DYNAMICS OF SOIL PROPERTIES AND CROP YIELDS UNDER CONSERVATION AGRICULTURE PRACTICES IN A HUMIC NITISOL, EASTERN KENYA

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Dynamics of Soil Properties and Crop Yields under Conservation Agriculture Practices in a Humic Nitisol, Eastern Kenya

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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 Jehovah God for His life and everlasting love. To my beloved wife, Irene Wawira Micheni and our children, Denis Muturi Micheni, Diana Lydia Kathambi Micheni and Cynthia Gakii Micheni for their patience and support.

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ABBREVIATIONS/ACRONYMS

ACIAR	Australian Centre for International Agricultural Research
AEZ	Agro-ecological zone
ANOVA	Analysis of variance
APSIM	Agricultural Production Systems Simulator
APSRU	Agricultural Production System Research Unit
asl	Above sea level
CA	Conservation agriculture
CAN	Calcium ammonium nitrate
CEC	Cation exchange capacity
cfu	Colony forming unit
CIMMYT	International Maize and Wheat Improvement Center
C:N	Carbon:Nitrogen ratio
CRF	Coffee Research Foundation
CV	Coefficient of variation
CVT	Conventional tillage
DAE	Days after emergence
DAP	Diammonium phosphate
FAO	Food and Agricultural Organization
FR	Furrows/ridges
FURP	Fertilizer use recommendation project
GDP	Gross domestic product
GoK	Government of Kenya
GTZ	German Agency for Technical Co-operation
HI	Harvest index
IFAD	International Fund for Agricultural Development
INM	Integrated nutrient management
ISFM	Integrated soil fertility management
IITA	International Institute of Tropical Agriculture
JKUAT	Jomo Kenyatta University of Agriculture and Technology

K	Potassium
KALRO	Kenya Agricultural and Livestock Research Organization
KARI	Kenya Agricultural Research Institute
KES	Kenya Shilling
LAI	Leaf area index
LL	Lower limit
LR	Long rains
LRPM	Land Resources Planning and Management
LSD	Least significant difference
MBI	Maize-bean intercrop
MC	Moisture content
Mg	Magnesium
N	Nitrogen
NB	Net-benefits
NARL	National Agricultural Research Laboratories
NCPD	National Council for Population and Development
NPK	Nitrogen, phosphorus and nitrogen
NRM	Natural resource management
OC	Organic carbon
P	Phosphorus
PDA	Potato dextrose agar
Ph.D	Doctor of philosophy
QAAFI	Queensland Alliance for Agriculture and Food Innovation
RCBD	Randomized complete block design
SAS	Statistical Analysis System
SIMLESA	Sustainable Intensification of Maize and Legumes in Eastern and Southern Africa
SM	Sole maize
SOC	Soil organic carbon
SOM	Soil organic matter
SR	Short rains
SSA	sub-Saharan Africa

TC	Total cost
TSBF	Tropical Soil Biology and Fertility
TSN	Total soil nitrogen
TSP	Triple super phosphate
TR	Total revenue
UK	United Kingdom
UM	Upper Midland
USD	United State of America dollar
WUE	Water use efficiency
ZT	Zero tillage

ABSTRACT

Soil nutrient depletion is one of the challenges limiting food production in Eastern Kenya where maize and legumes are grown under complex and risky farming systems. The main soil type is a humic Nitisol, characterized by moderate inherent fertility. Rainfall variability and unfavourable socio-economic environment adds up to the uncertainties farmers face. In the effort of providing sustainable approaches to alleviating food shortage problem, a four season study was conducted between 2011 and 2013 at KALRO - Embu farm situated on South-Eastern slopes of Mt. Kenya at 00^0 33.18'S; 037^0 53.27'E; 1425 m asl. The study's main objective was to evaluate and make recommendations on the effect of CA practices on soil properties and crop yields in a humic Nitisol. The experimental site had for over 50 years been tilled conventionally for maize production. Results from the initial site characterization showed soil texture to be clay loam with 59.3% clay, 20.8% sand and 20.0% silt particle distribution. The average soil bulk density was high at 1.2 kg m^{-3}. The soil pH was acidic at 4.8 and extractable soil P was low at 4.0 mg kg^{-1}. The total soil organic carbon and soil nitrogen was 1.9 and 2.00%, respectively. The trial was based on a randomized complete split-split-split-plot block design with three blocks. Three tillage methods, three cropping systems, six nitrogen application rates and two crop residue management methods were the fourteen tested independent variables. The tillage methods made up the main plots. Maize hybrid, DK8031 and common bean, Embean-14 were the two test crops planted either as sole or as intercrops. Data collected included soil quality before and after the four seasons of CA application. Seasonal crop growth and grain yields resulting from the application of CA practices were also measured, together with the crop leaf area index (LAI), water use efficiency (WUE) and profitability of adopting CA farming methods. Tests were also made on the effect of CA practices on soil micro-organism populations and capacity of APSIM computer model to simulate crop yields. Other tests were on the effect of soil liming and glyphosate herbicides weeds control on CA farm system productivity. Result showed that the application of CA practices was an appropriate approach for improving soil properties and crop yields. For example, the soil P concentration was significantly increased to over 19.1 mg kg^{-1} from 4.0 mg kg^{-1} under FR tillage practices combined with soil liming. Apart from improving the crop yields, FR tillage system significantly improved the populations of soil micro-organisms and also profitability of maize and bean crops. Indeed, higher net-benefits under FR and to some extent, ZT were observed resulting from labour saving costs on land preparation/weeding. The benefits of CA were further improved by combining the CA tillage practices with soil liming and herbicides weed control. In particular, soil pH was raised from 4.8 to above 5.0 due to soil liming. The soil exchangeable acidity was reduced from 3.9 to 3.0 cmol kg^{-1}, hydrogen ions from 0.5 to 0.4 cmol kg^{-1} and aluminium ions from 1.2 to 1.1 cmol kg^{-1}. In addition, liming significantly raised the soil available P concentration from 4.0 to 14.3 mg kg^{-1}, Ca from 2.0 to 2.1 cmol kg^{-1}, Mg from 3.8 to 3.9 cmol kg^{-1} and Fe ions from 24.4 to 24.9 cmol kg^{-1}). Application of N fertilizer positively increased maize and bean yields. However, bean nodulation was depressed by application of 20kg N ha^{-1}. Glyphosate herbicides led to over 80% weeds suppression and subsequently increased crop yields and net benefits under CA farming methods. APSIM computer model simulated crop yields that were not significantly different from those observed in the field. The study concluded that the application of CA practices is a feasible option for improving soil productivity and crop yields in Eastern Kenya. The APSIM model provided appreciable crop yield predictions under conventional and CA tillage systems. In-crop rainfall variability, rather than the amount is one of the key factors to define the crop in the region. The study recommended that the soil biology should be considered together with physical and chemical properties when defining soil fertility. A need was felt to support APSIM computer model towards interpreting the farm system observed and predicted biophysical research scenarios. Simplifying, packaging and scaling-out the validated CA practices such as furrows/ridges tillage, soil liming and herbicide weed control approaches to farmers and other land users was suggested as one of the immediate activities. It was also suggested that further studies be conducted to monitor long-term (over 10 year) effects of CA practices on soil properties and crop yields in Eastern Kenya.

CHAPTER ONE

INTRODUCTION

1.1 Background to the study

Agricultural sector accounts for more than 25% of Gross Domestic Product (GDP) for the majority of developing countries in sub-Saharan Africa (SSA) (DFID, 2003). Between 40 and 70% of rural households earn more than three-quarters of their income from agriculture (IFAD, 2012). The sector is particularly large in terms of aggregate income and total labour force in SSA (Dethier & Effenberger, 2012). Investment in agriculture contributes to food security and poverty reduction for the majority of the rural poor countries (IFAD, 2012). Human population in SSA is projected at 17.5 billion in 2050 (FAO et al., 2013). This is against per capita food availability that has over the decades lagged behind the population demand (Beintema & Stads, 2006). Land degradation, especially due to declining nutrient stock is the fundamental biophysical cause of declining per capita food production (Sanchez et al., 2000). Indeed nearly 3.3% of agricultural Gross Domestic (GDP) in SSA is lost annually due to soil nutrient depletion (Ngwira et al., 2013). The soil depletion is caused by overgrazing (49%), conventional farming (28%), deforestation (14%) and overexploitation of vegetation (13%) (Muchena et al., 2005). The resulting soil nutrient depletion is a decline in crop yields (Hresko et al., 2009). This therefore prompts for agricultural adaptation of sustainable land management practices (Curran et al., 2011).

The Eastern Kenya region has a rapidly growing population of over 700 people km^{-2} (GoK, 2007). The high population has contributed to small farm sizes of about 0.5 – 1.0 ha per household and even over cultivation on the fragile soils causing nutrient depletion (Jaetzold et al., 2006). Vanlauwe (2011) notes that the Eastern Kenya is one of the regions in SSA with the highest nutrient depletion, particularly in areas where subsistence farming activities are common. The two most severely depleted nutrients are nitrogen (N) and phosphorus (P), with annual losses estimated at 42 kg N and 3 - 4 kg P per hectare over 30 years of cropping (Shisanya, 2003). Studies by

Gitari (2008) in Eastern Kenya revealed that the high population density has greatly contributed to annual nutrient depletion to the tune of 126, 14 and 104 for N, P and K kg, respectively. Soil organic matter (SOM) is a key fraction for defining soil fertility (Bot & Benite, 2005). Long term studies in the Central Kenyan highlands showed a decline in SOM from 20 to 12 g kg^{-1} of soil within a period of 18 years (Mugwe et al., 2009). This is particularly in cultivated fields without crop residue retention (Malhi et al., 2006). In the past years, crop production was supported by indigenous practices such as shifting cultivation and fallowing (Jaetzold et al., 2006). However, because of increased population and pressure on agricultural land, these traditional practices are no longer applicable (FAO, 2014). Nitrogen and phosphorus application to food crops is low at 5 kg N ha^{-1} and 10 kg P ha^{-1}; against the recommended rate of 20 and 60 kg ha^{-1} for N and P, respectively (Recha et al., 2012). Reasons for limited use of the nutrient are farmers' low inputs purchasing power and limited knowledge on the general land management. As one of the basic resource of production, soil has not kept its productive capability (Kihanda et al., 2006). Thus, there can be large gaps between actual and attainable crop yields in the rain-fed farming systems (Temesgen et al., 2009).

The biophysical constraints causing low crop yields may be overcome through implementation of agricultural strategies capable of restoring SOM (Johansen et al., 2012). Wall (2007) notes that shifting from degrading conventional tillage methods to sustainable conservation agriculture (CA) based farming practices is one of the approaches that must be out-scaled to farmers and other land users. SAI (2009) defines sustainable agriculture as safe and an efficient production system. This is the system with ability to protect and improve the natural environment and socio-economic conditions of farmers (Wall et al., 2013). Conservation agriculture is part of sustainable agriculture where reduced soil disturbance, crop residues retention on the soil surface and diversification of crop varieties/species are the key principles (Wall et al., 2013). Adherence to appropriate crop sowing date(s) and adequate nutrient application are essential factors for enhanced crop productivity under CA systems (Vanlauwe et al., 2014).

In a related observation by Rockstrom et al., (2009), significantly higher benefits from CA are realized when uncertainties associated with poor prediction of rains are reduced. This could be achieved through timely crop sowing for efficient use of effective rainfall and nutrients in rain-fed agriculture (Ngwira et al., 2013). Retention of crop residue is viewed as low-cost soil fertility amelioration strategy that enhances SOM and soil health build-up (Twomlow et al., 2010; Baudron et al., 2014). Most of the past CA practices in Kenya involve water harvesting and nutrient concentration strategies without incorporating soil surface residue cover (Kaumbutho & Kienzle, 2007). Majority of farmers feed the crop residues to livestock, thus retaining insufficient quantities on the soil surface (Ngwira et al., 2013; Valbuena et al., 2012). Zero tillage alone on soils prone to crusting and compaction may not lead to higher crop yields (Baudron et al., 2013). For example, 0.6 t ha^{-1} extra maize grain yield was realized from short-term effect of residue retention under zero tillage (Guto et al., 2011). In addition, water harvesting alone without residues and *ex-situ* nutrient application may not significantly sustain crop yields (Parry et al., 2004). There is no enough evidence on the general effect of short, medium to long-term CA practices on soil nutrients and crop yield balances. Given the pivotal role played by the CA in improving food production elsewhere in the world, it was necessary to conduct detailed investigation on soil nutrient and crop yield balances under CA systems in a humic Nitisol in Eastern Kenya.

1.2 Problem statement

Low agricultural production leading to severe hunger and poverty amongst members of rural communities is a common phenomenon in Eastern Kenya. The situation is aggravated by soil nutrient degradation and inadequate resources to increase crop production for food security. Maize and common bean yields have remained low despite availability of high yielding cultivars from research institutions and seed companies. Climate variability and poor farming methods, including limited use of organic and inorganic fertilizers have greatly contributed to the low crop yields experienced at farm level. The situation can be improved by testing and recommending feasible conservation agriculture practices capable of improving soil productivity and subsequently crop yields (Ngwira et al., 2014). While positive impacts of conservation agriculture are demonstrated elsewhere in the world, not much is reported from Eastern Kenya. Hence, a need to test and recommend to farmers sustainable conservation agriculture options for improving soil and crop productivity in the region.

1.3 Justification

The Kenyan population is estimated at 40.6 million with a growth rate of 2.6% (World Bank, 2012). Maize *(Zea mays L.)* and common bean *(Phaseolus vulgaris L.)* are the most important food crops for over 90% of Kenyan households (Muui et al., 2007). Over the years the annual demand for maize and legume grains has lagged behind the Kenyan population (Godfray et al., 2010; World Bank, 2012). The problem is attributed to soil nutrient depletion particularly in the cultivated fields. The use of mineral fertilizer to replenish soil nutrients has for a long time been promoted as one of the major ways of counterbalancing the low soil fertility in the region. However, the rates applied by farmers are less than 5.5 and 10.7 kg ha^{-1} of nitrogen and phosphorus, respectively (Waithaka et al., 2007). These amounts are much lower than the area recommended rate (FURP, 1994) of 60 kg ha^{-1} for each of the nutrients. Use of inorganic fertilizers tend to be mostly on cash crops because of their high profitability, while food crops get less fertilizers because of unfavorable crop/fertilizer price ratios and financial constraints faced by farmers. Use of organic soil nutrients inputs as a low-cost soil fertility improvement option is constrained by their low nutritive values and high labour demand for preparation, transportation and application in the fields (Waithaka et al., 2007). Therefore, sustaining soil fertility and increasing productivity using inorganic and organic resources is limited in Eastern Kenya.

Improved adoption of conservation agriculture (CA) practices by farmers and other land users is singled as one of the ways for achieving adequate food production in the region (Giller et al., 2011). FAO, (2007) notes that the land use benefits are better defined when the CA farming systems are combined with activities meant to address soil nutrient depletion, pests infestation, high cost of inputs and adaptation to climate variability challenges. This is also when appropriate agronomic procedures such as cultivar selection, planting dates, planting densities, pest control and pre- and post-harvesting handling of crops are adhered to by farmers (Wall 2007). Moreover, the herewith study is justified because the results are based on testing and recommending appropriate CA practices for sustainably improving productivity and crop yields in a humic Nitisol in Eastern Kenya.

1.4 Research gaps

Various integrated soil fertility management (ISFM) options have been developed and adopted by farmers in the study area. However, few have focused on effect of conservation agriculture (CA) practices on soil and crop yield balances. Integrated soil fertility management (ISFM) focuses on application of *ex-situ* inputs such as nitrogen (N), phosphorus (P) and other nutrients. The challenge is to improve on the impacts of soil productivity and maize-bean yields through building up SOM from crop residue return *(in-situ).* Although rainfall variability is an important problem in rain-fed agricultural production systems, limited reports exist detailing the effect of tillage practices on crop productivity. This study was therefore designed mainly to validate potentials of CA practices on soil quality and crop yields under rain-fed condition in a humic Nitisol in Eastern Kenya.

1.5 Research questions

The study was guided by the following research questions:

1. What is the status of the initial soil properties at the study site?
2. How do conservation agriculture farming practices affect soil physical and chemical properties?
3. What is the effect of conservation agriculture practices on observed and APSIM's predicted crop yields?
4. Can conservation agriculture practices affect soil biology in maize-bean cropping systems?
5. What is the effect of soil liming on soil quality and crop yields under conservation agriculture farming methods?
6. Can conservation agriculture practices affect profitability of maize/bean cropping systems?

7. What is the effect of glyphosate based herbicides on weed control in maize-bean cropping systems under conservation agriculture farming practices?

1.6 Objectives

1.6.1 General objective

The study's general objective was to evaluate and recommend sustainable methods for improving soil productivity and crop yields using conservation agriculture practices in a humic Nitisol in Eastern Kenya.

1.6.2 Specific objectives

The study's specific objectives were to:

1. Determine soil properties before and after adaption of conservation agriculture practices.
2. Investigate the effect of conservation agriculture practices on soil physical and chemical quality.
3. Assess the effect of conservation agriculture practices on observed and APSIM's predicted maize and bean yields.
4. Investigate the effect of conservation agriculture practices on soil biology in maize-bean intensification systems.
5. Determine the effect of liming on soil nutrient and crop yields under conservation agriculture farming practices.
6. Establish profitability of maize-bean cropping systems under conservation agriculture practices.
7. Establish the effect of glyphosate based herbicides on weed control in maize-bean intensification under conservation agriculture farming.

1.7 Hypotheses

The study was meant test the following hypotheses:

1. There is variation in soil quality before and after application of conservation agriculture practices at the study site.

2. Conservation agriculture practices do not improve soil physical and chemical properties under maize-bean farming systems.
3. Soil microbes (bacteria, fungi and nematodes) are not significantly affected by the conservation agriculture tillage practices.
4. The observed crop yields may be comparable to those simulated by APSIM computer model.
5. Soil liming can improve soil properties and crop yields under conservation agriculture farming practices.
6. Used of glyphosate herbicide products for weed control in conservation agriculture farming can improve maize and bean yields.
7. It is profitable to grow maize and bean under conservation agriculture practices.

1.8 Scope of study

The study was conducted within the KALRO-Embu farm representing medium altitude agro-ecological zone. The zone is suitable for most of annual and perennial food crops. The crops are mainly grown by smallholder farmers, who over time have continuously worked on the land leading to severe soil nutrient depletion in the crop land. As part of coping strategy, farmers adopt improved and high yielding crop varieties with high harvest index. However, the strategy has not guaranteed high yields because the cultivars succumb to the low soil fertility, among other biotic and abiotic challenges. Fertilizer use on the degraded soils is low, a situation associated to farmers' low inputs purchasing power and limited knowledge on soil fertility improvement strategies. The study was expected to contribute scientific knowledge on the potentials of the conservation agriculture practices in restoring soil nutrient and in turn improve crop productivity for smallholder farmers. Apart from farmers, researchers, extension providers and students in agricultural fields are other expected beneficiaries of the research findings. The findings could further be utilized by persons and institutions promoting CA principles and practices as soil and water conservation options. Policy briefs are also expected to be availed to the relevant Kenyan National and County governments towards addressing the threat of nutrient depletion and land degradation in Eastern Kenya.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Low soil fertility is one of the major limiting factors to achieving household food sufficiency in sub-Saharan Africa (SSA) (Alexandratos & Bruinsma, 2012). The low fertility is attributed to depletion of plant nutrients from the croplands (Drechsel et al., 2001b). Loss of nutrients from harvested products and leaching represents some of the ways of nutrient depletion in croplands (Drechsel et al., 2001). In the process, macro- nutrients and micronutrients are lost from agricultural lands (Giller, et al, 2011). For example, 96, 48 and 72 kg ha^{-1} of nitrogen, phosphorus and potassium, respectively, are removed from the soil when 4.0 t ha^{-1} of maize grain is harvested (Zingore et al, 2014). The removal of plant nutrients in form of crop harvests is a desired form of loss (Drechsel et al., 2001). Studies by Bekunda et al., (2007) in SSA revealed negative N and P balances at 46 and 3 kg ha^{-1}, respectively.

Soil erosion, mainly from run-off is another important factor causing soil degradation (Liu et al., 2010). Sanchez (2000) observes that soil erosion is one of the most extensive soil constraints. The process (erosion) does not only remove plant nutrients, but also reduces topsoil depth and soil water holding capacity (Wall et al., 2013). According to Powlsen et al., (2011), farmers adoption of inappropriate farming methods is a major factor that aggravates soil erosion in cultivated lands. Similarly, the type of soil and landscape greatly influence the amount and the rate of soil loss from run-off (Jéan du Plessis, 2003).

The Eastern Kenya landscape ranges from gentle to steep topography that is prone to high soil erosion hazards (Jaetzold et al., 2006). Soil erosion control trials conducted at KALRO-Embu established that approximately 100 t ha^{-1} is annually lost from cultivated fields (O'Neil et al., 1997). In the same region, Angima et al., (2003) found that the total annual soil loss varied from 130 to 549 t ha^{-1} for slopes ranging between 10 - 53%. Another study in humic Nitisols at Kabete, Kenya reported 64%

maize grain loss due to erosion from a two-year erosion period trial (Gachene et al., 1999).

Despite numerous research programs proving positive to crop yield response and to mineral nitrogen and phosphorus fertilizer additions, lack of access due to prohibitive costs limit their use by smallholder farmers in Kenya (Odendo et al., 2006). Decomposition and mineralization of organic resources by soil micro-organisms remains the key approach for N supply to the soil (Deenik & Yost, 2008). Integration of modest amounts of inorganic fertilizers with residue retention may offer a strategy to meet crop nutrient requirements (Jama et al., 2000). This is particularly in areas in Eastern Kenya that are characterized by intensive maize-bean intercropping systems and other areas with similar soil types, climate, cropping systems and socio-economic circumstances (Mucheru-Muna et al., 2013).

2.2 Theoretical Review/conceptual framework

Jaetzold et al., (2006) observes that the Eastern Kenya region is dominated by humic Nitisols. These are soils of moderate to high inherent fertility due to their high mineral concentrations and available water (Nigussie & Kissi, 2012). Though naturally rich in minerals, soil productivity has continually declined over the years due to continuous cultivation combined with soil organic matter removal and nutrient loss through crop harvest and aggravated soil erosion (Mucheru-Muna et al., 2013). The region is further characterized by erratic bimodal rainfall patterns and hilly topographical features which have great variations in soil properties (Jaetzold et al., 2006). Figure 2.1 shows a theoretical review/conceptual framework to summarize the key factors influencing the low crop yields problem in Eastern Kenya.

Soil depletion problem is compounded by limited knowledge and low adoption of sustainable soil conservation agricultural practices by farmers (Kihanda et al., 2006). Investing in sustainable land management practices and cropping systems using improved crop species needed to be tested and scaled-out in the effort of reversing the downward crop yield trends (Panel, 2013). The aim of this study was therefore to evaluate and recommend sustainable methods for improving soil productivity and crop yields using conservation agriculture practices in a humic Nitisol in Eastern Kenya.

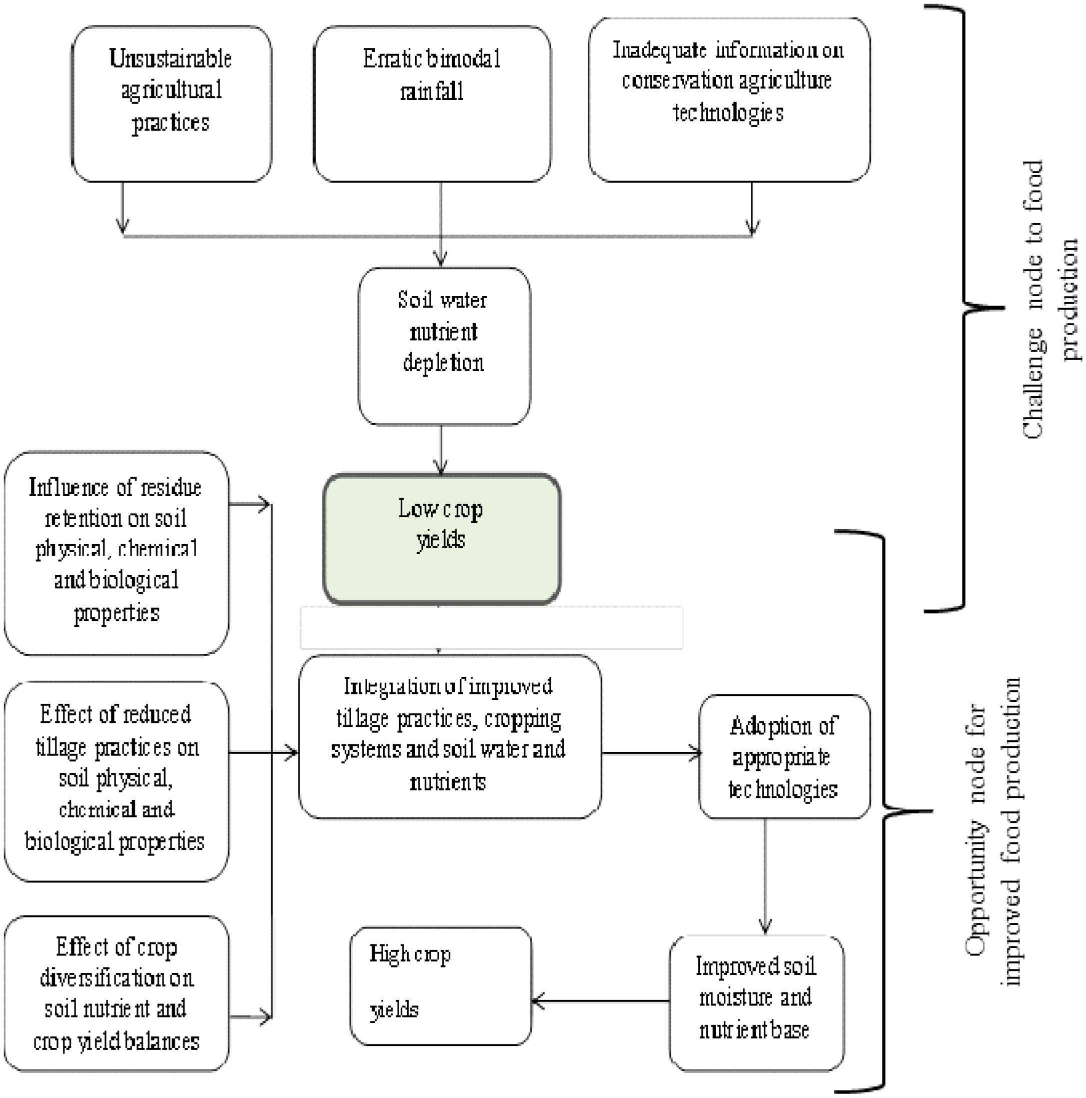

Figure 2.1: Theoretical review framework for a conservation agriculture study

2.3 Rainfall variability in Eastern Kenya

East Africa in which Eastern Kenya is located is characterized by diverse climates ranging from arid to humid areas. Season rainfall is complex and changes within tens of kilometers due to variations in altitude (Tadesse et al., 2014). The annual rainfall cycle is bi-modal ranging between 800 to 1250 mm. The wet seasons are from March to May and October to December (Jaetzold et al., 2006). The biannual cropping seasons are identified by the month of peak rainfall, and the rainfall for each season is assessed by summation of the total rainfall for October - January and March - June for the short rains (SR) and long rains (LR), respectively (Jaetzold et al., 2006). The rainfall is highly variable in amount and distribution (start and cessation dates). Much of the inter-annual rainfall variability comes from SR with 74% coefficient of variation compared with 35% for the LR (Shongwe et al., 2009). As a result, the SR are more predictable at seasonal level than the LR (Nicholson, 2000).

Over-estimating the probability of unfavourable outcomes is a known human condition (Rao et al., 2011). Indeed the smallholder farmers in arid Kenya over-estimate rainfall-related risks (Tittonell & Giller 2013). For example, recent results from baseline surveys and participatory crop modelling analysis suggest that over-estimating rainfall risks is also widespread in Eastern Kenya humid areas. The variability in seasonal rainfall is higher in the areas where yield risk reduction is also significantly higher due to crop water stress (Keating et al, 2010). The long-term rainfall variability is a critical limitation to crop production in rain-fed agricultural areas in Africa, including Kenya (Winterbottom et al., 2013). Thus, increasing yield productivity in such areas will need farmers to take more risks in farming (Carberry et al, 2013).

Farmers coping strategies to minimize rainfall variability and drought risks include crop diversification and growing drought escaping crop varieties that have short maturity cycles and high yield potentials (Micheni et al., 2011). Combined with low soil nitrogen, unreliable rainfall becomes even a severe crop production challenge (Mueller et al., 2012). For instance, it is noted that production of small grain cereals such as millets and sorghums in Sahelian zone of West Africa is primarily limited by nutrient deficiencies rather than 250-300 mm growing season rainfall (Schlecht et al., 2006). Related observation by Twomlow et al., (2010) showed that soil N supply is the key factor that limits maize production in Zimbabwe's semi-arid environments with 400-500 mm effective rainfall. As yet, no comparative assessment of rainfall variability and limitations on crop growth and yield has been undertaken in Eastern Kenya.

2.4 Soil fertility

Soil fertility refers to the quality of soil to supply plant nutrients in available forms, adequate amounts and balanced proportions necessary for plant growth when other factors are favourable (Sanchez et al., 2009; Thierfelder et al., 2013). Fertile soils are formed from mineral-rich parent material and accumulation of organic matter under favourable climatic conditions (Kiptot, 2008). Continuous cropping, a common practice in Eastern Kenya tends to deplete available water, SOM and other plant nutrients. This calls for measures to address challenge limiting improved soil productivity (Mugendi et al., 2006; Winterbottom et al., 2013).

In the relatively humid zones where rainfall exceeds evapotranspiration (ET) for a substantial part of the year, leaching of mineral N is common (Stenger et al., 2008). Two methods that for years have been used for restoring soil fertility are: (i) general litter fall or fallowing for several years to allow fertility to rebuild naturally, and (ii) application of organic matter inputs (Ekboir et al., 2002). Therefore soil nutrient management involves not only the chemical and physical, but also soil biological properties (Sanginga & Woomer 2009). Integrated nutrient management refers to an approach of combating nutrient depletion. This integrated soil fertility management (ISFM) approach and involves combining set of soil fertility management practices that include use of inorganic fertilizers, organic inputs and maintenance of soil biology (Vanlauwe et al., 2010). For it to be successful, the approach must adhere to the use of improved germplasms knowledge (Vanlauwe et al., 2010). The paradigm (ISFM) has been promoted by Tropical Soil Biology and Fertility Institute of the International Centre for Tropical Agriculture (TSBF), Kenya Agricultural and Livestock Research Organization (KALRO) and other research agencies to address the problem of soil fertility decline in Kenya (Odendo, 2009). However, adoption of ISFM approach by farmers has been dismally low (Rege, 2006). This is attributed to high cost of soil fertility inputs and lack of awareness of the technologies exacerbated by the wide communication gaps between researchers and farmers

(Sanginga & Woomer, 2009). Consequently, knowledge on soil nutrient management has not been optimally used to solve the diverse soil fertility problems (Rege, 2006).

Crops mine nutrients which can be partially recovered if the residues are returned to the soil after the crop harvest (Rege, 2006; Giller et al., 2011). Among the plant nutrients, nitrogen is the most deficient nutrient in Eastern Kenyan soils (Maghanga et al., 2013). Estimates indicate that legumes can fix up to 200 kg N ha^{-1} year^{-1} under optimal field conditions (Chemining'wa et al., 2004). However, use of legume residues and cover crop options can be employed to improve soil fertility (Giller & Wilson, 2001). Green manure legumes such as *Mucuna pruriens* and *Desmsodium intortum* are some of the species widely promoted in the region for soil fertility improvement and also as livestock feed (Gitari, 2008). However, their adoption remains low because farmers find it difficult to forego their croplands for green manure legumes production (Beshir, 2014).

2.5 Soil organic matter

Remains of plant material and soil organisms in various stages of decomposition and mineralization constitute soil organic matter (SOM) which is the key contributor to soil fertility and productivity of agricultural systems in the world (Powlsen et al., 2011). The SOM is the key driver or influencer of soil physical, biological and chemical properties (Holland, 2004; Mupangwa et al., 2013). Such properties include soil structure, soil stability, buffering capacity, moisture retention, biological activities, nutrient reserve/availability (Thierfelder et al., 2014). In addition, soil organic matter is determinant to variations in soil aggregate size and the aggregation indices in tropical soils (Gerzabek et al., 2001). Significance of SOM in agricultural systems has long been recognized on the basis of lowering soil susceptibility to compaction during farm operations (Franzluebbers, 2004).

The amount of SOM content may be affected by crop type, crop integration systems (rotation or intercrop) **(**Sombrero & Benito**,** 2010), the quality and quantity of crop residues left on or incorporated into the soil **(**Sombrero & Benito**,** 2010; Wall et al., 2013). Soils low in organic matter exhibit increased susceptibility to degradation upon cultivation especially when soil cultivation is inappropriate as is the case for conventional tillage systems (Wall et al., 2013; Michael, 2013). The quantity and quality of SOM is largely influenced by land management practices (Lal, 2004). Gradual to rapid decline of up to 50% of the SOM within 10 - 15 years is reported to take place when land is converted from forest to farmland (Briggs and Twomlow, 2002). Similarly, Powlsen et al., (2011) notes that some cultivated soils have lost over 50% of the original soil organic carbon pool with a cumulative loss of 30 - 40 t C ha^{-1}. Increased soil OC is a major factor for improving soil structure and water holding capacity (Lal, 2004). Improved soil carbon pool raises nutrient stores, providing energy to soil fauna for enhances land biodiversity. This is also an approach to mitigate the effects of climate change (Powlsen et al., 2011).

Maintenance of productivity through management of organic resources within the farming system has become a priority for research in past times (Briggs and Twomlow, 2002). Adoption of conservation tillage practices with residue return on the soil surface combined with water management can help restore depleted soil OC pool (Rockstrom et al., 2009). Giller et al., (2011) demonstrated the potential of minimum tillage and mulching in enhancing accumulation of SOM, mitigating CO_2 emissions. This partly addresses the mounting environmental problems associated with conventional farming practices. Implementation of soil conservation practices such as adoption of tillage practices that conserves moisture longer in the soil, combined with residue retention may provide a solution to the deteriorating quality of SOM in Eastern Kenya soil particularly in rain-fed farming environments.

2.6 Soil moisture and crop water use efficiency

Crop water use efficiency (WUE) is described as the ratio of dry grain yield to the total amount of water used (Zhang et al., 2014). Here, total amount of water used in production of grain is equivalent to evapotranspiration (ET) assuming that no rain water is lost to runoff and deep drainage. The ET may be estimated as the difference between cumulative seasonal rainfall and soil water content at physiological maturity (Tambussi et al., 2007).

Attempts to improve WUE have been made, and two broad approaches are identified: increasing total amount of water available for plant uptake and increasing the proportion lost through the transpiration stream (Cooper et al., 1987; Wallace, 2000; Zhang et al., 2014). The crop yield is directly proportional to the amount of water transpired (T) from the plant system. Thus, it is common practice that the pro-high WUE strategies target to reduce soil evaporation (E) and produce more grain per unit of T (Wallace, 2000).

Though the crop yield is largely determined by its genetic characteristics, other conditions such as available soil moisture and soil fertility have overriding role on crop yields (Raes et al., 2006). Similarly, Hooper, (2010) notes that the crop WUE is a function of multiple factors, including crop physiological characteristics, genotype, soil characteristics, meteorological conditions and agronomic practices. Modification of agronomic practices such as adopting simple changes to planting date, adapting short duration crops, planting patterns, tillage practice, soil surface residue retention/mulching, timely weed control, right fertilizer use and rain water harvesting strategies lead to improved WUE and the final crop dry matter. Knowledge of soil water management is therefore important for successful crop production under CA programmes (Jia & Shao, 2013; Okeyo et al., 2014).

2.7 Soil acidity and pH

Acidic soils have a pH of less 5.5 (Kisinyo et al., 2014). Such soils cover about 13% (7.5 million hectares) of Kenyan agricultural land (Kanyanjua et al., 2002; Kisinyo et al., 2014). Land degradation and inadequate resources has led to low agricultural production in Eastern Kenya where the problem is compounded by low soil pH even in humic Nitisols that are known to have 5.5 pH values (Obura et al., 2010). Acidic soils were developed through parent materials of acid origin, and have high Al (above 2 cmol Al kg^{-1}) and above 20% Al saturation) (Kisinyo et al., 2014). The soils are low in soil available P (less than 5 mg P kg^{-1} soil) due to moderate to high (107-402 mg P kg^{-1}) phosphate sorption (Opala et al., 2014). The soil's cation exchange capacity (CEC) becomes congested by positively charged hydrogen and aluminum ions (Ouma et al., 2013). This occurs more frequently in areas with high rainfall and on soils where removal of soil organic matter is frequent (Opala et al., 2014). The condition makes the nutrients needed for plant growth unavailable (Kanyanjua et al., 2002). For example the root growth and plant development of crops such as maize and bean suffer when soils become acidic at pH less that 5.6 (Kanyanjua et al., 2002; Ouma et al., 2013). The acidity problem is typically severe in the kaolinite and hydrous oxide rich soils common in humid tropical and sub-tropical climate regions. Plant root growth in acid soils is retarded by both plant nutrient deficiencies and toxicities of Al^{3+}, Mn^{3+}, and H^{+}. According to Obura et al., (2010), soil acidity is widespread, partially responsible for low maize and bean yields in several parts of Kenya. For example, maize yield averages at 1.5 t ha^{-1} compared to the research potential of over 5.0 t ha^{-1} in Kenyan highlands (Kisinyo et al., 2009).

On highly acidic soils, (pH less than 5.5), the rhizotoxic aluminum (Al^{3+}) is solubilized inhibiting root growth and function in the majority of food crops (Kochian et al., 2005). The Al^{3+} toxicity limits plant growth through inhibiting root growth and development (Ouma et al., 2013). The degree of toxicity depends upon how high the concentration of soluble of Al_3^{+} ions is. The soil acidifying problem is aggravated by continuous cropping systems combined with application of acidifying nitrogen based fertilizers such as Diammonium phosphate (DAP). The extent to which fertilizer application affects the pH depends on the types, when and the amount of N applied. This also depends on soil type and precipitation (Giller et al., 2011).

The methods of improving crop outputs from acid soils include adoption of integrated conservation agriculture (CA) practices (Giller et al., 2011). Such practices may include appropriate inorganic and organic fertilizers application, soil erosion control and liming (Opala et al., 2014). The latter (liming) is generally application of agricultural lime containing Ca or Mg compounds to acid soils to increase Ca^{2+} and Mg^{2+} ions and reduces Al^{3+}, H^{+}, Mn^{4+}, and Fe^{3+} ions in the soil solution. Besides neutralization of soil acidity, lime enhances root development, water and nutrient uptakes for healthy plant growth (Opala et al., 2010). In Kenya, acid soils are conventionally managed by liming the top soil layer to neutralize the exchangeable aluminium (Ouma et al., 2013). Thus, lime reduces the level of exchangeable Al^{3+}, Fe^{3+} and Mn^{4+} in acid soils leading to reduction in P precipitation by these ions (Kisinyo et al., 2009). In addition, management of acid soils makes both the native soil P and applied P fertilizers available for plant uptake. Similarly, adoption of crop species tolerant to Al^{3+}, Fe^{3+} and Mn^{4+} toxicity and/or low soil available P increases crop yields (Kisinyo et al., 2014). Liming leads to increased soil pH, hence, availing P due to reduction in P sorption (Kisinyo, 2011). As one of the CA practices, soil liming could therefore lead to increased soil productivity.

2.8 Soil biology

The essential practices of conservation agriculture (CA) embraces minimal soil disturbance, keeping the soil covered as much as possible, and rotating crops (Clapperton, 2014). The practice allows farmers to influence the ability of the soil ecosystem (Mathew, et al., 2012; Burns et al., 2013). This in turn, affects the nutrient quality of the food and forages and ultimately the human and animal health (Waring et al., 2013). Annual tillage collapses the soil lattice structure, soil pores, inhibits the carbon and micronutrient trading network of soil biota (Clapperton, 2014). The biota require below ground suitable soil habitat, with a stable soil pore systems to work effectively and efficiently (Mathew et al., 2012). Retained plant materials on the soil surface have an effect of improving soil organic matter (SOM) which is a key component for soil fauna build up (Reed & Martiny, 2013). Soil microbes mediate the biochemical transformations of SOM that underpins decomposition and mineralization of plant available nutrients (Njeru et al., 2012). By focusing on building SOM as opposed to using synthetic fertilizers, organic production systems differ greatly from conventional systems (Burns et al., 2013). Organic matter has been shown to improve soil fertility, reduce nutrient losses (Syswerda et al., 2012) and reduce global warming potential (Cavigelli et al., 2013).

The quantity and quality of SOM and N inputs are the overriding controls of soil microbial biomass and activities (de Vries et al., 2012). Thus, distinct organic amendments can stimulate microbial biomass in agricultural fields (de Vries et al., 2012). For example, an increase in the fungal:bacterial ratio has been linked to increases in soil C and the C:N ratio across farmlands (de Vries et al., 2012). The microbial activities tend to change rapidly in response to soil organic matter management in agricultural soils (Bernard et al., 2012). Crop rotation can be used together to create suitable and well-structured soils for multiplication of micro-organisms (Clapperton, 2014). Improved soil fertility largely depends on the processing in the soil food-web the organic substrates (mainly, root exudates soil organic matter) by micro-organisms (Feng, 2003). In a rotation system, diverse crop roots enhances soil structural stability, increases the amount and quality of soil organic matter (Feng, 2003; Vries et al., 2012). The process provides diverse sources of root exudates, increases the number and activities of most soil organisms (Waring et al., 2013). Thus, healthy farm soils are needed for improved biological activities that lead to higher rates of mineralization of organic into inorganic nutrients for crop use (Mathew et al., 2012). Agriculturalists practice different tillage methods, cropping systems, nitrogen application rate and crop residue managements and their interactions. All these have negative and positive impact on the soil micro-organisms (Kerte´sz et al., 2008). Soil bacteria, fungi and nematodes play important roles in plants life, including transportation of nutrients to the roots. Although various research agencies have increased efforts to address soil chemical and physical properties, soil biological aspects have not been adequately tackled (Vanlauwe et al., 2014).

2.9 Conservation agriculture

According to Shongwe et al., (2009), best-fit soil sustainable agricultural approaches and systems should be tested and recommended to increase skills of farmers to manage climate variability. Minimum soil disturbance, maintenance of soil surface cover and crop diversification (intercropping and rotations) are the three underlying principles of CA (Wall, 2007). Adherence to the CA principles leads to conserving soil moisture, increasing SOM, recycling nutrients and improve crop productivity (FAO, 2007). Farmers adopting the CA principles are therefore able to make better use of available soil water, nutrients and limited external inputs (Vanlauwe et al., 2011). Thus, appropriate fertilizer use is one of the essential practices that must be integrated into the CA farming for enhanced crop productivity (Vanlauwe et al., 2014). As the first CA principle, practicing minimum mechanical soil disturbance is essential for maintaining nutrients through halting soil erosion (Gupta, et al., 2007). The second principle is concerned with protecting the soil upper horizon with crop residues (FAO, 2007; Gupta et al., 2007). The third CA principle is practicing crop diversification with different crop species (FAO, 2007). The role of crop diversification in CA is firstly to act as biological control of pests in the crop cycle and secondly to efficiently use the soil moisture and nutrient (Giller, 2009). The CA crop diversification has ability to enhance soil N supply especially when a legume is one of the crops in association (Giller et al., 2011). Some of the benefits associated with CA may be realized almost immediately while others build up over the longer-term (Giller et al., 2011). One of the immediate benefits in dryland agriculture is improved rain water use efficiency by the crops (Benites et al., 2002). This is achieved through increased water infiltration and decreased evaporation from the soil surface (Ekboir et al., 2002). Shaxson & Barber (2003) noted improved soil porosity and water infiltration resulting from residue retention. In addition, there are higher biological activities under CA and also increased SOM stabilization (Six et al., 2002). The residues on the soil surface also regulate soil temperature, enhancing crop establishment in humid areas (FAO, 2007).

Adoption of CA principles at farm level is associated with lower labour, inputs, more stable yields and improved soil nutrient dynamism (Wall et al., 2013). Crop production profitability under CA tends to increase over time relative to conventional agriculture (FAO, 2001). According to Ringius (2002), environmentally the CA has ability to conserve soil biodiversity and decreases CO_2 in the atmosphere, thus helping to mitigate the effects of climate change. Successful application of CA practices therefore requires a change in production systems such as inputs provision, residue management, fertilization and weeds control strategies (FAO, 2001). Based on the level of organic residues left on the soil surface, two broad categories of tillage methods are used: conventional tillage where the residues are removed and conservation tillage system where the residues are return after the crop harvest (Mupangwa et al, 2013). Ploughing causes soil problems such as compaction and reduced water percolation (Wall, 2007). Conservation tillage practices includes zero tillage/minimum tillage, furrows/ridges tillage and other systems where 70% of residue cover remains on the soil surface after planting (Derpsch, 2005). The residue helps to reduce soil erosion, to improve water infiltration and also crop water use efficiency (WUE) (Guzha, 2004; Hartkamp et al., 2004).

Conventional tillage is predominant in maize-based cropping systems in Eastern Kenya and is carried out manually using hand hoes or animal drawn mould-board ploughs (Terry, 2002; Muthamia et al., 2004). The ploughs are common in semi-arid areas where they were introduced from Europe in the early 20th century (Terry, 2002). It was believed that tilling the soil would increase soil fertility through fast mineralization of soil organic matter (Gupta et al., 2007). Excess of soil tillage breaks down soil structure leading to soil surface crusting (Kerte´sz et al., 2008). For decades, tillage has been seen as a way of clearing crop residue to give way for cultivation (Benites, 2008). Conservation agriculture principles are opposed to excessive soil tillage methods which lead to degradation of soil quality (Wall, et al., 2013). Indeed it is one of the CA principles to minimal soil disturbance whereby the digging is done at points where seed and fertility inputs are placed in the soil (Wall et al., 2007).

2.10 Crop residue management

Crop residue retention as soil surface mulch, together with minimal soil disturbance and crop rotation forms the basis or principles of CA (Kassam et al., 2009). Indeed surface mulch prevents excessive moisture loss through evaporation and soil crusting (Giller et al., 2011). Mulching has been widely used with the main intention of conserving soil water as well as increasing SOM (Kassam et al., 2009). Crop residue return can have the greatest benefits in areas prone to soil erosion by surface runoff and high intensity rainfall (Rusinamhodzi et al., 2011). A major challenge in mulching in sub-Saharan Africa is that the crop residues are mainly fed to livestock (Herrero et al., 2010). Thornton, (2010) notes that the crop residue demand to feed livestock does not seem to decrease in near future due to increasing demand for animal products. A trade-off arises when a farmer is faced with more than one objective towards a resource allocation that cannot simultaneously be attained

(Valbuena et al., 2012; Baudron et al., 2014). Due to the multiple benefits provided by livestock, mixed crop-livestock farmers generally feed most of the crop residues to livestock and sacrifice on soil mulching (Thornton, 2010). The consequence of this is insufficient quantities of crop residues for mulching (Giller, 2011).

Minimum tillage alone without mulching is less effective particularly in areas where the rainfall amounts are low or high but variable (Stolte et al., 2009). Jalota & Prihar (1990) reviewed the effects of mulch on soil moisture content and found that lack of mulching in low rainfall areas lead to high evaporation from the soil surface. The solution to insufficient crop residue for soil mulching could be ex-situ sources (outside the farm) provision of residues. An alternative of this is to improve soil productivity leading to production of adequate residues to cater for both soil mulching and livestock feeding.

While retention of crop residue is viewed as low-cost soil fertility strategy to enhance SOM build-up, soil health should also be considered as one of the key component of soil fertility (Sanchez, 2009; Mupangwa et al., 2013). Studies have shown some yield improvements, at 0.6 t ha^{-1} extra grain yield under residue retention on the soil surface (Guto et al., 2011). Similarly, in the drier conditions of south-western Zimbabwe, maize yield response to residue return of up to 4 t ha^{-1} was noted (Mupangwa et al., 2012). Use of crop residues as mulch affects hydro-thermal regime of soils by moderating soil temperature and reducing soil water evaporation (Zingore et al., 2011). At least 75% of mulch should be left on the soil surface when practicing CA (Wall et al 2007). The mulch also controls weed growth by their smothering action (Arora et al., 2011). Since maize is grown by over 95% of farmers in Eastern Kenya, use of maize stovers as mulching material would be feasible option for improving land productivity and consequently the crop yields. However, scarcity of information exists on the effects of residue return in combination with minimum tillage on soil nutrient and crop yield balances in the region. Decomposition and mineralization of organic resources by soil micro-organisms remains the principle approach for N supply in the majority of East African farming systems (Deenik & Yost, 2008). Integration of modest amounts of inorganic fertilizers with residue retention may offer a strategy to meet crop nutrient requirements in areas characterized by intensive maize-bean intercropping systems in Eastern Kenya (Mucheru-Muna et al., 2013).

2.11 Weed control

Weeds competition with the crops for growth resources is singled out as one of the challenges faced by farmers (Chhokar, et al., 2014). Weeds compete with agricultural crops for light, nutrients, water and space (Norsworthy & Frederick 2005). The impacts of weeds on crop yields depend on the type and intensity of interference with the crop growth (Mashingaidze et al., 2012). Effective control of weeds lead to more efficient use of water (Peterson & Westfall 2004). The deleterious effects of weeds is mostly managed conventionally using hand tools in Eastern Kenya (Berca, 2004). The conventional weeding is constrained by limited labour and weeds that are difficult to control due to their great diversity in terms of species and nutrient scavenging systems (Mutegi et al., 2012).

Competition for labour during the peak weeding periods have negative effects on maize production and yields (Waithaka et al., 2006). Over 80% of the farm labour is provided by family members and with other income generating enterprises (Ouma et al., 2011). In a socio-economic study on adoption of herbicide technologies in maize based cropping systems, Muriithi et al., (1999) recognized that the use of herbicides is the most economical method for weeds control in maize production systems. Similarly, Muthamia et al., (2004) in their studies on CA reported increased net benefits from managing weeds using herbicides. Feeding the weeds to livestock or using specific ones as cover crops and human food (vegetables) are other ways of removing and economically utilizing the weeds (Muthamia et al., 2004)

2.12 Glyphosate herbicides weed control

Weeds are more efficient in competing with crops for nutrients, water and light (Shrestha et al., 2002). In Eastern Kenya, weed control is mainly conducted using hand hoes by resource poor farmers (Muoni et al., 2013). Increasing the intensity of hand hoe weeding reduces the total weed density and the number of weed species

(Mashingaidze et al., 2012).According to Thierfelder & Wall, (2012), conventional tillage practices often lead to reduced soil quality such as poor soil porosity and nutrient loss through soil erosion. Weed management challenges is one of the major causes of low maize and bean grain yields in eastern Kenya.

To alleviate this challenge, a more sustainable method must be encouraged. FAO, (2010) defines CA as a farming system based on three interlinked principles. These are maintenance of a soil cover using crop residues (mulch), crop diversification and observing minimum soil disturbance. The CA has a potential to make more efficient use of natural resources through integrated management of soil, water and biological resources (FAO, 2010). Use of crop residues has positive impact on soil moisture retention for crop use during mid-season dry spells (Thierfelder & Wall, 2010). Returned crop residues of the soil surface have ability to suppress weeds during the growing season (Dube et al., 2012).

Use of herbicides is an effective and economical strategy for managing weeds by the smallholder farmers (Muoni et al., 2013). Glyphosate based herbicides are most common because of their availability at farm level and their fast action. The glyphosate products are non-selective systemic herbicides capable of controlling weeds that have underground rhizomes (Wall, 2007). The products contain approximate 480 grams liter^{-1} of the active ingredient (glyphosate) in the form of its isopropylamine salt. They are used as post-emergence, systemic herbicides. The products do not have soil residual activity.

2.13 Status of maize and bean production

The upper midlands (UM_3) zones of Eastern Kenya are characterized by intensive land use and high population densities of over 700 people km^{-2} (NCPD, 2012). Maize and common bean are predominant food crops grown by over 98% of resource poor farmers in complex and risky rain-fed farming systems (Ouma et al., 2011). The two food crops are grown as intercrops mainly for their grains (Micheni et al., 2013). They also provide residues that are fed to livestock (Guto et al., 2011). Additionally, the bean provide cheap dietary protein source and income for majority of rural households (Muui et al., 2007).

The per capita consumption of maize and bean in Kenya is estimated at 98 kg year^{-1} (Mwaura, 2011) while that of bean is estimated at 14 kg year^{-1} (Buruchara, 2007). Based on trends in Kenyan population growth is estimated at 40 million in 2014, demand for grains is expected to increase by 3 - 4% annually (GoK, 2007). In 2009 Kenya’s production of maize and bean was estimated at 2.5 and 0.3 million metric tonnes, against a consumption requirements of about 3.6 and 0.9 million metric tonnes, respectively (World Bank, 2012). A farm profile study conducted in the region revealed that the yields of the two crops are low at 1.2 and 0.5 t ha^{-1} against the expected 6.0 and 2.3 t ha^{-1} season^{-1} for maize and bean, respectively (Micheni et al, 2014). Although crop production varies between households, low soil fertility, climate variability, pests and high cost of inputs are among the most common challenges faced by farmers (Ouma et al., 2011).

2.14 Maize-legume cropping systems

Intercropping is defined as growing of two or more crop species simultaneously in the same field during a season. The practice is common among the smallholder farmers in Eastern Kenya where maize is intercropped with food legumes. The canopy structures and root systems of cereal crops are generally different from those of legumes (Tsubo et al., 2005). In cereal-legume intercropping, cereal crops form relatively higher canopy structures than legume crops and the roots of cereal crops grow to a greater depth than those of legume crops (Tsubo, 2005). This indicates that the component crops probably have differing spatial and temporal use of environmental resources (Willey, 1990). Crop growth and final yield of an intercropping system are also closely related to the spread of roots, which determines the uptake and utilization of nutrients (Liu, et al., 2010).

The legume-cereal intercropping system provides substantial yield advantage over sole cropping (Ojiem, 2006). Mucheru-Muna et al., (2010) observes that farmers intercrop maize with legume species to maximize utilization of land and labour. The practice also provides greater yield stability and risk evasion against natural disasters in areas subject to weather challenges (Latati, 2013). In particular, planting maize as a sole crop is not sustainable (Rusinamhodzi et al., 2012). The practice leads to soil erosion due to limited ground cover. Additionally, intercropping provides several environmental benefits. Such benefits include mitigation of runoff, soil erosion and biodiversity (Rusinamhodzi et al., 2012).

The crop yield advantage of intercropping systems could further be attributed to above and below-ground interactions between intercropped species (Latati et al., (2013). They found that superior crop yields in intercropping systems were related to additional advantages in root distribution and reduced below ground competition. Although some legume species could be N fixers, the fixed amounts are too low to contribute to soil N reserves to benefit the crop in association (Giller & Wilson, 2001). For instance, common beans are poor fixers of nitrogen (Vargas et al., 2000). However, the amount of nitrogen fixed by any common bean variety cereal-legume intercropping system depends on the legume crop species and morphology (Dawo et al., 2007). This also depends on the type of management as well as the competitive abilities of the component crops (Dawo et al., 2007). Contribution of fixed N by legumes to cereal crop is likely to be small (Siame, 1998). Crops in intercrop competes for growth factors (e.g. mineral nutrients, water, light and space). The competition is greatly minimized when the crops chosen to form the intercrop have different growth habits so as to exploit different growth niches of the intercrop environment (Willey, 1990). In addition, competition is greatly minimized by manipulating the planting densities and spatial arrangements of the component crops (Ofori & Sterm, 1987). Tsubo (2005) notes that intercropping systems exhibit positive influence on the crop yields. For example, 19% yield increase from an intercrop was realized in Sri Lanka intercropping studies compared to monoculture.

Land equivalent ratio (LER) is an important tool for evaluating intercropping systems (Dariush et al., 2006). Mead and Willey, (1980) defines LER as the relative land area required for a sole crop to produce the same yields as intercropping. Theoretically, if the agro- ecological characteristics of each crop in a mixture are exactly the same the total LER should be 1.0 (Dariush et al., 2006). The LER value of 1.0 indicates that there is no difference in yield between the intercrop and the sole crop, and any value greater than 1.0 indicates advantage for intercrop (Mehdi et al., 2009; Mohammed, 2012). An intercropping study by Mucheru-Muna et al., (2010) in semi-arid Mbeere sub-County, Eastern Kenya had maize-cowpea intercropping resulting to improved crop yields and economic benefits relative to the conventional sole crop systems. Thus, the maize-bean intercropping strategy is likely to improved soil fertility in Eastern Kenya, mainly through N and SOM contribution from bean leaf fall as explained by Thierfelder et al., (2012).

2.15 APSIM Modelling in Conservation agriculture farming systems

Smallholder farming systems in sub-Saharan Africa (SSA) countries are characterized by widespread rural poverty and lower agricultural productivity. Variable rainfall patterns, nutrient and moisture stress, pest and diseases, unimproved genotypes, poor research and extension services are some of the constraints faced by farmers (Bouma & Jones, 2001). The ability to overcome these constraints depend largely on the government's capacity to disseminate relevant information to support decision making processes at farm level. This information has to be generated through cost-effective research methods that take into account the complexities of the farming systems (Cox et al., 2010). The complex interactions of bio-physical and socio-economic factors can be eased by use of computer models (Bouma & Jones, 2001). The models may help to analyze crop, water and nutrient management options under variable climatic conditions (Meinke et al., 2001). Additionally, modelling aids researchers to generate profitable and sustainable information for the diverse farming systems (Keating et al., 2003). One way of generating such information is the use of model assisted agricultural experimentation (Giller et al., 2009). Moreover, Keating et al., (2003) states that the integration of simulation modelling in research helps in:

i) Identification of research gaps in existing knowledge;
ii) Generation of the various hypotheses for testing;
iii) Determination of the most influential parameters of a system; and,

iv) Bringing researchers and farmers together to discuss food production challenges and the available opportunities in participatory modelling exercises.

The use of simulation models, for example, the Agricultural Production Systems Simulator (APSIM) model helped to improve the understanding of crop performance (Keating et al., 2003). The model allows a researcher to answer fundamental questions on rainfall variability and cropping systems (Rodriguez et al., 2011). The model functional modules include a diverse range of crops, soil processes, including soil water balances, N and P transformations, soil pH and a range of farm management aspects (McCown et al., 1996; Mupangwa et al., 2011). According to Keating et al., (2003), APSIM model is an effective tool for analyzing whole-farm systems, including intercrops and rotations. The model allows the user to improve their understanding on the impact of climate, soils, cultivars and the general farm management (Keating et al., 2003). According to APSRU, (2008), APSIM modelling framework is made up of different modules that feeds and get outputs from the engine (Figure 2.2).

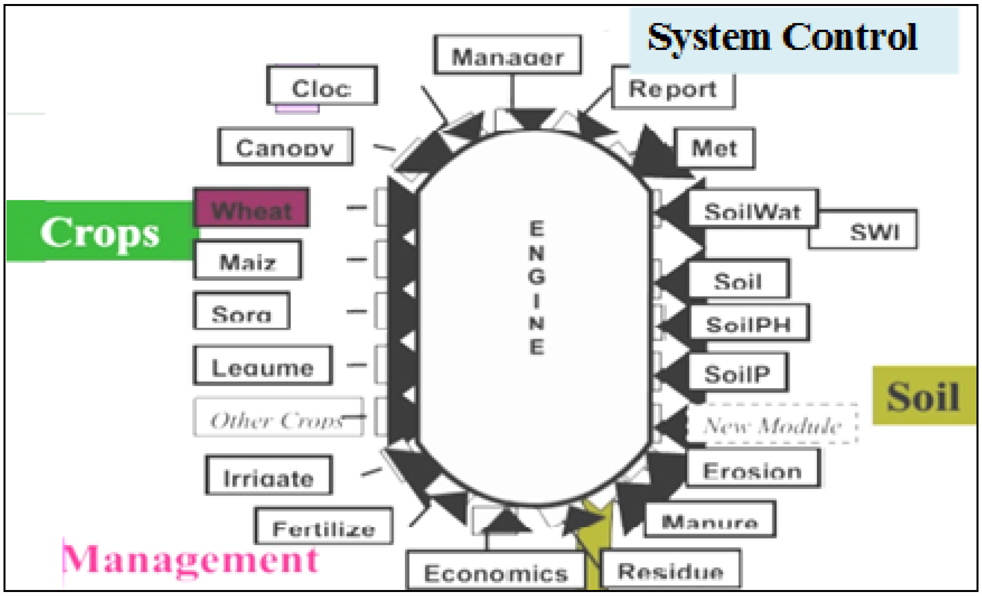

Figure 2.2: A flow chart showing structure of APSIM model. (Source: APSRU, 2008; Keating et al., 2003)

According to Keating et al., (2003) the agronomy APSIM’s structure has four main components or modules. The farm management module allows the user to specify the intended management rules that characterize the scenario being simulated and controls the simulation. The crops and soil module allows the user to select the cultivar and the type to input in the model engine. The system control module facilitates communication between the independent modules in the engine, - and the model and the user.

APSIM outputs can significantly reduce production losses from rainfall variability (Whitbread et al., 2010). For example, prediction for Australia's wheat industry for the year 2070 through crop simulation showed that the benefits from changing varieties and planting dates could be worth as much as A$ 550 million a year (Yunasa et al., 2004). The APSIM model was also used to predict short and long-term maize yields in Nebraska (Lyon et al., 2003). While there has been extensive testing and calibration of plant and soil modules of APSIM in America, Asia and Australia, not much has been done in Eastern Kenya. Sustainable Intensification of Maize-Legume farming systems in eastern and Southern Africa (SIMLESA) project invested in building African-based capacity for application of the cropping systems model. To effectively test APSIM’s capabilities to simulate crop intensification strategies under CA, good quality field experimental data sets are required (Keating et al., 2003). The data comprises contrasting treatments effects of crop growth/yields, climate and soil conditions across seasons (Whitbread et al., 2010). As part of this effort, intensively monitored field experimentation was conducted to compare the observed and APSIM predicted crop yields under conservation agriculture practices in Eastern Kenya.

CHAPTER THREE

MATERIALS AND METHODS

This section describes relevant features of the study site and research methods. These includes the experimental design, replications and variables measured. In addition, the section provides a list and descriptions of the collected data sets and procedures used for theirs analysis.

3.1 Study site

The study was conducted for four seasons (short rains 2011, long rains 2012, short rains 2012 and long rains 2013) at the Kenya Agricultural and Livestock Research Organization (KALRO - Embu) farm on the South-Eastern slopes of Mt. Kenya at 00^0 33.18'S; 037^0 53.27'E; 1425 m above sea level (asl) and in the upper midlands (UM_3) zone (Jaetzold et al., 2006) (Figure 3.1). The site is approximately 125 km North -East of Nairobi

Figure 3.1: Map of Kenya showing the site location in Embu County

The trial site receives 1250 mm average annual bimodal rainfall and warm temperatures ranging from 21-28 ^{0}C and 16 - 21^{0}C mean maximum and minimum, respectively (Jaetzold et al., 2006). The area is further characterized by varying weather conditions where rainfall changes within tens of kilometers (Shongwe et al., 2009). The wet seasons are from March to May and October to December (Nicholson, 2000). The biannual cropping seasons are identified by the month of peak rainfall (Tittonell & Giller 2013) (Appendix 3.1). The rainfall for each season is assessed by summation of the total rainfall for October-January and March-June for the short rains (SR) and long rains (LR), respectively (Jaetzold et al., 2006).

The main soil type at the site is a humic Nitisol, which according Jaetzold et al., (2006) is deeper than 1.5 m, well-drained with above 30% clay particles in sub-surface horizon (Appendix 3.2). According to Mucheru-Muna et al., (2013), this is soil with moderate to high inherent fertility due to its high content of minerals, moderate available water and moderate cation exchange capacity levels. However, the fertility has over the years declined resulting from inappropriate soil nutrient depletion (Ngetich et al., 2012). The Eastern Kenya region has different agro-ecological zones (AEZs) that according to (Tittonell & Giller 2013) have direct impact on farming and cropping systems adopted by smallholder farmers (Appendix 3.3). Dairy cattle rearing and growing of coffee are some of the main enterprises the smallholder farmers embark on for revenue generation (Ouma & DeGroote, 2011). Among the food crops, maize and bean are the most common (Gitari, 2008).

3.2 Experimental design

Three tillage methods (furrow/ridges (FR), zero tillage (ZT) and conventional tillage (CVT), three cropping systems (sole maize, sole bean and maize-bean intercrop), six nitrogen application rates (20 kg N ha^{-1} for bean, 0 kg N ha^{-1} for bean, 60 kg N ha^{-1} for maize, 0 kg N ha^{-1} for maize, 80 kg N ha^{-1} for maize-bean intercrop, 0 kg N ha^{-1} for maize-bean intercrop) and two crop residue management methods (residue retention and residue removed) were the 14 tested independent variables laid out on a randomized complete split-split-split-plot block design (Table 3.1). Each treatment was replicated three times (Appendices 3.4, 3.5, and 3.6).

Table 3.1: The main conservation agriculture treatments

Main factor	Independent variable	Abbreviation
Tillage method	Zero tillage	ZT
	Furrows/ridges	FR
	Conventional tillage	CVT
Cropping system	Sole maize	SMz
	Sole bean	SBn
	Maize-bean intercrop	Mz/Bn
Residue management method	Returned after the crop harvest	R_1
	Removed after the crop harvest	R_0
Nitrogen application rate	60 kg N ha^{-1} in maize	N_{60}Mz
	0 kg N ha^{-1} in maize	N_0Mz
	20 kg N ha^{-1} in bean	N_{20}Bn
	0 kg N ha^{-1} in bean	N_0Bn
	80 kg N ha^{-1} on maize-bean intercrop	N_{80}MzBn
	0 kg N ha^{-1} for maize-bean Intercrop	N_0MzBn

N = Nitrogen; kg = kilogram; ha = hactare

The three tested tillage methods were the conventional tillage, zero tillage and furrows/ridges tillage systems that had land preparation, weed control and residue management carried out as follows:

i) **Conventional tillage:** A conventional land preparation system involving seasonal land ploughing and harrowing using conventional tools such as jembes and pangas. At least two hand weeding events were conducted every season using hand tools such as jembes and pangas. Over 75% of crop residues were removed at the end of each season from the plots.

ii) **Zero tillage:** A conservation agriculture tillage practice where land is not ploughed. Only seeding holes made to hold the seed and fertility input(s). Weeds were controlled using pre- or post-emergence herbicide(s) as needs be.

Over 75% of crop residues were retained each season on the soil surface after the crop harvest.

iii) **Furrows/ridges:** A conservation agriculture tillage practice where furrows/ridges were made at the time of trial establishment, and then maintained later on with minimal soil disturbance. The furrows or ridges were spaced at 75 cm apart and maintained in subsequent seasons. Weeds were controlled using pre- and post-emergence herbicide(s) as needs be. Over 75% of crop residues were retained on the plots each season after the crop harvest.

While the tillage methods formed the main plots in the treatment structure, cropping systems, rate of N application and crop residue management made up the sub-plots, sub-sub plots and sub-sub-sub plots in a randomized complete plot design with three blocks. Allocation of treatments in the various blocks or plots was done by using random numbers generated from excel computer software. The treatments therefore were randomized between and within blocks. Any two plots within a block were separated by a 1.0 m buffer zone path to guard treatments from spilling over between plots. Similarly, any two replications were separated by a 2.0 m buffer zone for the same purpose. The sub-plots, sub-sub-plots and sub-sub-sub-plots were separated with 1.0 m paths. An individual plot measured 3.5 m x 3.0 m. The plots were maintained without being shifted during the four seasons of experimentation. The samples for determination of soil quality and crop yields were taken from within the net plots measuring 3.0 m x 2.25 m (Appendix 3.7).

3.3 Soil sampling and analysis for initial site characterization

Initial soil characterization was done to provide background information on soil chemical and physical properties at the trial site. The activity was done in October 2011 after identifying an experimental field measuring 140 m x 45 m that was also subdivided into 3 equal blocks. Fifteen soil sampling points were randomly identified using zigzag sampling pattern to minimize error due to variations within a given block. This was followed by taking 7 composite samples from each of the sampling points at 0-15, 15-30, 30-60, 60-90, 90-120, 120-150 and 150 – 180 cm soil depths.

Approximately 250 g sub-samples from each of the samples were air dried for 72 hours and ground to pass through 2.0 mm sieves and analyzed for pH (1:3 soil:water), physical and chemical properties as provided in Appendixes 3.8 - 3.11. Further soil samples were taken at the end of the four seasons of experimentation and analyzed to determine the effect of conservation agriculture on soil quality. Unlike during the initial site soil characterization that the samples were taken randomly from a few points within each block, soil samples were taken from all 108 plots in the three replicates (Appendixes 3.4 – 3.6) and analyzed as provided in Appendixes 3.8 - 3.11.

3.3.1 Soil pH

Soil pH was determined at 1:3 (soil:water) ratio suspension using a conventional pH glass electrode (MTR PHEP 0-14 model). Dry soil sample was sieved using a 2 mm sieve and 5 g transferred into a beaker. This was following by adding 15 ml of distilled water. The content was shaken on an electric shaker for 30 minutes after which the mixture settled for 15 minutes before taking the pH readings.

3.3.2 Soil texture

As indicated in Appendix 3.8, soil particle size distribution analysis was done using the hydrometer method as outlined and explained by Okalebo et al., (2002). The trial site soil was generally deep (above 2.0 m), dusty red and with thick humic topsoil. Clay particles was dominating at 66.77%, while sand and silt accounted for 16.73% and 16.50%, respectively in the 0 - 180 cm profile pits.

3.3.3 Soil bulk density

Initial soil bulk density was determined from profile pits dug within the experimental area. Undisturbed soil samples were taken from 0-15, 15-30, 30-60, 60-90, 90-120, 120-150 and 150-180 cm soil depths using metal core rings of 100 cm^3. The rings were pushed into the soil using the accompanying ring holder. The rings with the soil were carefully dug out and oversized soil edges trimmed off. Care was taken to prevent soil compression in the rings. The samples were oven dried at 105^0 C to constant weight (g) that together with core volume (cm^3) were used to calculate the

BD ($grms/cm^3$). This was done by dividing the weight of dry soil with the volume for each target ring as showed in the following formula:

$$\text{Bulk density (g cm}^{-3}) = \frac{\text{Weight of dry soil (g)}}{\text{Volume of core ring (cm}^{-3})}$$

Note: The measured bulk density in g cm^{-3} was later on converted to kg m^{-3}.

3.3.4 Soil organic carbon and nitrogen

Soil organic carbon was determined using sulphuric acid and aqueous potassium dichromate as described by Nelson & Sommers (1975) and outlined by Okalebo et al., (2002) (Appendix 3.19). The TSN was determined using Kjeldahl digestion method (Anderson & Ingram, 1993) and quoted by Okalebo et al., (2002) (Appendix 3.10).

3.3.5 Extractable soil phosphorus and potassium concentrations

The extractable soil P was determined using the Mehlich double acid method which involves extracting P from the oven dry soil in a 1:5 ratio (w/v) with a mixture of 0.1 N HCl and 0.025 N H_2SO_4 (Appendix 3.11).

3.3.6 Soil sampling and analysis at the end of experimentation

After the four seasons of experimentation, more soil samples were taken and analyzed to determine the effect of practicing CA farming methods on soil quality. The same soil analysis methods used for the initial (October 2011) site soil characterization (Appendixes 3.8 - 3.11) were also used to analyze soil samples taken in October 2013.

3.3.7 Monitoring soil moisture

To monitor soil water dynamist under various treatments was one of the key activities in the study. Unfortunately the installed access tubes that were to be used with neutron probe to read soil moisture at different soil depths collapsed. The only available neutron probe equipment at KALRO – NARL was not available at the study site. A decision was therefore made to define the effect of the various conservation agriculture practices on basis of calculating the crop use efficient (WUE) as explained and reported in sections 3.10 and 4.8 of this document.

3.4 Soil liming in conservation agriculture

Low soil pH problem was identified at KALRO - Embu farm and was attributed to over 50 years of continuous cultivation that was characterized by removal of soil organic matter (SOM). The farm soil had 4.8 pH value. As one of the major approaches for mitigating low soil pH in agricultural lands in Kenya, use of lime was proposed as a way of managing the low soil pH for the research farm. The liming activity involved the following sub-activities:

i) Characterization of the farm to define soil qualities before and after liming.
ii) Calibration of lime requirement to raise soil pH from 4.8 to at least 5.6 value.
iii) To conduct a trial to determine the effect of liming on soil quality and crop yield dynamics under CA practices.

3.4.1 Determination of lime requirement

From the oven dry and sieved composite soil sample, six soil sub-samples, each measuring 25 g were put in six beakers containing 0.00, 0.02, 0.05, 0.10, 0.20 and 0.30 grms of lime ($CaCO_3$). The soil and lime in the beakers were thoroughly mixed and wetted to saturation with known amount of de-ionized water. The beakers had their mouths covered to prevent water evaporation of water from the mixture which was incubated under room temperature (approximately 16 ^{0}C) for 7 days. While in the process of incubation, the soil, lime and water mixtures were stirred daily for 20 minutes at 10.00 am to make sure that the soil and lime were well mixed. After 7 days of incubation, de-ionized water was added in each beaker at 1:3 (soil:water) ratio. The pH was then determined using a general purpose pH electrode, MTR PHEP 0-14 model. The readings facilitated to draw the lime requirement curve and also to calculate the amount of lime requirement for raising KALRO-Embu farm soil pH from 4.8 to 5.6 pH value.

The lime requirement curve was prepared based on the outcome of lime/soil/water seven day incubation period. The results gave 0.75 grms of lime requirement for modifying pH of 25 grms of soil from 4.8 to 5.6. Having developed the lime requirement curve (Appendix 3.12), calculations for lime requirement for pH modification was done in two steps: first, to determine the amount of soil (S) in the farmland where the liming is required, and secondly, to determine the amount (kg) of lime material required (R) for 1.0 hectare. The calculations were done as follows:

(i) Determination of the amount of soil (S) in farmland where the liming is to be done;

S = A x D x 1000 x BD;

Where; S = mount of soil (kg);

A = Area (m^2); D = Depth (m); 1000 = Constant; BD = Bulk Density (kg m^{-3}).

Thus, S = 10,000 m^2 * 0.15 m x 1000 * 1.04 kg m^{-3} = 1,560,000 kg (the amount of soil in 1.0 ha (farmland to be limed)

ii) Determination of the amount (kg) of lime material required (R) for liming 1.0 hectare. Having known S, (see step (i) above), R was calculated as:

R = L x (S/25) x (1/1000);

Where; R = Amount of lime material required (kg) for liming 1.0 hectare;
L = Amount of lime preferred pH (5.6) from the calibration curve (kg);
S = Amount of soil in farmland where the liming is to be done.

Thus, R = 0.000075 kg x (1,560,000 kg/ 0.025 kg) x (1/1000 kg)
= 4.7 t ha^{-1} (for liming 1.0 ha changing soil pH from 4.8 to 5.6 value).

3.4.2 Liming trial

A liming trial was conducted where furrows/ridges (FR) and conventional (CVT) tillage practices were the main farm management factors (Table 3.2). The trial was based on a randomized complete split-plot block design with 3 replicates (Appendix 3.13). Reference to the calculated 4.7 t ha^{-1} lime requirement, adequate amount of $CaCO_3$ was weighed and uniformly spread on the dry soil surface and then incorporated into 0 - 15 cm soil depth. Care was taken to spread and incorporate the lime within the crop rooting depth. These operations were conducted a week before the start of the seasonal rains.

Table 3.2: Treatments for liming trial

Treatment code	N fertilizer input(kg ha^{-1})	Residue input (kg ha^{-1})	Lime input (kg ha^{-1})
N0R0L0	0	0	0
N1R0L0	80	0	0
N0R1L0	0	2.5	0
N1R1L0	0	0	4.7
N1R1L0	80	2.5	0
N0R1L1	0	2.5	4.7
N1R0L1	80	0	4.7
N1R1L1	80	2.5	4.7

N0R0L0 = No N fertilizer; No residue returned and No lime applied.

N1R0L0 = N fertilizer applied; No residue returned and No lime applied.

N0R1L0 = No N fertilizer applied; residue returned and No lime applied.

N1R1L0 = No N fertilizer applied; No residue returned and lime applied.

N0R0L1 = N fertilizer applied; residue returned and No lime applied

N0R1L1 = No N fertilizer applied; residue returned and lime applied.

N1R0L1 = N fertilizer applied; No residue returned and lime applied.

N1R1L1 = N fertilizer applied; residue returned and lime applied.

3.5 Determination of soil biology

Soil samples were taken at maize silking stage and just after bean harvesting from within the net plots of the sub-plots during LR2013 (the fourth season of experimentation). Three soil sub-samples were taken within 0 - 20 cm soil depth using sterilized trowel. The samples were put in a well labelled plastic bags placed in an ice box with ice to prevent them from heating up. The samples were immediately transferred to the laboratory for extraction and enumeration of bacteria, fungi and nematode populations.

3.5.1 Test for bacteria and fungi

Each soil sample was carefully mixed with a spatula in the sampling bottle. One gram of each sample was weighed on a sterile aluminium foil and immediately transferred into a test tube containing 9 ml of sterile distilled water. The mixture was gently homogenized using a vortex shaker for 30 seconds after which the soil suspension was aseptically diluted serially by adding 1 ml of the soil suspension to 9 ml test tube of sterile distilled water. Each time the solution was shaken and 1 ml of aliquots rapidly transferred to another 9 ml tube. Dilution ratios included: 10^0, 10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5} and 10^{-6}. 100 µl (0.1 ml) aliquot from dilution 10^{-6} was aseptically transferred to plates containing nutrient agar and potato dextrose agar for bacteria and fungi determination, respectively. The aliquot was then spread over the plate surface with a sterile glass rod in laboratory hood. The plates were inverted and incubated in the dark at 25^0 C for 72 hours after which counting of colony forming units (cfu)/ml of bacteria and fungi was done.

3.5.2 Test for nematodes

A 10 cm length rubber tubing was attached to the funnel stem and tubing clumped on. The funnel was mounted on ring stand, and then water was added to the funnel to two-thirds full and a wire-mesh basket placed on top to support tissue from falling off. The sieved soil sub samples were spread evenly on tissue paper whose edges were folded and the funnel was filled with water such that the water level was about 5 mm above wire-mesh. Water and soil were not allowed to lose contact during extraction period to prevent dehydration. Hence, water was added as needs be. The temperature was maintained between 22 - 25^{0}C which is usually conducive for nematode development (Barker, 1985). After 48 hours, nematodes were extracted by releasing 20 ml of water from stem of funnel into a counting dish. Counting of nematodes which were in their active stages was done using microscope.

3.6 Weeds control using glyphosate based herbicides

A weed control trial was conducted during SR2011, LR2012 and SR2012 on a randomized complete block design with four replicates. A given replicate had six plots, each measuring 3.75 m (6 maize rows) x 4.00 m. The treatments were made of three rates, 1.5, 2.5 and 3.0 liters ha^{-1} of Roundup Weather Max (RWMX) herbicide and one rate, 2.5 liters ha^{-1} of Roundup Turbo (RTB) (Table 3.3). Unweeded and conventionally tilled weed control systems were the fifth and sixth treatments, respectively. The six weed control treatments were randomized within and between blocks, and any two plots within a block were separated by a 1.0 m buffer zone path to guard treatments from spilling over between plots. Likewise any two replications were separated by a 2.0 m buffer zone for the same purpose.

Table 3.3: Treatments for glyphosate herbicides based trial

Treatment	Treatment description	
	Herbicide application rate (liters ha^{-1})	Active ingredient (g Glyphosate lit^{-1})
1. Roundup Weathermax (RWMX)	1.5	540
2. Roundup Weathermax (RWMX)	2.5	540
3. Roundup Weathermax (RWMX)	3.0	540
4. Roundup Turbo (RTB)	2.5	450
5. Un-weeded control	Not applicable	Not applicable
6. Conventional Weeding (CVT)	Not applicable	Not applicable

Glyphosate herbicide sprays were prepared and applied on the actively growing weeds every season. This was done approximately one week after the on-set of rains. The one week planting delay was meant to allow weeds to start growing actively after having gone through a period of *dormancy* observed during dry spells witnessed prior to the start of the rains. Plots were marked out in weedy experimental fields, planted with maize (*var.* DK 8031) spaced at 0.75 m (between rows) and 0.50 m (between hills) and maintain two plants per station. Three maize seeds were sowed in the weedy plots by carefully parting the weeds to access the ground and using a sharp pointed hand tool; pangas (machetes) to make planting holes while minimizing rigorous soil disturbance. Approximately 10 g of N_{23}:P_{23}:K_0 fertilizer material was applied in each of the seeding holes in all plots. The conventional tillage plots were prepared and planting holes made using folk jembes to achieve fine tilth for maize production. The glyphosate herbicide treatments were applied immediately (same day) after the crop wet sowing. Adequate amounts RTB and RWMX herbicide products were drowned from their containers using graduated syringe and transferring the contents into the mixing buckets. The herbicide/water solutions were thoroughly mixed before transferring the contents into a pre-calibrated CP3 15-liter Knapsack hand sprayers fitted with low volume herbicide application nozzle to deliver 200 - 250 liters ha^{-1} of the solutions. The solutions were then evenly applied on the weeds in all but hand weeded and un-weeded plots.

The first monitoring activity in the study was to identify the most common weed species at the site. Identification of weed species was done the same day of treatment application. The aim of the exercise was to get baseline information on weed species and biotypes within species which may ultimately compete with the crop if not managed. Later on as the study progressed, percent weed ground cover parameter was used to provide guidelines on how weeds were suppressed by the various herbicide products and rates. This was achieved by using a 1.0 m^2 quadrant randomly thrown in a given plot, followed by visually recording weed suppression status therein.

The activity was conducted three times in each season and the events recorded as: WS^1, WS^2 and WS^3 observed 1, 2 and 3 months after treatments application. The information collected from the three events was later worked out into percent weed suppression (% WS) using the following formula:

$$\%\mathrm{WS} = \frac{(\mathrm{Msut} - \mathrm{Mst})}{\mathrm{Msut}}\, x\ 100$$

Where: WS = Weeds suppression;

Msut = Mean score of unweeded treatment, and

Mst = Mean score of a treatment.

Weed vigour was another monitored parameter. Information on weed vigour was recorded at 0th, 70th and 120th day after the crop emergence or at treatments application, crop flowering stage and crop physiological maturity stage, respectively. This was achieved by visually observing the average weed vigour using scales of 1, 2, 3 and 4 representing “very low”, “low”, “medium” and “high” weed vigour, respectively. Plant phytotoxicity was also monitored where phytotoxicity was considered to be any plant deviation from normal morphological or physiological changes due to biotic, abiotic or artificial influence. Scorching of the whole or parts of the plant; de-colouration of plant parts from the normal green colour for a healthy plant; deformation or dwarfing of all or some plants within a given plot were the parameter looked upon to define phytotoxicity in the current study. Extra ordinary maturity of plants was also taken as phytotoxicity aspect. The assessments were conducted at 30th, 70th and 120th day after the crop emergence using scores of 1, 2, 3 and 4, denoting “low”, “medium”, “high” “very high” levels of phytotoxicity, respectfully.

Other field operations included thinning extra plants per station (leaving two plants per station,- equivalent to 53,333 plants ha^{-1}). The activity was done each season four days after the crop emergence. Insect pest control was also conducted in all plots, irrespective of the treatments. The plants were dusted with borer-cide (*Bulldock®* 0.05 GR) at the rate of 6.5 kg ha^{-1} to control stalk borers. Two hand weed control events were conducted each season only in conventionally tilled plots. Crop growth and grain yields data sets were appropriately collected as explained in section 3.8 of this study document.

The NB of different weed management methods was done using information inputs/operations costs and output prices collected during the time of experimentation. The information came from the local agro-stockiest(s), scientists, farmers and other partners involved in maize industry in Eastern Kenya. The exercise assumed that the average annual interest rate for money in a bank savings account as 12%; the herbicides were priced at KES 1,200 liters^{-1}. Assumptions related to this activity were that:

- The total cost for any herbicide was based on the rate(s) the product was applied at.
- Maize took six months while the bean took four months from sowing to marketing using farm-gate prices of KES 2,000 per ton of stovers collected from the farms by buyers using their own labour and transport; and that grains were sold at 3,000 and KES 6,000 per 90 kg bag for maize and bean, respectively.
- The number of empty bags needed to hold the grains was based on the total grain yield per treatment.
- The grains were harvested, packed and sold out immediately after harvest. Thus, no storage cost to incurred by the farmer.

The NB was finally calculated using the following formula:

$$NB = TC - TR$$

In the formula,

NB = net-benefits
TC = total costs
TR = total revenue

3.7 Crop culture

3.7.1 Test crops and planting densities

The test crops were maize (*var*. DK 8031) and common bean (Embean-14 or *Mwende)* (Figure 3.2). The maize variety was a commercial medium maturity hybrid variety taking approximately 130 days from emergence to physiological maturity in medium altitude (1400 m asl) areas. The variety was has a potential grain yield of 6.5 t ha^{-1} season^{-1} when the seasonal rainfall is adequate and fairly distributed. This is also when appropriate agronomic practices are adhered to during the crop growing period. The bean variety was a determinate bush bean with a potential grain yield of 2.5 t ha^{-1} season^{-1} in upper midland zones. The variety takes approximately 95 days from emergence to physiological maturity.

Figure 3.2: Maize (var. DK 8031) cobs and bean (var. Embean-14) seeds

The trial was rain-fed and seeding of maize and bean was done every season at the on-set of the rains. Sole maize was spaced at 75 cm (between rows) and 50 cm (within rows) (Figure 3.3). Three seeds were sown per hole and thinned later to 2 plants per hole at approximately 7 days after the crop emergence to give 53,333 plants ha^{-1} season^{-1} (Appendix 3.14). The bean spacing depended on whether the crop was planted sole or in an intercrop with maize. Irrespective of the tillage method, sole bean was spaced at 50 cm (between rows) and 15 cm (within rows) while maintaining 1 plant per station towards attaining 133,333 bean plants ha^{-1} season^{-1} (Figure 3.4). In case of maize-bean intercrop, maize was planted at the same spacing or density as in the sole maize configuration (Figure 3.3), then, 1 row of bean was planted in-between the 2 maize rows at 10 cm between holes. One plant per station was maintained to attain 133,333 bean plants ha^{-1} season^{-1} (Figure 3.5).

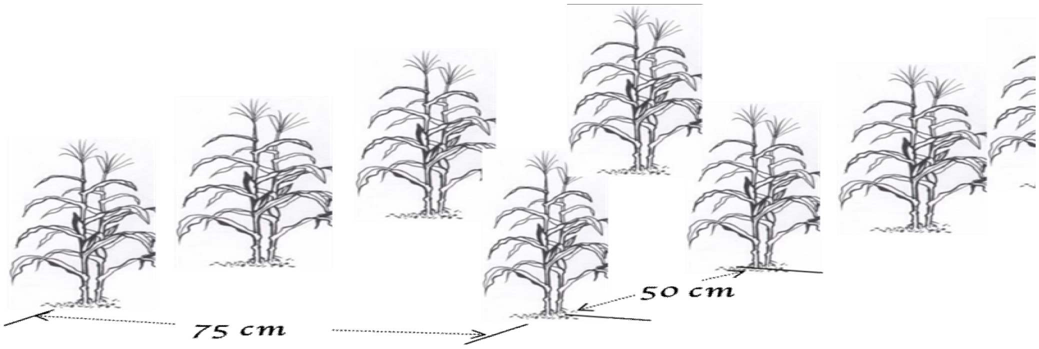

Figure 3.3: Layout for pure maize spacing

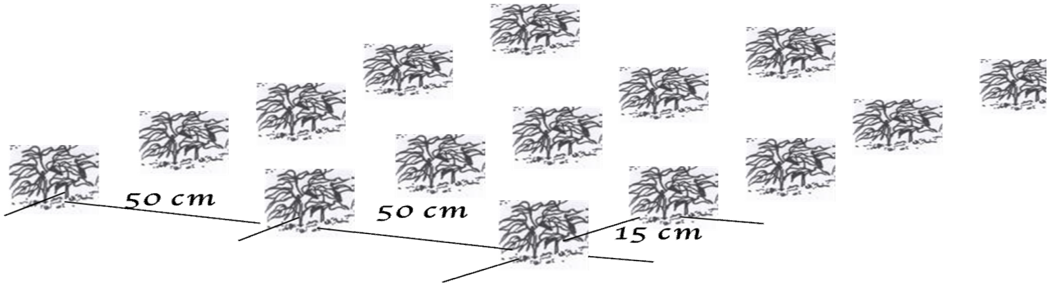

Figure 3.4: Layout for pure bean spacing

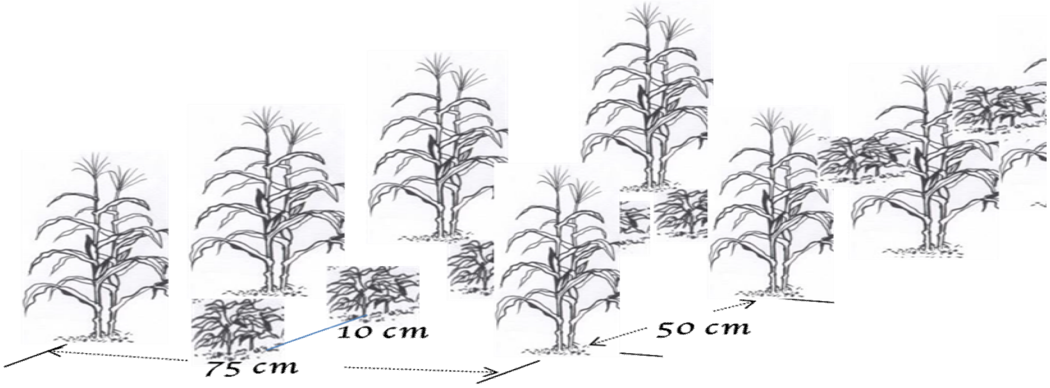

Figure 3.5: Layout for maize-bean intercrop spacing

The same intercrop configuration was maintained in furrows/ridges tillage system where the maize was planted on the lower parts of the structure (furrows) spaced at

75 cm apart. The beans were then planted 10 cm apart on the raised parts of the structure (ridges). Thus, to ensure no confounding effects due to population differences, the two crops' populations in both sole and intercrop arrangements were maintained the same.

3.7.3 Crop fertility inputs

Irrespective of the applied tillage method or cropping system, P nutrient was basal applied at sowing. The source of P nutrient was triple super phosphate (TSP) (N_0:P_{46}) fertilizer for plots where maize and bean were grown as pure stand. The fertilizer, N_{23}:P_{23} was the source of P and N for sole maize that was to be applied with both nutrients applied at the rate of 60 kg ha^{-1}. Diammonium phosphate (DAP) (N_{18}:P_{46}) provided P and N nutrients to bean crop at the rate of 51 and 20 kg ha^{-1}, respectively (Appendix 3.15).

3.7.4 Herbicides weed control

With respect to the CA practices, weeds in maize and bean crops were controlled as needs be. For example, weeds control in zero tillage plots was done by use of post-emergence glyphosate (Roundup Turbo) based herbicide at the rate of 2.5 liters ha^{-1} to actively growing weeds. This was done three days after the on-set of the rains and before germination of the crop. Afterward, a pre-emergence herbicide, Dual-Gold *(Metolachlor 960 g lit^{-1})* was applied at the rate of 1.5 liters ha^{-1}. The product's spray was applied on wet soil before the emergence of both the crops and weeds. While Roundup was meant to kill weeds already in the field, Dual-Gold was meant to kill emerging weeds at their juvenile stage. Later on in each season, a post-emergence herbicide, Basagran *(Bentazon)* was applied at the rate of 1.5 liters ha^{-1} on the actively growing weeds in already established crops. Application of Basagran herbicide was meant to kill weeds that came up later in the seasons after the emergence of the crops. According to Miri et al., (2014), legume flower buds damage occurs from application of post-emergence herbicides such the Basagran. Thus, the Basagran herbicide was applied before beans started flowering. Application of the three herbicides was done using pre-calibrated CP3 15-liter Knapsack hand sprayers fitted with low volume herbicide application nozzle to deliver 200 - 250 liters ha^{-1} of the herbicide/water solutions.

3.7.5 Pests control in maize and bean crops

Maize stalk borer (*Chilo* spp.) was the major insect pest in maize. The borers start invading maize plants immediately after the crop emergence and can cause up to 40% yield loss if not controlled (Mulaa, 1995; Pingali, 2001). The pest was controlled using Bulldock (0.05 GR) insecticide (*Beta-cyfluthrin)* at the rate of 6.5 kg ha^{-1}. The product was applied every season 30 days after the crop emergence. Aphid *(Aphis spp.)*, leaf miner *(Liriomyza trifolii)* and thrips *(Thysanoptera spp.)* were the major insect pests in bean crop and were controlled by applying *Dimethoate (Organophosphate)* insecticide sprays fortnightly at the rate of 1.0 litre ha^{-1}.

3.7.6 Crop residues chemical composition

Except for the first season, maize and bean residues from the previous season were applied on the CA based treatments every season after the crops' harvests. As indicated in Table 3.4, stover samples were taken each season and their chemical composition established in the laboratories.

Table 3.4: Chemical composition of maize residues

Season	Nitrogen (%)	Organic carbon (%)	C:N Ratio	Phosphorus (%)	Potassium (%)
SR2011	N/A	N/A	N/A	N/A	N/A
LR2012	0.44	48.86	111.05	0.02	0.32
SR2012	0.49	47.67	97.29	0.03	0.49
LR2013	0.51	48.43	95.00	0.03	0.48
Mean	0.47	48.32	102.81	0.03	0.43

SR = short rains; LR = long rains; N/A = not applicable

3.8 Maize yields under conservation agriculture

Maize response to the effect of conservation agriculture (CA) practices was determined each season by monitoring both growth and grain yields. The growth parameters; germination (emergence) stand count was determined by physically counting all maize plants at 10th day after the crop emergence (DAE). The results were translated into the percentages of the expected plant population per hectare. Similarly, harvest plant stand count was also determined each season by physically counting all plants at crop harvesting time. The crop was closely monitored to establish the number of days to 50% tasseling as explained by Ihsan et al., (2005). Intensity of chlorophyll on leaves was also determined using SPAD-502Plus chlorophyll reader. The SPAD reading events were conducted each season at 45th, 65th, 85th, 100th and 120 DAE. Care was taken not to sample very old, very young or damaged leaves in a plant. The crop was monitored closely to establish the number of days from DAE to 50% physiological maturity. This was determined by general crop visual observation and also dislodging the kernels to show black spots at the point where the kernels are attached to the cob as explained by Kumar et al., (2005).

Apart from the growth, maize yield parameters were each season monitored from every plot. Five maize plants were randomly sampled from every net plot and measurements for height (m) taken where an individual plant's height was measured from the ground level to the tip of uppermost leaf or tassel. The results were averaged to give average plant height per plot and later on per treatment. As part of the yield, the average number of plants per plot and cobs per plant were determined at harvesting time. This was achieved by physically counting the number of plants per plot or cobs per plant within the net plot. The results were later tabulated into the number of cobs ha^{-1}. In addition, the average cob length was monitored by randomly picking 10 cobs from a given net plot and recording their lengths in centimeters. The results were later averaged to provide the mean cob length per treatment. Maize harvesting was done early enough at physiological maturity to avoid field yield loss. This is the time when the maize shoot biomass was determined by weighing stalks minus grains in all net plots. A sample of 5 stalks was taken and chopped into small pieces and weighed to provide "stalk wet weight" per plot. Each sample was dried for 48 hours at 105^0 C to constant weight to provide "stalk dry weight". The crop total shoot biomass per hectare was calculated using the following formula:

$$\text{Maize biomass (t ha}^{-1}) = \frac{10{,}000\ \text{m}^2 \text{ x net plot dry biomass weight (kg)}}{\text{Net plot area (m}^2)} / 100$$

After the crop harvest, maize cobs were dried in the sun before grain shelling was done for all cobs from a given net plot. After the shelling the grains were dried in the oven at 60^0 C for 48 hours to adjust the grain moisture content to 12.5%. The crop total grain per hectare was calculated using the following formula:

$$\text{Maize grain yield (t ha}^{-1}) = \frac{10{,}000\ \text{m}^2 \text{ x net plot dry grains weight (kg)}}{\text{Net plot area (m}^2)} / 100$$

Apart from the crop growth and grain yields data sets, further information were compiled to assist in calculating the net-benefits (NB) of growing maize and bean under conservation agriculture practices. The exercise had the following assumptions: the average annual interest rate for money in a bank savings account as 12%; the herbicides were bought at KES 1,200 liters^{-1}. the total cost of any herbicide was based on the rate(s) the product was applied at; maize crop took six months while the bean took four months from sowing time; marketing using farm-gate prices of KES 2,000 t^{-1} stovers collected from the farms by buyers using their own labour and transport; the shelled grains were sold at KES. 3,000 and KES 6,000 per 90 kg bag of dry maize and bean grains, respectively; the number of empty bags needed to hold the maize or bean grains was dictated by the total grain yield per treatment; the grains were harvested, packed and sold out immediately after harvest, - thus, no storage cost incurred by the farmer. The NB was finally calculated using the following formula:

$$\text{Net-benefit} = \text{Total cost} - \text{Total revenue}$$

3.9 Bean yields under conservation agriculture practices

Common bean response to the effect of conservation agriculture practices was determined each season by monitoring growth and yield parameters. Emergence plant stand count was the first bean growth factor to be measured by physically counting all plants at 10th DAE. The results were translated into the percentages of the expected (seeded) plant population per hectare. Likewise the number of plants at harvest was determined every season by physically counting all bean plants within the net plot at the time crop harvesting. The results were translated into the percentage of the expected (seeded) plant population per hectare.

The crop was monitored closely to establish days from DAE to 50% flowering. The average number of fertile flowers per plant is also another parameter collected and synthesized. This was achieved by randomly picking five plants within a net plot, counting and averaging the total number of fertile flowers. Leaf chlorophyll intensity was also determined. This was achieved by use of a SPAD-502Plus chlorophyll reader where four readings were taken at 15th, 35th, 45th and 60th DAE. Days to bean 50% physiological maturity was further established when 50% of the pods had turned yellow.

The bean fertile root nodules were also monitored every season. This was achieved by randomly and gently digging up within the net plots three plants at 15th, 35th, 45th and 60th DAE. The exercise was conducted after the rains or when the soil was moist. The dug out plants had their roots washed with clean tap water before counting and recording the number of fertile nodules that were generally pinkish in colour. Bean plant height was also determined at the crop harvesting time. This is where five plants per net plot were randomly sampled and their heights taken. An individual plant’s height was measured from the ground level to the tip of uppermost leaf or tendril.

The average number of pods per plant was another yield component monitored every season at harvesting time. This was achieved by counting the number of pods in 10 randomly selected plants. Bean shoot biomass yield parameter was also determined at harvesting time. All plants in a given net plot were handpicked and threshed to separate the residues from grains. A sample of 20 stalks was taken and chopped into small pieces and weighed to provide “stalk wet weight” per plot. Each sample was dried for 48 hours at 105^0 C to provide “stalk dry weight”. The bean total shoot biomass per hectare was calculated using the following formula:

$$\text{Bean biomass (t ha}^{-1}\text{)} = \frac{10{,}000\ \text{m}^2 \text{ x net plot dry biomass weight (kg)}}{\text{Net plot area (m}^2\text{)}} / 100$$

Bean grain yield was determined at harvesting time. All plants in a given net plot were handpicked threshed to separate residues from grains. The grains were dried in the sun to approximately 13.0% MC before taking the final grain weight (t ha^{-1}) per plot. The following formula was used:

$$\text{Bean grain yield (t ha}^{-1}\text{)} = \frac{10{,}000\ \text{m}^2 \text{ x net plot dry grains weight (kg)}}{\text{Net plot area (m}^2\text{)}} / 100$$

3.10 Soil water and water use efficiency

The current study adhered to the right planting procedures, germplasms selection, intercropping maize-bean configuration, tillage methods, soil surface residue retention; weeds control and fertilizer use. At harvest, maize and bean were harvested and grain yield (kg ha^{-1}) measured. The total effective rainfall was obtained from Embu Meteorological Station, located on the South Eastern slopes of Mt. Kenya at 1450 m asl and $00^0$33.18’S: $037^0$53.27’E coordinates. The crop’s WUE was calculated as: the total grain yield produced from each mm of rainfall using the following formula:

$$\text{WUE} = \frac{\text{Total crop yield (kg DM ha}^{-1}\text{)}}{\text{Total effective rainfall}}$$

3.11 Economics of conservation agriculture practices

The economic benefits of conservation agriculture (CA) practices were determined by calculating net-benefits (NB) for the various tillage systems. This was achieved by analyzing inputs/operational costs and output prices for conventional tillage (CVT) and the CA based farming practices. The information was collected from local agri-stockists, scientists and farmers in Eastern Kenya. The information was tabulated in relation to the monetary difference between the total revenue and total variable costs per hectare. The unit of costing was the Kenya Shilling (KES) and was converted to USD. On average, KES 85.00 was equivalent to USD 1.00 at the time of the study.

The exercise assumed that the test crop maize (DK 8031) and bean (Embean 14) varieties, respectively, took 6 and 4 months from seeding to marketing using farm-gate prices; the maize and bean grains were harvested and packaged in 90 kg bag size; the number of empty bags required to hold the grains was dictated by the total grain yield (kg) per treatment; the maize and bean stovers were sold immediately after crop harvesting at an average of KES 2000 t^{-1} $season^{-1}$ and that the buyers collected the stovers from the farm using their own labour and transport; a 90 kg bag of maize and bean grains were sold at KES 3000.00 and KES 6000.00, respectively. Other assumptions were that the average cost of labour for all operations was KES 350.00 per man-day (8 working hours for a mature person); the average cost of all herbicides used in the study was KES 1200 $litre^{-1}$. The costing of herbicides was only done on CA based treatments. The following formula was used to calculate the NB for the various treatments:

NB = TC – TR;

Where; NB = Net-benefit

TC = Total cost (acquired from variable cost of inputs/operations for maize and bean growing under each treatments)

TR = Total revenue (acquired from stover and grain sales at the end of the season).

3.12 Application of APSIM model in conservation Agriculture

Weather data sets (rainfall, temperatures, radiation and evaporation) covering the four seasons of experimentation were collected from Embu Meteorological Station and saved in APSIM excel spread-sheet format (Appendix 3.16). The crop varieties, soil and field management practices were used to initialize and run the model. The initial soil water (ISW) content was set at lower limit (LL). This was equivalent to zero plant available water (PAW = 0 mm). Initial mineral-N was 10 kg available N ha^{-1} for 1.2 m soil depth with 7 kg as NO_3^- and 3 kg as NH_4^+. The measured soil inputs were added to an existing APSIM soil description with water holding capacity (PAWC) changing from 164 to 150 mm. The soil C:N ratio was set at 14, run-off curve number was 80 and soil evaporation coefficients of 3 mm and 6 mm day^{-1} for the first and second stage of evaporation, respectively. The model was run for four seasons without weed competition. The residual soil moisture and nutrient balances were simulated with potential cumulative effects on crop growth and grain yield in subsequent seasons.

3.12 Data analysis

Data was subjected to analysis of variance (ANOVA) using statistical Analysis system (SAS, 2002). Differences between treatment means was separated using LSD at 5% level of significance. Net-benefits were computed to determine profitability of maize-bean intensification under the CA practices. Comparisons were also made for field observed crop grain yields with simulations from APSIM computer model.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Effect of conservation agriculture on soil properties

The section highlight dynamics of soil chemical and physical properties after the four seasons of application of conventional (CVT) and conservation agriculture (CA) based farming practices.

4.1.1 Soil pH

After the four seasons of practicing CA farming methods, the soil pH averaged at 4.9, against 4.8 (1:3 soil:water) determined in October 2011 at the time of trial establishment. The pH level was still within the strong acid range (Kisinyo et al., 2014). The pH was only slightly improved by application of both CVT and CA farming methods during the four seasons of continuous cropping (Figure 4.1).

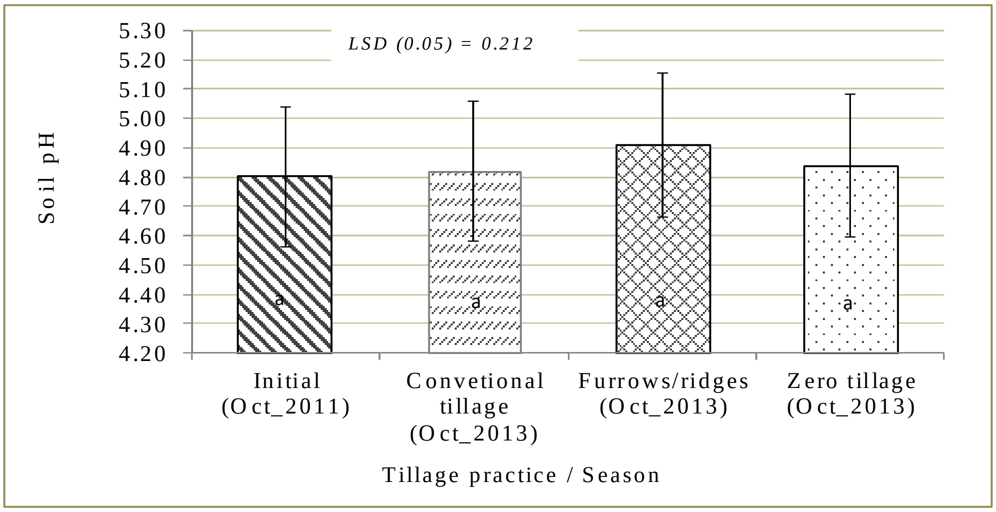

Figure 4.1: Initial and after the study soil pH values

The soil acidic condition was attributed to past continuous cultivation that was characterized by removal of SOM via crop and residues harvests from cropland. In addition, the research station cropland was on continuous CVT cultivation which was further characterized by application of acid forming fertilizers, mainly Diammonium

Phosphate (DAP). According to Sombrero & Benito, (2010), the almost 0.1 increase in pH value may have been attributed to factors such as: (i) use of non-acidifying fertilizer ($N_{23}P_{23}$) for maize and limited amount of DAP ($N_{18}P_{46}$) fertilizer for bean in the CA treatments; (ii) soil organic matter improvement through crop residues retention on the soil surface. The mulches were expected to decompose and mineralize to provide extra organic carbon for pH buffering as explained by Kisinyo et al., (2014). Significantly higher pH values (5.0 – 5.6) may be expected to come forth in longer-term due to non-application of acidifying fertilizers and SOM build up as described by Sombrero & Benito, (2010).

4.1.2 Soil texture and bulk density

Comparing the observed initial 1.2 kg m^{-3} bulk density (BD) from 0 – 15 soil depth, the value averaged at 1.0 kg m^{-3} due to application of both the CVT and CA based tillage practices (FR and ZT) (Figure 4.2). The initial BD reading significantly ($p \leq 0.05$) differed from an average of 1.08 kg m^{-3}) recorded from the FR treatment. Otherwise the initial BD did not significantly differ from those ZT (1.05 kg m^{-3}) and CVT (1.02 kg m^{-3}).

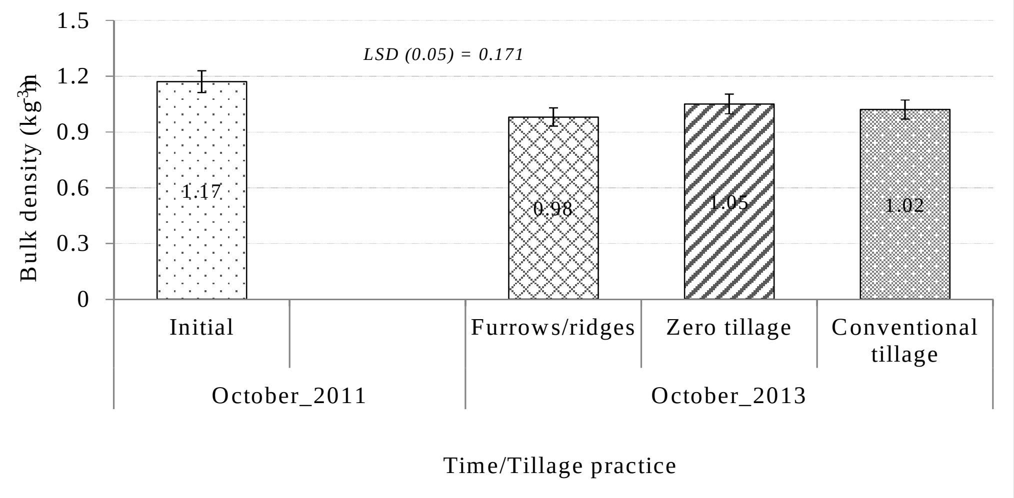

Figure 4.2: Effect of tillage practices on average soil bulk density

The low BD value under the FR treatment was attributed to presence of crop residues on the soil surface that might have conserved some moisture that kept the soil more moist and porous throughout the four seasons of experimentation. This could also have been caused by soil disturbance during making and repairing furrows/ridges. The non-reduction of BD under the CVT system related to report by McGarry, (2001) that the soil compaction leading to high BD is the most serious environmental problem caused by conventional agriculture, but the most difficult type of degradation to locate on arable lands since it may show no clear marks on the soil surface.

4.1.3 Soil organic carbon and total organic nitrogen

According to Jobba´gy & Jackson (2000), both the soil organic carbon (SOC) and total soil nitrogen (TSN) are related. The two parameters were first determined in October 2011 at the start of the experimentation and in September/October 2013 (end of experimentation) within 0 - 15 cm soil depth. The initial SOC and TSN averaged at 1.99 and 2.00%, respectively (Tables 4.1). The showed increase corroborate with the finding by Kassam et al., (2009) that residue retention on the soil surface has greater benefit on SOM build up.

Table 4.1: Effect of cropping and residue management on soil carbon and nitrogen

Cropping system	Residue management	Soil organic carbon (SOC)	Total soil nitrogen (TSN)
Maize-bean	Residue retained	1.99	0.20
Maize-bean	Residue removed	1.97	0.20
Sole maize	Residue retained	1.99	0.20
Sole maize	Residue removed	1.94	0.20
Sole bean	Residue retained	1.99	0.20
Sole bean	Residue removed	1.97	0.20
Mean	-	1.97	0.20
CV (%)	-	8.42	0.08
LSD (0.05)	-	0.23	8.22

LSD = least significant difference; CV = coefficient of variation.

The table indicates that SOC and TSN were not significantly altered by interactions of cropping systems and the methods of residue management. Reference to furrows/ridges, SOC averaged at 1.97% while TSN averaged at 0.20% irrespective of cropping system or residue management method. Although not significantly different, the SOC was higher (1.99%) under all cropping systems that had crop residue returned. The deployed tillage methods (FR, ZT and CVT) did not have impact of either SOC or TSN.

4.1.4 Extractable soil phosphorus concentration

The average available phosphorus concentration in October 2013 for the three tillage treatments was significantly ($p \leq 0.05$) higher at 16.6 mg kg^{-1} compared to 4.00 mg kg^{-1} observed at the beginning of the CA based trials in October 2011 (Table 4.2).

Table 4.2: Effect of tillage methods on soil P after four seasons of testing

Treatment	Season measured	P (mg kg^{-1})
Baseline (control)	Oct. 2011	4.0a
Conventional tillage	Oct. 2013	14.8a
Furrows/ridges	Oct. 2013	32.5b
Zero tillage	Oct. 2013	15.1a
Mean	-	16.6
LSD (0.05)	-	17.65

Tillage methods had positive effect on soil P builds up after the four seasons of experimentation. This is where the FR recorded significantly ($p \leq 0.05$) higher (32.5 mg kg^{-1}) P concentration compared to 15.1 and 14.8 mg kg^{-1} from ZT and CVT, respectively. Higher seasonal P application at sowing was attributed to the higher P concentration in maize-bean intercropping system compared to sole maize and sole bean that was receiving 60 and 51 kg P ha^{-1}, respectively.

Like the tillage methods, cropping systems significantly affected P concentration in the soil after the four seasons of experimentation. Significantly higher (24.6 mg kg^{-1}) P concentration was observed under the maize-bean intercrop compared to (4.0 mg kg^{-1}) observed at the time of trial establishment (Figure 4.3). The P concentration from the intercrop was also significantly ($p \leq 0.05$) higher than 19.7 and 12.9 mg kg^{-1} observed from sole maize and sole bean, respectively. Table 3.4 in section 3.7.6 shows that the average chemical composition of maize stovers seasonally applied on the CA plots had N, OC, P and K accounting for 0.47, 48.32, 0.03 and 0.43%, respectively. The amount of residue applied P was therefore too low, meaning that the main sources of the observed soil P at the end of the four seasons of experimentation could have been from soil P-pools (4.00 mg kg^{-1} based on the initial soil characterization) and from residual P from the amount applied to maize and bean crops over the four seasons.

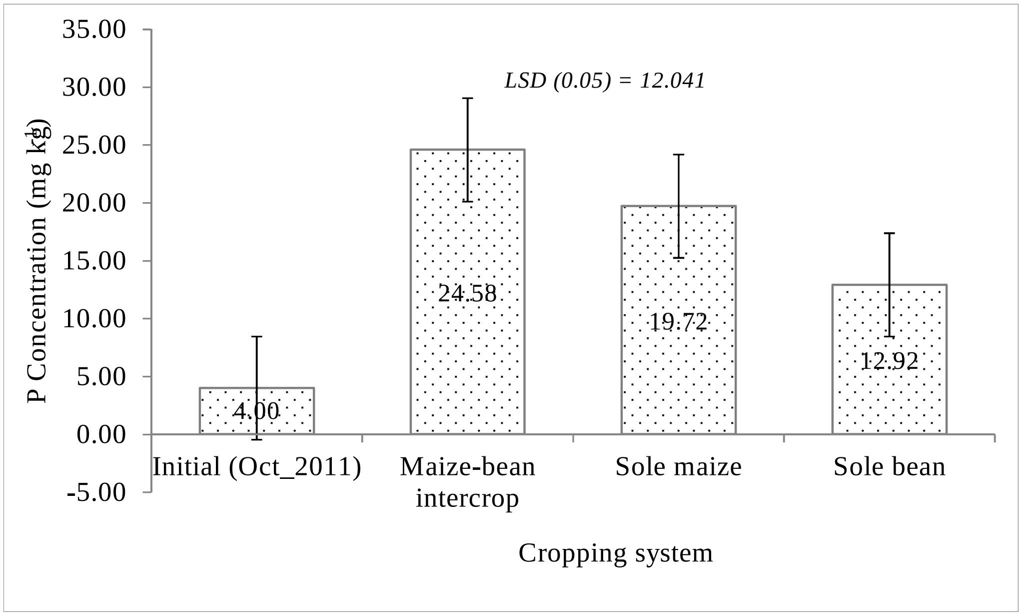

Figure 4.3: Effect of cropping systems on soil phosphorus

Higher seasonal P application at sowing was led to the higher P concentration in maize-bean intercropping system compared to sole maize and sole bean that receiving 60 and 51 kg P ha^{-1}, respectively. Nair, et al., (2010) notes that a range of 16 - 20 mg kg^{-1}available-P is ideal amounts for maize and legumes production.

4.2 Effect of conservation agriculture on maize performance

The section highlights the effect of conservation agriculture practices on maize growth and grain yields after four seasons of application of conventional (CVT) and conservation agriculture (CA) based farming methods.

4.2.1 Rainfall amount and distribution

For the four seasons, the crops were planted at the onsets of the rainy seasons. This is when adequate rains (over 50 mm) to effect germination and emergence of the crop had fallen in the region. The seasonal rainfall varied between seasons. For example, season 1 (SR2011) and season 2 (LR 2013) recorded on average the lowest at 562.3 and 460 mm effective rainfall, respectively. The other seasons (LR2012 and SR2012) had between 800 and 820 mm of rainfall (Table 4.3).

Table 4.3: Monthly rainfall and temperatures during the four seasons of testing

Measured Parameter	Season				Mean
	Short Rains 2011	Long rains 2012	Short rains 2012	Long rains 2013	
Total Rainfall (mm)	562.3	822.1	802.6	460.4	661.9
Average maximum temperature (^{0}C)	25.6	24.3	25.3	24.3	24.9
Average minimum temperature (^{0}C)	14.5	14.1	14.0	15.5	14.6

According to Jéan du Plessis (2003), maize needs between 450 to 600 mm of water per season to complete the growth cycle. Depending on the soil type and soil moisture, crop failure would be expected if less than 300 mm of in-crop rain were received (Belfield & Brown 2008). Based on the above argument, the effective rainfall amounts during the four seasons of experimentation were sufficient to support maize and bean production. However, the amounts were generally poorly distributed within the seasons, especially in SR2011 that had precipitation only during the first two months of crop sowing.

4.2.2 Maize growth yields

One of the recommendations in maize production in Eastern Kenya is to plant the crop just before or at the on-set of rains (FURP, 1994; Nyangena et al., 2014). In the current study, maize and bean were planted every season after adequate (over 50 mm) or effective rainfall had been received at the site. The seeds took between 7 to 8 days to emerge (Table 4.4). Significantly higher plant stand count of 77.2 and 80.6% were observed in SR2012 and LR2013, respectively. The seeds sown under ZT took an average of 7 days while those under the CVT and FR took 8 days to emerge. The one day difference in crop emergence might have been caused by deep sowing of seeds in the CVT or that the residues left on the soil surface lowered soil temperature in CVT and FR, respectively.

In a related study, Barut & Celik, (2010) observes that tillage system has a significant impact on plant emergence and plant stand of maize and wheat. In their study it was found that the plant stand uniformity was better in conventional tillage than in no-till which registered the lowest establishment and also crop yield. In all seasons, higher crop establishment percentage was observed under FR compared to ZT. The finding corroborates with that by Belfield and Brown (2008) who noted that maize establishes better in CA systems where stubble are retained on the soil surface, and that the adapted tillage practice is able to capture and retain sufficient moisture longer in the soil for crop use. Their argument further notes that the stubble provides good microclimate for crop establishment. Such a system allows greater rainfall infiltration for more water storage in the soil profile for crop use throughout the growing season (Belfield and Brown, 2008). Although not significantly different, CVT provided relatively higher plant germination percentage compared to ZT across the seasons. This was attributed to the effect of soil tilling that may have facilitated faster roots development under the CVT compared to ZT for better soil water and nutrients usage during the early stages of the seasons. The figure further shows that the overall number of leaves per plant determined after the crop anthesis stage averaged at 13.5 with the FR tillage system provided an increasing trends from season 1 (SR2011) season 4 (LR2013). As reported by Jéan du Plessis (2003), maize plants have between 8 to 20 leaves depending on the variety and environment factors such as rainfall, temperatures and the available soil nutrients.

Table 4.4: Maize growth yields in relation to seasons and tillage practices

Season	Tillage practice	Days to 50% emergence	Percent emergence stand count	Number of leaves per plant	Leaf area index (HI)
Short rains 2011	Furrows/ridges	7.7b	74.1a	10.9b	5.0a
	Zero tillage	7.5a	69.0a	11.7a	4.1b
	Conventional tillage	8.0b	68.0a	11.8a	5.0a
	Mean	7.6	70.1	11.4	4.7
	LSD (0.05)	0.281	21.301	0.510	0.311
Long rains 2012	Furrows/ridges	8.2a	95.6a	12.3a	5.0a
	Zero tillage	7.3b	95.5a	11.9b	4.3b
	Conventional tillage	8.3a	93.4a	12.1a	5.1a
	Mean	8.00	94.8	12.0	4.8
	LSD (0.05)	0.010	0.474	0.365	0.003
Short rains 2012	Furrows/ridges	8.0b	66.8a	15.8a	7.4a
	Zero tillage	7.6c	77.2b	15.2a	6.7b
	Conventional tillage	8.4a	72.7c	15.5a	7.6a
	Mean	8.0	74.50	15.5	7.2
	LSD (0.05)	0.311	3.452	0.771	0.626
Long rains 2013	Furrows/ridges	7.7a	78.8a	15.5a	7.8a
	Zero tillage	7.1b	80.6b	14.8b	7.0b
	Conventional tillage	7.8a	78.0a	15.1a	7.9a
	Mean	7.5	79.8	15.1	7.6
	LSD (0.05)	0.281	2.409	0.610	0.313

Means within the same column with the same letter are not significantly different ($p \leq 0.05$). CV = coefficient of variation; LSD = least significant difference.

The observed number of leaves was therefore within the Jéan du Plessis (2003) range. The leaf area index (LAI) calculated using the leaf length and diameter values, had similar trends as the number of leaves per plant. As suggested by Wall (2007), the observed increasing trends in the maize growth parameters are some of the positive benefits accrued from short to medium-term adoption of CA principles and practices.

The shortest, 1.2 and 1.0 m maize heights were observed during SR2011 and LR2012 seasons, respectively (Table 4.5). The average maize plant heights for the three seasons of experimentation were not significantly taller than those under the CVT control plots. These results confirmed work by Nandwa (1995) who registered increased maize height under CA plots when compared to CVT treatment during the last two out of the six consecutive seasons of experimentation in similar soils in the Central highlands of Kenya. According to Giller et al., (2009), crop growth benefits are better defined from long-term (above 10 years of continuous cropping) than in short periods of CA implementation as is the case of the current study. Days from emergence to flowering (tasselling) in maize averaged between 66 and 69 days, respectively. There were no significant differences in days to flowering among the tillage methods or cropping seasons. However, maize grown during LR2013 season that had adequate and well distributed rainfall flowered 2 days earlier compared to other seasons.

The tendency for maize to flower early was an indication of lack of moisture stress as suggested by Uhart & Andrede, (1995) in their study to investigate the effect of N availability on crop development. They further found that N deficiencies delayed tasselling and silking of maize relative to the control. Maize physiological maturity is reached when a ‘black layer’ is formed at the tip of each kernel, where cells die and block further starch accumulation into the kernel (Belfield & Brown, 2008). The current study recorded an average of 126 physiological maturity days for DK 8031. The parameter differed ($p \leq 0.05$) significantly due to tillage practices in SR2011 and LR2012 where the ZT recorded 124 days followed by FR with 123 days to physiological maturity. These values were significantly (p≤0.05) higher than 122 days from CVT practice in SR2011 season.

Table 4.5: Effect of tillage practices on maize performance in different seasons

Season	Tillage practice	Plant height (m) at harvest	Days 50% tasseling	Days to 50% physiological maturity
Short rains 2011	Furrows/ridges	1.1a	70.1a	123.0ab
	Zero tillage	1.2a	69.1b	124.0a
	Conventional tillage	1.2a	69.2b	122.1b
	Mean	1.2	69.0	123.2
	LSD (0.05)	0.138	1.101	1.501
Long rains 2012	Furrows/ridges	1.1a	69.0a	121.2b
	Zero tillage	1.0b	69.0a	120.8c
	Conventional tillage	1.1a	69.0a	122.7a
	Mean	1.0	69.1	122.0
	LSD (0.05)	0.023	0.339	0.001
Short rains 2012	Furrows/ridges	1.7a	66.1ab	133.7a
	Zero tillage	1.6b	66.7a	134.5a
	Conventional tillage	1.7a	65.9b	133.8a
	Mean	1.7	66.2	134.0
	LSD (0.05)	0.070	0.756	1.326
Long rains 2013	Furrows/ridges	1.3a	68.4a	126.1a
	Zero tillage	1.3a	68.4a	126.4a
	Conventional tillage	1.3a	68.2a	126.2a
	Mean	1.3	68.3	126.3
	LSD (0.05)	0.077	0.732	0.943

Means within the same column with the same letter are not significantly different (p≤0.05). CV = coefficient of variation; LSD = least significant difference.

The tendency of plants under the CA treatments, exceptionally under the FR tillage system to mature late was associated to water harvesting in FR system that kept the plant drawing soil moisture for longer days compared to control that had crops maturing earlier due to dry spells witnessed at the later part of the season. Maize root length determined two weeks after the crop anthesis was low, ranging from 22 cm in SR2011 to 38 cm in LR2013 at the end of the trial under the ZT practice (Figure 4.4).

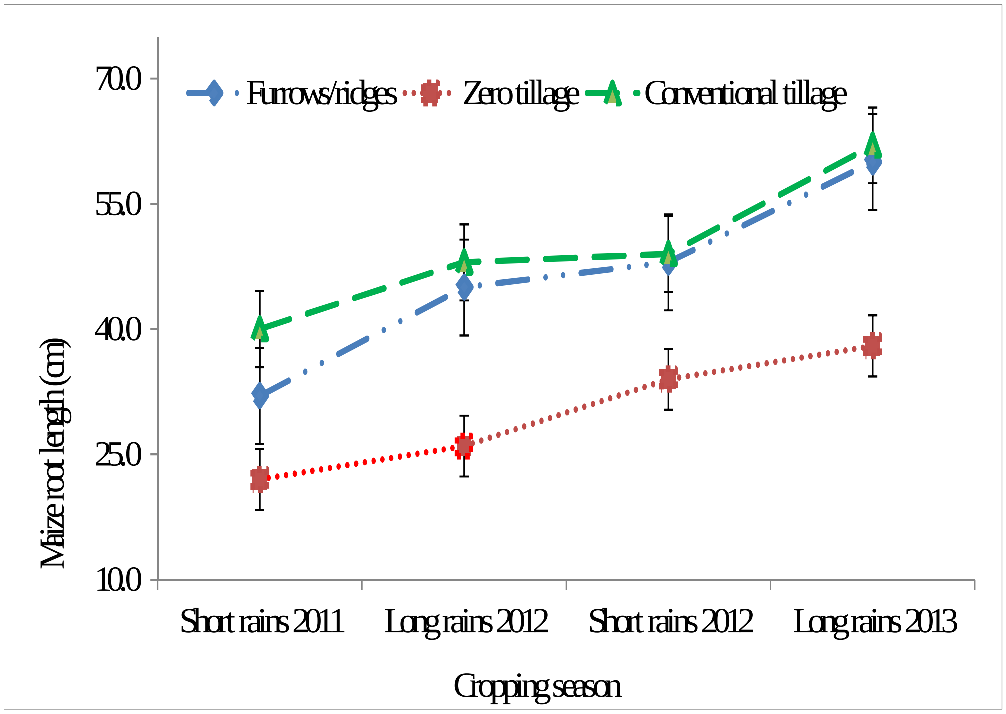

Figure 4.4: Effect of tillage practices on maize root length in different seasons

Ideally the maize length would grow to 1.0 m soil depth in humid areas (Yang et al., 2010). The poor maize roots development under ZT treatments was associated to mainly undisturbed and compacted clay loam soil whose bulk density at the top horizon (0 - 15 cm) averaged at 1.2 kg m^{-3} against less than 1.0 kg m^{-3} in the lower 15 - 30 cm soil horizon. There was no clear difference between root length due to the effect of CVT and FR tillage systems over the four seasons of experimentation. The general increase of root lengths was observed under all tillage methods from the first to the last season of continuous cropping. This suggested that there are increased benefits resulting from practicing conservation agriculture tillage methods.

4.2.3 Maize number of cobs per plant and cob length

The low number of cobs during the first season of experimentation was attributed to poorly distributed seasonal rainfall. However, the CA based treatments, particularly the FR treatment, exhibited relatively higher number of cobs in all seasons. This may have been attributed to better moisture retention and improved water use efficiency (WUE) by maize crop under this water harvesting tillage system. The ZT did not have the same effect as the FR treatment. This was perhaps because the ZT did not have furrow structures to facilitate water retention for crop use during cessation of seasonal rains. The average cob length was 11.8 cm across the four seasons of experimentation (Table 4.6).

Table 4.6: Effect of tillage practices on average maize cob length

Tillage practice	Cob length (cm)			
	Short rains 2011	Long rains 2012	Short rains 2012	Long rains 2013
Furrows/ ridges	12.4a	9.4a	13.9a	12.1a
Zero tillage	11.7a	9.8a	14.0a	11.8b
Conventional tillage	11.5a	9.9a	14.3a	12.0a
Mean	11.5	9.7	14.1	12.0
CV%	5.31	1.61	8.83	3.62
LSD (0.05)	13.801	0.711	0.720	0.212

Means within the same column with the same letter are not significantly different ($p \leq 0.05$). CV = coefficient of variation; LSD = least significant difference.

Although not significantly different, the CA based tillage treatment, FR had the highest (12.0 cm) average cob length compared to 11.8 and 11.9 cm from ZT and CVT during the first season, respectively. The shortest, 9.4 cm (FR), 9.8 cm (ZT) and 9.9 cm (CVT) average cob lengths were observed during the second season. Irrespective of tillage practice, SR2012 and LR2013 seasons gave the highest average cob length of 14.1 and 12.0 cm, respectively.

4.2.4 Maize shoot biomass yield

While seasons two, three and four had an average biomass yield of above 4.0 t^{-1}, season one recorded about 50% less of this yield (Figure 4.5). This was attributed to almost total crop failure associated to poor rainfall distribution.

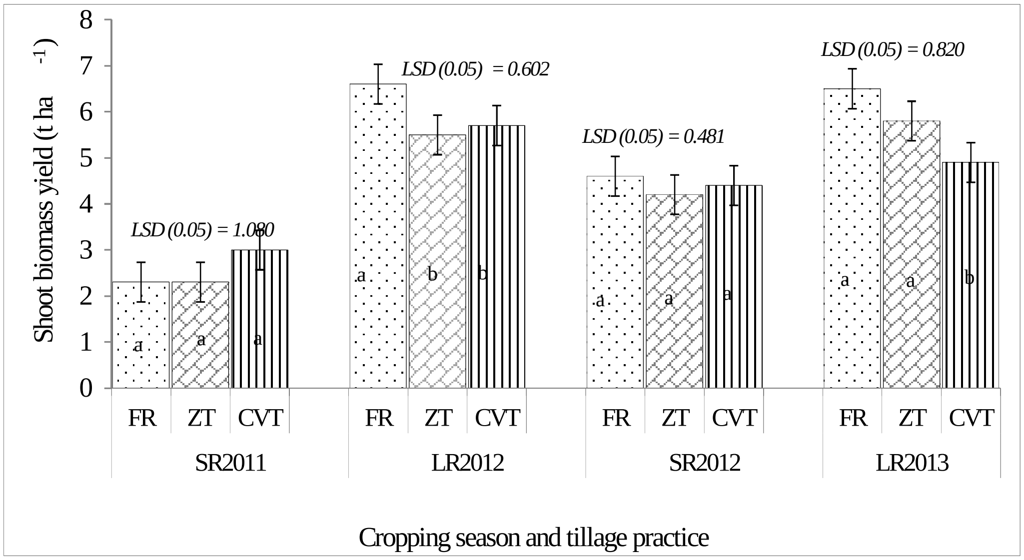

Figure 4.5: Shoot biomass yield as affected by tillage practices. SR = short rains; LR = long rains; FR = furrows/ridges; ZT = zero tillage; CVT = conventional tillage; LSD = least significant difference.

The highest (30.9%) coefficient of variation (CV) was also recorded during the first season when the effective rainfall had stopped. The results were in agreement with the findings by Khalili et al., (2013) in their study to determine the effects of drought on maize yields. They noted that the water deficit during crop development stage leads to severe loss in maize yield components. The tillage systems significantly ($p \leq 0.05$) affected maize shoot biomass yield during the second and fourth seasons. The biomass yield from FR during the second season was 36.5%. This was significantly ($p \leq 0.05$) higher than 31.4 and 32.4% from ZT and CVT practices, respectively. The higher biomass yield under the FR was attributed to SOM build up from the returned crop residues. The results strongly corroborate with Ngome et al., (2011) finding that the maize performance is improved by good soil conditions resulting from better management of Ferralsol, Acrisol and Nitisols in Western

Kenya. Similarly, Ozpinar (2009) noted increased maize biomass resulting from ZT practices in a study conducted in Western Turkey.

4.2.5 Maize grain yield

The average maize grain yields of 1.5, 4.0, 2.9 and 3.7 t ha^{-1} were recorded during SR2011, LR2012, SR2012 and LR2013 cropping seasons, respectively (Figure 4.6).

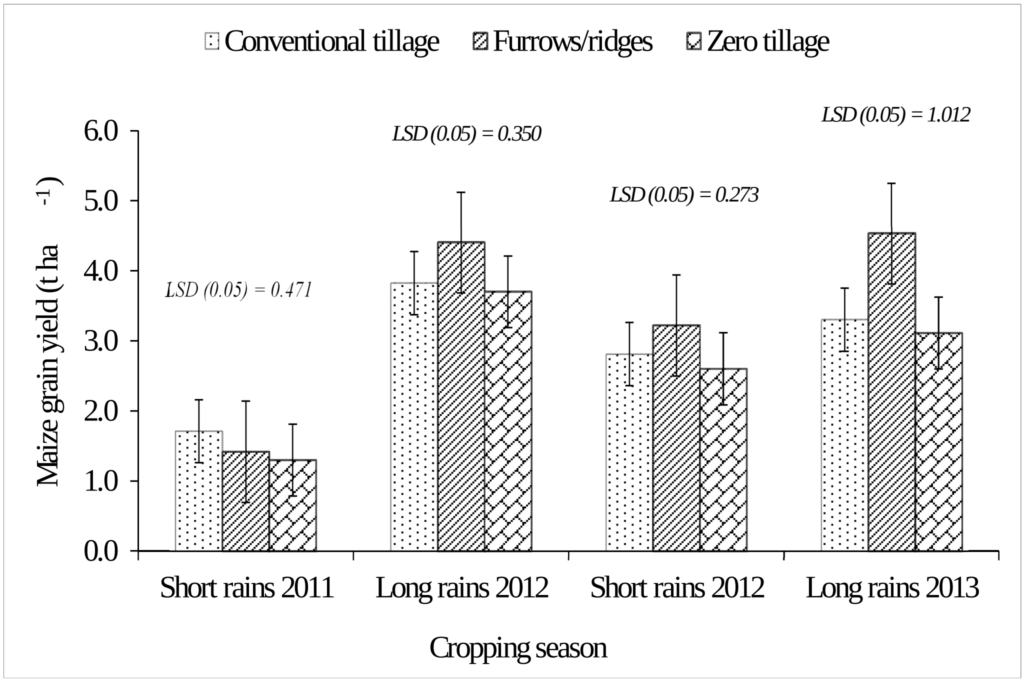

Figure 4.6: Maize grain yield (t ha^{-1}) as affected by tillage practices. SR = short rains; LR = long rains; LSD = least significant difference. Vertical bars are standard deviation of means.

Except during the first season (SR2011) of experimentation, the yields were significantly ($p \leq 0.05$) affected by the type of tillage practices during the three seasons (LR2012, SR2012 and LR2013). The 1.5 t ha^{-1} average grain yield during the first season was the lowest in the four seasons. The low yield was attributed to poor effective rainfall distribution, especially after 60 DAE, and as reported by Winterbottom et al., (2013) rainfall variability is a critical limitation to crop production in rain-fed agricultural areas (Winterbottom et al., 2013), and that increasing yield productivity in such areas will need farmers to take more risks in farming (Carberry et al, 2013). Though not significantly different, this is also the season when CVT tillage practice had higher (1.7 t ha^{-1}) grain yield compared to FR (1.4 t ha^{-1}) and ZT (1.3 t ha^{-1}). The first season of experimentation recorded the highest CV (54.5%). The scenario was also attributed to poor distribution of effective rainfall in SR2011. The results were therefore in agreement with findings by Rusinamhodzi et al., (2011) that most of the food crops under CA practices are unable to withstand drought which is more devastating especially if it occur at or after the crop anthesis stage. Thus, the benefits of CA principles are realized when the supporting practices, including availability of some rains are in place (Rusinamhodzi et al., 2011).

From the second season, furrows/ridges tillage practice performed significantly better than either the conventional or zero tillage practices. The higher yields under the conventionally tilled plots in the first experimental seasons was probably due to improved agronomic practices such as correct germplasm, early sowing, appropriate spacing weed control and fertilizer application. Secondly, this could have been due to the short period of practicing the CA farming. Digging up the soil, as was the case for conventional tillage practices could have initially but in shorter terms enhanced *in-situ* water infiltration, thereby improving land productivity. According to Rusinamhodzi et al., (2011), crops under CA practices are unable to withstand prolonged drought spells. This is particularly when less mulch is left on the soil surface and when the drought is prolonged and when it occur at the time of crop flowering and seed filling stage (Baudron et al., 2014).

Higher crop grain yields under FR in later part of experimentation were associated to extra moisture retention and nutrients concentration by mulch left on the soil surface. The current results corroborated with studies conducted in Ethiopia on the use of furrows for *in situ* soil and water conservation. The studies concluded that the use of permanent raised beds is an important component for the development of sustainable CA practices (Gebreegziabher et al., 2009). Better weed control is the other of option. In this case, Dual Gold *(Metolachlor*) pre-emergence herbicide was used to manage weeds at their juvenile stage and then Basagran *(Bentazon)*, a post-emergence herbicide used to control of broad leafed weeds in already established crops might have led to weed free environments and in turn improved crop grain yields under the FR compared to ZT and CVT practices. This is because the furrows were able to hold crop residues and soil together better than in the other tillage practices. In all seasons of experimentation the ZT performed poorer than the CVT method. This was linked to higher bulk density observed under this tillage practice. This was more pronounced during the first seasons when the impact of residue retention had not been felt.

4.2.6 Maize harvest index

Maize harvest index (HI) was higher, averaging at 40.1, 39.7 and 38.7% during the last three seasons (LR2012, SR2012 and LR2013) of experimentation when seasonal rainfalls were fairly distributed. This was the unlike the first season (SR2011) when the HI was lowest at 36.1% and did not significantly differ between the CA based (ZT and FR) and conventional tillage practices (Table 4.7). The low HI in drier season was mainly attributed to reduced production and translocation of assimilates to the developing plant tissues, including stovers and grains (Nandwa, 1995).

Table 4.7: Effect of tillage practices on maize harvest index

Tillage practice	Short rains 2011	Long rains 2012	Short rains 2012	Long rains 2013
Furrows/ridges	36.1a	40.0a	41.0a	33.7b
Zero tillage	36.1a	40.2a	39.1b	43.7a
Conventional tillage	36.2a	40.0a	38.9b	38.8a
Mean	36.1	40.1	39.7	38.7
LSD (0.05)	1.14	0.51	0.38	1.53

Means with the same letter are not significantly different ($p \leq 0.05$). LSD = least significant difference.

The average HI did not differ significantly due to the effect of tillage practices during the second season. Significant effects resulting from tillage practices were observed in the last two seasons. Furrows/ridges had significantly ($p \leq 0.05$) higher HI value of 41.0% compared to 39.1 and 38.9% from ZT and CVT systems, respectively. Season four of the experimentation had an average of 38.7% HI with zero tillage practice having the highest (43.7%) HI value within the season. A general observation was that the HI increased with increase in time of continuous or longevity of adapting CA practices. The increase in HI in the CA tillage treatments during the last two seasons of testing might have been due to an increase in yield components. The current study's HI results is close to the findings by Amanullah et al., (2010), who observed significantly higher HI of maize due to adaptation of improved cultivar and crop husbandry and more favourable ecological conditions.

4.2.7 Effect of crop residue retention on maize performance

In all seasons of experimentation, residue management (either returned or removed at the end of the seasons) did not significantly affect 50% days plant emergence and days to flowering. Days to physiological maturity averaged at 135 days across the season and differed significantly during the last two seasons (SR2012 and LR2013). The difference was attributed to the method of residue management. Plants in the plots where residues were returned on the soil surface had approximately three days later than those grown in plots where the residues were removed. In the same seasons, the maize root lengths were longer, averaging at 0.85 m in residue returned against 0.7 m in residue removed plots.

Residue management did not significantly influence maize leaf area index (LAI) that averaged at 7.2 across the seasons. However, maize plants grown in plots with residue retained on the soil surface had relatively higher LAI values than those under residue removed treatments. The average maize height was 1.7 m across the seasons. The parameter was not significantly affected by the method of residue management (remove or retained) at the end of the seasons. The seasonal rainfall had significant effects on plant height. For example, the shortest (1.2 m) average maize plants were observed during SR 2011 when the rainfall was lowest and poorly distributed (Figure

4.7). This is the same season when the trial was established and therefore no crop residue was available for application to the CA plots.

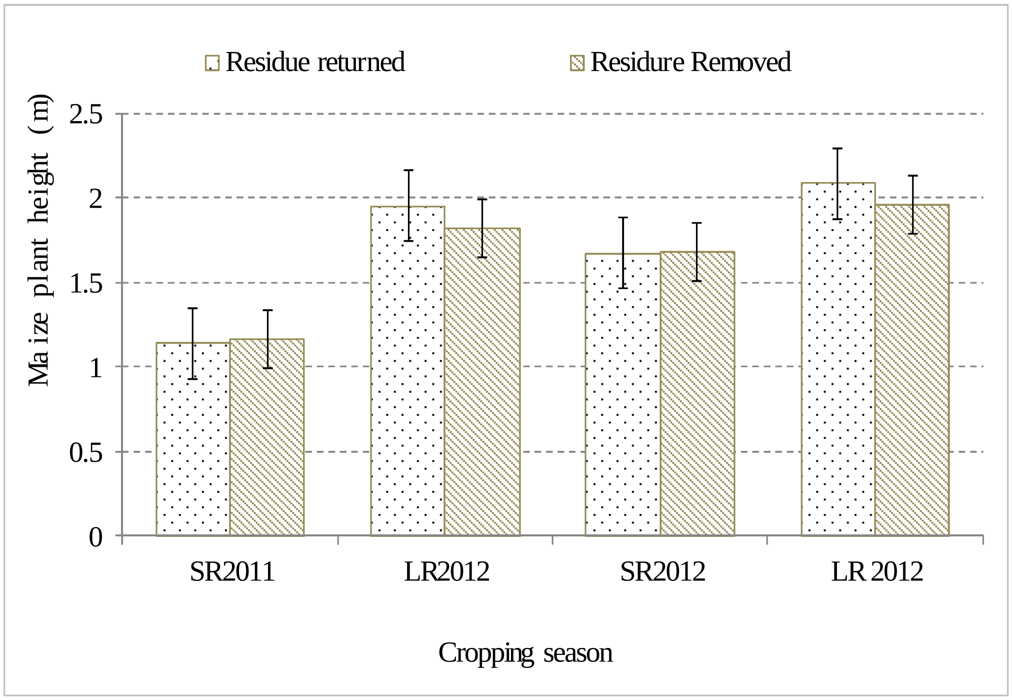

Figure 4.7: Maize plant heights at harvesting time. SR = short rains; LR = long rains

The effect of crop residue on plant height was monitored during LR2012, SR2012 and LR2013 seasons where 1.9, 1.7 and 2.1 m plant heights were measured during the second, third and fourth seasons, respectively. Higher maize plant height values during the last three seasons of the trial indicated that the residue treated plots were not significantly taller than in the conventional tillage practice. This is in contract with Nandwa's (1995) working in similar type of soils within the central highlands of Kenya at Kabete, registered increased maize height in stover incorporated plots when compared to the removal treatments. Both maize average shoot biomass and grain yields were affected significantly ($p \leq 0.05$) by the method of residue management (Figure 4.8). This took place during the last three seasons of experimentation when both parameters were significantly higher under the residue retention compared to residue removed treatments.

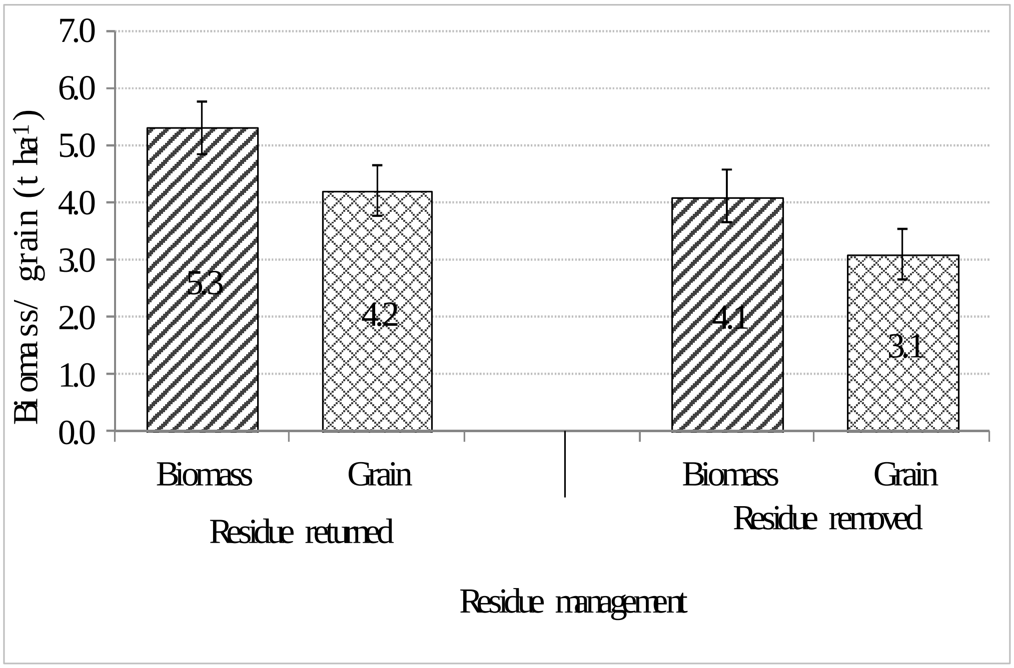

Figure 4.8: Effect of residue management methods on maize yields

4.3 Effect of conservation agriculture practices on bean yields

This section highlights the effect of bean growth and grain yields after the four seasons of practicing conventional (CVT) and conservation agriculture (CA) based farming methods.

4.3.1 Number of branches per plant

The bean average number of branches per plant varied from 3.3 (first season) to 15.4 (fourth season) recorded under ZT and FR tillage practice, respectively. The observation was not affected by tillage methods during the first season (Figure 4.9). The observation changed during the last three seasons where the FR tillage practice yielded significantly higher number of branches when compared with ZT and CVT practices. The higher number of branches under the FR tillage practice was attributed to improved soil. Crop yield is influenced by physiological characteristics of the crop, soil, weather conditions and agronomic practices (Sadras & Rodriguez, 2010).

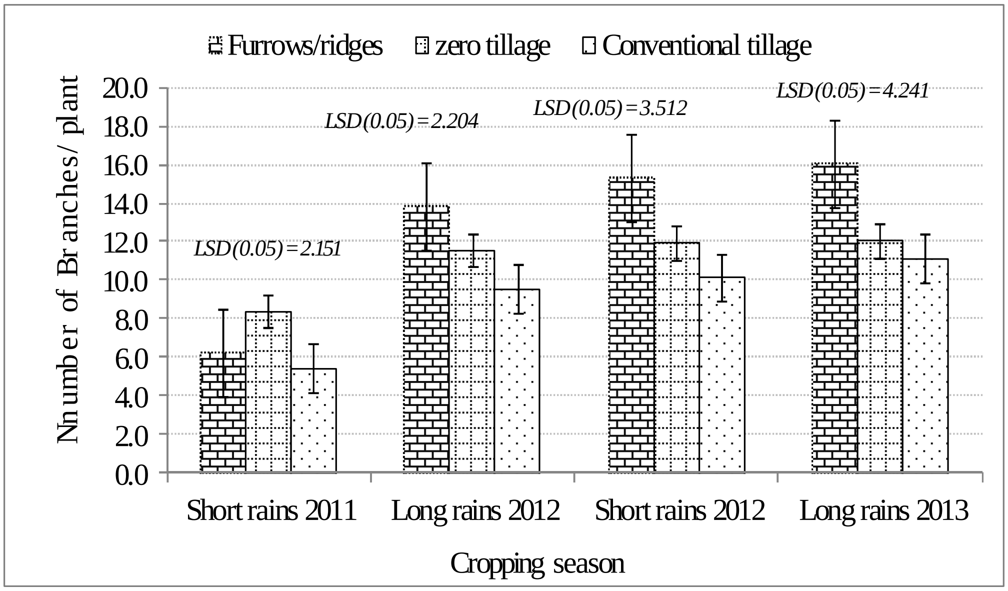

Figure 4.9: Effect of tillage practices on bean number of branches

The number of branches per plant was also significantly affected by cropping system. Irrespective of the applied tillage practice, bean intercropped with maize had approximately 25% less number of branches compared to counts from sole bean. This was attributed to maize and bean crops competition for growth resources. In this case maize plants being taller than those of bean, have higher advantage for utilization of the growth resources over the shorter crops grown in association. The number of branches per plant was greatly influenced by variation in in-crop rainfall. Hence, fewer numbers of branches were recorded during the first season of testing that had poor rainfall distribution compared to other seasons. As shown in Figure 4.10, application of nitrogen fertilizer at the rate of 20 N kg ha^{-1} significantly increased the overall number of branches per plant under all tillage practices, but at varying proportions. The observation was in agreement with that of Ogutu et al., (2012) who noted positive increase in growth and yield components of common bean in western Kenya resulting from basal application of N based fertilizer on bean crop. Interaction between FR tillage practice and N application provided the highest (16.63) number of branches per plant recorded during the last season of experimentation. No significant interaction was observed between N application and cropping system. The current results are in agreement to those of Amanullah et al., (2010) who reported significant variation in number of branches per bean plant due to adherence to good crop agronomic practices.

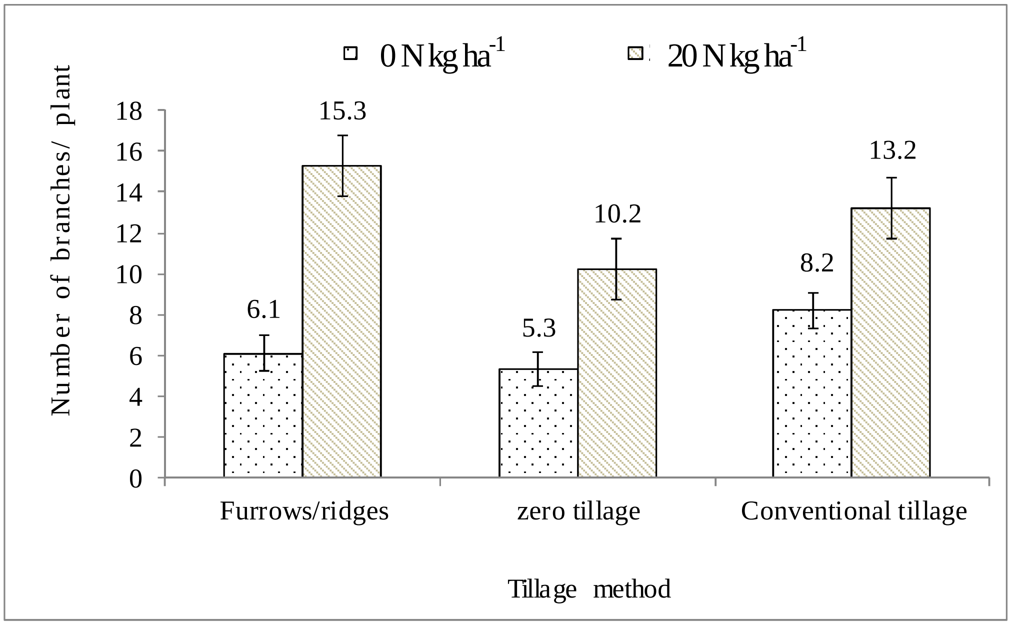

Figure 4.10: Effect of nitrogen application on bean number of branches

4.3.2 Maize days to maturity and plant height at harvest

Days for bean (var. Embean-14) from days after emergence (DAE) to 50% physiological maturity varied significantly from 83.2 to 86.3 days across the four seasons of experimentation. The relatively late maturity in FR was observed during seasons three and four. This was attributed to improved moisture status in the FR due to furrows that might have harvested more water for crop use. As described by Pramanik, (1999), the rotting crop residues on the soil surface contributes extra carbon, nitrogen and moisture for increased bean water use efficiency (WUE). The current study had the improved agronomic practices taken care of by ZT and FR where residue return and moisture conservation within the plots were adhered to. The days to physiological maturity of the crop was further significantly affected by N fertilization application. Plants that never received N fertilizer at sowing time matured 2.5 days earlier (average 84.0 days) than those that received 20 kg N ha^{-1} (86.8 days).

The average plant height varied significantly ($p \leq 0.05$) from 0.3 m in ZT to 0.9 m in FR across the seasons. Average plant height under CVT was 0.8 m which did not significantly differ from that of FR during the four seasons. The variation in plant height resulted from: (i) Cropping system: plants under maize-bean intercropping system were relatively taller than those under sole crop. This may be attributed to bean being shaded by maize canopy. Additionally, part of the crop residues/mulches applied every season might have decomposed/mineralized, thus contributing some nitrogen and carbon into the soil for plants use, and (iii) the discrepancy in effective rainfall during the four season of testing.

4.3.4 Number of fertile root nodules per plant

Fertile bean root nodule count per plant averaged at 5.5 across the four seasons of experimentation. The parameter differed significantly between FR and both the ZT and CVT practices at 30, 45 and 60 DAE (Figure 4.11). There were no large differences in nodulation between ZT and CVT practices during the four seasons of experimentation. The number of nodules under all tillage methods decreased as plant age advanced to maturation. The first season recorded the lowest average number

(1.7) of nodules from the three tillage methods at 30 DAE compared to above 5.00 nodules in the second, third and fourth seasons.

Factors affecting plant development, also affects formation and growth of nodules (Ramos et al., 2003). For example a decrease in soil water potential can markedly affect root hair and retard nodule growth and nitrogen fixation (Ramos et al., 2003). The low root nodule count during the first season that was characterized by poorly distributed rainfall was therefore attributed to a decrease in soil water, besides other plant growth factors.

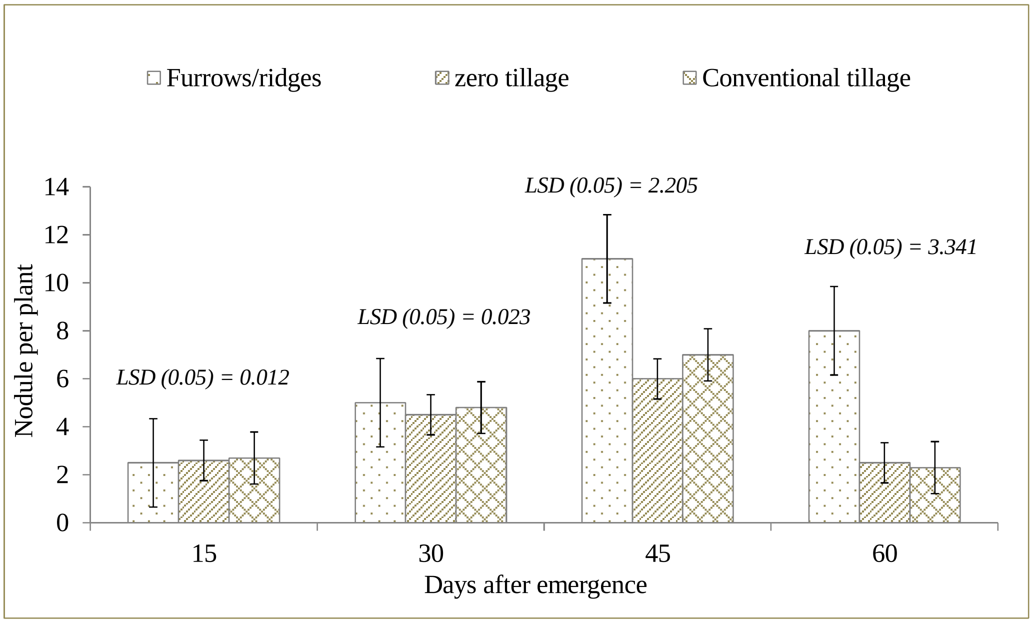

Figure 4.11: Effect of tillage practices on bean root nodules per plant. LSD = least significant difference.

Nodulation was always higher in plots that had crop residue left on the soil surface. Nitrogen fertilizer application in bean resulted into significantly lower nodule yields compared to non- fertilized treatments under all three tested tillage practices (Figure 4.12). As explained by Kihara et al., (2011), lower nodulation with application of inorganic N fertilizer is expected to reduce due to lower plant demand for fixed nitrogen with respect to the amount of applied at seeding time.

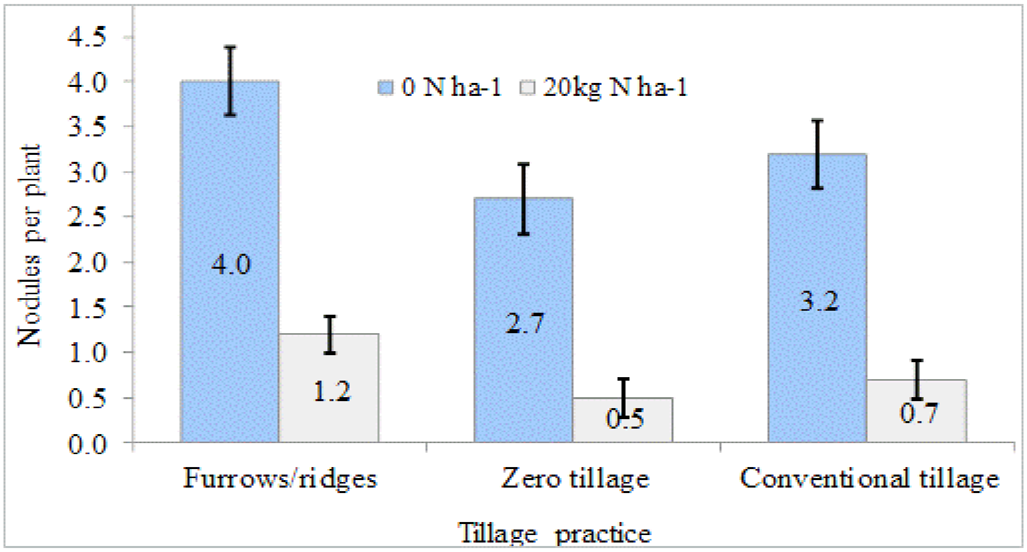

Figure 4.12: Effect of nitrogen application on bean nodules per plant

4.3.5 Bean grain yield

Bean grain yields averaged at 1.0 t ha^{-1} during the first season. The observed grain yield did not significantly ($p \leq 0.05$) differed due tillage practices (Table 4.8). Besides other factors, the low yield was attributed to poor rainfall distribution during the four seasons of experimentation.

Table 4.8: Effect of tillage practices on bean grain yields

	Cropping season			
Tillage method	2011 Short rains	2012 Long rains	2012 Short rains	2013 Long rains
Conventional tillage	1.20a	1.32a	1.26ab	1.42ab
Furrows/ridges	0.71a	1.31a	1.32a	1.55a
Zero tillage	0.92a	1.11b	1.11b	1.21b
Mean	1.00	1.23	1.23	1.23
CV (%)	2.01	8.23	28.05	28.05
LSD(0.05)	0.180	0.171	0.10	0.260

Means with the same letter in the same column are not significantly different ($p \leq 0.05$). CV = coefficient of variation; LSD = least significant difference.

4.4 Effect of liming on soil properties and crop yields under conservation agriculture

A trial was conducted during the SR2013 season to determine the effect of soil liming on soil properties and crop yields. The study's main activities included site characterization and calibration of lime ($CaCO_3$) requirement to raise the soil pH from 4.8 to at least 5.6. The effective rainfall, soil nutrient status (before and after liming), maize and bean growth/yield parameters were measured and reported on.

4.4.1 Soil properties before and after liming

The average soil chemical and physical properties determined before and after liming are shown in Table 4.9. Due to high clay (59.3%) content compared to sand (20.9%) and silt (19.9%) the soil was described as clay loam.

Table 4.9: Soil properties before and after soil liming

Soil property	Value		
	Before liming (§)	After liming (µ)	Effective change (µ-§)
pH (1:3 soil:water)	4.76	5.08	+ 0.32
Exchangeable acidity (cmol kg^{-1})	3.89	3.00	- 0.89
Exchangeable Hydrogen (cmol kg^{-1})	0.50	0.44	- 0.06
Exchangeable aluminium (cmol kg^{-1})	1.12	1.11	- 0.01
Exchangeable calcium (cmol kg^{-1})	2.03	2.12	+ 0.09
Exchangeable potassium (cmol kg^{-1})	78.01	78.00	- 0.01
Exchangeable magnesium (cmol kg^{-1})	3.83	3.88	+ 0.05
Exchangeable sodium (cmol kg^{-1})	0.17	0.22	+ 0.05
Exchangeable iron (mg kg^{-1})	24.4	24.9	+ 0.50
Exchangeable phosphorus (mg kg^{-1})	4.00	14.27	+ 10.27

Chude et al., (2005) notes that soils with pH value of less than 5.5 are considered as acidic. Soil liming gave 0.3 pH increase, from approximately 4.8 to 5.1. This was a positive effect of liming within a season of incorporating the liming material into the soil. Though insignificant, acidity saturation and Al^{3+} ions were decreased due to liming. Similarly, some increase in pH, Ca^{2+}, Fe^{2+} Mg^{2+} and Na^{+} ion concentrations showed the importance of liming as one of the CA key practices. According to Onwuka et al., (2009), liming material contains basic cations and basic anions (CO_3^{-2}) that are able to pull H^+ from exchange sites to form $H_2O + CO_2^-$, the cations then occupy the space left behind by H^+ on the exchange bonds. Exchangeable P concentration also increased from 4.0 to 10.3 mg kg^{-1} during the period of experimentation. While increase in P concentration may be attributed to enhanced P availability due to the effect of liming, the large percentage may have come from the residual of ex-situ P applied to maize and bean at sowing time. The exchangeable aluminum was slightly lower (0.01 cmol kg^{-1}) in the soil. This could have enhanced nutrient uptake by maize leading to increased plant growth and yield components.

4.4.3 Maize growth yields

Although not significantly different, maize took 7 – 9 days to emerge after sowing. The parameter was not significantly affected by soil liming, tillage practices, methods of residue management, N fertilizer application or interactions of these treatments. The plots with residue returned on the soil surface are the ones that took 8 days to emergence. Two reasons for the above seed emergence theories in residue applied plots took more days to emerge were: i) the mulch might have lowered soil temperature, thus leading to slow germination and emergence of the young seedlings as noted by Graham, (1981), and ii) the mulch on the soil surface temporally hindered the emerging plantlets as explained by Essien et al., (2009). Maize days to tasseling averaged at 67.0. This was not significantly affected by the effect of the main treatments or their interactions. However, plants in non-limed and no N fertilized plots flowered 3 days before the 67.0 observed average number of days to flower. The tendency for maize to flower early was an indication of nutrient stress (Betran et al., 2003). The number of leaves per plant determined after the crop flowering stage averaged at 16.0 and differed ($p \leq 0.05$) significantly due to the effect of soil liming. The limed and non-limed had an average of 16.5 and 15.6 leaves per plant, respectively. The higher number of leaves under limed plots was attributed to the effect of the liming material in the soil. The lime may have reduced the Al^{3+} ions concentration leading to availability of P and other elements for crop use. The main treatments: tillage, N fertilizer application and the methods of residue management did not have significant effect on the number of leaves per plant as was the case for liming. As reported by Jéan du Plessis (2003), a normal maize plant has between 8 to 20 leaves depending on the variety, altitude soil fertility. The observed number of leaves was therefore within the Jéan du Plessis (2003) specified range. Chlorophyll SPAD reading values were significantly ($p \leq 0.05$) increased by N application and liming at 80 kg N ha^{-1} and 4.7 t $CaCO^3$ ha^{-1}, respectively (Table 4.10).

Table 4.10: Effect of liming on leaf chlorophyll concentrations

Treatment	Chlorophyll concentration			
	15 Days after emergence	55 Days after emergence	80 Days after emergence	100 Days after emergence
FR+R+No liming (0.0 t $CaCO_3$ ha^{-1})	42.70b	51.98b	49.40b	26.86b
FR+R+Liming (4.7 t $CaCO_3$ ha^{-1})	45.29a	56.05a	53.60a	29.84a
Mean	44.00	54.01	51.5	28.35
LSD (0.05)	2.243	2.874	2.592	2.222

FR = Furrows/ridges (tillage); R = Residue applied; Means with the same letter in the same column are not significantly different ($p \leq 0.05$); LSD = least significant difference.

The highest chlorophyll concentration due to lime and N inputs was recorded at the onset of the crop flowering stage. Thereafter the concentration decreased gradually as the crop got to maturity. The high average chlorophyll values due to liming and N fertilizer application was associated to the increased plant nutrition and therefore the increased photosynthesis processes. This finding agree with Agamy et al., (2012) findings that improved plant nutrient have positive impacts on plant growth and yield factors, - including chloroplasts in leaf cells. In a related observation, Nursu'aidah et al., (2014) noted increased photosynthetic rate resulting from application of N fertilizer to legumes. Maize leaf area index (LAI) averaged at 8.0 and was significantly affected by soil liming. Incorporation of liming ($CaCO_3$) material into 0 – 15 cm soil depth led to higher (8.9) compared to 7.0 LAI in non-limed treatment (Table 4.11).

Table 4.11: Effect of liming on maize growth parameters

Lime application	Leaf area index	Plant height (m)	Days to 50% physiological maturity
Limed (4.7 t $CaCO_3$ ha^{-1})	8.90a	2.30a	132.60a
Not limed (0.0 t $CaCO_3$ ha^{-1})	7.00b	0.97b	131.40a
Mean	7.95	1.64	132.00
CV (%)	11.988	12.310	1.931
LSD (0.05)	0.561	0.685	1.499

LSD = least significant difference; Means with the same letter in the same column are not significantly different ($p \leq 0.05$).

The table shows that the maize plant height determined at the time of crop harvesting significantly ($p \leq 0.05$) differed due to the effect of liming. In addition, the days from emergence to physiological maturity averaged at 132 and was significantly affected by liming. Plants in non-limed plots matured 2 days earlier than those grown in limed plots. According to Bolland et al., (2004), excess Al^{3+} in the soil interferes with the crop root growth and other function. The acidity also restricts plant uptake of nutrients because roots development is inhibited (Bolland et al., 2004). According to Njeru et al., (2012), liming acid soil reduces the aluminium ions concentration leading to improved plant root and stalk biomass development. Interactions between liming, residue retention and N fertilizer application had varying effects on maize growth (Figure 4.13). For example, the average maize height under liming + N fertilization and liming + N + residue retention were significantly taller than those under residue retention and with no liming or N application.

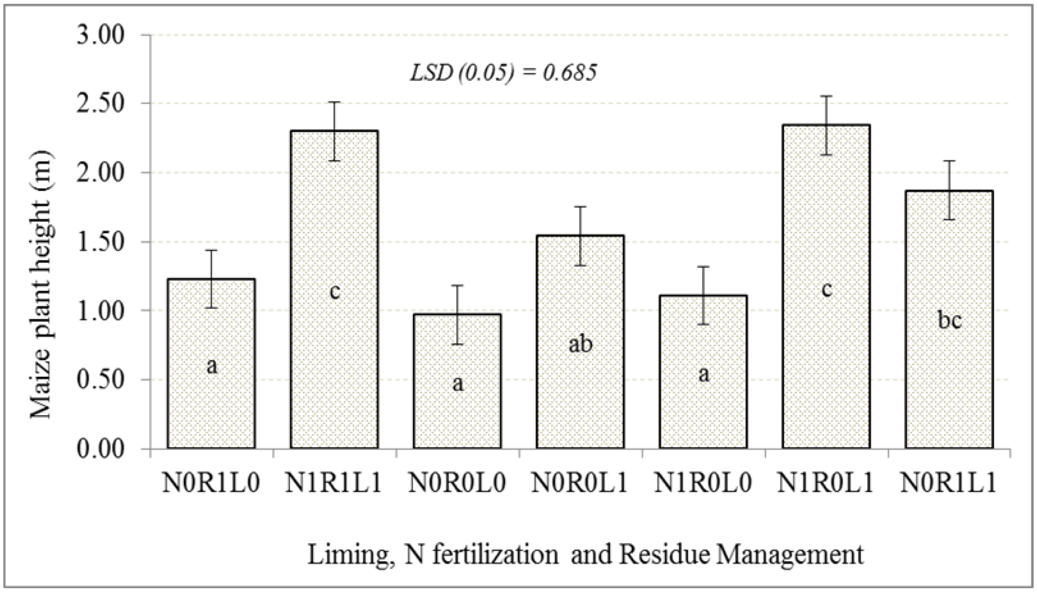

Figure 4.13: Effect of liming, nitrogen and crop residue management on number of leaves. LSD = least significant difference; N0R0L0 = No N fertilizer; no residue retention and no liming; N1R0L0 = N fertilizer; no residue retention and no liming; N0R1L0 = No N fertilizer; residue retention and no liming; N0R0L1 = No N fertilizer; no residue retention and liming; N1R1L0 = N fertilizer; residue retention and no liming; N0R1L1 = No N fertilizer; residue retention and liming; N1R0L1 = N fertilizer; no residue retention and liming; N1R1L1 = N fertilizer; residue retention and liming.

As suggested by Wall (2007), the observed increasing trends in the maize growth parameters are some of the positive benefits accrued from short to medium term of practicing CA farming methods. Liming alone resulted into maize plant height that did not significantly differ from plant heights observed in nitrogen + liming treated plots. Application of N fertilizer combined with soil liming gave significantly higher number of leaves per plant compared with those of fertilizer application combined with residue application. The finding showed that liming low soil pH could leads to improved crop underground/aboveground parts development, hence higher shoot biomass and grain yields.

4.4.4 Effect of liming on maize grain yields

Tillage and residue management methods without liming did not significantly affect maize yields (Table 4.12). However, FR had slightly higher (1.0) average number of cobs per plant compared to those contributed from CVT practice. The number of cobs per plant, shoot biomass and grain yield were higher due to retention of crop residues that might have reduced water evaporation from the soil surface. The same effect might have occurred due to evaporation reduction due to residue retention on the soil surface. Irrespective of the tillage and residue management methods, maize yields were significantly ($p \leq 0.05$) higher resulting from seasonal 80 kg N ha^{-1} application and soil 4.7 t CaCO^{3} ha^{-1} (liming) in maize-bean intercrop plots.

Table 4.12: Effect of tillage, residues, N application and liming on maize yields

Class	Treatment	Harvest stand count (ha)	Number cobs ha^{-1}	Number cobs plant^{-1}	Shoot biomass yield (t ha^{-1})	Grain yield t ha^{-1}
Tillage practice	Conventional tillage	52833.00a	51890.00a	0.98a	7.83a	4.30a
	Furrows/ridges	52779.00a	54337.00a	1.02a	7.48a	4.24a
	Mean	52806.00a	53114.00a	1.01a	7.65a	4.27a
	CV (%)	2.20	11.20	11.10	15.30	16.20
	LSD (0.05)	677.200	3504.600	0.070	0.690	0.410
Residue management	Retained (2.5 t DM ha^{-1})	53092.00a	53975.00a	1.02a	7.87a	4.40a
	Removed	52520.00a	52252.00a	1.00a	7.44a	4.14a
	Mean	52806.00	53114.00	1.01	7.65	4.27
	CV (%)	2.20	11.20	11.1	15.30	16.20
	LSD (0.05)	677.200	3504.600	0.066	0.690	0.410
N application	0 kg N ha^{-1}	52653.00a	50129.00a	0.95a	6.15a	3.37a
	80 kg N ha^{-1}	52959.00a	56098.00b	1.06b	9.16b	5.17b
	Mean	52806.00	53114.00	1.01	7.65	4.27
	CV (%)	2.20	11.20	11.10	15.30	16.20
	LSD (0.05)	677.200	3504.600	0.070	0.690	0.410
Lime ($CaCO_3$) application	0 t $CaCO_3$ ha^{-1}	52932.00a	50357.00a	0.95a	6.75a	3.71a
	4.7 t $CaCO_3$ ha^{-1}	52680.00a	55870.00b	1.06b	8.55b	4.83b
	Mean	52806.00	53114.00	1.01	7.65	4.27
	CV (%)	2.20	11.20	11.1	15.30	16.20
	LSD (0.05)	677.200	3504.600	0.070	0.690	0.410

LSD = Least significant difference; CV = Coefficient of variation; Means with the same letter in the same column are not significantly different ($p \leq 0.05$).

4.4.5 Bean growth yields

Plant emergence percentage ranged between 90.8 to 93.0%. The values differed significantly due to soil liming material and nitrogen fertilizer application (Figure 4.14). Significantly lower percentage (90.8 – 91.3%) plant emergence was exhibited in plots that had received nitrogen fertilizer at 80 kg N ha^{-1} and $CaCO_3$ at 4.7 t ha^{-1}. This might have been caused by scorching of some of the young seedlings by nitrogen fertilizer as noted by Singh et al., (2011).

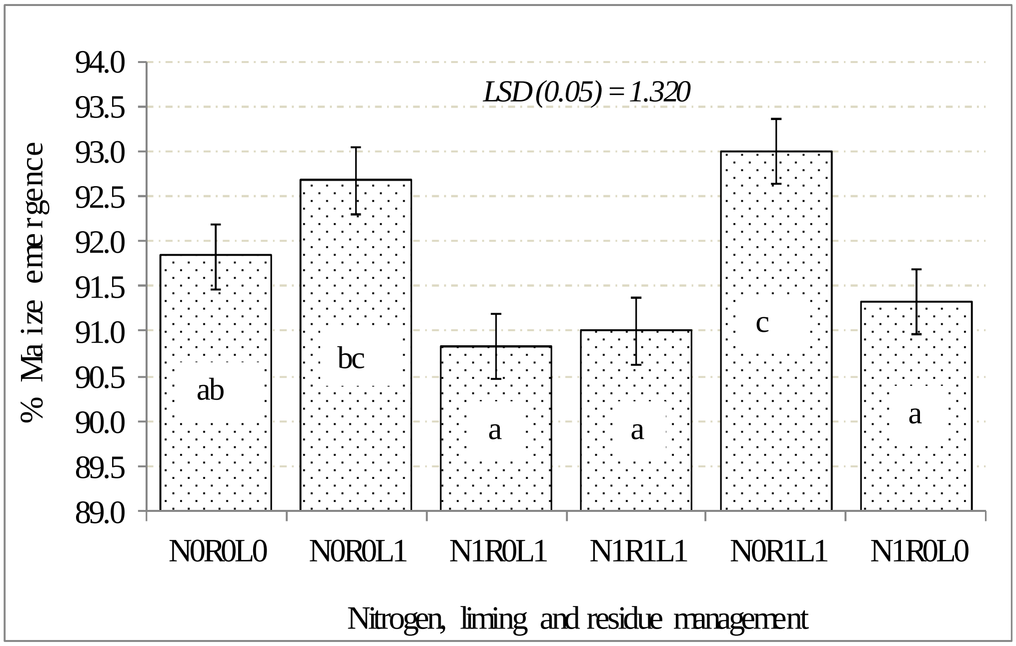

Figure 4.14: Interactions between liming, nitrogen fertilizer application and crop residue management method on percent bean emergence. LSD = least significant difference; N0R0L0 = No N fertilizer; no residue retention and no liming; N1R0L0 = N fertilizer; no residue retention and no liming; N0R1L0 = No N fertilizer; residue retention and no liming; N0R0L1 = No N fertilizer; no residue retention and liming; N1R1L0 = N fertilizer; residue retention and no liming; N0R1L1 = No N fertilizer; residue retention and liming; N1R0L1 = N fertilizer; no residue retention and liming; N1R1L1 = N fertilizer; residue retention and liming.

Bean average plant height varied ($p \leq 0.05$) significantly from 0.4 m exhibited from the control (N0R0L0) to 0.8 m from N1R1L1 treatment that had nitrogen, crop residue and $CaCO_3$ applied simultaneously. Liming alone or liming combined nitrogen fertilizer application resulted into significantly taller bean plants compared to plants grown and applied with crop residue and nitrogen fertilizer (N1R1L0) treatment. The variation in plant height could have been as a result of nutrient availability differences caused by the effect of liming. The number of branches per plant varied significantly from 3.1 to 17.3 depending on the applied soil fertility or amendments. The highest number (17.34) of branches per plant was recorded under application of 80 kg N ha^{-1} and $CaCO_3$ at 4.7 t ha^{-1} treatment (N1R0L1). The values were closely followed by those from N1R1L1 treatment that had nitrogen, crop residue and lime applied simultaneously. The number of nodules per plant varied ($p \leq 0.05$) significantly due to both time (within a season) of nodule sampling and the type of soil fertility management (liming or N fertilizer application) (Figure 4.15).

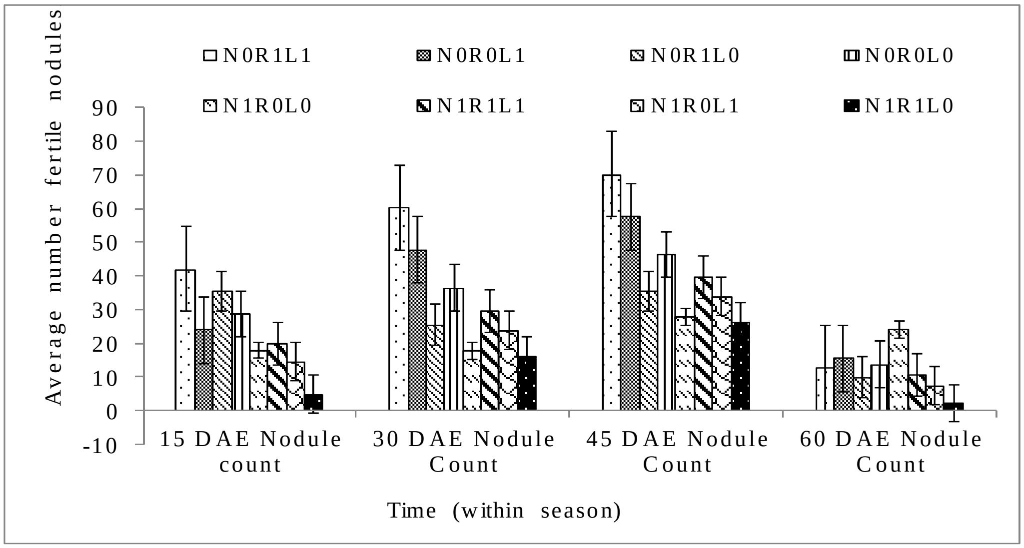

Figure 4.15: Interactions between liming, nitrogen fertilizer application and crop residue management method on bean number of fertile root nodules. LSD = least significant difference; DAE = days after emergence; N0R0L0 = No N fertilizer; no residue retention and no liming; N1R0L0 = N fertilizer; no residue retention and no liming; N0R1L0 = No N fertilizer; residue retention and no liming; N0R0L1 = No N fertilizer; no residue retention and liming; N1R1L0 = N fertilizer; residue retention and no liming; N0R1L1 = No N fertilizer; residue retention and liming; N1R0L1 = N fertilizer; no residue retention and liming; N1R1L1 = N fertilizer; residue retention and liming.

The lowest, 3.1 number of branches (3.1) per plant was recorded from the control (N0R0L0) treatment that did not have N applied, residue retained or liming done. The results agreed with those of Peoples & Craswell (1992) in their study on biological nitrogen fixation that the crop residue retention affects SOM decomposition, microbial activities and therefore nodulation in legumes. Irrespective of soil fertility management, nodule count were highest at 33.4 and 43.4 at approximately 30 DAE (bean pre-flowering) and 45 DAE (crop flowering), respectively. The low average nodule harvest (25.0) was recorded 15 DAE (crop branching) and pod maturation stage (60 DAE) had an average of 12.7 nodules. Andreeva et al., (1998) observes that the low nodule count after flowering was attributed to death of nodules and their associated nitrobacteria and also due to translocation of proteins starch molecules from the nodule cells to the developing seeds. Application of N based fertilizer alone (N1R0L0) or N fertilizer in combination with crop residue retention (N1R1L0) resulted into significantly lower nodule count at all stages of crop development.

Kihara et al., (2011) in a study to determine the effect of tillage and crop residue application on soybean N fixation observed lower nodulation with application of inorganic N due to lower plant demand for fixed nitrogen. The no soil fertility improvement treatment (N0R0L0) had overall higher nodule count than the N fertilized treatments. Application of lime in combination of N fertilizer (N1R0L1) and lime in combination of residue retention (N0R1L1) resulted to significantly higher nodule count at all stages of crop development. As noted by Kisinyo et al., (2014), the higher nodule count under liming may be attributed to the lime effect to reduce soil acidity. Similarly, Salvagiotti et al. (2008) noted that crop residue retention could influence soil temperatures, and also moisture retention; hence, promoting biological activities, including those of nodules under liming treatments. Reduced number of plants were observed in plots applied with both N fertilizer at the rate of 80 kg N ha^{-1} and liming material at 4.7 t CaCO^{3} ha^{-1}. This might have been caused by scorching of some of the young seedlings by applied lime or nitrogen fertilizer (Singh et al., 2011).

The lowest average number of pods per plant was observed under no inputs treatment (N0R0L0). Otherwise plants in limed and N applied plots had significantly higher number of pods. The higher nodule count under liming was associated to more nutrients being made available to the crop and therefore improved crop growth yields. The lowest average plant height was 0.6 m under no inputs treatment (N0R0L0). The parameter was significantly improved by application of N fertilizer, crop residue return on the soil surface and liming. The same parameter was further improved by combinations of the all tested soil fertility amendment inputs. Irrespective of the crop residue management methods, the number of branches per plant was significantly improved by soil liming and N fertilizer application. Table 4.13 shows that the number of branches ranged between 9.1 and 17.3 due to the effect of N and lime compared to between 3.1 and 5.1 for no N application and no liming.

Leaf chlorophyll concentration varied significantly based on time in the season when the measurements were taken using SPAD meter chlorophyll reader, and the type of soil amendment used. For example, significantly ($p \leq 0.05$) higher values were reported 30 DAE compared with 15, 45 and 60 DAE (Figure 4.16). The values were relatively the same for 15 and 45 DAE time of SPAD readings. Irrespective of the type soil amendment, the lowest values were from 60 DAE. This was expected because of plant ageing and loosing chloroplast elements in the leaves. The effect of liming had also positive increase on leaf chlorophyll concentration. In this case the limed treatments (N1R1L1, N0R1L1, N1R0L1 and N0R0L1) recorded higher chlorophyll values than non-limed treatments (N1R0L0, N0R1L0, N0R0L0 and N1R1L0).

The lowest chlorophyll concentrations were observed under no soil amendment input treatment (N0R0L0). Application of crop residue alone (N0R1L0) did not increase the SPAD chlorophyll values irrespective of the adapted tillage practices. However, residue retention combined with nitrogen fertilizer application showed slight increase in SPAD values, but lower than those observed under liming treatments.

Table: 4.13: Effect of liming on bean growth parameters and days to maturity

Treatment	Pods per plant	Plant height (m)	Branches per plant	Days to 50% maturity
N0R1L1	20.00b	0.72a	10.03b	96.00a
N0R0L1	16.56c	0.75a	9.12b	95.00ab
N0R1L0	6.23d	0.68b	5.05c	94.00bc
N0R0L0	7.75d	0.43c	3.12c	93.00c
N1R0L0	12.86c	0.65b	11.00b	94.00bc
N1R1L1	25.85a	0.83a	16.04a	96.00a
N1R0L1	21.54b	0.75a	17.34a	96.00a
N1R1L0	19.63bc	0.79a	15.01a	95.00ab
Mean	16.30	0.70	10.84	94.88
CV (%)	14.75	13.24	9.45	1.13
LSD (0.05)	4.102	0.1430	2.004	1.855

Mean values with similar letter(s) in the same column do not differ significantly ($p \leq 0.05$). LSD = least significant difference; CV = coefficient of variation; LSD = least significant difference; N0R0L0 = No N fertilizer; no residue retention and no liming; N1R0L0 = N fertilizer; no residue retention and no liming; N0R1L0 = No N fertilizer; residue retention and no liming; N0R0L1 = No N fertilizer; no residue retention and liming; N1R1L0 = N fertilizer; residue retention and no liming; N0R1L1 = No N fertilizer; residue retention and liming; N1R0L1 = N fertilizer; no residue retention and liming; N1R1L1 = N fertilizer; residue retention and liming.

As noted by Onwuka et al., (2009), liming provides basic cations, for example calcium that suppresses toxicity of aluminum in the soil creating better environment for the release of phosphorus. The available soil phosphorus helps in whole plant development, especially stimulating root growth and photosynthesis in leaves. Significantly higher average chlorophyll values were therefore associated to increased plant nutrition and photosynthesis.

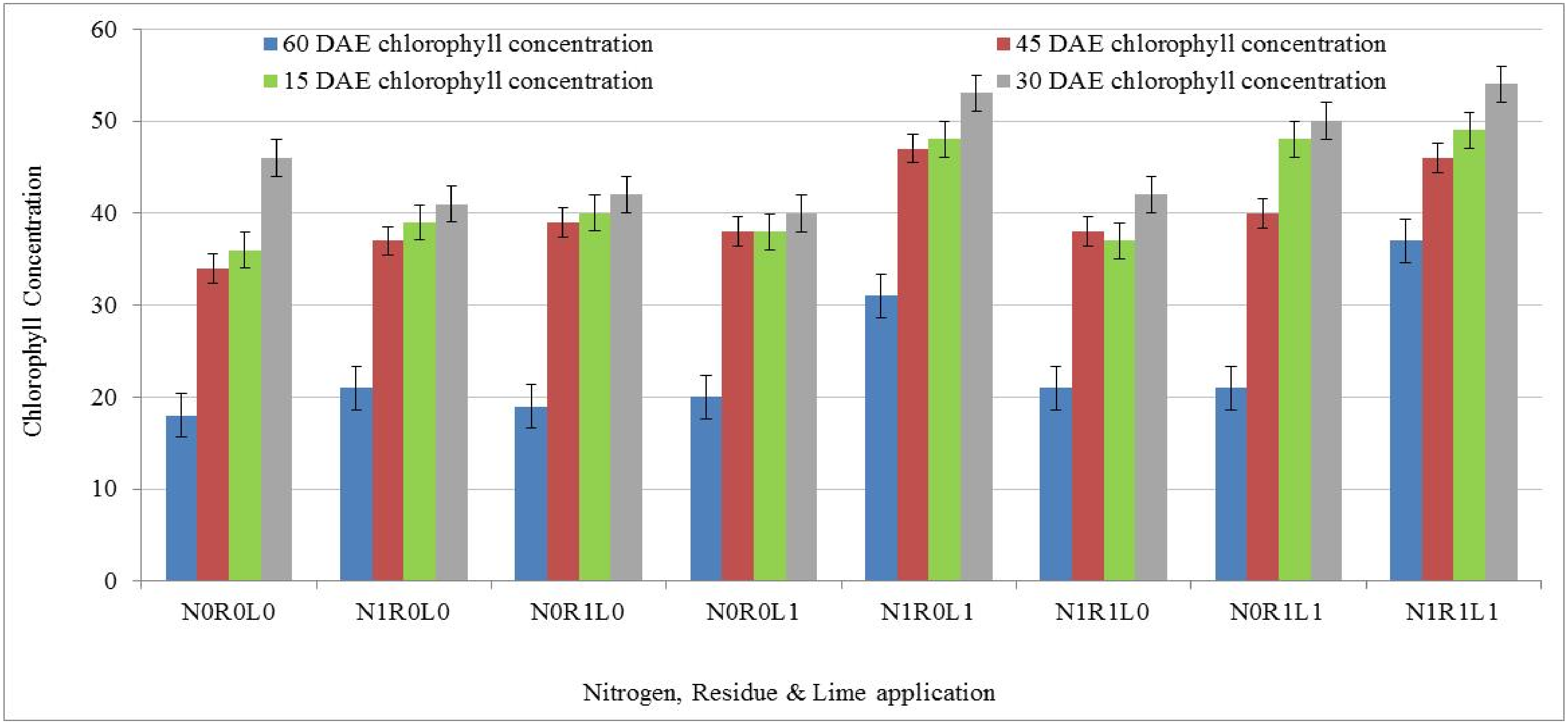

Figure 4.16: Interactions between liming, nitrogen fertilizer application and crop residue management method on chlorophyll concentrations. DAE = days after emergence; LSD = least significant difference; N0R0L0 = No N fertilizer; no residue retention and no liming; N1R0L0 = N fertilizer; no residue retention and no liming; N0R1L0 = No N fertilizer; residue retention and no liming; N0R0L1 = No N fertilizer; no residue retention and liming; N1R1L0 = N fertilizer; residue retention and no liming; N0R1L1 = No N fertilizer; residue retention and liming; N1R0L1 = N fertilizer; no residue retention and liming; N1R1L1 = N fertilizer; residue retention and liming.

4.4.6 Bean flower and grain yields

Number of flowers per plant varied ($p \leq 0.05$) significantly due to the adapted type of soil fertility management input (Figure 4.17). The highest (35.3) and lowest (14.1) number of flowers per plant were obtained under liming combined with nitrogen fertilizer and residue retention treatment (N1R1L1) and no soil amendment (N0R0L0), respectively. Both liming and nitrogen fertilizer application had similar positive effect on fertile flower yields per plant.

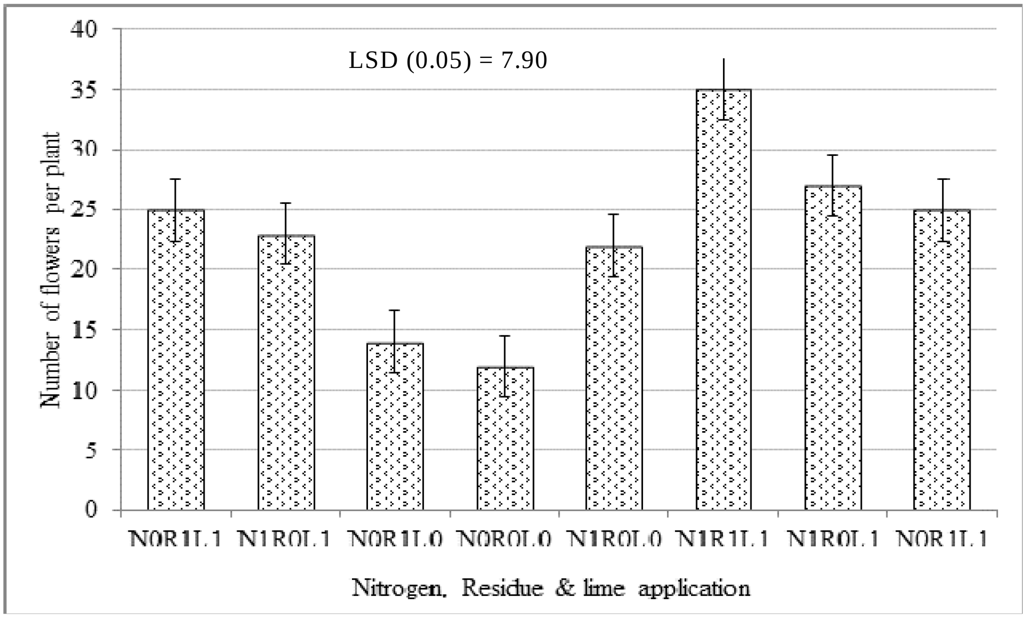

Figure 4.17: Effect of liming, nitrogen fertilizer application and crop residue management on bean flowers and grain yields. LSD = least significant difference; N0R0L0 = No N fertilizer; no residue retention and no liming; N1R0L0 = N fertilizer; no residue retention and no liming; N0R1L0 = No N fertilizer; residue retention and no liming; N0R0L1 = No N fertilizer; no residue retention and liming; N1R1L0 = N fertilizer; residue retention and no liming; N0R1L1 = No N fertilizer; residue retention and liming; N1R0L1 = N fertilizer; no residue retention and liming; N1R1L1 = N fertilizer; residue retention and liming.

The bean grain yields had similar trends as those of flower counts. The highest (2.2 t ha^{-1}) grain yield was obtained from liming combined with nitrogen fertilizer application and residue retention treatment (N1R1L1) (Figure 4.18).

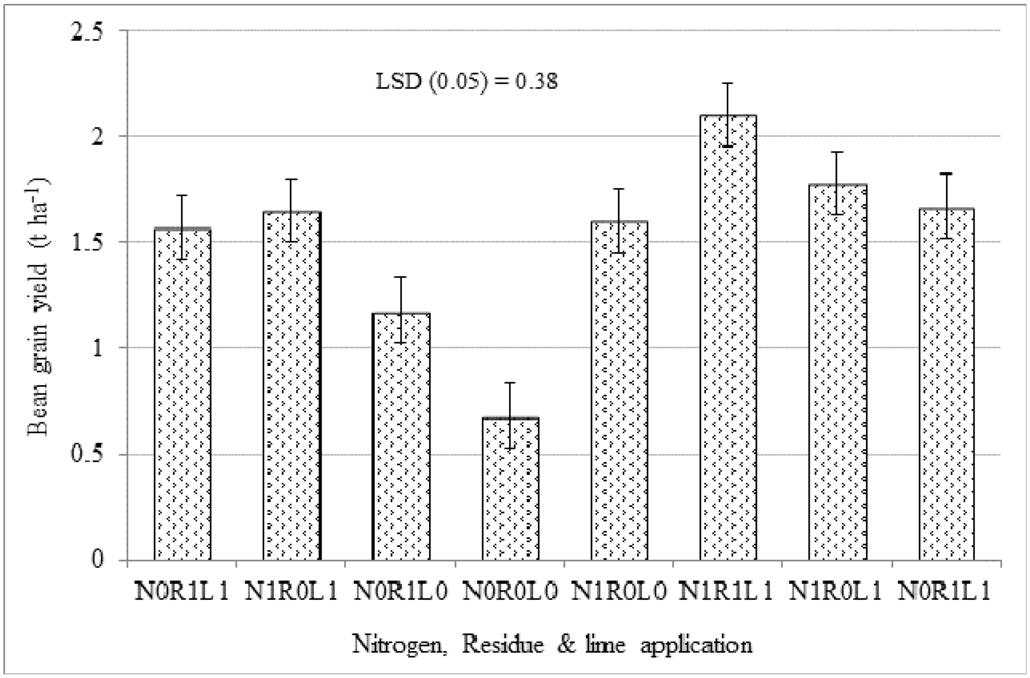

Figure 4.18: Effect of liming, nitrogen fertilizer application and crop residue management on bean flowers grain yields. LSD = least significant difference; N0R0L0 = No N fertilizer; no residue retention and no liming; N1R0L0 = N fertilizer; no residue retention and no liming; N0R1L0 = No N fertilizer; residue retention and no liming; N0R0L1 = No N fertilizer; no residue retention and liming; N1R1L0 = N fertilizer; residue retention and no liming; N0R1L1 = No N fertilizer; residue retention and liming; N1R0L1 = N fertilizer; no residue retention and liming; N1R1L1 = N fertilizer; residue retention and liming.

The no soil amendment treatment (N0R0L0) had the lowest grain yield of 0.6 t ha^{-1}. Similar results were reported by Amanullah & Hatam, (1999) in their evaluation of common bean germplasms in North Western Pakistan. Moreover, the yield variation in the current study might have resulted from nutrient availability to bean due to the effect liming and N fertilizer application in acidic soils. In a related study in Brazil, an increase in bean yield after soil liming was reported by Fageria (2001) in the conventional planting system under Oxisols.

4.5 Effect of conservation agriculture on soil biology

A study was conducted to determine the effect of applying conservation agriculture practices on bacteria, nematodes and fungi populations in maize-bean cropping systems. The following sub-sections provide highlights on the study's results. Appendix 4.1 shows the analysis of variance for bacteria, fungi and nematodes. The tillage methods, cropping systems and residue management methods interactions significantly ($p \leq 0.05$) influenced population of nematodes (Table 4.14).

Table 4.14: Effect of tillage practices on bacteria, fungi and nematode populations

Main factor	Treatment	Bacteria (cfu x 10^6)	Fungi (cfu x 10^6)	Nematodes Count (g^{-1} soil)
Tillage practices	Conventional tillage	261.44a	23.500b	139.47ab
	Zero tillage	248.28a	33.250ab	90.43b
	Furrows/ridges	242.03a	50.44a	150.89a
Cropping systems	Maize-bean intercrop	254.44a	39.361a	170.56a
	Sole maize	253.75a	36.89a	128.42ab
	Sole bean	243.56a	30.944a	81.57b
Nitrogen	Applied	251.41a	37.32a	115.13a
	Not applied	249.76a	34.15a	139.64a
Residue Management	Retained	253.44a	35.35a	155.57a
	Removed	247.72a	36.11a	98.43b

Means with the same letter in the same column are not significantly different ($p \leq 0.05$). cfu = colony forming unit.

No treatment appeared to significantly change the soil bacteria populations in maize-bean cropping systems (Tables 4.15 and 4.15). Vanlauwe et al., (2014) notes that the nitrogen positively influences nutrition and survival of many soil micro-organisms. Fungi and nematode populations were significantly ($p \leq 0.05$) higher under FR tillage than under either CVT or ZT method. Nematode populations differed significantly under cropping system and residue regimes. This could have been attributed to development of suitable environment such as improved moisture and pH conditions as observed by Scheepmaker & Butt, (2010).

Table 4.15: Interactions between tillage methods and maize-bean cropping systems on bacteria, fungi and nematode populations

Treatment	Bacteria	Fungi	Nematodes
	(cfu x 10^6)	(cfu x 10^6)	Count (g^{-1} soil)
Conventional tillage x Sole bean	274.08a	16.92a	87.50bc
Zero tillage + Sole maize	260.50a	35.17ab	69.17c
Conventional tillage + Maize-bean	260.08a	28.58ab	151.67abc
Zero tillage + Maize bean	254.58a	38.75ab	131.25bc
Furrows/ridges + Sole maize	250.58a	50.50a	136.83abc
Conventional tillage + Sole maize	250.17a	25.00ab	179.25ab
Furrows/ridges + Maize bean	248.67a	50.75a	228.75a
Zero tillage + Sole bean	229.75a	25.83ab	69.09c
Furrows/ridges + Sole bean	226.83a	50.08a	87.08bc

Means with the same letter in the column are not significantly different ($p \leq 0.05$). cfu = colony forming unit.

The nematode populations were significantly higher under maize-bean intercrop and also under residue retention plots compared to observations made in sole maize, sole bean and under situations where residues were removed. The lowest nematode populations of 69.2 and 69.1 g^{-1} of soil were observed under sole maize and sole bean, respectively. The tillage + cropping system interaction had nematode populations significantly higher at 228.7 cfu x 10^6 under maize-bean cropping system with FR tillage system. This could have been caused by combined higher maize-bean root biomass providing suitable environment for nematodes multiplication and growth. Bacteria population in CVT + residue retention was significantly higher at 269.4 cfu x 10^6 compared to (241.6 cfu x 10^6) and (235.9 cfu x 10^6) in ZT + residue removed and FR + residue retained interactions, respectively (Table 4.16).

Table 4.16: Interactions between tillage and residue management methods on microbial populations

Treatment	Bacteria	Fungi	Nematodes
	(cfu x 106)	(cfu x 106)	Count (g^{-1} soil)
Conventional tillage + Residue retained	269.39a	20.00b	162.00ab
Zero tillage + Residue removed	255.00ab	33.50ab	92.50c
Conventional tillage + Residue removed	253.50ab	27.00b	116.94bc
Furrows/ridges + Residue removed	248.11ab	48.33a	89.56c
Zero tillage + Residue removed	241.56b	33.00ab	88.24c
Furrows/ridges + Residue retained	235.94b	52.56a	212.22a

Means with the same letter within the column are not significantly different ($p \leq 0.05$**).**
cfu = colony forming unit.

The higher bacterial populations in treatments under CVT and particularly where residues were returned may be attributed to improved soil aeration during conventional land ploughing that led the soil becoming more porous and aerated. As noted by Gowhar et al., (2013), improved aeration could have provided better oxygenated soil environment that favoured the growth of bacteria colonies. The fungi population under FR + residue removed was 48.3 cfu x 10^6 and FR + residue retained was 52.6 cfu x 10^6. Nematode count in FR + residue retained was 212.2 g^{-1} of soil, and significantly ($p \leq 0.05$) differed from all other treatments. These observations differed ($p \leq 0.05$) significantly from CVT + residue retained that had 20.0 cfu x 10^6 and CVT + residue removed treatment combinations. Cropping system + residue management interaction had differences occurring only in nematode populations. The maize-bean + residue retained combination had the highest nematode population of 220.8 g^{-1} of soil. This differed significantly from all other treatment combinations (Table 17).

Table 4.17: Interactions between cropping systems and residue management methods on microbial populations

Treatments	Bacteria (cfu x 10^6)	Fungi (cfu x 10^6)	Nematodes Count (g^{-1} soil)
Maize-bean + Residue retained	259.56a	36.94a	220.83a
Sole maize + Residue retained	257.39a	40.39a	163.94ab
Sole maize + Residue removed	250.11a	33.39a	92.89c
Maize-bean + Residue removed	249.33a	41.78a	120.28bc
Sole bean + Residue removed	243.72a	33.17a	81.18c
Sole bean + Residue retained	243.39a	28.72a	81.94c

Means with the same letter within the same column are not significantly different ($p \leq 0.05$)**.** cfu = colony forming unit.

Interaction between bacteria populations between the three cropping systems (maize-bean, sole bean and sole maize) and the three tillage systems (CVT, FR and ZT) are shown in Figure 4.19. The bacteria populations in sole bean differed from those under conventional and furrows/ridges tillage practices. However, at ($p \leq 0.05$) these differences were not significant between FR and CVT. Figure 4.20 shows interaction of fungi populations between the three cropping systems (maize bean intercrop, sole bean and sole maize) and the three tillage systems (conventional, furrows and zero). The fungi populations in the three cropping systems differed significantly ($p \leq 0.05$) due to furrow/ridges and those of either conventional or zero tillage. Fungi survive under wide range of conditions (Gleason et al. 2010), explaining why their populations were hardly significantly influenced by cropping systems or residue management. However, the higher fungi populations under furrows and ridges were associated to more moisture retention that in turn might have promoted growth of fungi under FR tillage system.

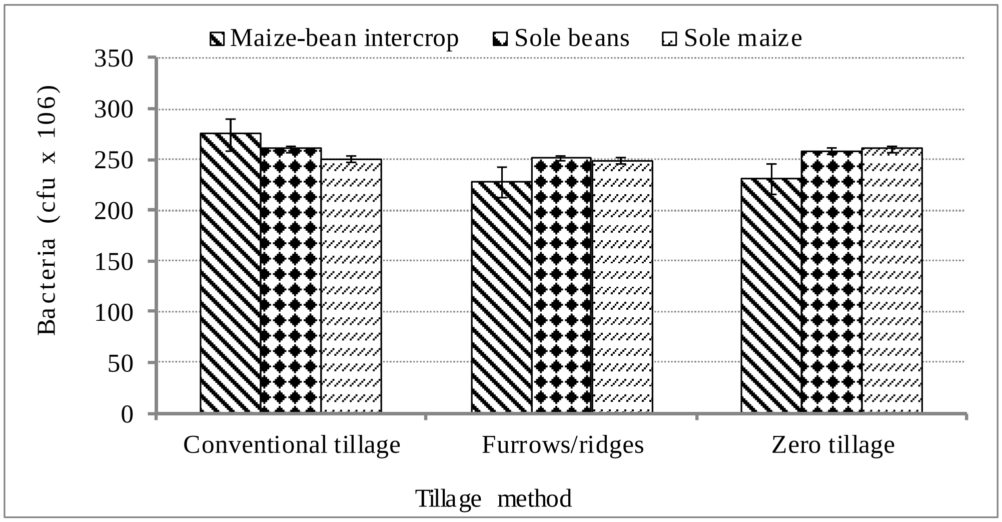

Figure 4.19: Effect of tillage and cropping system interactions on bacteria populations. cfu = colony forming unit.

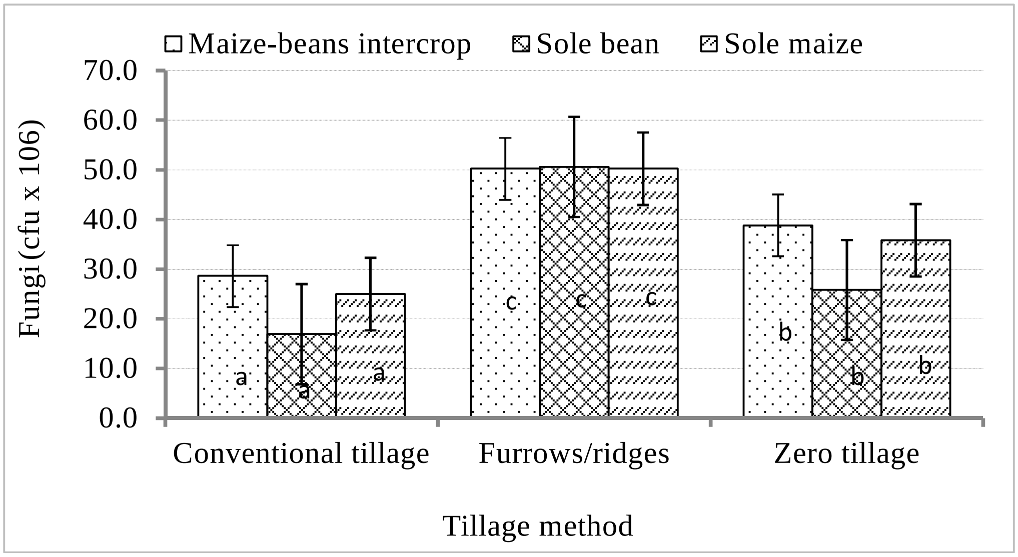

Figure 4.20: Effect of tillage and cropping system interactions on fungi populations. cfu = colony forming unit.

Figure 4.21 shows interaction between nematode populations in maize-bean intercrop, sole bean and sole maize cropping systems in reference to conventional, furrows/ridges and zero tillage systems. The nematode populations in sole bean did not differ significantly from other cropping systems across the three tillage systems. However, the parameter differed significantly in sole maize and maize-bean intercrop under all three tillage methods ($p \leq 0.05$). The highest nematode population count (229) was observed in maize-bean intercrop under furrows/ridges tillage system. This might have been caused by increased soil moisture as indicated by Giller et al., (2009) that the nematodes thrive well under moist soil environment. The furrow structures and residue retention on the soil surface may have contributed some extra moisture in the soil leading to higher nematode populations.

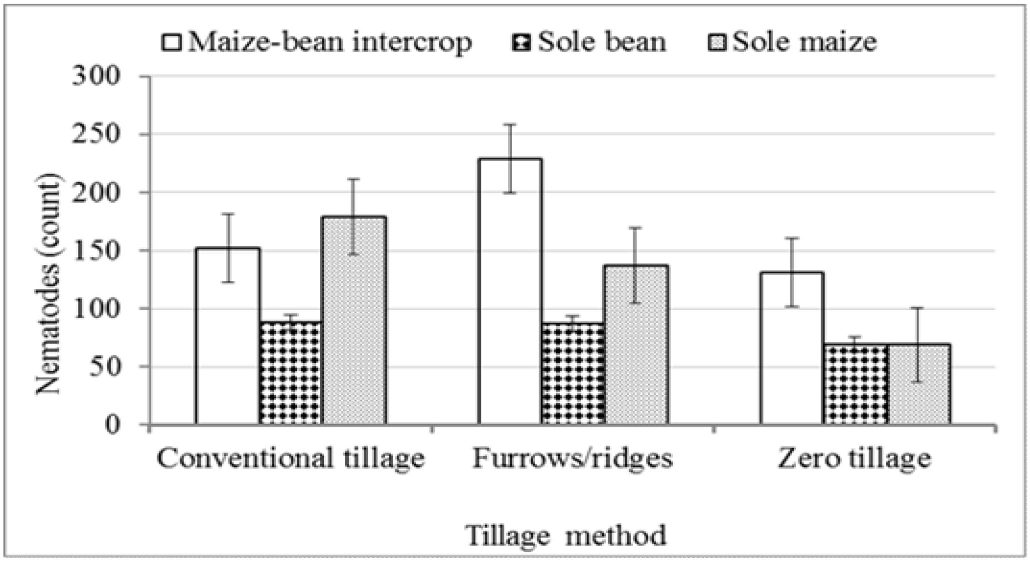

Figure 4.21: Effect of tillage and maize-bean cropping systems on nematode count

The maize-bean intercrop systems were generally preferred by nematodes than either the sole maize or bean cropping systems. The reason for this may require detailed studies,- however, as argued by Larson et al. (2000) there are possibilities that the intercrops of maize and legumes may have roots exudates providing favourable environment or nutrition for nematodes.

4.6 Herbicides weed control under conservation agriculture systems

Divers broad and narrow leafed weeds were found within the trial site. The most common in terms their percentages were *Elymus repens* or couch grass (86%), *Richardia scabra (82%)* and *Oxalis (67%)* (Appendix 4.2). In addition, *Bidens pilosa, Galinsoga parviflora, Cyperus spp., Amaranthus spp. and Commelina spp.* were other common weed species across the four seasons of experimentation. Whiles maize and bean seeds emerged after 7 days, majority of weeds emerged after five days after the start of the rains. This indicated that the weeds may have started competing with the crop very early in the season.

The percent weeds suppression (%WS) were not significantly different between glyphosate herbicides or their rates. Average weed suppression, 58.3% was observed resulting from the use Roundup Turbo (RTB) at the rate of 2.5 liters ha^{-1} and the two rates (2.5 and 3.0 liters ha^{-1}) of Roundup Weather Max (RWMX). This was the same time that the lowest (49.5%) weed suppression (WS) percentage was observed from the lowest rate (1.5 liters ha^{-1}) of RWMX. The %WS was at optimal (90.9%) due to herbicides application approximately 2½ months after application of the herbicides and conventional weed control treatments. This implied that the optimal weed control using glyphosate herbicides is effected within 0 - 80 days of treatment application. Indeed, this is the period when maize and bean plant require weed free environment because of higher nutrient requirements for biomass and grains developing.

Conventional weeds management had significantly ($p \leq 0.05$) higher average WS of 90.2% compared to less than 2% under the unweeded treatment. This observation was attributed to thorough two hand weeding events conducted in each season on the convention plots. As expected, the unweeded treatment exhibited significantly low %WS throughout each season. This was observed in the unweeded treatment whose %WS significantly ($p \leq 0.05$) differed from those of herbicides and conventional tilled plots during the three seasons that the parameter was monitored. The herbicides treated plots had significantly better weed suppression compared to unweeded and conventional tilled plots (Table 4.18).

Table 4.18: Effect of weeding method on percent weed suppression

Weed control method	Herbicide rate (liters ha^{-1})	% Weed suppression		
		%WS1	%WS2	%WS3
Unweeded control	Not applicable	0.00d	0.00d	0.00d
Conventional tillage	Not applicable	88.52a	35.01a	91.80a
Roundup weather max	1.5	49.51c	82.82c	75.31c
Roundup weather max	2.5	59.02b	89.51b	83.30b
Roundup turbo	2.5	58.82b	94.81ab	89.00ab
Roundup weather max	3.0	66.01b	96.30a	87.52ab
Mean	-	53.61	66.40	71.10
LSD (0.05)	-	9.20	5.31	5.80
CV(%)	-	11.41	5.30	5.41

Means in the same column with the same letter are not significantly different ($p \leq 0.05$). CV = Coefficient of variation; LSD = Least significant difference; WS^1 = Weed suppression event 1 observed 1 month after glyphosate herbicides application; WS^2 = Weed suppression event 2 observed 2½ months after glyphosate herbicides application; WS^3 = Weed suppression event 3 observed 3½ months after glyphosate herbicides application.

Decaying mulch was found on the soil surface at the end of the seasons in the herbicides treated plots. This could have helped to conserve moisture for crop use during dry spells normally observed in later on after almost 10 days of the seasons. On a similar observation, maize grain yields were increased due to conserved moisture caused by retention of mulch on the soil surface (Baudron et al., 2013). Only plants in unweeded treatments showed phytotoxicity (de-colouration); not due the effect of herbicides but due weeds/crop competition for growth resources and perhaps insufficient soil moisture due to rainfall variability. In this case there was yellowing plant leaves and dwarfing of the affect plants (Table 4.19). The plants in the said plots died in approximately 10 days earlier than those under conventional or herbicide treated plots. This was attributed to crop/weeds competition for growth resources when the weeds overcame the crops because of their high diversity and populations within a given plot.

Table 4.19: Effect of glyphosate based herbicides on plant phytotoxicity

Weed control method	Herbicide rate (liters ha^{-1})	Plant phytotoxicity		
		Score 1	Score 2	Score 3
Unweeded control	Not applicable	3.0a	3.5a	3.8a
Conventional tillage	Not applicable	1.3b	1.3b	1.5b
Roundup weather max	1.5	1.5b	1.5b	1.8b
Roundup weather max	2.5	1.5b	1.5b	1.0b
Roundup turbo	2.5	1.5b	1.5b	1.3b
Roundup weather max	3.0	1.5b	1.5b	1.5b
Mean	-	1.7	1.8	1.8
LSD (0.05)	-	0.6	0.8	0.8
CV (%)	-	24.5	31.0	28.1

Means in the same column with the same letter are not significantly different ($p \leq 0.05$); CV = Coefficient of variation; LSD = Least Significant Difference;
Phytotoxicity Score 1 = assessment done 30 days after the crop emergence;
Phytotoxicity Score 2 = assessment done 70 days after the crop emergence;
Phytotoxicity Score 3 = assessment done 123 days after the crop emergence.

Maize days to physiological maturity averaged at 126, 133 and 136 in SR2011, LR2012 and SR2012 seasons, respectively. The unweeded plots had the crop maturing significantly ($p \leq 0.05$) earlier than those under the hand and herbicides treated plots. This was attributed to weeds withdrawing essential growth resources from the crop leading to nutrient and moisture deficiencies. Such plants reached physiological maturity earlier than 135 days (expected from DK 8031) maize variety. Both shoot biomass and grain yields determined at harvesting time significantly

($p \leq 0.05$) differed between unweeded and the herbicide applied and conventionally tilled plots (Table 4.20).

Table 4.20: Effect of herbicides weed control on maize biomass and grain yields

Weed control method	Herbicide rate (liters ha^{-1})	Biomass yield (t ha^{-1})	Grain Yield (t ha^{-1})
Roundup weather max	3.0	9.20a	4.30ab
Unweeded control	N/A	1.00c	0.11c
Conventional method	N/A	7.01b	3.61 b
Roundup weather max	2.5	9.52a	4.02a b
Roundup turbo	2.5	8.60ab	4.42ab
Roundup weather max	1.5	8.50ab	4.51a
Mean	-	7.31	3.52
LSD (0.05)	-	1.901	0.911
CV (%)	-	16.30	22.51

Means in the same column with the same letter are not significantly different ($p \leq 0.05$). CV = coefficient of variation; LSD = least significant difference.

The three seasons average shoot biomass was 7.3 t ha^{-1}. The three rates, 1.5, 2.5 and 3.0 liters ha^{-1} of RWMX provided significantly ($p \leq 0.05$) higher average biomass yields at 8.5, 9.5 and 9.2 t ha^{-1}, respectively compared to unweeded control that had 1.0 t ha^{-1}. Conventional tillage treatments had 7.0 t ha^{-1} average shoot biomass yields which significantly differed from that of unweeded control. The observed grain yields had also similar trends as the ones of shoot biomass. The ZT treatments in particular gave 4.4, 4.3 and 4.0 t ha^{-1} grain yields from RTB (2.5 liters ha^{-1}), RWMX (3.0 liters ha^{-1}) and RWMX (2.5 liters ha^{-1}) treatments, respectively. The yields from ZT treatments were not significantly different from one another in the three seasons that the study was conducted. Conventionally tilled plots had an average grain yield of 3.6 t ha^{-1}. This was not significantly different from those from ZT treatments. The lowest average grain yield was 0.1 t ha^{-1} from unweeded treatment and significantly ($p \leq 0.05$) differed from those of conventional and herbicides treated plots. Improved yields from CVT and ZT managed plots were attributed to better weeds control under compared to unweeded control plots. By comparing the total net revenue (TR) and total costs (TC) for each treatment, net benefits (NB) were calculated. This was achieved by subtracting TC from TR. Working with Kenya shilling (KES), 99797, 90123 and 94392 were respectively reported for SR2011, LR2012 and SR2012 seasons (Figure 4.22). The seasonal average NB from unweeded treatment was significantly ($p \leq 0.05$) lower than what was observed from the ZT and CVT tilled plots.

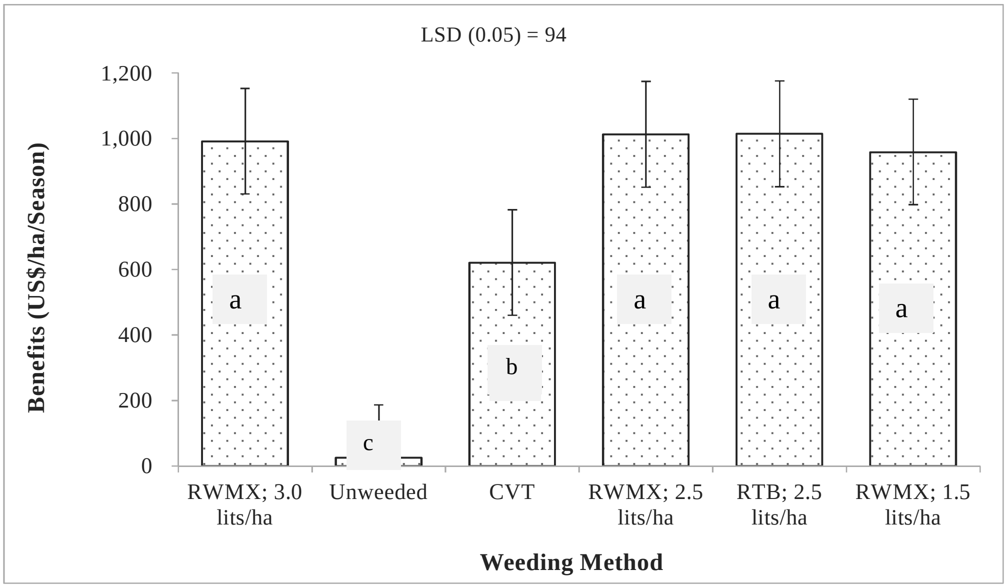

Figure 4.22: Effect of herbicides weed control on maize net-benefits. RWMX = Roundup Weathermax; RTB = Roundup Turbo; CVT = Conventional tillage. Bars with the same letter are not significantly different ($p \leq 0.05$).

4.7 Application of APSIM computer model in conservation agriculture

The following write-up highlights on the effect APSIM model on predicting crop yield under CA practices (Figure 4.23). There were lengthy dry spells at key crop growth stages, particularly at and after crop anthesis. The poor in-crop seasonal rainfall distribution in SR2011 growing season and dry spells in other seasons might resulting from poor rainfall distribution negatively affected maize and bean growth and yields. However, ccomparable outputs were observed for the measured and the APSIM predicted maize and bean crop grain yields. This was apparent under sole maize cropping system conventional tillage practice (CVT_SMz) across the 4 seasons of experimentation. The model under-predicted maize yields when intercropped with bean under the conventional tillage treatment (CVT_MzBn). This under prediction was extended to maize-bean intercrop under zero tillage treatment (ZT_MzBn). This was apparent in seasons 1 (SR2011) and 4 (LR 2013).

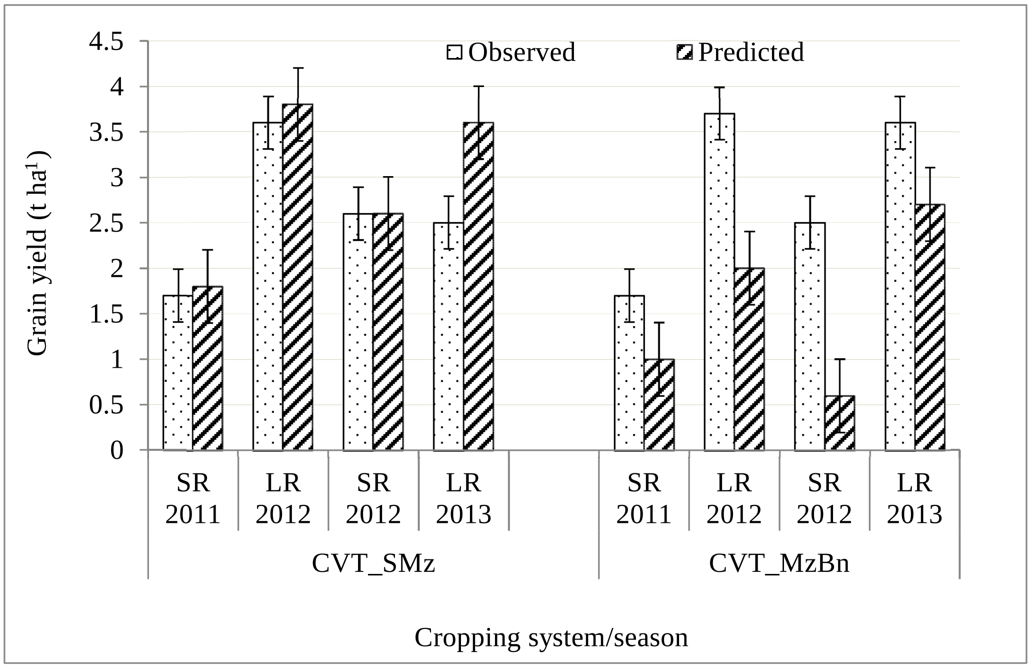

Figure 4.23: Observed and APSIM simulated maize grain yields from conventional farming treatments. CVT_SMz = conventional tillage planted with sole maize; CVT_MzBn = conventional tillage planted with maize-bean intercrop.

Under-prediction was noted in only season 2 (LR2012) for the case of furrows/ridges treatment (FR_SMz). Otherwise there were good maize yield predictions in all other seasons for sole maize (FR_SMz) and maize-bean intercrop (FR_MzBn) under FR tillage practice. Despite the model being configured for enhanced water capture through application of residue, it simulated little benefit to maize yield under sole maize under zero tillage practice (ZT_SMz) in season 2 (LR2012), maize-bean intercrop under zero tillage practice (ZT_MzBn) in seasons 1 (SR2011) and 4 (LR2013) and under (FR_SMz) in season 2 (Figure 4.24).

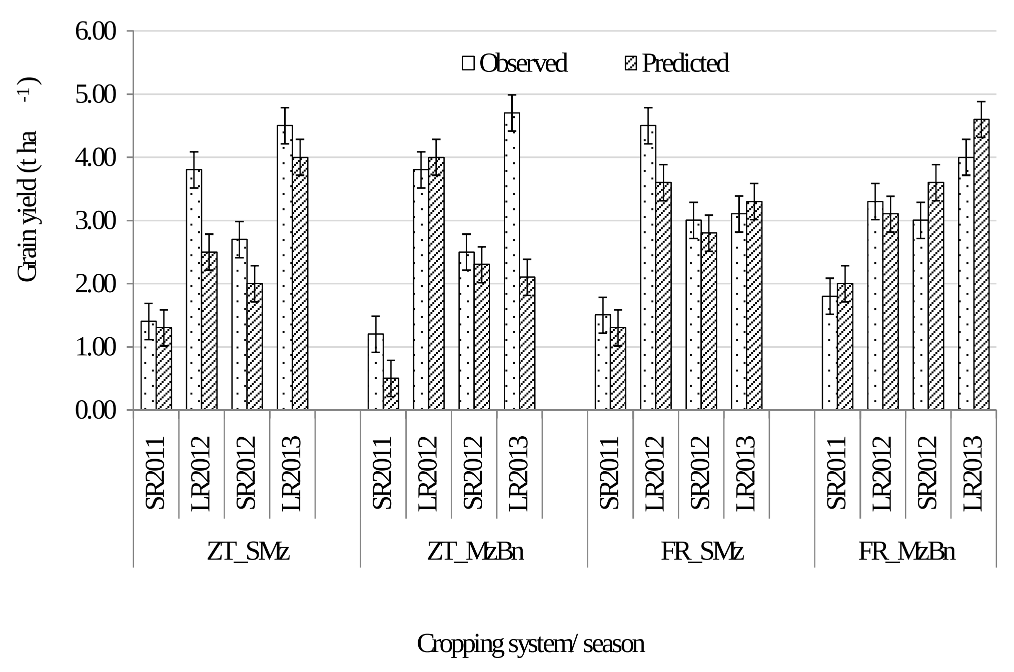

Figure 4.24: Observed and simulated maize grain yields from conservation agriculture treatments. ZT_SMz = Zero tillage planted with sole maize; ZT_MzBn = Zero tillage planted with maize-bean intercrop. FR_SMz = Furrows/ridges tillage planted with sole maize; FR_MzBn = Furrows/ridges planted with maize-bean intercrop.

The scenario may have been caused by N immobilisation resulting from seasonal (except in season 1) application of residues with high (102) C:N ratio (Section 3.7.6; Table 3.4). Application of high C:N ratio mulch increases biological activities leading to greater microbial demand for nitrogen. In this case, nitrate (NO_3-) and ammonium (NH_4^+) are taken up by soil microbes, thus becoming unavailable to crops (Grahmann et al., 2013). Appreciable model yield predictions under the FR could have resulted from better initial model calibration where the curve-number was set at 70 from 80 to reflect higher moisture capture for the FR treatment. As the case of CVT_MzBn), the model did not perceive nutrient competition between maize and bean crop under the FR treatments. Alternatively, the model may have perceived limited N immobilization resulting from application of high C:N ratio crop residue; or seasonal application of maize residues in FR may have provided moisture benefits for the simulated crop yields. The model starting moisture was set 90% full within the soil profile.

Under predicted yield when maize was intercropped with bean, was interpreted to over prediction of the intercrop bean yield during the same seasons for CVT_MzBn treatment. The model simulation may have perceived that the bean out-competed maize for growth resources. This is further thought to be related to an input coefficient for the bean module that made its initial leaf area dominant over that of maize. This rationale is supported by good prediction for sole bean in seasons 2, 3 and 4 across tillage treatments (Figure 4.25). All bean yields in the drought-affected season 1 were over-predicted by a sizeable margin. This may require further investigation.

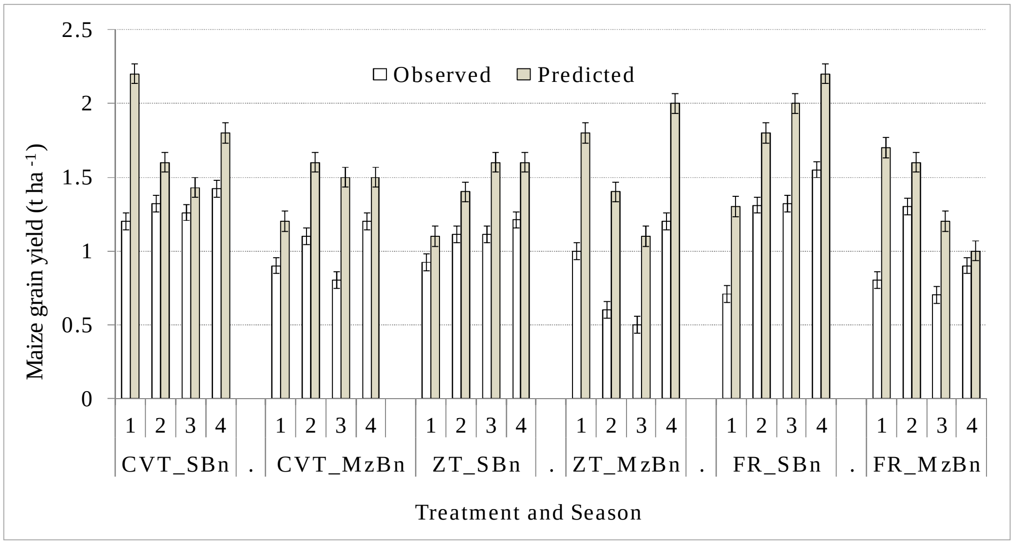

Figure 4.25: Observed and simulated bean grain yields

4.8 Crop water use efficiency

The average water use efficiency (WUE) ranged between 4 to 13 kg mm^{-1} of rainfall over the experimentation period. During the first season (SR2011), an average of 5.18 kg ha^{-1} mm^{-1} WUE was obtained under conventional tillage compared to the CA practices, furrows and ridges (3.79 kg ha^{-1} mm^{-1}) and zero tillage (3.95 kg ha^{-1} mm^{-1}) (Figure 4.26). The findings were against those reported in CA trials in Nigeria by Osuji (1984) that the WUE and maize grain yields were significantly higher under ZT than under the CVT.

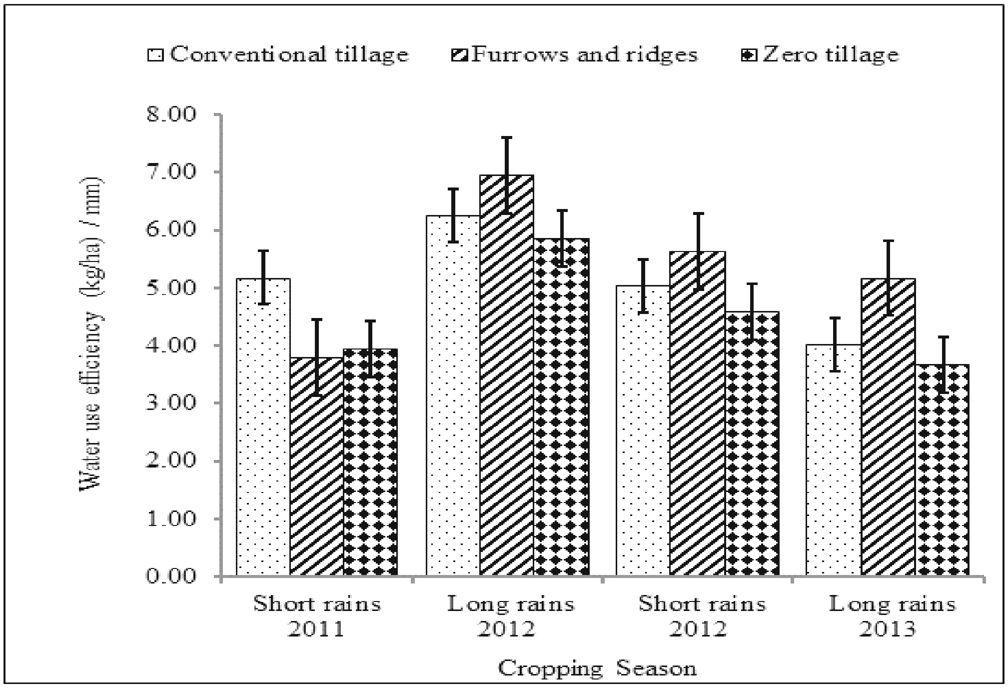

Figure 4.26: Crop water use efficiency as affected by tillage practices

As explained by Hartkamp et al., (2004), the CA tillage systems should have some advantage over the CVT. The CA plots were meant to have residue retained on the soil surface. The first season (SR2011) of experimentation did not have mulches on the CA plots. Thus, the CA treatment did not have an advantage over the CVT tillage practice on moisture capture. However, enhanced WUE and subsequently higher grain yields were later observed under the CA plots in seasons 2, 3 and4. The findings were similar to those reported by Rockström et al., (2009) that there is a tendency to improve water harvesting for crop use by applying CA compared to

CVT farming methods. Thus, in seasons LR2012, SR2012 and LR2013 higher water efficiencies were attained under the CA practices. This meant that the CA tillage practices combined with crop residue retention harvested more moisture than the CVT system for crop use. For example, significantly higher WUE of 5.2 kg ha^{-1} mm^{-1} was recorded from FR treatment compared to 4.0 and 3.7 kg ha^{-1} mm^{-1} for from CVT and ZT tillage systems, respectively. Utilization of resources by crops is greatly affected by weeds when the crop and weeds compete for light, nutrients and moisture. This is supported by Peterson & Westfall (2004) who reported that the impact of weeds competition with the crop depends on the crop species and the level of weed control. Good weed control under the CA plots using pre- and post-emergence herbicides might have contributed greatly to improved crop WUE.

4.9 Economics of conservation agriculture practices

4.9.1 Labour requirement

Calculations for the net benefits (NB) were achieved by collecting and analyzing inputs/operation costs and output prices for CVT and CA based tillage practices. The unit of costing was the Kenya Shilling (KES) which was converted to USD. On average, KES 85.0 was equivalent to USD 1.0. The economic performance of the tillage practices was assessed and summarized into net benefits (NB) with focus on labour productivity. Labour requirements remained high in CVT plots compared to FR and ZT practices whose labour requirements for land preparation and weeding declined significantly from the first to second, third and fourth seasons. Preparation of FR structures took 56.6 man-days during the first season compared to less than 10 man-days ha^{-1} in the subsequent seasons. This decline in labour requirement during the second, third and fourth seasons was attributed to reduced tillage and weed control under FR treatment. The cost of making and maintaining FR changed from USD 200.0 ha^{-1} in SR2011 to USD 52.0, 60.7 and 65.7 ha^{-1} following LR2012, SR2012 and LR2013 seasons, respectively (Figure 4.27).

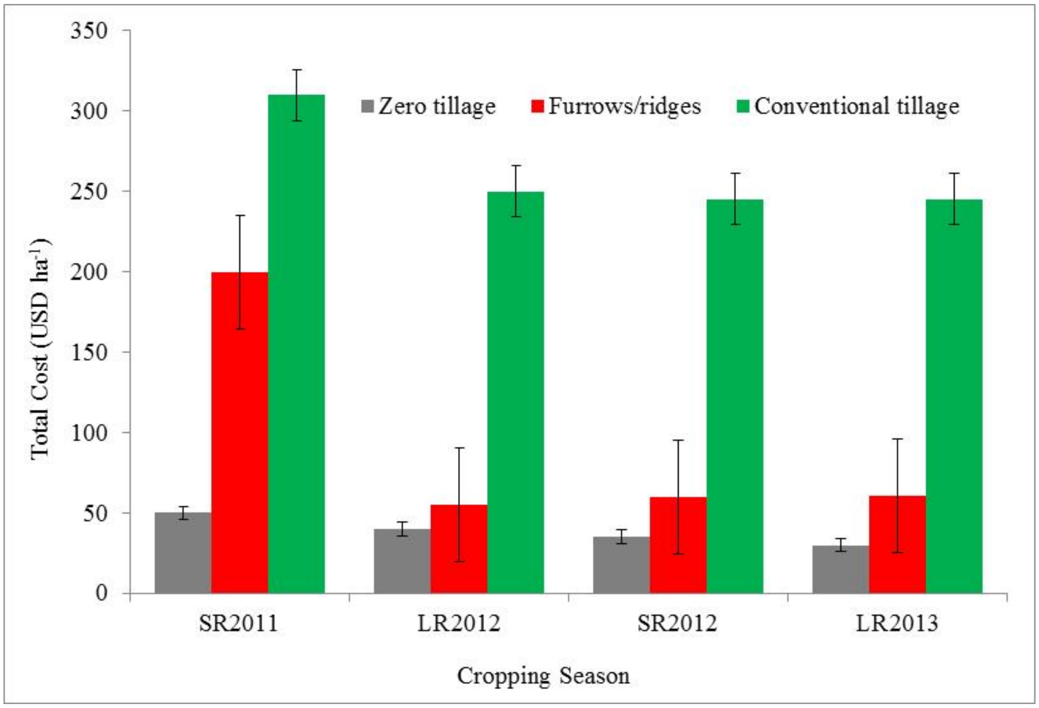

Figure 4.27: Effect of tillage practices on land preparation and weeding costs

There was minimum variation in production cost in land preparation under ZT because the soil was not disturbed or ploughed, except for seed and fertilizer holes that were made according to the crop spacing (Appendix 3.14). Weeds control under the ZT was done using pre- and post-emergence herbicides. Only during the first season that the operational cost under FR was significantly ($p \leq 0.05$) higher (USD 200.0) than that from ZT (USD 50.0). Otherwise the costs did not significantly differ between the two CA tillage systems during the second, third and fourth seasons of experimentation. Land preparation under CVT system was the highest (USD 320.0) operational cost resulting from the first (digging) and second (harrowing) land preparation costs during SR2011. The total costs remained constantly high at USD 250.0, 295.0 and 293.0 ha^{-1} for LR2012, SR2012 and LR 2013 season, respectively. The high cost of operation under CVT practice was caused by per season land ploughing followed by harrowing and two hand weeding events. Low labour requirements under CA tillage practices showed that more labour could be released for off-farm activities.

4.9.2 Maize-bean net-benefits

The net benefits (NB) were comparable to those obtained by Guto et al., (2011) in their study to investigate socio-ecological niches for ZT and crop residue retention under continuous maize cropping systems in Central Kenyan highlands. Their study found significantly higher NB resulting from practicing CA farming methods compared CVT tillage systems. Except during the first season (SR2011) that the CVT and the CA based treatments presented less than USD 50.00 ha^{-1} average NB, the rest of the seasons had higher than USD 500.00 ha^{-1} (Figure 4.28). In particular, FR treatment exhibited significantly ($p \leq 0.05$) higher NB values during the third and fourth seasons. The third and fourth seasons had the FR presenting significantly higher (USD 1,100.00 and USD 1,250.00 ha^{-1}, respectively) NB compared to between USD 800.00 ha^{-1} and USD 1,000.0 ha^{-1} season^{-1} under CVT and ZT systems. The low net-benefits during the SR2011 season was linked to low and poorly distributed effective rainfall. In all seasons, the net-benefits did not differ significantly between the CVT and ZT treatments. The higher NB under the FR tillage system resulted from low labour demand compared to what was needed the CVT system. The meaning of this is that the benefits are defined in short-term but much better under long-term period of applying the CA principles and practices.

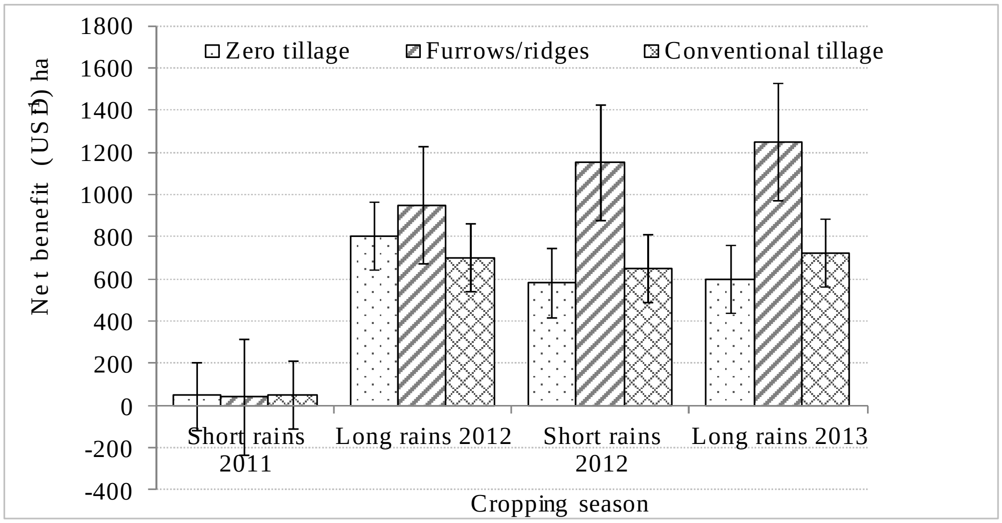

Figure 4.28: Effect of tillage practices on maize-bean net benefits

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

- Application of conservation agriculture principles and practices led to improved soil properties and maize and crop growth and grain yields. This is particularly when furrows/ridges tillage system combined with soil liming, nitrogen fertilizer application and herbicides weed control practices. However, application of nitrogen fertilizer to common bean depressed the number of fertile root nodule yields.
- Among the tested tillage systems, application of furrows/ridges led to improved soil biology (bacteria and fungi populations) in maize-bean cropping systems. However the practices did not seem to change the bacteria colony forming units that defines the microbe's population.
- Irrespective of tillage or residue management methods, soil liming was singled out as one of the conservation agriculture practices. Soil liming improved the soil pH, extractable phosphorus crop yields within one or two seasons of applying the technology.
- Crop retention on furrows/ridges tillage system, combined with soil liming and N fertilizer application practices significantly improved crop growth, grain yields and water use efficiency.
- Application of glyphosate based herbicides had improved the percent weed suppression, thus grain yields and net-benefits of crops grown under conservation agriculture farming methods.
- The APSIM computer model was able to predicting maize grain yields under conventional and conservation agriculture based tillage systems.
- Maize and bean growth and grain yields were negatively affected by in-crop rainfall variability rather than the amount of rainfall per season.

5.1 Recommendations and areas for further research

5.2.1 Recommendations

The study made the following recommendations:

- Simplify, package and promote the feasible conservation agriculture technologies (e.g. furrows/ridges, crop retention, herbicide weed control and soil liming) to farmers and other land users.
- Support soil liming as one of the key conservation agriculture practices for maize and bean intensification systems.
- Consider soil biology together with soil physical and chemical properties when defining soil fertility.
- Encourage and support use of herbicides for weed control in conservation agriculture farming systems.
- Support ASPSIM computer model towards interpreting short-term (less 5 years) and long-term (above 10 years) soil and crop dynamics under conventional and conservation agriculture farming systems.
- Consider system profitability together with biophysical outputs from conservation agriculture farming.

5.2.2 Areas for further research

The study suggested the following topics for further research:

- Establish long-term (above 10 years) trials for monitoring soil quality and crop yield benefits of applying conservation agriculture principles and practices.
- Determine soil water dynamisms in maize-bean intensification under conservation agriculture farming systems.
- Determine the contribution of soil micro-organisms on soil quality and crop yields under conservation agriculture farming systems.
- Develop APSIM model, - towards calibrating the various modules (e.g. climate, cultivars, soil and field operations).
- Establish the effect of rainfall (seasonal) amount and variability as a key driver for sound outputs from application of conservation agriculture.

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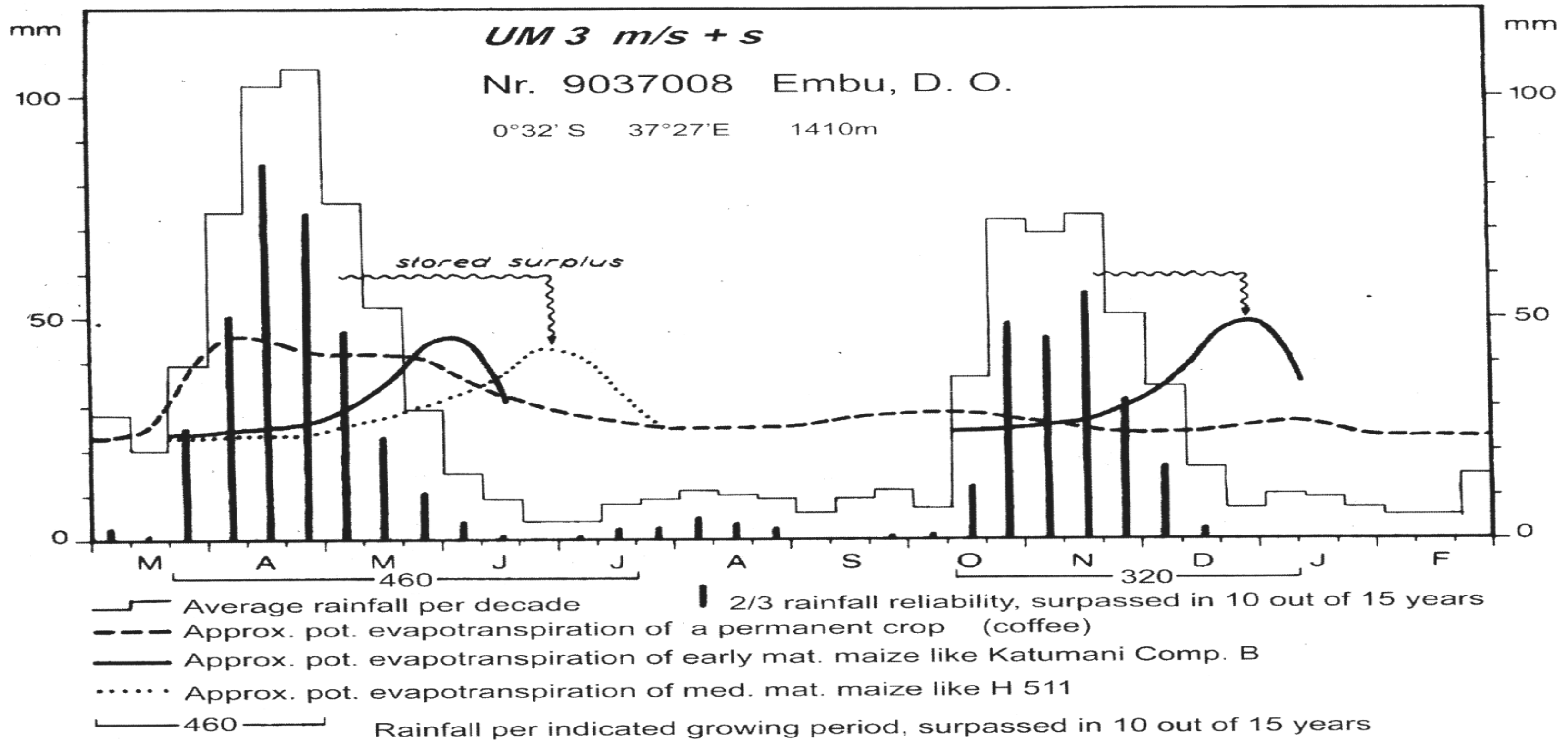
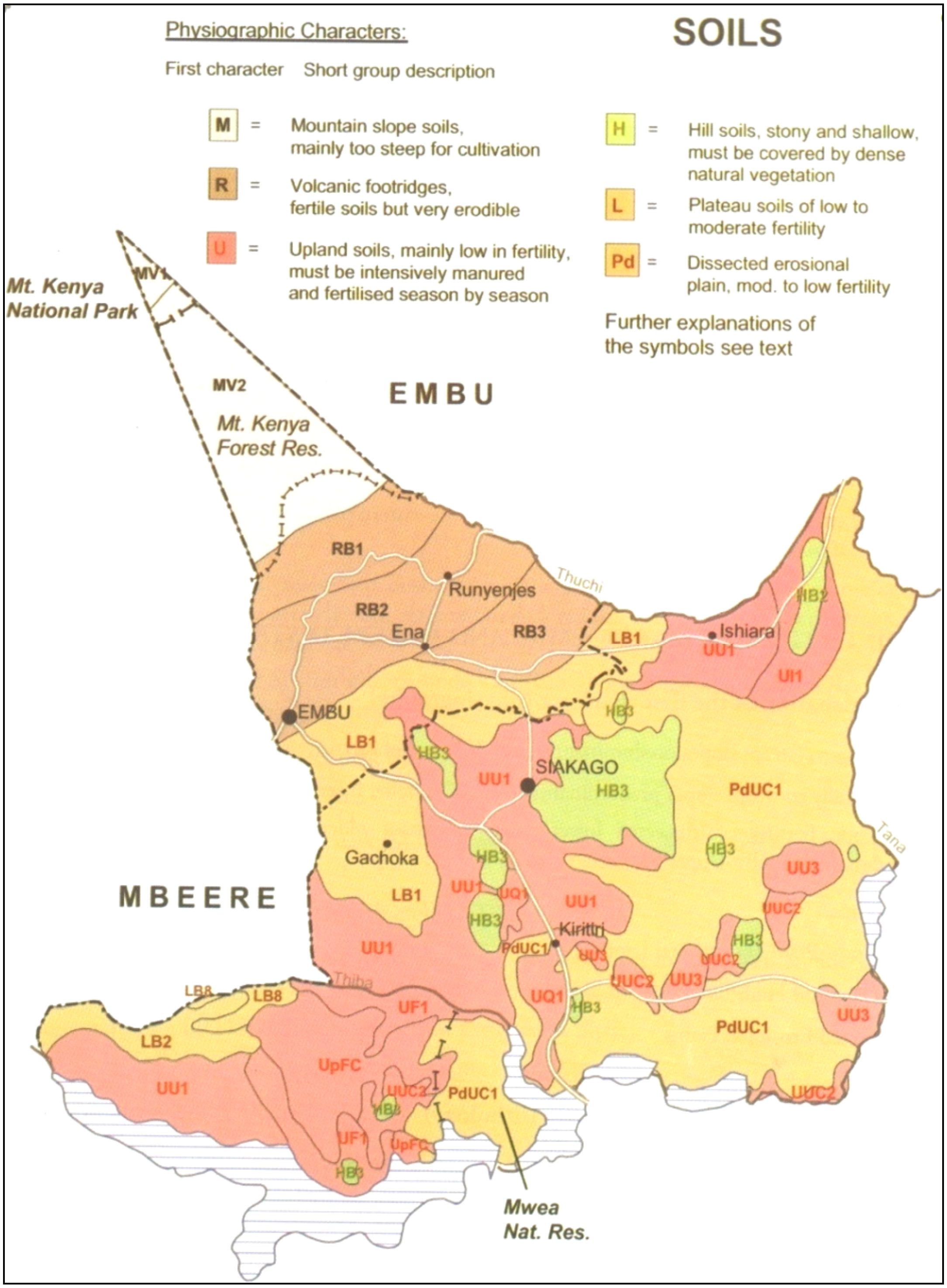
APPENDICES



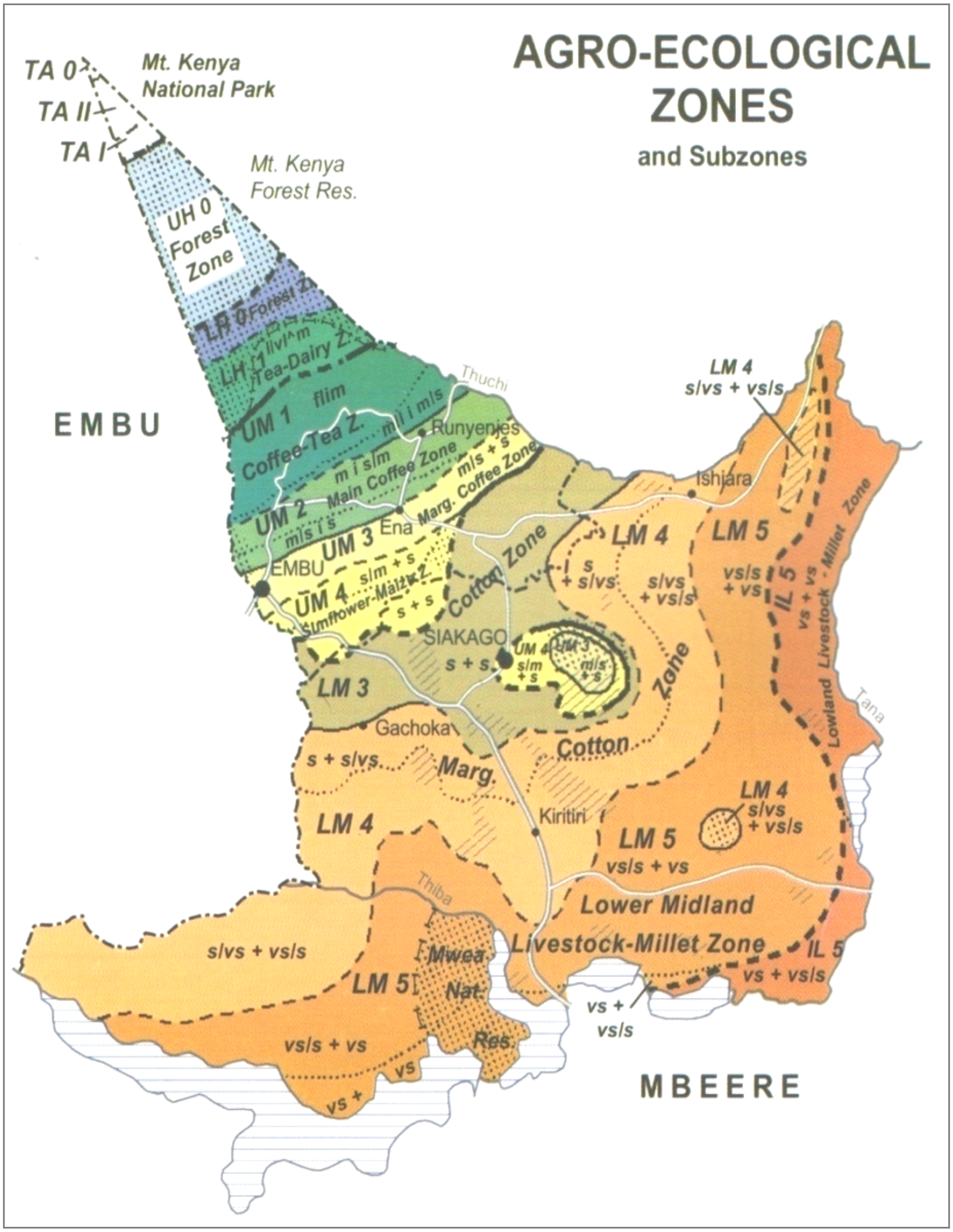
Source: (Jaetzold et al., 2006).

Appendix 3.1: Bimodal rainfall patterns for Eastern Kenya



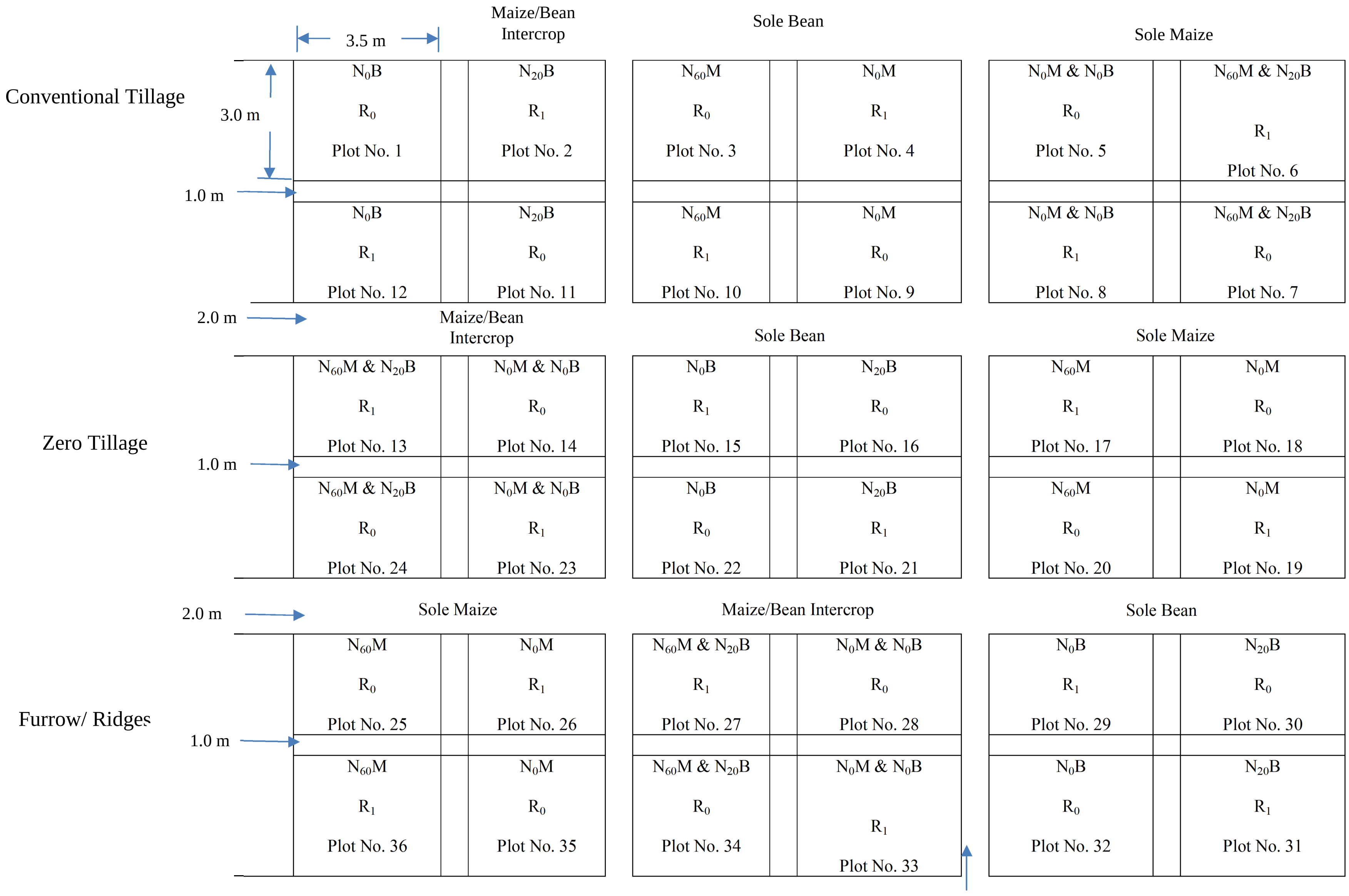
Source: (Jaetzold et al., 2006).

Appendix 3.2: Diverse soil types in Embu County in Eastern Kenya

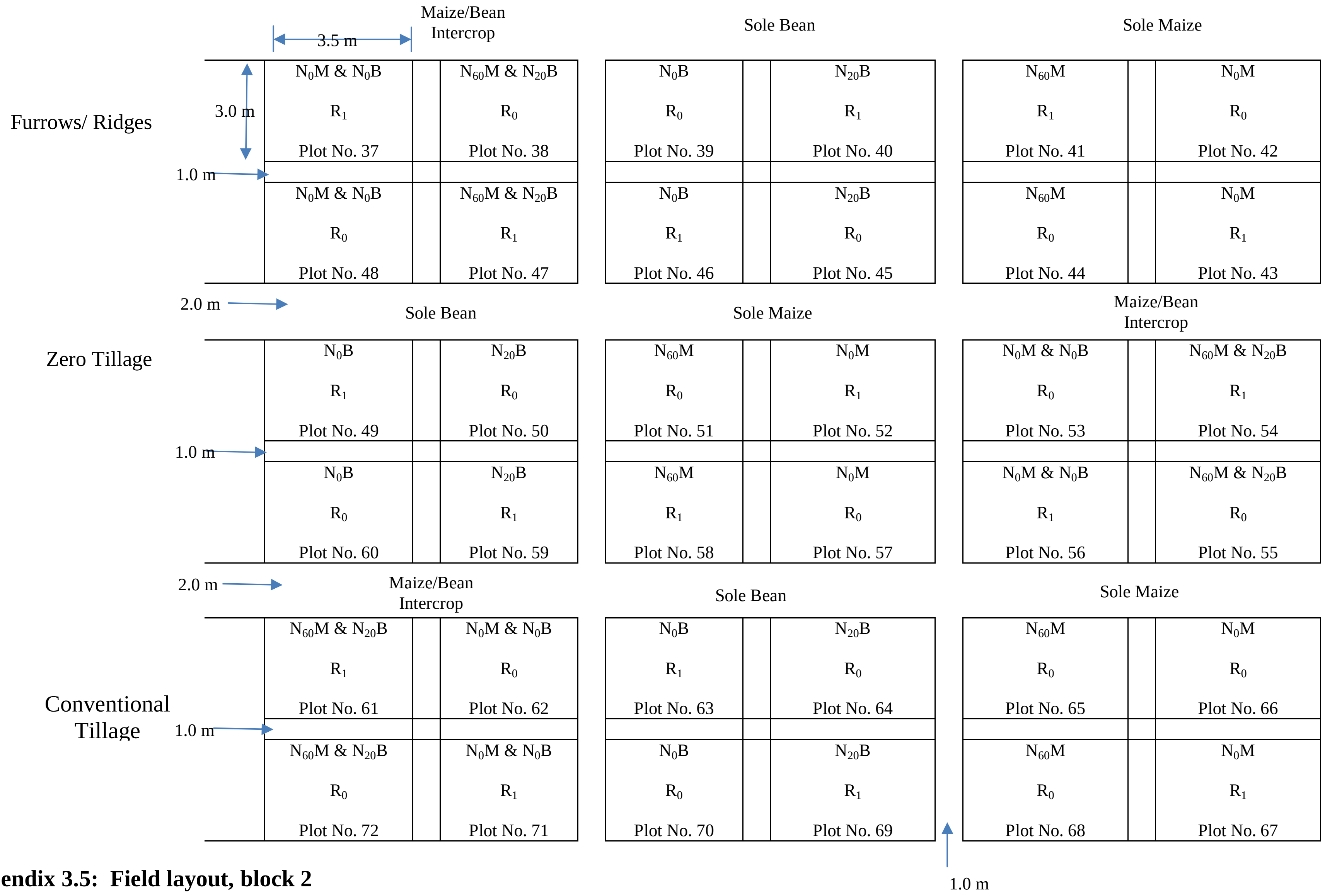


Source: (Jaetzold et al., 2006).

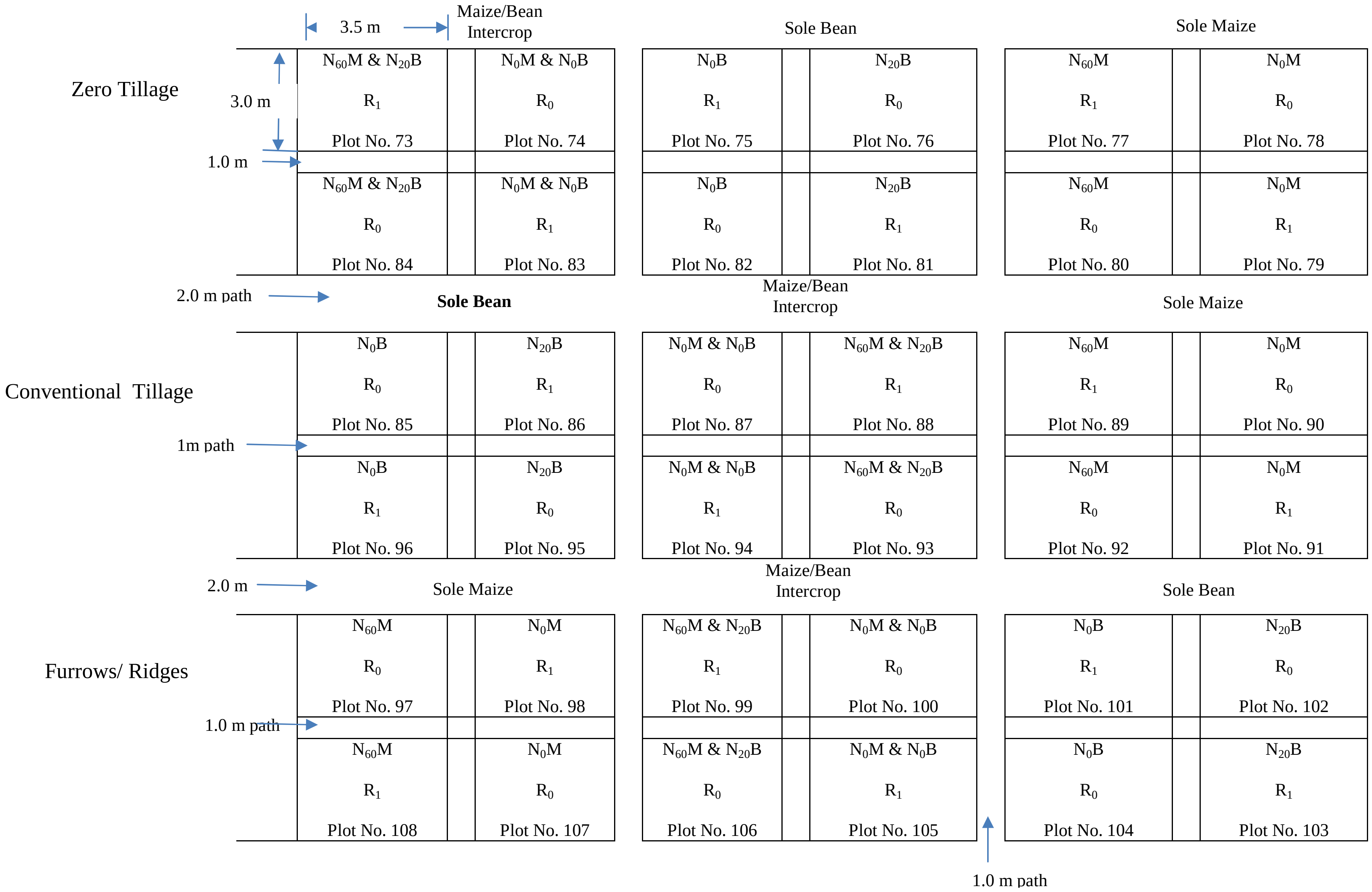
Appendix 3.3: Diverse agro-ecological zones in Embu County in Eastern Kenya



Appendix 3.4: Field layout, block 1



Appendix 3.5: Field layout, block 2

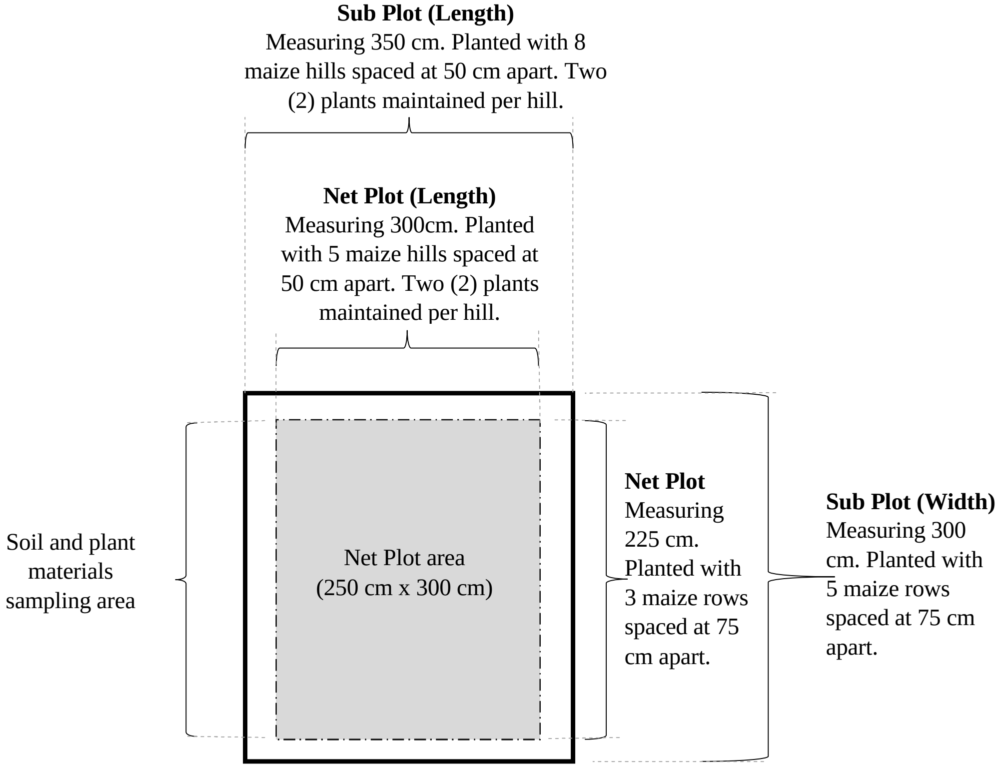


Zero Tillage	Maize/Bean Intercrop		Sole Bean		Sole Maize	
	$N_{60}M$ & $N_{20}B$ R_1 Plot No. 73	N_0M & N_0B R_0 Plot No. 74	N_0B R_1 Plot No. 75	$N_{20}B$ R_0 Plot No. 76	$N_{60}M$ R_1 Plot No. 77	N_0M R_0 Plot No. 78
	$N_{60}M$ & $N_{20}B$ R_0 Plot No. 84	N_0M & N_0B R_1 Plot No. 83	N_0B R_0 Plot No. 82	$N_{20}B$ R_1 Plot No. 81	$N_{60}M$ R_0 Plot No. 80	N_0M R_1 Plot No. 79

Conventional Tillage	**Sole Bean**		Maize/Bean Intercrop		Sole Maize	
	N_0B R_0 Plot No. 85	$N_{20}B$ R_1 Plot No. 86	N_0M & N_0B R_0 Plot No. 87	$N_{60}M$ & $N_{20}B$ R_1 Plot No. 88	$N_{60}M$ R_1 Plot No. 89	N_0M R_0 Plot No. 90
	N_0B R_1 Plot No. 96	$N_{20}B$ R_0 Plot No. 95	N_0M & N_0B R_1 Plot No. 94	$N_{60}M$ & $N_{20}B$ R_0 Plot No. 93	$N_{60}M$ R_0 Plot No. 92	N_0M R_1 Plot No. 91

Furrows/ Ridges	Sole Maize		Maize/Bean Intercrop		Sole Bean	
	$N_{60}M$ R_0 Plot No. 97	N_0M R_1 Plot No. 98	$N_{60}M$ & $N_{20}B$ R_1 Plot No. 99	N_0M & N_0B R_0 Plot No. 100	N_0B R_1 Plot No. 101	$N_{20}B$ R_0 Plot No. 102
	$N_{60}M$ R_1 Plot No. 108	N_0M R_0 Plot No. 107	$N_{60}M$ & $N_{20}B$ R_0 Plot No. 106	N_0M & N_0B R_1 Plot No. 105	N_0B R_0 Plot No. 104	$N_{20}B$ R_1 Plot No. 103

Appendix 3.6: Field layout, block 3



Appendix 3.7: Net plot where soil and plant samples were measured from

Appendix 3.8: Soil particle determination

The procedures used are as outlined by Okalebo et al., (2002). Five soil samples were randomly taken within each of the three experimental blocks. Hence, there were fifteen samples delivered to the laboratory for sand, clay and silt % determination. The samples were air-dried and sieved with a 2 mm size sieve. Sub-samples weighing 51 g were taken from each sample were weighed and transferred to a "milkshake" mix cup. The 51 g air dry sample represents approximately 50.0 g of oven-dry soil. Fifty (50) ml of 5% sodium hexametaphosphate was added along with stirring rods in each samples and stirred for 15 minutes using the multimix machine while in cups. The suspensions were later on transferred from the cup into the glass cylinder. With the hydrometer in the suspension, distilled water was added to make the volume to 1130 ml and then hydrometer was removed. Each cylinder was covered with a tight-fitting rubber bung and inverted several times until the suspension was thoroughly mixed. The cylinders were then placed on a flat surface, added 3 drops of amyl alcohol to remove froth. Soil hydrometer was slowly placed into the suspension. The hydrometer floated, followed by taking first “hydrometer reading”. Temperature of the suspension was also taken with a thermometer. This first reading was meant to determine the percent silt in the suspension.

The suspension was left to stand for three hours before taking the second hydrometer and thermometer readings to determine the percent clay. The temperature readings were converted from ^{0}C to Fahrenheit scale. For every degree over 68^{0}F, 0.2 was added to the hydrometer reading to compensate for the added dispersing agent. On other hand, 0.2 was subtracted from the hydrometer reading in cases where the temperature values where less than 68^0 F. A check on the 40 seconds reading was made by sieving the entire suspension through a 300-mesh sieve to remove sand. It was then dried in the oven at 100^{0}C and strained to remove any remaining silt before weighing. The weight was then multiplied by 2. This formed the percentage of sand in the soil. The final parameters are as follows:

1a.Hydrometer reading at 40 seconds, H_1 = 18;

1b. Temperature reading at 40 seconds, T_1 +75^{0}F;

2a. Hydrometer reading at 3 hours, H_2 = 63^{0}F;

2b.Temperature at 3 hours, T_2 = 63^{0}F;

3. Temperature correction added to hydrometer reading = 0.2 (T-68).

Where T = degrees Fahrenheit, then, silt correction to be added to hydrometer reading = -2.0

Appendix 3.9: Determination of soil organic carbon

Organic carbon was determined by the sulphuric acid and aqueous potassium dichromate ($K_2Cr_2O_7$) mixture. After complete oxidation from the heat of solution and external heating (Nelson & Sommers, 1975) the unused or residual ($K_2Cr_2O_7$) (in oxidation) was titrated against ferrous ammonium sulphate. The used ($K_2Cr_2O_7$), the difference between added and residual ($K_2Cr_2O_7$), gave a measure of organic C content of the soil. The chemical reaction in this method is;

$2Cr_2O_7^{2-}+3C+16H^+ \longrightarrow 4Cr^{3+}+3C0_2+8H_2O$

An additional method was provided where the amount of chromic Cr^{3+} ions formed during the oxidation process was determined colorimetrically to give total of organic carbon present in the soil sample. This method is suitable for soils with higher (above 2%) carbon content and has the following reagents and procedure:

Reagents

1. 1N Potassium dichromate solution: Dissolve 49.029g of dry ($K_2Cr_2O_7$) in about 800 ml of distilled water, and dilute to 1000 ml.
2. Sulphuric acid, concentrated.
3. Ferrous ammonium Sulphate solution, 0.2 M. Dissolve 78.39 g ferrous ammonium sulphate in 50 mi conc.H_2SO_4, and dilute to 1000ml with distilled water.
4. Indicator solution 1.10 Phenanthroline monohydrate –ferrous sulphate (ferroin). $[C_{12}H_8N_2]_3FeSO_4$.Dissolve 1.485 g of 1,10 ortho-phenathroline monohydrate ($C_{12}H_8N_2.H_2O$) in 100 ml of 0.025 M ferrous sulphate(0.695 g of ferrous sulphate $FeSO_4.7H_2O$) in 100ml of distilled water.

Procedure

1. Weigh out 0.1 to 0.5 g of ground (60 mesh) soil into a block digester tube sample weight).Add 5 ml potassium dichromate solution and 7.5ml conc.H_2SO_4.
2. Place the tube in a pre-heated block at 145-155^{0}C for exactly 30 minutes.
3. Quantitatively transfer the digest to a 100ml conical flask, and 0.3ml of the indicator solution. Using a magnetic stirrer, to ensure good mixing, titrate the digest with ferrous ammonium sulphate solution; the end point is reached with a colour change from greenish to brown.
4. Record the titre and correct for the mean of 2 reagent blanks (T).

Calculation

$$\text{Organic carbon (\%)} = \frac{\text{T x 0.3 x 0.2}}{\text{Sample weight}}$$

Appendix 3.10: Determination of total soil nitrogen

The method involves digestion of nitrogen in organic matter using concentrated sulphuric acid containing potassium sulphate (Kjeldahl, 1883). In this method, soil is oxidized with sulphuric acid in the presence of selenium mixture as a catalyst, during which nitrogen is converted to ammonium sulphate (Okalebo et al., 2002). The procedure entails weighing 1 g of air-dried soil ground to pass through 0.5 mm sieve into the digestion tube. One (1) g of catalyst mixture ($CUSO_4$ +K_2SO_4 + Selenium) 10 mls and concentrated H_2SO_4 were added. The mixture was heated on a digestion block for 2-3 hours at 250 - 350^0C until the mixture became colourless. Any remaining sand had turned white at this stage. The sample was cooled down and then transferred into a 100 ml volumetric flask, made up to volume and allowed to settle until the supernatant liquid was clear. This was followed by pipetting 10 ml of the digest into the Kjedahl flask and adding 10 ml of 46% NaOH. The aliquot was distilled for 2 minutes after the indicator turned from pick to green. Ammonia (NH_3) was released during distillation and captured into 50 ml boric acid containing four drops of the mixed indicator. The distillate was then titrated with 0.01 NHCL until the colour changed back to pick. The percentage N content in the soil was calculated as follows:

$$\text{\% Nitrogen in the soil sample} = \frac{(T - B) \times M \times 14 \times V \times 100}{100 \times S \times al}$$

Where:, T = Volume of the titre HCL for the sample; B = Volume of the titre HCL for the blank; M = Molarity of the HCL; V = Final volume of the digest; S = Weight of the sample in milligrams; al = aliquot of solution taken.

Notes:

i. 100 ml of digest was used from which 10 ml aliquot was distilled.

ii. 0.01 N acid in the titration is equivalent to 0.14 mg ammonium nitrogen.

Appendix 3.11: Determination of soil phosphorus concentration

The extractable soil P was determined using the Mehlich double acid method. The method involved extracting P from the oven dry soil in a 1:5 ratio (w/v) with a mixture of 0.1 N HCl and 0.025 N H_2SO_4. The same method was used to extract Mg, Ca, K and

Na from the soil samples. Mehlich method was preferred over the others because the soil had pH value below 7.0. The procedure involved grinding the soil sample to pass through the 0.5 mm sieve, weighing and putting 10.0 g of the soil into 100 ml plastic bottles for shaking. This was followed by adding 50 ml of the double acid solution (0.1 N HCL+0.025 N H_2SO_4) and shaking for 30 minutes and filtering the mixture using number 42 Whatman filter papers, 5 ml of the soil extract, standard series and blank was pipetted into test tubes and 1 ml of ammonium vanadate-ammonium, molybdate solution added. The solutions were mixed and the colour intensity read after 1 hour using UV-visible spectrophometer (Unican SP 500 series 2 ultra violet and visible) at 430 nm. The P concentration in the samples was determined from standard curve and with calculated as follows:

$$\text{P (mg kg}^{-1}\text{)} = \frac{[(a-b) \times v \times f \times 1000]}{(1000 \times w)}$$

Where,

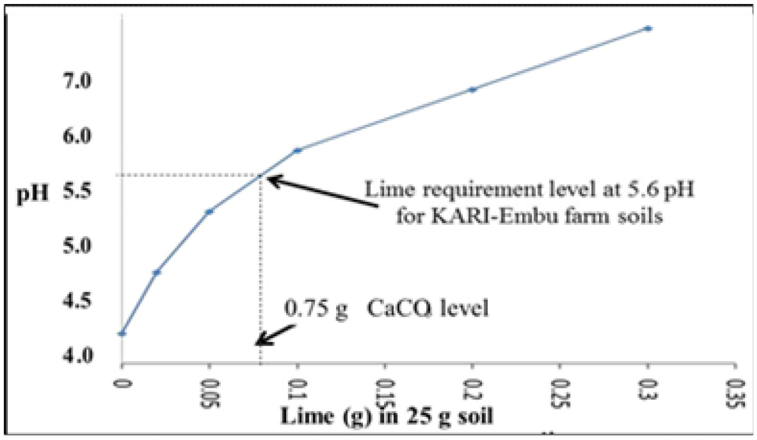
a = P concentration in the sample;

b = P concentration in the blank;

v = Volume of the extracting solution;

f = Dilution factor;

w = Weight of the sample in g.



Appendix 3.12: Developed lime requirement curve for KALRO-Embu farm

Furrows/ridges tillage method

	$N_1R_0L_0$	$N_1R_0L_1$	$N_0R_0L_1$	$N_1R_1L_1$	$N_0R_1L_1$	$N_0R_0L_0$	$N_1R_1L_0$	$N_0R_1L_0$
	Plot	Plot	Plot	Plot	Plot	Plot	Plot	Plot
Rep. 1	1	2	3	4	5	6	7	8

Conventional tillage method

$N_0R_0L_0$	$N_1R_0L_1$	$N_1R_1L_0$	$N_0R_1L_0$	$N_1R_1L_1$	$N_0R_0L_1$	$N_1R_0L_0$	$N_0R_1L_1$
Plot	Plot	Plot	Plot	Plot	Plot	Plot	Plot
9	10	11	12	13	14	15	16

Conventional tillage method

	$N_0R_1L_0$	$N_1R_1L_1$	$N_0R_1L_1$	$N_1R_1L_0$	$N_1R_0L_0$	$N_0R_0L_1$	$N_1R_0L_1$	$N_0R_0L_0$
	Plot	Plot	Plot	Plot	Plot	Plot	Plot	Plot
Rep. 2	32	31	30	29	28	27	26	25

Furrows/ridges tillage method

$N_0R_0L_1$	$N_1R_1L_1$	$N_0R_1L_1$	$N_1R_0L_0$	$N_0R_0L_0$	$N_1R_1L_0$	$N_1R_0L_1$	$N_0R_1L_0$
Plot	Plot	Plot	Plot	Plot	Plot	Plot	Plot
24	23	22	21	20	19	18	17

Furrows/ridges tillage method

	$N_1R_1L_0$	$N_0R_0L_1$	$N_1R_0L_1$	$N_0R_0L_0$	$N_0R_1L_0$	$N_1R_1L_1$	$N_1R_0L_0$	$N_0R_1L_1$
	Plot	Plot	Plot	Plot	Plot	Plot	Plot	Plot
Rep. 3	33	34	35	36	37	38	39	40

Conventional tillage method

$N_1R_0L_1$	$N_0R_0L_0$	$N_1R_1L_0$	$N_0R_0L_1$	$N_1R_0L_0$	$N_0R_1L_1$	$N_0R_1L_0$	$N_1R_1L_1$
Plot	Plot	Plot	Plot	Plot	Plot	Plot	Plot
41	42	43	44	45	46	47	48

Appendix 3.13: Field lay-out for the liming trial.

N0R0L0 = No N fertilizer; no residue retention and no liming; N1R0L0 = N fertilizer; no residue retention and no liming; N0R1L0 = No N fertilizer; residue retention and no liming; N0R0L1 = No N fertilizer; no residue retention and liming; N1R1L0 = N fertilizer; residue retention and no liming; N0R1L1 = No N fertilizer; residue retention and liming; N1R0L1 = N fertilizer; no residue retention and liming; N1R1L1 = N fertilizer; residue retention and liming.

Appendix 3.14: Maize and bean spacing in pure and intercrop configurations

Crop configuration	Crop species	Inter-row spacing (cm)	Inter station spacing (cm)	No. plants (station^{-1})	Plant (m^{-2})	Plant (ha^{-1})
Sole Maize	Maize	75	50	2	5.3	53,333
Sole bean	Bean	50	15	1	13.3	133,333
Maize/bean intercrop	Maize	75	50	2	5.3	53,333
Maize/bean intercrop	Bean	75	20	2	13.3	133,333

Appendix 3.15: Fertilizer material and their equivalent nutrient applied in maize and bean

Treatment			Fertilizer material	Nitrogen	Phosphorus	Fertilizer material
Description	Abbreviation	Target crop		(kg ha^{-1})	(kg ha^{-1})	(kg ha^{-1})
P and N based fertilizers	N_{60} P_{60}_Mz	Maize	NP(23:23:0)	60	60	261
P based fertilizer	N_{0} P_{60}_Mz	Maize	TSP (0:46:0)	0	60	130
P and N based fertilizers	N_{20} P_{51}_Bn	Bean	DAP(18:46:0)	20	51	111
P based fertilizer	N_{0} P_{51}_Bn	Bean	TSP (0:46:0)	0	51	111

N = nitrogen; P = phosphorus; K = potassium; TSP = Triple super phosphate; DAP = Diammonium phosphate; N_{60} P_{60}-Mz = N and P fertilizer basal applied to maize at the rate of 60 kg ha^{-1} of each of the nutrient; N_{0} P_{60}-Mz = P fertilizer basal applied to maize at the rate of 60 kg P ha^{-1}; N_{20} P_{51}-Bn = N and P fertilizer basal applied to bean at the rate of 20 kg N ha^{-1} and 51 kg P ha^{-1}; N_{0} P_{51}Bn = P fertilizer basal applied to bean at the rate of 51 kg P ha^{-1}.

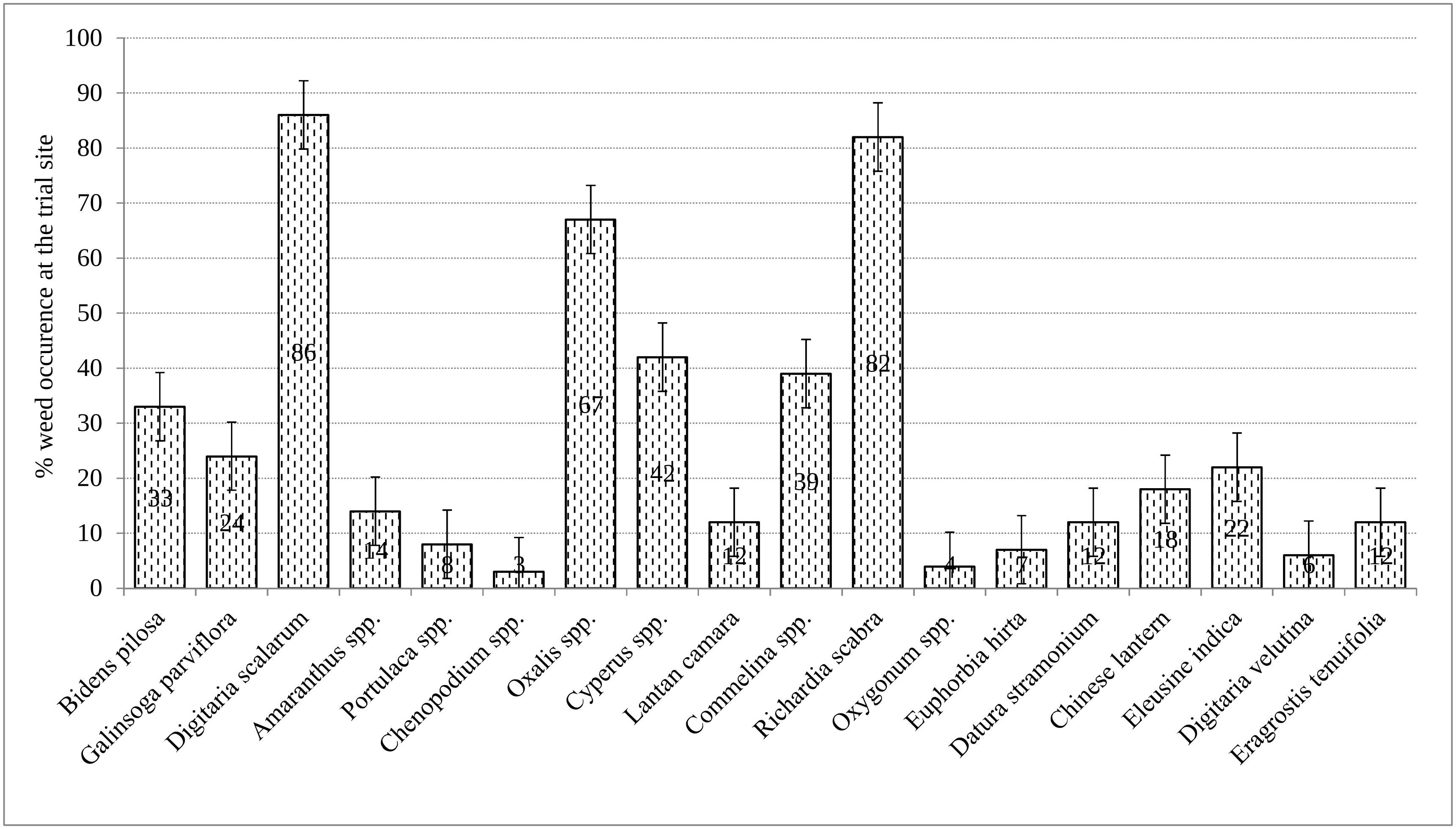
Appendix 3.16: Format for weather data for use with APSIM model

Site	Year	Date	Month	Day	Temp. (max.)	Temp. (min.)	Rainfall	Evap.
( )	( )	( )	( )	( )	(^{0}C)	(^{0}C)	(mm)	(mm)
Embu	2011	1	October	274	26.8	16.9	0.9	4.9
Embu	2011	2	October	275	26.6	16.6	4.9	4.4
Embu	2011	3	October	276	26.0	16.1	0.0	4.5
Embu	2013	29	September	271	18.0	14.0	0.0	0.7
Embu	2013	30	September	272	19.0	13.2	0.8	2.8
Embu	2013	1	October	273	25.0	15.0	0.0	5.2
Embu	2013	2	October	274	19.0	14.0	0.0	0.7
Embu	2013	3	October	275	19.0	13.2	0.8	2.8
Embu	2013	4	October	276	25.0	18.0	25.1	5.4
Embu	2013	5	October	277	19.0	14.0	0.0	0.7
Embu	2013	6	October	278	19.0	14.2	0.8	2.5
Embu	2013	7	October	279	25.0	16.0	00.4	5.0

Appendix 4.1: ANOVA for bacteria, nematodes and fungi populations under tillage methods, cropping systems, nitrogen application rate and crop residue management methods and their interactions

		Bacteria		Fungi		Nematodes	
Class	DF	Type 1 SS	Pr≥F	Type 1 SS	Pr≥F	Type 1 SS	Pr≥F
Tillage method	2	7073.00	0.12	13401.00	0.00	73359.00	0.01
Cropping system	2	2676.00	0.44	1347.00	0.48	145972.00	0.00^f
Tillage*cropping	4	11356.00	0.15	580.00	0.96	62498.00	0.11
Nitrogen input	1	73.00	0.83	271.00	0.59	14625.00	0.18
Tillage*nitrogen	2	335.00	0.90	507.00	0.76	21626.00	0.26
Cropping*Nitrogen	2	312.00	0.91	347.00	0.83	5641.00	0.70
Tillage*cropping*nitrogen	4	140.00	1.00	1185.00	0.86	13505.00	0.78
Residue management	1	884.00	0.46	16.00	0.90	90358.00	0.00^f
Tillage*residue	2	4347.00	0.26	588.00	0.73	63536.00	0.02^f
Cropping*residue	2	534.00	0.85	813.00	0.64	48430.00	0.05
Tillage*cropping*residue	4	6838.00	0.38	1448.00	0.81	41368.00	0.27
Nitrogen*residue	1	317.00	0.66	1784.00	0.17	114.00	0.90
Tillage*nitrogen*residue	2	4943.00	0.22	7.00	1.00	3471.00	0.80
Cropping*nitrogen*residue	2	2253.00	0.50	3941.00	0.12	983.00	0.94
Tillage*cropping*nitrogen*residue	4	13916.00	0.08	6255.00	0.16	24360.00	0.54

ANOVA = analysis of variance; DF = degree of freedom; SS = sum of squires; Pr = probability.



Appendix 4.2: Main weed species at the trial site