatial distribution creates high pest and disease pressure zones that significantly reduce legume productivity. Soil pH, Ca, Mg and micronutrients, particularly iron and manganese, have significant impact on legume productivity. Knowledge of the spatial and temporal distribution of these legume production constraints, and their impacts on bean productivity is critical for informed technology testing and the scaling out of production options that match biophysical contexts to improve legume productivity in the heterogeneous smallholder systems. In addition, results of this study can be used to inform the formulation of national policies seeking to increase agricultural productivity by availing spatial information to policy makers for integration into guidelines for the promotion of legumes to improve household nutrition and smallholder productivity. These results can also be used to reform and improve the delivery of agricultural services. By incorporating spatial variability into technology dissemination frameworks, legume production technologies with the greatest potential to succeed in particular biophysical environmental contexts can be identified and disseminated. This study was however carried out for 2 seasons only (Shorts 2016, and long rains 2017 growing seasons). Further research is needed to generate more temporal data to observe the trends of pests and disease hotspots in the study area.

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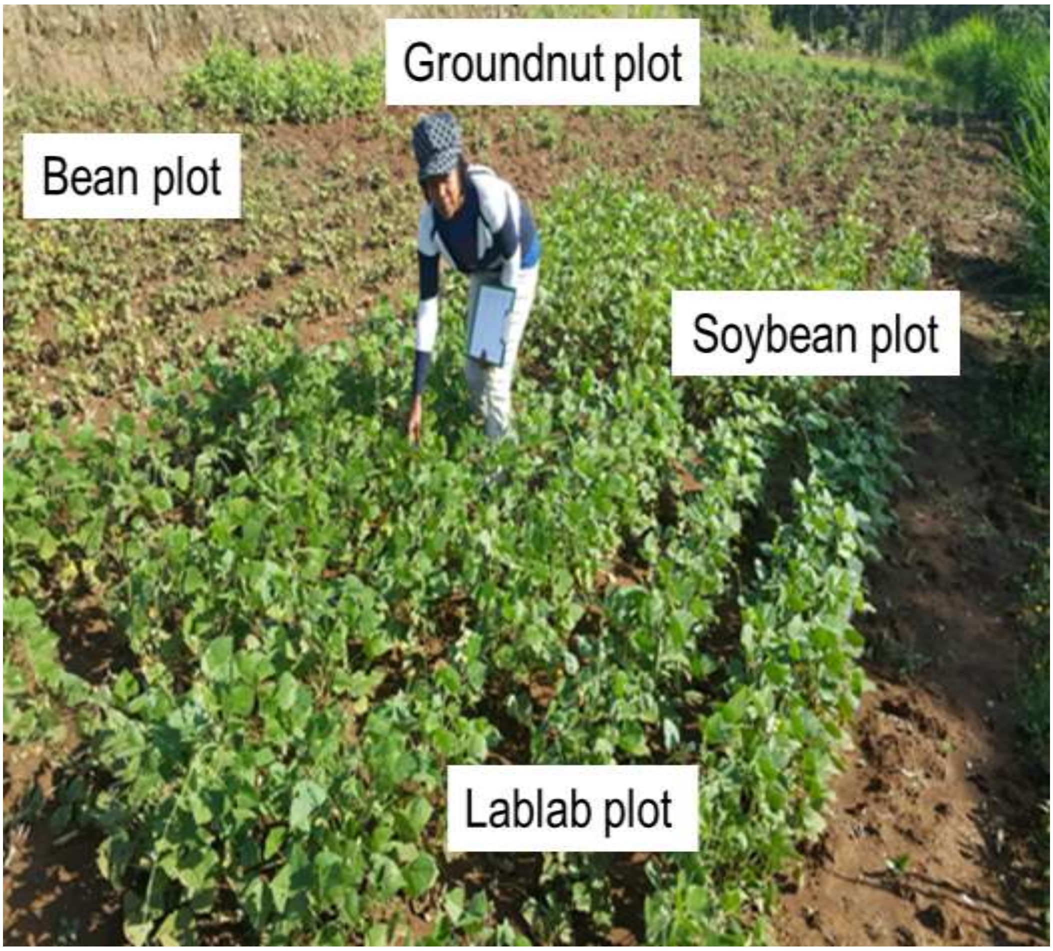
APPENDICES

Appendix I: Field activities for legumes growth and disease condition



Taking notes on legumes growth and disease condition at Koibem site in the long rains 2017 growing season

Appendix II: Assessing pest damage in the bean plot just before weeding

Assessing pest damage in the bean plot just before weeding at Kapkerer site, during the short rains 2016 growing season

Appendix III: Installing a rain gauge and leaving a thermometer

Installing a rain gauge and leaving a thermometer with a farmer at Koibem for collection of daily rainfall and temperature

Appendix IV: Leaf sample taken to the lab for disease assessment

Leaf sample taken to the lab for disease assessment