SORGHUM PRODUCTION USING *ZAI* PITS AND INTEGRATED SOIL FERTILTY MANAGEMENT IN KITUI COUNTY, KENYA

BY

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DECLARATION

DECLARATION BY THE CANDIDATE:

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

Signature …………………………. Date………………………………

Getare Ednah Kerubo- N50/33084/2015

DECLARATION BY SUPERVISORS

We confirm that the work reported in this thesis was carried out by the candidate under our supervision and has been submitted for examination with our approval as university supervisors.

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DEDICATION

I dedicate this thesis to my loving parents Esther Sarange and Francis Mosongo for the support they have shown me throughout this period. Thank you very much.

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LIST OF ACRONYMNS AND ABBREVIATIONS

ANOVA	Analysis of Variance
ASALS	Arid and Semi-Arid Lands
BCR	Benefit Cost Ratio
FAO	Food and Agriculture Organization
GHG	Green House Gases
ICRISAT	International Crop Research Institute for Semi-Arid tropics
INTSORMIL	International Sorghum and Millet program
ISFM	Integrated Soil Fertility Management
KARI	Kenya Agricultural Research Institute
LSD	Least Significant Difference
NGOs	Non-Governmental Organizations
SDGs	Sustainable Development Goals
SSA	Sub Saharan Africa
SR	Short Rains
LR	Long Rains
UNDP	United Nations Development Program
UNEP	United Nations Environment Programme

ABSTRACT

Food insecurity in the arid and semi-arid land regions of Kenya is partly caused by climate change and variability resulting to prolonged dry periods and water scarcity directly affecting crop production. The dry lands of Kitui County have been facing soil fertility decline over the years as well as low crop yields due to crop failure resulting to food insecurity and low economic returns. This is associated with the poor soil and water conservation methods practiced in the area. The objectives of the study were: i) to determine the effect of *zai* pits in combination with selected integrated soil fertility management (ISFM) technologies on the chemical properties of soils in Kabati, Kitui County, ii) to determine the effect of *zai* pits combined with selected integrated soil fertility management(ISFM) technologies on sorghum yield in Kabati, Kitui County and iii) to assess the economic feasibility of using *zai* pits combined with selected integrated soil fertility management (ISFM) technologies on sorghum production in Kabati, Kitui County. An experiment was set up in a randomized complete block design (RCBD) with 8 treatments replicated thrice, sorghum gadam variety used as the test crop. The treatments were; *zai*+ manure, *zai*+60kg N ha^{-1}, *zai*+manure+30kg N ha^{-1}, *zai*+ no inputs, conventional + manure, conventional + 60kg N ha^{-1}, conventional+manure+30kg N ha^{-1} and conventional + no inputs. Soil sampling was done at a depth of 0-15 cm before setting up the experiment and at the end of the experiment. The samples were analyzed in the laboratory for total nitrogen, available phosphorous, soil pH, soil organic carbon and electric conductivity using standard methods. Data on sorghum yield and economic returns was subjected to analysis of variance and mean separated using Standard Error of Difference at $p<0.05$. The results indicated that total nitrogen reduced significantly ($p<0.05$) in *zai* with sole manure and *zai* with manure and fertilizer treatments after the two cropping seasons. Organic carbon significantly ($p<0.05$) reduced in conventional without input, *zai* with fertilizer and *zai* with manure and fertilizer treatments. Soil electrical conductivity significantly ($p<0.05$) increased in *zai* with fertilizer, *zai* with manure and *zai* with manure and fertilizer treatments. Available phosphorous increased significantly ($p<0.05$) in conventional with sole manure, *zai* with fertilizer and *zai* with manure. Sorghum grain yields were significantly ($p<.005$) higher in *zai* with manure, *zai* with fertilizer and *zai* with manure and fertilizer compared to the conventional counterparts during the SR2018 season. In the same season stover yields were significantly ($p<0.05$) higher in *zai* with manure and mineral fertilizer compared to their conventional counterpart. During the SR2018 season, return to labour was significantly higher ($p=0.0269$, $p=0.0252$, $p=0.0379$, respectively) in *zai* with fertilizer, *zai* with manure and *zai* with manure and fertilizer compared to their conventional counterparts. The findings of this study highlight the importance of rain water harvesting using *zai* pits and the use of manure in combination with mineral fertilizer supplements in improving soil fertility, enhancing crop yields and profitability. To enhance crop yields, this study recommends that *Zai* pits should be used with a combined application of both organic resources and inorganic soil fertility inputs. The farmers should also be trained on the importance of using *zai* pit as a soil and water conservation technique in ASALs to improve crop production.

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

The world is facing a lot of challenges in this 21st century including; food insecurity, poverty and water scarcity which have been associated with climate change (Leonard *et al*., 2010; Ali and Erenstein 2017; Ouda and Zohry, 2020). Globally, food security problems are often associated with factors such as water scarcity, frequent and prolonged drought, and soil fertility decline. Prolonged drought events negatively affect food security and this has also been associated with the changing climate and variability of the weather patterns (Tumushabe, 2018). Most countries in the world primarily depend on rain as a source of water for agricultural production which negatively affects the overall agricultural production (Wani *et al*., 2009; Ali *et al.*, 2017). Additionally, low crop productivity experienced in areas depending on rainfall for crop production is further caused by degraded and poorly managed lands, poor infrastructural development, prolonged dry periods, and lack of market for their produce (Joshi *et al*., 2009; Mganga *et al*., 2015).

In the dry lands of Africa, it is estimated that about ninety percent of the total population depend on subsistence agriculture as a source of livelihood and they live in rural areas (Bationo *et al.*, 2003). The arid and semi-arid (ASALs) lands are areas characterized by low and erratic rainfall that is poorly distributed within the growing period, degraded soils that have low water retention capacity, crusted soils, and low nutrients (Zougmore *et al.*, 2014). These regions make over 40% of the global landmass with 80% of Kenyan land being arid and semi-arid (ASAL) (Kaluli *et al*., 2013). A study by FAO (2010) indicates that about 60% of crop produced in the world depend of rain with the Sub-Saharan Africa (SSA) leading in rainfed agriculture. High temperatures and prolonged dry periods affect the amount, intensity, distribution of rainfall, cropping pattern and the type of livestock kept which determines the type of crops grown (Obanyi *et al.*, 2009; Ayal *et al*., 2017). Agricultural productivity is declining in these regions with the economic returns from crop production declining every season making it difficult to attain the crop yield potential of the region (Macharia *et al*., 2012).

Sorghum is a cereal crop that performs well in ASALs and areas with relatively low soil fertility. It is widely grown by small holder farmers because of its ability to do well in the ASALs compared to other cereals (Mwadalu and Mwangi, 2013). A greater part of Eastern Kenya consists of arid and semi-arid climate which continually experience prolonged drought, erratic rainfall patterns, soil fertility decline and high atmospheric heat. The drylands of Eastern Kenya generally record low crop yields because of poor degraded soils as well as water scarcity resulting from low and unreliable rainfall (Joshi *et al*., 2009; Mganga *et al*., 2015). The small holder farmers in the Eastern Kenya region generally rely on rainfall for crop production which is a limiting factor during the growing season threatening their livelihood (Kiboi *et al*., 2017; Ogada *et al*., 2020). Relying by the farmers on rainfall for crop production increases their vulnerability to the impacts of climate change relatively high (Adimassu and Kessler, 2016; Kogo *et al*., 2021).

Soil fertility and water scarcity problem has driven more innovative approaches in agriculture to strengthen subsistence and food security more especially among the small holder farmers through adoption of the suitable technologies (Nyang'au *et al*., 2021). To curb the problem of water scarcity, soil fertility and low crop yields, several strategies to conserve soil and water such as irrigation, planting trees (mangoes, oranges, neem) and improved crop seeds have been used as remedies of the changing climate (Gebru *et al*., 2020; Wawire *et al*., 2021). These strategies have also been employed by the local farmers for soil fertility improvement, increasing overall crop yield and hence improving the economic returns. This involves use of conservation practices to improve livelihoods and reduce vulnerability to drought (Sawadogo *et al.,* 2011; Funk *et al*., 2020). These conservation practices have been used by small holder farmers to support rain-fed agriculture in the ASALs of Kenya (Mati, 2006; Kimaru-Muchai *et al*., 2020).

Water harvesting technologies have been used to increase water supply for agricultural use in an event of prolonged drought (Liang and Van Dijk, 2011; Patle *et al*., 2020). Pitting increases soil moisture content and restores productivity in areas where rainfall is insufficient (Biazin *et al*., 2012; Kimaru-Muchai *et al*., 2020; Ndeke *et al*., 2021). The economics surrounding the use of various water harvesting techniques and nutrient inputs which include the organic inputs and inorganic fertilizers application to improve crop production have been studied. Vanlauwe *et al*. (2010) noted that integrated soil fertility management technologies have been used as a strategy to improve crop production in a more cost-effective and eco-friendly way. Some of the conservation strategies include use of mulch, organic and inorganic fertilizers application (Bationo *et al*., 2003; Mucheru-Muna *et al.,* 2010). Mucheru-Muna *et al*. (2010) also noted an improvement in the net benefits of using the MBILI system of intercropping with adjusted nutrient inputs compared to the conventional intercropping method.

Declining soil fertility also remains the main biophysical problem in crop production by the small holder farmers in the dry lands of Eastern Kenya. This is because of high rates of soil erosion, continuous cultivation without adequate addition of fertility inputs and the removal of crop residues from the field (Njeru, 2011). Smaling *et al*. (1997) noted that the average loss of nutrients in soils in Kenya ranged from 42 kg nitrogen, 29 kg of potassium (K) and 3 kg of phosphorous (P) ha^{-1} making it among the greatest in Africa. Hence managing nutrients is important in sustainable agricultural production and alleviation of poverty in the region. The small holder farmers in the region commonly use crop residues, mineral fertilizers, farmyard manure and composts for short term supply of nutrients (Ngetich *et al*., 2012). Research has been done on the use of *zai* pits as a soil and water conservation strategy with the use of both inorganic and organic inputs to improve fertility consequently improving crop production in the west African countries (Danjuma and Mohammed, 2015), but this technique is limited in the ASALs of Kenya hence the focus of this research.

1.2 Statement of the Problem

In Kenya, over ten million people are suffering from food insecurity and food nutrition problems (Lokuruka, 2020). Some of the causes of food insecurity include; land degradation and fragmentation, climate change and variability, soil fertility decline, over-dependence on rainfed agriculture and low investment in drought resistant crops in the dry lands of Kenya (Mugalavai *et al.,* 2008). A greater part of Kitui County is mainly an ASAL which is prone to prolonged and frequent drought events, soil fertility decline, and inappropriate soil and water conservation measures (Mwadalu and Mwangi, 2013). This negatively affects agricultural production threatening the small holder farmers livelihood (Kiboi *et al.,* 2017).

For over ten years, Kenya has been experiencing a decline in agricultural production evident from low crop yields of major crops (Kogo *et al.,* 2021). This has negatively affected the economic returns of the small holder farmers leading to local farmers investing in local in-situ management strategies such as mulching, use of organic and inorganic fertility inputs to improve crop yields (Bationo *et al.,* 2003; Mucheru-Muna *et al.,* 2010). Improved crop production and economic returns can be achieved by using innovative ways of water management and improving soil fertility. Therefore, the study mainly focused on how the use of *zai* pits in combination with cattle manure and organic fertilizer would improve soil fertility and sorghum production in Kitui County.

1.3 Research Questions

The study sought to answer the following questions:

1. How do *zai* pits combined with integrated soil fertility management technologies affect selected soil chemical properties in Kitui County?
2. How do the interaction between the use of *zai* pits and integrated soil fertility management technologies influence sorghum yield in Kitui County?
3. How do the use of *zai* pits combined with integrated soil fertility management technologies affect the economic returns of sorghum production in Kitui County?

1.4 Objectives

The objectives of the study were;

1. To assess the effects of *zai* pits combined with integrated soil fertility management technologies on selected soil chemical properties in Kitui County.
2. To determine the effect of *zai* pits combined with integrated soil fertility management technologies on sorghum yield in Kitui County
3. To assess the economic feasibility of using *zai* pits combined with integrated soil fertility management technologies on sorghum production in Kitui County

1.5 Hypotheses

The following hypotheses guided the research:

1. Use of manure and *zai* pits have a significant effect on the chemical properties of the soils
2. *Zai* pits and integrated soil fertility management significantly increases sorghum yield

3. *Zai* pits and a combination of mineral fertilizer and manure significantly increases the economic returns of sorghum production

1.6 Significance of the Study

The research findings were beneficial in identifying the best soil fertility amendments and the best cultivation system of the study area in terms of profits earned, increased sorghum yield (grain and stover). The findings of the study also provided information to the extension service providers, small holder farmers and legislators on the benefit of *zai* pit, a rain water harvesting technology, integrated soil fertility management technologies to improve soil fertility and the economic benefits of using *zai* pits and integrated soil fertility management (ISFM) technologies. This will help the small holder farmers in the ASAL regions to make better decisions when choosing technologies to harvest rain water and improve soil fertility for increased crop production to achieve food security. The findings of the study will also help the extension service workers in planning and designing effective agricultural policies both at the local and the National levels for the small holder farmers in the ASALs.

1.7 Conceptual Framework

The small holder farmers in the dry lands of Eastern Kenya (ASALs) often rely on rainfall for agricultural production (Zougmore *et al.*, 2014). The unsustainable cultivation methods as well as the low use of fertility inputs used in these areas have led to soil fertility decline over the past years. The ASALs are characterized with low erratic rainfall, high temperatures and poor nutrient soils often pose a challenge to crop production more especially when water is scarce (Biazin *et al.*, 2012). This is evident by the low crop yields recorded each season due to crop failure negatively affecting profitability and hence the economic returns (Figure 1.1). Various interventions by the government and other non-governmental organizations have been established to curb this problem including water harvesting technologies and soil fertility management practices (Mati, 2006). For instance, *zai* pits a water harvesting technology has been used to increase water infiltration, reduce soil erosion, maximize nutrient intake and more water retention in the soil. Integrated soil fertility management options (cattle manure and mineral fertilizer) have also been used to enrich the soil with nutrients hence improved crop production. Figure 1.1 shows the influence of *zai* pits and integrated soil fertility management (ISFM) technologies on sorghum production in Kitui County.

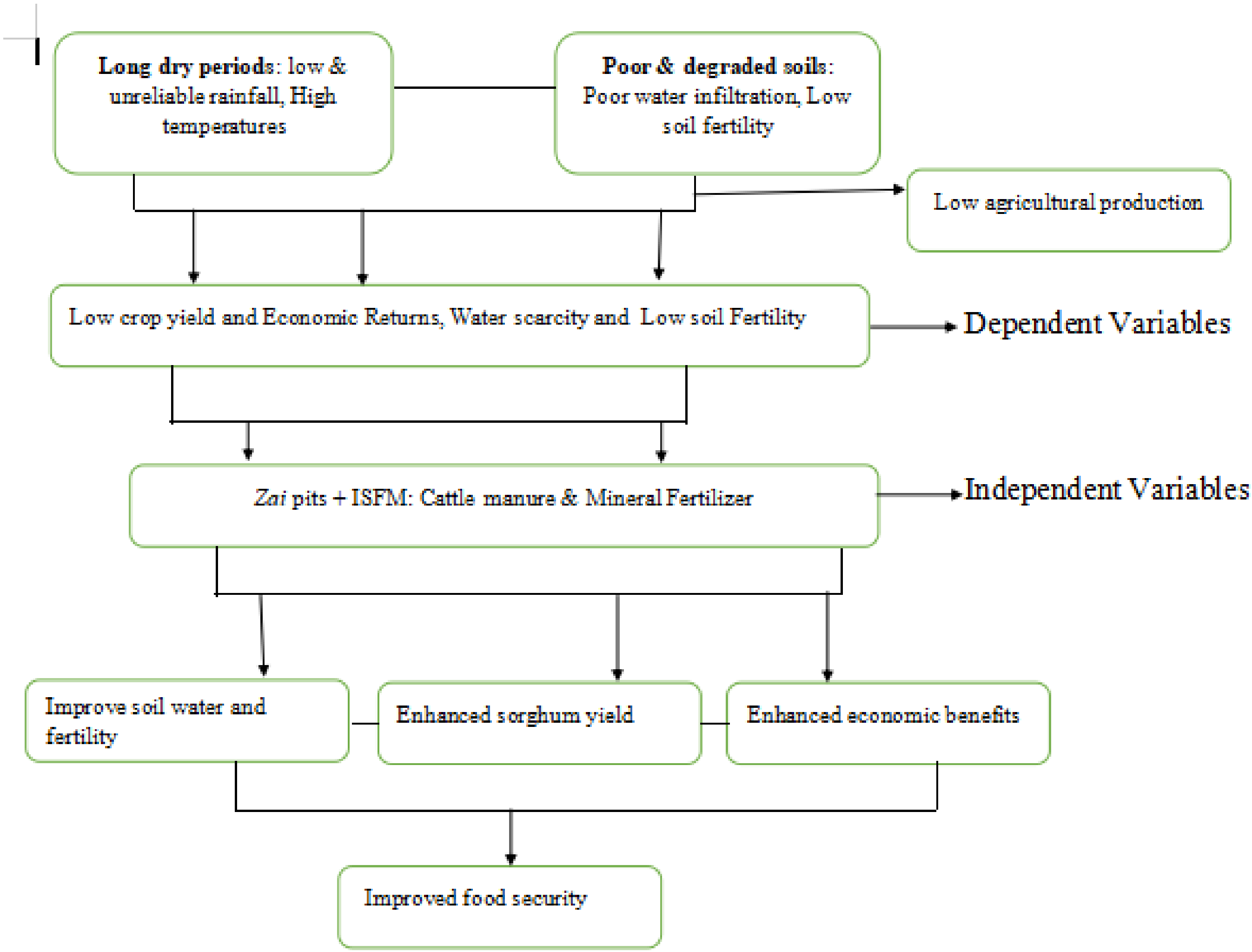

Figure 1.1 Conceptual framework showing the influence of *zai* pits and ISFM technologies on sorghum production in Kitui County

1.8 Definition of Terms

Climate change- It is the change in the average weather conditions or variability over an extended period (Pachauri and Meyer, 2014).

Climate variability- It refers to the seasonal, annual temperature and rainfall variations within and between regions or countries (Recha *et al*., 2017).

Integrated soil fertility management- These are practices whose purpose is to improve fertility in the soil, improving crop production and increasing agronomic use efficiency through use of inorganic fertilizers, organic inputs and improving germ-plasm (Roobroeck *et al*., 2015).

Rain-fed agriculture- It is a type of farming that primarily relies on rainfall for water (Jaramillo *et al*., 2020).

Rainwater harvesting- It is the process of collecting runoff from rainfall to be used for different purposes (Lee and Kim, 2012).

Soil fertility- Ability of the soil to supply the essential nutrients needed by plants in sufficient quantities, proportions, forms, as well as the appropriate for growth to obtain optimum growth (Schjoerring *et al*., 2019).

***Zai* pits-** They are small pits that are used to harvest rain water for agricultural production with a diameter of 20-30 cm and a depth of 10-20 cm (Danjuma and Mohammed, 2015).

1.9 Scope and Limitations

This study focused on the effects of *Zai* pits in combination with integrated soil fertility management technologies on soil chemical properties, sorghum yields and economic returns at Kabati in Kitui County. Soil moisture content was not measured directly during the study and the use of *zai* pits is considered as a water harvesting technology, this was a limitation for the study. On soil fertility, measurement on nutrient losses through different channels such as denitrification, percolation, soil erosion and biomass taken away after harvesting.

CHAPTER TWO: LITERATURE REVIEW

2.1 Overview

In Kenya today, agriculture is identified as one of the main sectors that drive economic development in the economic pillar of vision 2030 (Government of Kenya, 2010). Agricultural production directly depends on factors of climate for agricultural production. However, crop and livestock production are vulnerable to changes in climate as well as variability making food security a challenge. The Global Hunger Index report (2011) ranked Kenya to be among the food insecure countries. Food insecurity is primarily caused by poor infrastructure, fast growing population, changing climate, land degradation and fragmentation, over dependence on rainfed agriculture and low investment in drought resistant crops (Gemeda and Sima, 2015).

Most small holder farmers in the ASALs of Kenya primarily depend on livestock and crop production as a form of livelihood (Omoyo *et al.*, 2015). Small holder farms in Eastern Kenya are not suitable for rain-fed agriculture due to unreliable rainfall, prolonged drought, and declining soil fertility (Nezomba *et al*., 2014). Precipitation in the ASAL regions is lower than the potential evaporation which results to frequent droughts during the growing season (Opiyo *et al*., 2015). The frequent droughts negatively affect food security usually to the pastoralists and small-scale agriculturalists (Ondiko *et al.*, 2018). This has led to interventions by Government and Non-Governmental Organizations (NGOs) to harvest rain water and options to manage soil fertility to improve crop productivity in these regions.

2.2. Sorghum Production in Kenya

Sorghum is listed as one of the major cereal crops that is grown around the globe because of its importance and production. Its production in Kenya is declining despite the fact that it's one of the crops that is suitable for the ASALs regions (Naik *et al*., 2016). According to US Grain council (2010) grain sorghum is a cereal that is grown in the world mainly for food security in the rural areas of the ASALs of Africa. Grain sorghum is mainly used as food in the tropical regions and a raw material for alcoholic beverages (Mwadalu and Mwangi, 2013). It is a traditional crop grown in Kenya's arid and semi-arid regions but due to changes in climate such as prolonged dry periods its production is still low (Muui *et al.,* 2013). It is ranked third after maize and wheat in cereal production and does well in soils with low fertility (Amelework *et al*., 2016). Sorghum is widely grown by small holder farmers because of its ability to do well in the ASALs compared to other cereals (Chepng'etich *et al*., 2015).

In Kenya the total area under production of sorghum significantly increased by 50,804 ha in a span of four years (2005-2009) from 122,368 ha to 173,172 ha but its yield has reduced significantly (Government of Kenya, 2010). Several interventions have been put in place to improve sorghum production. For instance, ICRISAT& INTSORMIL have promoted breeding and pest-disease tolerant sorghum for improved sorghum production for instance sorghum gadam variety (Chepng'etich *et al*., 2015). Karanja *et al*. (2009) noted that there is variability between the potential and actual production of sorghum by the small holder farmers in the lower part of Eastern Kenya for instance, the expected potential for sorghum gadam was 2-2.5 t ha^{-1} but farmers only produced upto1.2 t ha^{-1}.

Sorghum gadam variety is drought tolerant and fast maturing which was introduced in Kenya as an adaptation to its changes to climate (Njeru *et al*., 2016). It is well adapted to the dry lands of

Kenya and has a direct market to the East African breweries limited for beer making (Kavoi *et al*., 2013). This crop is beneficial and is grown by African subsistence farmers who use little or no fertilizer. Therefore, the crop has a potential in reducing the risks and adapting to the changing climate and variability. In Kenya it is a staple food for numerous households who are low-income earners (Bryan *et al*., 2020). It is mostly grown in Eastern, Western, Nyanza and Rift valley provinces the formers administrative boundaries which collectively produce over 99 percent of the total sorghum produced in Kenya (MoA-ERA, 2012).

2.3 Effects of Drought on Crop Production

Variables of climate such as temperature and precipitation directly affect crop and livestock production. These variables often control their growth, health, and yield (Liang *et al*., 2017). As highlighted by Troy *et al*. (2015), the weather extremes were expected to rise with changes in climate negatively affecting agricultural production (Troy *et al*., 2015). Drought is a phenomenon that naturally occurs, and the availability of water is constrained over a long period (Vicente-Serrano *et al*., 2013). In many parts of the world disasters such as drought and floods that arise from extreme changes in weather patterns have destabilized agricultural production threatening food security (Lesk *et al*., 2016).

Shortage of rainfall and soil erosion causing soil fertility decline remains a challenge to agricultural production. These factors combined are a threat to small holder farmers in Sub-Saharan African countries (Duncan, 2016). These small holder farmers are most vulnerable to drought and soil fertility decline due to high food insecurity as well as poverty (Hellmuth *et al*., 2009; Tabu *et al*., 2013). In rise to these, practices to conserve soil and water have been introduced such as half-moon, *zai* pits, soil bunds and stone terraces were introduced to improve crop production and the farmers' general income through improved climate resilience (Ayande *et al*., 2018). *Zai* pits and half-moon technologies are commonly used due to their convenience to the socio-economic conditions of the small holder farmers. There potential have also been proven in improving soil fertility, soil and water conservation, and reduction of crop diseases, weeds, and insects (Manda *et al*., 2016).

The potential direct effects of the changing climate on agricultural systems include increase in diseases, weed and pest populations, changes in rainfall and temperature patterns affecting the availability of water and alteration of evapo-transpiration (Rosegrant *et al*., 2008; Hatfield *et al*., 2020). In the ASAL regions, water shortage is the main factor affecting agricultural production with crop production directly affected by precipitation and temperature (Liang *et al*., 2017). Studies have shown that drought directly affects crop production. Huho and Mugalavi (2010) indicated that drought affected crop production negatively in the dry regions of Laikipia Kenya in a study carried out between the year 1990 and 2005. Farmers reduced their farmlands by 30 to 60% due to rampant crop failure during the dry period. Crop yield also reduced significantly during this period. Ray *et al*. (2018) recorded the lowest crop yields in 2011in Texas when a severe drought event was recorded.

2.4 The *Zai* Pit System

Zai pits are described as pits for harvesting water originally used by farmers in Northern part of Burkina Faso (Danjuma and Mohammed, 2015). It is a traditional technique to conserve soil and water that was first practiced in Dogon, Mali. The pits measured 20-30 cm in diameter with a depth of 10-20 cm and a spacing 60-80cm between the pits. The term *zai* was first coined in Burkina-Faso referring to small planting pits filled with manure (Motis *et al*., 2013). They are often referred to as planting pockets with a spacing of 70 to 80 cm apart which results to approximately ten thousand pits per hectare. The *zai* pit technique hence is the small pits for planting which are filled with organic matter to improve crop productivity. Planting of seeds is done in the pits after the addition of fertilizer or manure to enhance soil fertility (Motis *et al*., 2013). It was discovered in 1980s after a great drought event and has widely been practiced in western Sahel with low soil fertility, low and highly variable rainfall (Danjuma and Mohammed, 2015).

In Sub-Saharan Africa, the main issues affecting crop production include; land degradation, declining soil moisture and fertility which have been addressed with innovation of *zai* pit because it allows the concentration of water and nutrient close to the roots of the crops (Biazin *et al*., 2012). They are best suited in areas receiving annual rainfall ranging from 300-800 mm but can also be effective in highland areas which receive an excess of 1300 mm rainfall annually but have problems water infiltration due to hardpans, crusted soils (Motis *et al*., 2013). Organic matter in the soil is beneficial in maintaining the soil structure through its ability to attract termites and soil insects. They are best suited in holding water in the soil with Danjuma and Mohammed (2015) indicating that *zai* pits have over 500% water holding capacity. Therefore, *zai* pit technology is used to improve fertility of poor soils particularly in dry conditions.

Pits have been practiced in some countries in West Africa including Burkina Faso, Mali and Niger with studies indicating that they increase crop yield and improve soil fertility over time (Zougmore *et al*., 2003). In Kenya the pit system has been promoted and is used for crop production in the ASAL areas. The common type of *zai* pits known in Kenya is “five by nine” which is used to refer to five seeds of maize in dry areas and nine seeds of maize in wet areas (Mati, 2006). They have also been experimented in Eastern parts of Kenya and proved successful (Kathuli and Itabari, 2014). *Chololo* pits a modification of zai pits which were invented in Dodoma region of Tanzania have also been used for crop production (Mati, 2006).

Digging pits help more rain water infiltration and with the application of both organic and inorganic fertility inputs there is an improvement in soil fertility (Kar *et al.*, 2013). The pit system has been used mainly by farmers on dry eroded valley soils and bush fields to increase and retain soil moisture, soil erosion reduction and soil fertility improvement through applying manure in the pits before planting is done (Zougmore *et al*., 2014). Cow peas (*Vigna unguiculata*), sorghum (*Sorghum bicolor*) and millet (*Pennisetum glaucum*) are some of the crops that have been reported by small holder farmers to do well in the pit techniques hence an improvement in production of the major food crops (Wildemeersch *et al.*, 2015). Therefore, this study focused on the use of *zai* pit and integrated soil fertility management technologies for sorghum production in Kitui County.

2.5 Soil Fertility Management Options

Depletion of soil nutrients has been associated with the low and unsustainable agricultural practices leading to food insecurity (Mbingo, 2013). Declining soil nutrients is one of the major issues in Africa and for more than a decade agricultural production has dwindled evident by low yield of the major crops in Kenya (Mbakaya *et al*., 2010; Muchai *et al*., 2020). Loss of soil nutrients and the use of fertilizers below recommended rates is a threat to agricultural production Canning *et al*. (2015) and with the continuous cropping without adequately applying fertility inputs had contributed to the reduction of soil organic carbon and the soil microbial biomass when compared to sole application of fertilizer or in combination with farmyard manure. Farmers therefore have taken an initiative to improve this by either using both organic and inorganic inputs for supply of nutrients and traditional fallows where possible (Gicheru, 2012).

Agricultural intensification in SSA is a necessary move to address poverty in the rural areas and degradation of natural resources. Soil fertility problem is a major concern of Kenya in agricultural production more especially in the ASALs which are characterized by soil fertility problems (Gicheru, 2012). The problem of soil fertility is worsened by poor and erratic rainfall which is highly variable making crop failure a common feature (Gichangi *et al*., 2006; Raimi *et al*., 2017). Soil fertility therefore focuses on supplying of nutrients from external sources. The most common soil fertility management strategies include; crop rotation, agroforestry, intercropping, growing of cover crops, use of organic and inorganic amendments and conservation tillage practices. All these practices aiming at sustaining and maintaining soil fertility.

2.5.1 Integrated Soil Fertility Management (ISFM)

As defined by Vanlauwe *et al*. (2010), it is a means of improving crop production in an environmentally friendly and profitable way. It is the use of technologies which improve crop production through the use organic matter application, use of inorganic fertilizers, improved germ-plasm and the adaptation to the local conditions by the small holder farmers (Fairhurst, 2012). It consists of best practices which are commonly used in a combination for instance, use of fertilizers, organic inputs, and other agronomic practices. The current integrated soil fertility management (ISFM) interventions include dual crop legume-cereal rotations, intercropping and a combined use of organic manure and inorganic fertilizers (Vanlauwe *et al*., 2015).

Integrated soil fertility management (ISFM) is used to address the problem of soil fertility facing small holder farmers. Proper use of these technologies can improve crop production and reduce soil organic losses (Zhang *et al*., 2018). The integration of legumes in ISFM often maximizes profitability and cereal-legumes intercropping being a common practice in East Africa (Vanlauwe *et al.*, 2019). Research has shown that a two staggered (MBILI) system of intercropping increases crop production and the net benefits. Mucheru-Muna *et al*. (2010) noted an increase of 40% net benefits in the MBILI system comparing to the conventional method. Legumes that were used include cow peas (*Vigna unguiculata*), common beans (*Phaseolus vulgaris*) and groundnuts (*Arachis hypogaea*) where the common bean intercrop was the most profitable.

Increased nutrient cycling efficiency is a major composition in integrated soil fertility management. The common inputs used in the farms include; organic inputs (livestock manure and crop residues) and small rates of inorganic fertilizers. A combination of fertilizer and organic resources have been known to increase the efficiency of using fertilizers and crop productivity (Tittonell *et al*., 2008). This has been advocated for a sustainable method of crop production for small holder farmers since none of the inputs is found in enough quantities (Vanlauwe *et al*., 2010). Studies have shown that the integrated use of inorganic and organic fertilizers increases crop production. Mugwe *et al*. (2009) noted an increase in maize yield in treatments that had a combination of both organic inputs and inorganic fertilizers. Maize yield increased by 253% in cattle manure +30kg N ha^{-1} treatment and 284% for Calliandra + 30 kg N ha^{-1} comparing to 169% increase in inorganic fertilizer treatment. Hence the study focused on ISFM technologies to improve the soil nutrients and sorghum as the test crop in the study area.

2.5.2 Inorganic Fertilizers

They are essential concentrated nutrients that are needed by crops that are readily available for plant uptake used to supplement the nutrients in the soil (Fairhurst, 2012). Effectively, balancing the application of inorganic and organic inputs is important in achieving improved crop production in sub-Saharan Africa (Zingore *et al*., 2008; Smith *et al*., 2015). The inorganic fertilizers are often classified according to the minerals they have for instance nitrogen fertilizers provide N into the soil. The sources include ammonium and nitrate forms as well as urea. Ammonium sulphate is widely used and it contains about 21% N and 11% S. Other fertilizers that are known to supply both N and P include, ammonium phosphate and Diammonium phosphate (DAP) (Muriuki, 2009). These fertilizers are water soluble and can cause damage to seeds especially in soils with high soil pH (Silva and Uchida, 2000).

Inorganic fertilizers have been used extensively in East Africa with small holder farmers using these fertilizers for commercial crops including tea, coffee and tobacco (Mati, 2006). The inorganic fertilizers have been used to overcome soil fertility problems in Kenya and East African region in general (Mugwe *et al*., 2009). Most soils in Eastern Kenya there are huge losses of nitrogen and phosphorous through leaching and therefore a need to compensate them each planting season. It has been noted that the rate of addition of fertilizer is insufficient in restoring soil fertility and compensate the nutrients lost and generally, fertilizers are an expensive fertility input and therefore the poor resource farmers cannot be able to buy enough fertilizer to comply with the rates recommended for application (Bedada *et al*., 2014).

The main sources of inorganic nutrients include DAP, CAN, 17.17.0, 23.23.0 and 20.20.0. and in Kenya's semi-arid regions inorganic fertilizers are used in small quantities due to the high cost and the perception by farmers that they negatively affect soils (Mugwe *et al*., 2009). The rate of inorganic fertilizer use in the sub-humid parts of eastern Kenya has been estimated to be between 15-20 kg N ha^{-1} and research has shown that fertilizer application increases crop production more especially maize production (Gicheru, 2012). Tittonell (2008) reported that the use of mineral N and P widely induced maize yield across fields of individual farms.

The recommended fertilizer application rates for sorghum in Kenya is DAP: 120 Kg per hectare, MAP: 180 kgs/hactare, NPK 23:23:0: 100 kgs per hectare (Ministry of Agriculture, 2012). The actual rates used in the study was 60 kg N ha^{-1} /60 kg P ha^{-1} which was similar to the recommended rates of DAP application by the ministry of agriculture. Studies have shown that there's a yield gap in the ASALs of Kitui County despite the different strategies that have been used to optimize yield. Karanja *et al*. (2009) notes that the production of sorghum gadam variety is 1.2 tons per hectare with the expected potential yield for the variety being 2 to 2.5 tons per hectare. This study therefore opted to use mineral fertilizer as an option in soil fertility management in the study area.

2.5.3 Animal Manure

Using organic resources is important source of nutrient inputs with manure being the major source of nutrients (Chivenge *et al*., 2009). Animal manure contains all the micro and macro elements required for growth of plants. It also contains organic matter this therefore increases soil organic carbon when it is applied (Stockmann *et al*., 2013). Mugwe *et al*. (2009) noted that manure is widely used in central Kenya by about 80% of households because it is affordable compared to inorganic fertilizers. Cattle manure is readily obtained by the small holder farmers in high quantities to enhance soil organic matter (Dunjana *et al*., 2012). The stock of organic carbon present in animal manure generally increases the soil organic carbon upon its application.

Research has also shown that animal manure is able to restore soil fertility in small holder farms because it adds soil organic matter into the soil, increases soil pH, available P, and base saturation (Zingore *et al*., 2008). Mugwe *et al*. (2009) also noted that cattle manure significantly increased soil pH and amounts of soil K, Ca, Mg and C after four years of cultivation in Chuka, Central Kenya. Elsewhere in the south eastern United States, the stock of soil surface organic carbon (0-

20cm) increased after applying poultry litter for 10 years when compared to plots that had sole application of mineral fertilizer (Sainju *et al.*, 2008). In another study by Huang *et al*. (2015) pig manure application increased the soil surface layer (0-15cm) soil organic carbon compared to soils that had application of fertilizer alone an indication of the significant contribution in improving soil fertility and enhance crop production. Nitrogen loss through ammonia volatilization is seen as a major constraint in its quality (Gichangi *et al*., 2006). The study used cattle manure as a form of organic manure in sorghum production in Kitui County.

2.6 Effect of *Zai* Pits and Soil Fertility Management Options on the Soil Chemical Properties

Continuous cropping has constrained agricultural intensification because of low nitrogen and phosphorous available in the soil. Studies on the effect of *zai* pit technology and use of organics and mineral fertilizers on soil properties have yielded different results. Some studies have noted that some nutrients significantly increase, and others reduce or no effect at all to the soil nutrients. Bedada *et al*. (2014) and Kihara *et al*. (2016) noted that a combination of compost and (Nitrogen phosphorous) NP fertilizer increased stock of total nitrogen and organic carbon in 0-10cm when compared to the control and NP fertilizer alone treatments. Similar results have also been reported by Chivenge *et al*. (2011) on SOC whereby soil organic carbon (SOC) increased after applying organic resources in both the organic alone and combination with the nitrogen fertilizer comparing to the control. Mucheru-Muna *et al*. (2007), Dunjana *et al*. (2012) and Zhou *et al*. (2015) also noted soil carbon increase with the addition of organic manure. Organic carbon in the soil plays a role in maintaining soil fertility because it is a source and sinks for nutrients (Bationo *et al*., 2005; Lahmar *et al*., 2012). Mucheru-Muna *et al.* (2014) also noted that the manure treatments had a significant increase in soil available K and P contents.

Application of cattle manure has been attributed to the increase of organic carbon in the soil in poor fertility soils. For instance, Dunjana *et al.* (2012) recorded a significant increase in organic carbon and improving aggregate stability at in clay soils and soil organic carbon increased significantly in sandy soils. This showed that cattle manure plays a great role in soil organic matter enhancement. Organic manure has been known to have a significant effect on soil pH. Mucheru-Muna *et al*. (2014) noted a significant increase of soil pH in the sole application of organic manure from strongly acidic soils to less strongly acidic soils with a complete opposite with the application of sole mineral fertilizer which reduces soil pH. This was same with Mugwe *et al*. (2009) and Opala *et al*. (2013) who reported that farmyard manure and cattle manure improved soil fertility by increasing soil pH respectively. Soil organic carbon (SOC), Ca, K and Mg were also increased with the application of cattle manure (Mugwe *et al*., 2009). Sole mineral fertilizer application reduces the soil pH in comparison with the compost which has an effect of increasing soil pH (Bedada *et al*., 2014).

A study by Yegon *et al*. (2016) on the effects of planting pits on soil properties indicated that soil total nitrogen (TN) increased by 0.4 mg kg^{-1}, potassium level by 0.4-0.54 $cmol_c$ kg^{-1} and total organic carbon (OC) by 0.06 mg kg^{-1} in areas where pits were used compared to the control. Kimaru (2017) also indicated that soil pH significantly (p=0.014) increased with total nitrogen increasing significantly(p=0.05) with the application of manure under the *zai* pit system. The change of pH was associated with the manure application. Matusso *et al.* (2013) noted that the uptake of nitrogen in maize and soybean crops was significantly affected by the patterns used to intercrop where the MBILI intercropping had the highest total nitrogen.

2.7 Impact of *Zai* Pit and Soil Fertility Management on Crop Yield

Scientists are focusing on soil and water conservation to increase crop productivity (Banwart, 2011). Research has shown that soil properties greatly influence productivity (Matsumoto *et al*., 2013). Mucheru-Muna *et al*. (2007), Chivenge *et al*. (2011), Dunjana *et al*. (2012), Mucheru-Muna *et al*. (2014) and Bedada *et al*. (2014) reported that the application of organic inputs alone or combined with inorganic fertilizers led to yield increment of crops when compared with where fertility inputs were not used. This is due to its ability in sustaining soil health and improving fertility in the soil (Satyanarayana *et al*., 2002). Dunjana *et al.* (2012) also noted that a maize yield significantly increased where combined cattle manure and mineral fertilizer were applied.

Chivenge *et al*. (2011) reported higher maize harvest from treatments that combined organic resources and fertilizers with a 114% increase and the sole application of organic inputs at 60% compared to the control. Amede *et al*. (2011), Biazin *et al*. (2012) and Kar *et al*. (2013) reported that rain water harvesting in combination with use of both inorganic and organic inputs increases the nutrients in the soil improving crop productivity. Amede *et al*. (2011) reported that *zai* pits and a combination of fertilizer additions increased the yield of potatoes by 500% to 2000% and bean yield by 250%. Kimaru (2017) also noted that cattle manure + *zai* pit had the highest sorghum yield of 4.18 kg ha^{-1}. *zai* pit combined with nutrient management options recorded higher sorghum yield compared to the conventional method of crop production. The study focused on the use of *zai* pits and selected ISFM technologies to improve crop yield in the study area with sorghum as the test crop

2.8 Economic Benefit of *Zai* Pits and Soil Fertility Management

The economic benefit of an enterprise is often determined by cost-benefit analysis (CBA) because it determines the options that are more profitable. Kalungu *et al.* (2015) noted that zai pits are labour intensive in nature as it takes approximately 450 hours ha-1 to dig holes and an estimate of 250 hours for fertilizer application. However, the benefits are considered positive in the end. Hatibu *et al*. (2006) found that economic returns land and labour increased in Tanzania water harvesting, as water harvesting gave an opportunity for the farmers to grow vegetables and rice. Similarly, Mazvimavi and Twomlow (2008) noted that higher yields were recorded in the planting pits compared to the conventional practices where manure was broadcasted.

The cost effectiveness of integrated nutrient management on productivity has been reported due to its ability to improve crop yield. Adamtey *et al*. (2016) reported that ISFM produced products influenced profitability in both local and regional markets. The organically produced crops whose profit was twice compared to that was produced conventionally. This provided alternative to the farmers because of its economic viability. For instance, Mucheru-Muna *et al*. (2010) where a two staggered (MBILI) system of intercropping (a form of ISFM) had a 40% increase in net benefits compared to the control. The intercropping of maize and the legumes where N fertilizers were applied yield increased and hence the economic benefits. Kearney *et al*. (2012) noted that greater net benefits were recorded in combined manure and mineral fertilizer compared with the application of sole manure and sole mineral fertilizer.

Elsewhere, Ojiem *et al*. (2014) also noted that the components of ISFM e.g., legume-cereal rotation generally reduced application costs of N while the yield of one crop increased without reducing the performance of the crops rotated. Thimmaiah *et al*. (2016) noted that a combination of NPK, vermin-compost and farmyard manure had the highest yield of grain finger millet and the gross benefits. Matusso *et al*. (2014) noted that the intercropping of maize and soybean has a significant effect on the net returns, gross monetary returns, and benefit cost ratio (BCR).

2.9 Water and Nutrient Balance

Soil and water nutrients are the most limiting agricultural resources (Sharma *et al*., 2015). However, Wang and Li (2019) notes both irrigated and rainfed agriculture are affected by soil nutrients depletion through losses such as leaching and surface runoff on rainfall events. Nutrient balance is defined as the nutrient input such as fertility amendments and output i.e., leaving the system through uptake by crops (Rafique *et al*., 2012). Nutrient input is an important aspect in farming systems because it has critical importance in crop productivity. However, surplus nutrients in the soil can also lead to nutrient losses which may cause economic inefficiency to farmers as well as cause a potential harm to the environment through pollution (Kumar *et al*., 2019). Nitrogen and phosphorous are two main nutrients that are potential indicators of pollution which are presented in tons of nutrient per hectare.

2.9.1 Nitrogen and Phosphorous Gain and Losses from the Root Zone

2.9.1.1 Nitrogen and Phosphorous Gain in the Soil

Nitrogen is gained to the soil through various processes such as biological fixation, application of chemical fertilizers as well as organic sources and atmospheric N (Schroder, 2014). Biological fixation is a natural process by free-living micro-organisms known as diazotrophic (Norman and Friesen, 2017). Nitrogen fixation is the major source of nitrogen in the soil where the micro-organisms transform nitrogen to biologically available forms for uptake. Leguminous crops can be used to fix large amounts of N_2 through biological N fixation.

Research shows that more than 90 percent of nitrogen in the soil in bound to organic matter and its availability in the soil is controlled by microbial mineralization which is also dependent on temperature and soil moisture (Agehara and Warncke, 2015). Therefore, with increased precipitation and moisture in the soil, microbial activities increase which accelerates the mineralization of nitrogen as well as nitrogen immobilization in the microbial biomass. The application of chemical fertilizers also acts as a source of nitrogen in the soil. Anhydrous ammonia is used in the manufacture of nitrogen fertilizers that supplement other sources of N for crop nutrition (Lamb *et al*., 2014). Other sources of N in the soil include organic sources such as manures, crop residues and soil organic matter.

Phosphorous is also gained into the soil through application of chemical fertilizers and released from rock formations and sediments in a form of phosphate salts (Jupp *et al.*, 2021). Unlike nitrogen, phosphorus does not have any atmospheric component since it is not found in gaseous form. Weathering and dissolving of the phosphate rocks in soil water makes it available for crop uptake. However, the quantities released are small therefore, farmers apply commercial fertilizers to supplement the small quantities found in the soil (Schroder *et al*., 2011).

2.9.1.2 Nitrogen and Phosphorous Loss from the Soil

In agriculture, nitrogen (N) and phosphorus (P) nutrients are lost through different ways including when the crops are harvested and soil erosion (Bashagaluke *et al*., 2018). Consequently, the application of mineral fertilizers maintains and build soil fertility. However, when applied at excess levels the (N and P) nutrients may be lost through leaching, crop removal by harvest, erosion, and run-off. Additionally, nitrogen is lost from the soil through processes such as denitrification, anaerobic ammonium oxidation and volatilization (Zhu *et al*., 2015).

Precipitation is the main factor that affects cycling of nitrogen (N) because of its significant effect on soil erosion, microbial activity and leaching (Cregger *et al*., 2014). Increased levels of precipitation decrease nitrogen retention and increases nitrogen losses through run-off and leaching (Ershadi *et al*., 2020). Leaching involves the loss of soluble NO_3^- which moves with water in the soil below the root zone which commonly occurs in coarse-textured soils with lower water holding capacity.

Nitrogen is lost from the soil through denitrification where NO_3^- is lost when soils are saturated with water (Castaldelli *et al*., 2019). Volatilization also contributes to the loss of nitrogen from the soil where N is lost as ammonia gas (NH_3). This is common in manure and fertilizer products that contain urea. Nitrogen is also lost from the soil through uptake by the crops under saturated soil moisture conditions (Hamoud *et al*., 2019). Under high soil moisture conditions, there's an increased competition for nitrogen between plants and the micro-organisms.

2.9.2 The Effect of N and P Loss and Gain on Crop Production

Nitrogen and phosphorus are considered as elements that limit plant growth as well as a limiting factor for profitable and sustainable crop production (Haileselassie *et al*., 2011). However, the application of this elements more than the crops need can reduce crop yields. Morris *et al*. (2018) notes that economically profitable yields can only be achieved by applying the recommended rates of N and P. However, the yield potential for crops varies with climatic conditions, nutrient cycling, species of crops and competition with pests and weeds. Nitrogen and phosphorus fertilizers are applied to enhance crop yield. Dai *et al.* (2013) notes that omission of P fertilizer induces a deficit of the available nitrogen in the soil as well as the concentrations of extractable phosphorous. This is an indication that phosphorous is beneficial in growth of crops since it is linked to the availability of nitrogen in the soil.

2.10 Research Gap

Based on the previous studies, ISFM and *Zai* pits promotes agricultural sustainability through curbing the soil fertility and soil moisture problems. However, studies that have been done in Kabati, Kitui County have concentrated more on organic and inorganic fertility inputs with little attention being given to the potential of ISFM and *zai* pits a water harvesting technology. In addition, economic analysis on the *zai* and ISFM technologies presents a better basis of comparing the most cost-effective cultivation method suitable for the small holder farmers in the study area.

CHAPTER THREE: METHODOLOGY

3.1 Study Area Description

The study was conducted at Kauwi primary, Kabati town, Kitui east sub-county in Kitui County. Kitui County lies to the south east of Nairobi with latitudes 0^{0}10, and 3^{0}0 South and longitudes 37^{0} 50 and 39^{0} 0 East with an altitude ranging between 400m and 1800m above sea level (Figure 3.1).

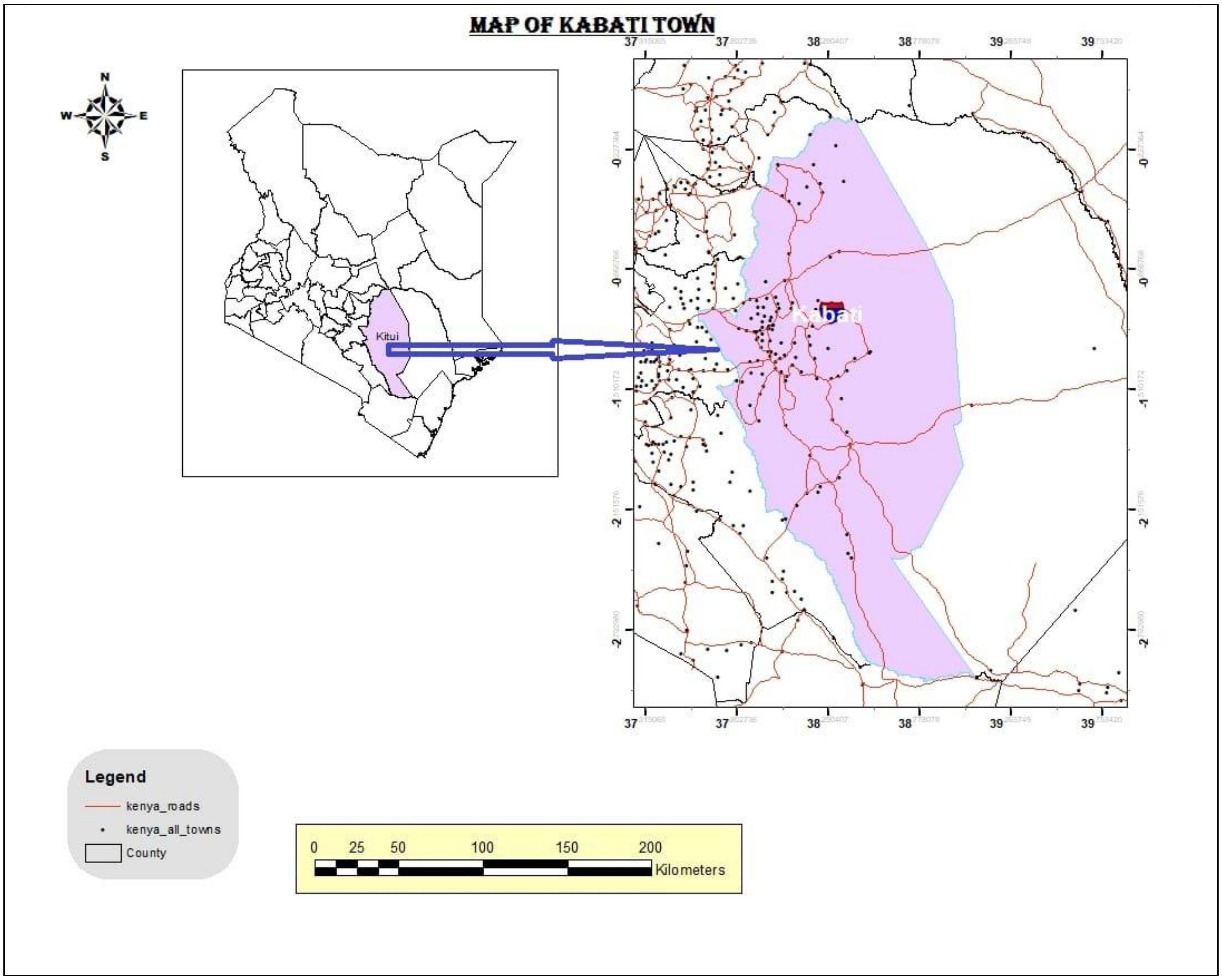

Figure 3.1: Map of the study area

Kitui County experiences unreliable rains ranging from 250mm to 1050mm per annum with a bimodal rainfall pattern. The short rains are experienced from October to December and the long rains being experienced from March to May while the rest of the year is dry. The hot months are July to September and January-February with the temperatures ranging from14^{0}C to 34^{0}C and this increases the rate at which evapo-transpiration takes place (Dolschak *et al*., 2019). The climatic conditions of Kabati are suitable for sorghum production because of its ability to do well in the ASALs compared to other cereals.

The topography of the area is described as hilly rugged uplands and lowlands. The general landscape of the area is flat with plains gently rolling down towards the east where the altitudes are as low as 400 metres above sea level. The soils found at Kabati are lixisols consisting of strongly weathered, leached and finely textured materials with high base saturation (Nezomba, 2016). The soils are thin and brown with low amounts of available nutrients as well as low organic carbon levels and well drained which makes it suitable for sorghum production in the study area. The soils have also been classified as stable since they have soil aggregate stability of more than 0.84mm in mean weight diameter (MWD) as described by Skidmore and Powers (1982). Kabati is in the upper midland 3-4 (semi-arid farming zone) with various natural resources including forests, rivers, hills and wildlife. The semi-arid zone has good agricultural potential used for agricultural production but frequent crop failures are recorded. The main socio-economic practices in the area include crop, livestock production, fish production and tourism.

The major crops grown for food in the area include; legumes such as green grams (*Vigna radiata*), cowpeas (*Vigna unguiculata*), pigeon peas (*Cajanus cajan*) and beans (*Phaseolus vulgaris*). Cereals include maize (*Zea mays*), sorghum (*Sorghum bicolor*) and millet (*Pennisetum glaucum*) with tuber crops being cassava (*Manihot esculenta*) and sweet potatoes (*Ipomoea batatas*). Fruits include avocado (*Persea americana*), watermelon (*Citrullus lanatus*), pawpaw (*Carica papaya*) and mangoes (*Mangifera indica*) (Mutie *et al*., 2020).

The recommended fertilizer application rates for sorghum in Kenya is DAP: 120 kg per hectare, MAP: 180 kgs/hactare, NPK 23:23:0: 100 kgs per hectare (Ministry of Agriculture, 2012). In both LR and SR seasons the rainfall ranges between 500 mm and 1050 mm. Sorghum gadam variety which has maturity between 110-130 days approximately requires 450 to 650 mm of water during the growing season but the water varies depending on the stage of growth (Assefa *et al*., 2010). In Kabati, the SR2018 season received a total of 382.31 mm and LR2019 receiving a total of 116.3mm. This shows a water deficit in the two cropping seasons which negatively affects sorghum yields.

3.2 Experimental Layout, Treatment Combinations and Management

The experiment was laid out as a randomized complete block design (RCBD) with 8 treatments that were replicated thrice (Table 3.1). The plot size measured 6m by 4.5m, a spacing of 1m between the plots and 1m for the guard zone. Figure 3.2 shows the plot layout at Kabati, Kitui County.

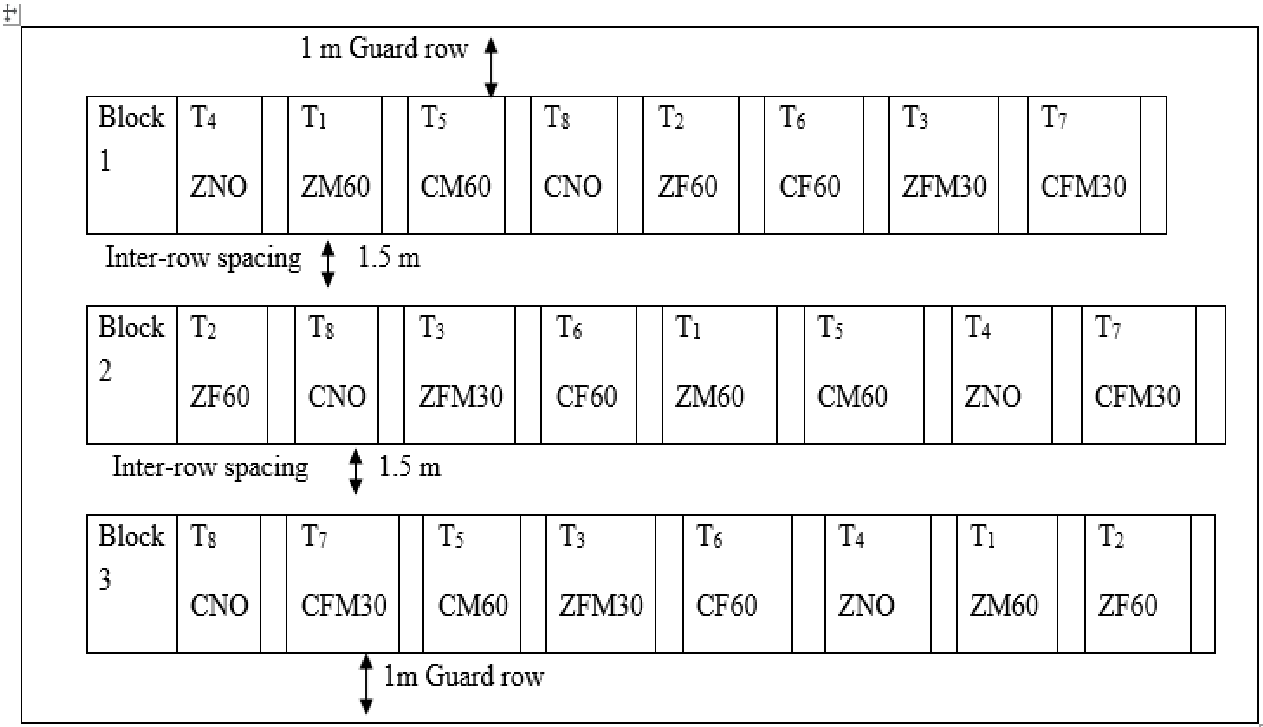

Figure 3.2 Plots Layout at Kabati, Kitui County

CMF30=Conventional + Cattle Manure + 30 kg N ha^{-1}, CNO= Conventional with no inputs, CM60= Conventional + Manure, CF60=Conventional+ 60 kg N ha^{-1}, ZNO=*zai* with no inputs, ZMF30=*Zai*+ Cattle manure+ 30 kg N ha^{-1}, ZM60=*Zai* + Manure, ZF60=*Zai*+ 60 kg N ha^{-1}

The *zai* pits were made by digging out the top soil to make 60cm wide, 60 cm long and a depth of 30cm (Danso-Abbeam *et al*., 2020). The top soil was then refilled to a level of 15cm before the fertility amendments were added. Sorghum gadam seeds variety a drought tolerant crop was sown at a spacing of 75 cm (inter-row) and 20 cm (intra-row) with two sorghum plants planted per hill.

Weeding was done twice during the planting period using a hand hoe with no diseases being observed on the sorghum plants during the two cropping seasons. Six out of the eight treatments had three external fertility amendments inputs in both *zai* and conventional planting (1) Cattle manure (2) cattle manure+30 kg N ha^{-1} /30 kg P ha^{-1} (3) 60 kg N ha^{-1} /60 kg P ha^{-1} were applied at the beginning of every season to give an equivalent of 60 kg N ha^{-1} and 60 kg P ha^{-1} the KARLO recommended rate of application for N and P for sorghum totaling to six treatments (Karanja *et al.,* 2014). The seventh and eight treatments were absolute control in both conventional and *zai* planting where no external fertility inputs were applied. Table 3.1 shows the treatments in the experiment at Kabati, Kitui County.

Table 3.1: Treatment combinations of the experiment at Kabati in Kitui County

Treatments	**N from manure Kg ha $^{-1}$**	**N and P from inorganic fertilizer Kg ha $^{-1}$**
Zai pits + Manure	60	0
Zai pits + Inorganic fertilizer	0	60 N and 60 P
Zai pits+ Manure+ Inorganic fertilizer	30	30 N and 30 P
Zai pits +No inputs	0	0
Conventional + Manure	60	0
Conventional+Inorganic fertilizer	0	60 N and 60 P
Conventional+Manure + Inorganic fertilizer	30	30 N and 30 P
Conventional + No inputs	0	0

3.3 Data Collection

3.3.1 Soil Sampling

The experiment was conducted in two seasons i.e., short rains of 2018 and the long rains of 2019. Soil sampling was done before setting up the experiment in SR2018 season (October, 2018) and the end of LR2019 season (March, 2019). Soil sampling in all the plots was done at a depth of 0-15 cm by use of a soil auger. The soil samples were then taken in each plot from five points within the plot. The soil samples were put in a clean bucket and mixed thoroughly. A representative soil sample was taken from the mixture, put in a bag and marked clearly for identification of the sample. The bags were then tied at the opening tightly to avoid contamination and taken for analysis in the laboratory.

3.3.2 Soil Laboratory Analysis

3.3.2.1 Soil Chemical Properties

All the laboratory analyses on the chemical properties of the soil were done using the standard methods for analyzing soils by Motsara (2008). Total nitrogen was analyzed using the Kjeldahl method, the available phosphorus (P) was measured using the Brays method, potassium (K) was estimated with a flame photometer, soil pH was measured by an electronic pH meter, electric conductivity of the soil was measured by electric conductivity meter, and organic carbon (OC) was analyzed by the ignition method.

3.3.2.2 Soil Physical Properties

Soil aggregate stability (dry sieving) was determined as highlighted by Ekwuea *et al*. (2018). As described by Motsara (2008), bulk density of soil was determined by the core sampling method with the soil particle size determined by the hydrometer method. Table 3.2 shows the averages for the initial soil characteristics at Kabati, Kitui County.

Table 3.2: Initial soil characteristics of Kabati, Kitui County

Parameter	Min	Max	Mean
Sand (%)	52	70	61
Silt (%)	5	11	8
Clay (%)	23	37	30
Bulk density (g/cm^3)	1.15	1.29	1.22
Soil aggregate stability (MWD) mm	1.20	2.42	1.81
TN (%)	0.31	0.46	0.39
EC (S)_dS/m	183.8	249.8	216.8
pH (H_2O)	5.40	5.59	5.50
OC (%)	1.07	1.45	1.26
Phosphorous (ppm)	6.37	12.75	9.56

Note: Min=Minimum values of each parameter, Max=Maximum value of each parameter, Mean=Average of each parameter

3.3.3 Sorghum Yields

Sorghum heads and stover were harvested from the net area of each plot at maturity, weighed (field weight) and recorded. The sorghum heads were sundried and the dry weight recorded as well. The sorghum heads were then threshed and the sorghum grain weighed to get the dry weight. Grain moisture content was then measured using a moisture meter and adjusted to 12.5% after sun drying.

3.3.4 Rainfall Measurement

Rainfall data was collected using a simple rain-gauge calibrated in millimeters and daily rainfall measured and recorded with monitoring visits done to ensure accuracy of the rainfall data.

3.3.5 Economic Analysis

For evaluation of economic returns of using *zai* pits and integrated soil fertility management (ISFM) technologies on sorghum production, partial budgeting was used to compare the costs and financial benefits of each treatment. The benefits and costs of each treatment was evaluated comparing to not using the ISFM technologies with *zai* pits. The costs included; fertility enhancing inputs (manure and inorganic fertilizer), pitting and labour with benefits being increased sorghum yield. The prevailing market prices in the study area were used to derive the input and output prices with the values that were used in the economic analysis shown in Table 3.3.

Table 3.3: Parameters used in cost-benefit analysis

Parameters	Cost (US Dollars)
Cost of NPK (per kg)	0.687
Labour cost (man/day ha^{-1})	3.602
Cost packet of sorghum seeds (2 kg)	3.435
Price of sorghum grains (per kg)	0.785
Cost of cattle Manure (tonnes)	5.888

Official exchange rate (September 2019) 1USD=Ksh.101.9

Detailed data on the labor was collected in the two seasons for all the various field operations including; Pitting, land preparation, application of cattle manure and inorganic fertilizer, weeding and harvesting. A stop watch was used to record the time taken for every activity with the labor valued at the local (study area) wage rate (USD man/day^{-1}) (USD 3.602) per working day (8 hours). To assess profitability, three economic tools i.e., the net benefit, benefit cost ratio (BCR) and return to labour were used which were calculated using the following formulas;

$$\text{Net benefits} = \text{Total benefits} - \text{Total costs}$$

$$\text{Benefit cost ratio} = \frac{\text{Net benefits}}{\text{Total Cost}}$$

$$\text{Return to labour} = \frac{\text{Net benefits}}{\text{Labour costs}}$$

3.4 Data Analysis

3.4.1 Soil Chemical Properties

Data on soil chemical properties was subjected to Analysis of Variance (ANOVA) in the proc ANOVA procedure in SAS 9.2 software and means separated using standard error of differences (SED) at $p<0.05$. Comparisons on soil nutrients from soil samples collected before setting up the experiment and the end of the experiment were analyzed using t-test.

3.4.2 Sorghum Yields

Data on sorghum yields was subjected to Analysis of Variance (ANOVA) in the proc ANOVA procedure in SAS 9.2 software and means separated using standard error of differences (SED) at $p<0.05$. To compare the effects of each treatment on sorghum yield, conversion of relative increases in comparison to the control were done. Changes in yield were compared between the two seasons using t-test

3.4.3 Economic Returns

To compare the effects of the treatments and tillage systems on the economic returns, the data collected was analyzed using analysis of variance (ANOVA) using the proc ANOVA procedure in SAS 9.2 software and means separated using standard error of differences (SED) at $p<0.05$.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Distribution of Rainfall During SR2018 and LR2019 Seasons

The two growing seasons (SR2018 and LR2019) recorded varying amounts of the rainfall received with SR2018 season receiving a total of 382.31mm and LR2019 receiving a total of 116.3mm (Figure 4.1). During the SR2018 season rain was experienced in 33 days and the LR2019 cropping season, rainfall was experienced in 10 days only with the rest of the season being dry. Out of the 33 days that rainfall was received during the SR2018, 22 days received rainfall less than 15 mm with the highest amount of the received rainfall recorded in the season being 45.2 mm which was received on the 48th day of the growing season. During the LR2019 season only 3 days received rainfall more than 15 mm with the highest amount of rainfall received being 40 mm at the 19th day of the growing period. Seven days received rainfall below 15 mm in the LR2019 season.

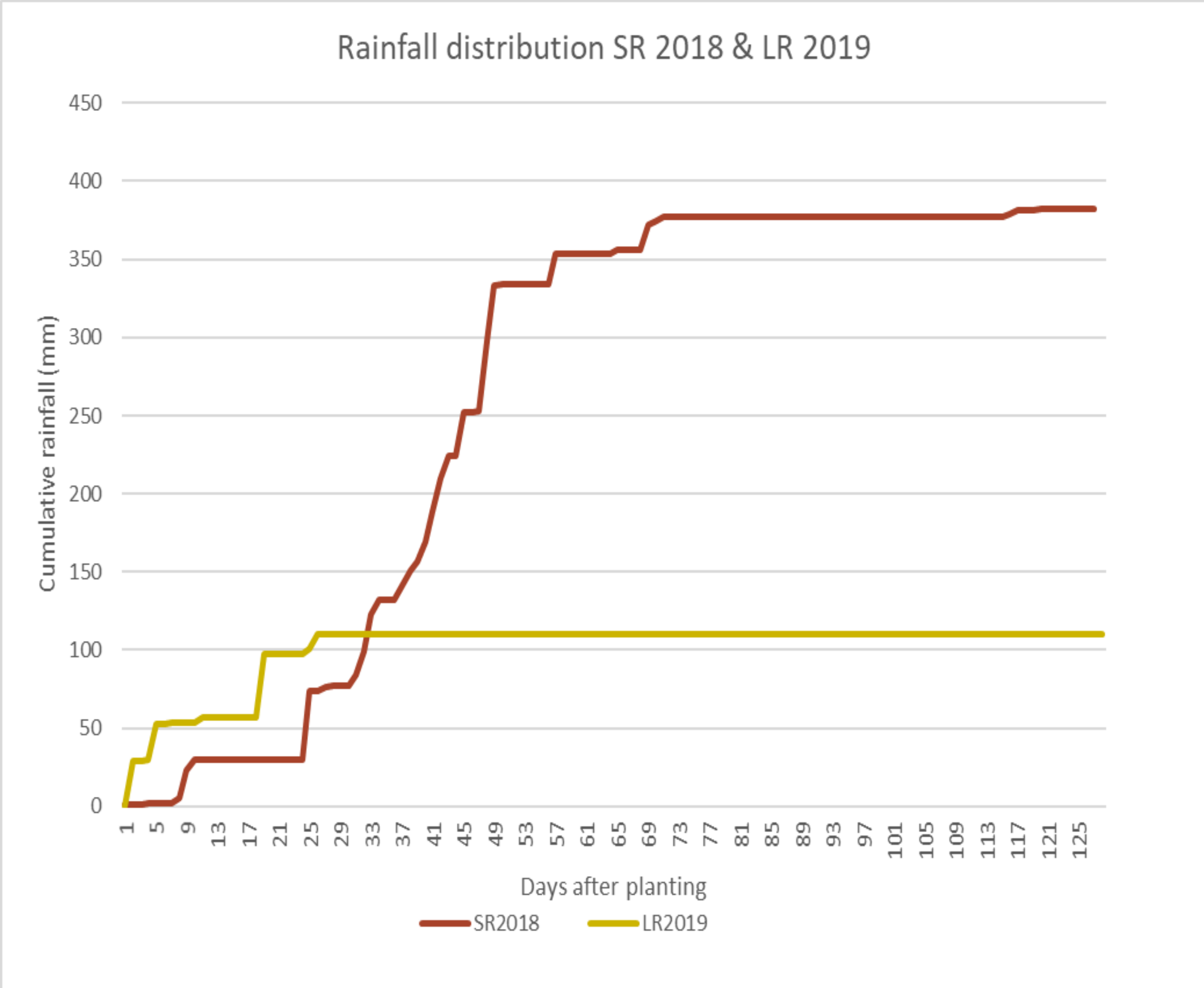

Figure 4.1: Distribution of rainfall during the SR2018 and LR2019 seasons at Kabati, Kitui County

During the SR2018 season, the daily rainfall recorded ranged between 0.01 mm and 45.2 mm with the LR2019 season ranging between 0.5 mm and 40 mm. During the SR2018 season, the highest rainfall event was recorded on the 25th and 48th days of the growing period with 44.2 mm and 45.2 mm respectively. During the LR2019 season the highest rainfall event recorded was 28.6 mm and 40 mm in the 2nd and 19th day of the growing season. High rainfall intensity is likely to increase surface runoff and high quantities of sediments causing soil erosion as described by Mohamadi and (Kavian, 2015) hence carrying away the soil nutrients. The high rainfall events recorded in the two cropping seasons would have likely increased the surface runoff affecting soil fertility. The prolonged dry spell during the LR2019 season was detrimental to the growth of sorghum because it coincided with the flowering stage leading to low crop production and almost a complete crop failure.

Small holder farmers in the ASAL regions often experience low yields resulting from water stress (Nyakudya and Stroosnijder, 2011). In sub-Saharan Africa, the agroecosystems are faced with dry spells as well as meteorological droughts (Rockstrom *et al*., 2010; Biazin *et al.*,2012) which gives an explanation made over the study period. Dry spells and a meteorological drought were experienced in the two planting seasons with SR2018 season experiencing two rainfall events between day 11 to day 24 and between day 74 to day 115 respectively after planting. In the LR2019 season, several dry spells were experienced between day 11 to day 18, day 27 and day 101 and day 103 and day 130 after planting. Research has shown that dry spells create a high evaporative demand which in turn creates severe constraints in growth of crops and yield in the sub humid and dry lands of East Africa and this often coincides with the critical stages such as the flowering stage (Wildemeersch *et al.,* 2015). Several strategies are being used by the small holder farmers to effectively cope with the effects of dry spells being experienced which include drought tolerant crop production and diversifying crop production to avert high food insecurity. Mavhura *et al*. (2015) noted that despite the measures taken by small holder farmers to avert the negative effects of drought, these strategies are insufficient to cope with the uncertainty in rainfall variability. Rain water harvesting techniques have played a role in averting the associated risks with dry spells within the seasons which then serves to bridge the gap between the rainfall events.

4.2 Effect of *Zai* Pit and ISFM on Soil Chemical Properties at Kabati, Kitui County

Nitrogen content was significantly (p=0.0214) influenced by *zai* pit and ISFM technologies at the end of LR2019 season. Under the *zai* tillage system, nitrogen content significantly (p=0.0390, p=0.0310 and p=0.0005, respectively) reduced in *zai* pit with manure and half rate mineral fertilizer, *zai* with sole manure and *zai* without input treatments at the end of the two cropping seasons. Under the conventional tillage system, nitrogen content reduced significantly (p=0.0212, p=0.0198, p=0.0007, respectively) in conventional with manure and fertilizer, conventional with sole manure and conventional with sole mineral fertilizer treatments (Table 4.1). *Zai* planting with sole mineral fertilizer had the highest percentage reduction in nitrogen content by -65.22% and conventional with manure recording the lowest percentage reduction -38.71% at the end of the experiment.

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Table 4.1: Soil chemical properties (0-15cm) at the beginning of SR2018 and end of LR2019 seasons at Kabati, Kitui County

Soil Parameters	**Total Nitrogen (%)**			**Soil pH (H_2O)**			**Electrical conductivity (dS/m)**			**Organic Carbon (%)**			**Available Phosphorous (ppm)**		
Treatments	Beg	End	t-test *p*	Beg	End	t-test *p*	Beg	End	t-test *p*	Beg	End	t-test *p*	Beg	End	t-test, *p*
CF60	0.40^{a}	0.15^{a}	0.0007	5.43^{a}	5.40^{a}	0.7607	192.3^{a}	288.3^{a}	0.0037	1.28^{a}	1.17^{a}	0.0596	6.37^{a}	18.68^{a}	0.1508
CM60	0.31^{a}	0.19^{bc}	0.0198	5.58^{a}	5.76^{a}	0.1836	194.1^{a}	311.1^{a}	0.2710	1.35^{a}	0.82^{a}	0.2602	7.11^{a}	21.03^{ad}	0.0266
CMF30	0.38^{a}	0.21^{b}	0.0212	5.53^{a}	5.63^{a}	0.5950	234.8^{a}	384.3^{b}	0.0415	1.44^{a}	0.59^{a}	0.0631	15.30^{a}	37.70^{bd}	0.0773
CNO	0.31^{a}	0.16^{a}	0.0737	5.44^{a}	5.50^{a}	0.7098	183.8^{a}	289.5^{a}	0.0180	1.07^{a}	0.32^{a}	0.0015	8.83^{a}	20.02^{a}	0.1142
ZF60	0.46^{a}	0.16^{a}	0.1196	5.49^{a}	5.48^{a}	0.9018	210.7^{a}	352.4^{b}	0.0010	1.37^{a}	0.87^{a}	0.0146	10.20^{a}	61.30^{c}	0.0114
ZM60	0.38^{a}	0.18^{ab}	0.0390	5.59^{a}	5.87^{a}	0.0909	209.9^{a}	342.4^{b}	0.0175	1.45^{a}	0.51^{a}	0.1055	11.02^{a}	26.62^{abd}	0.0258
ZMF30	0.39^{a}	0.19^{ac}	0.0310	5.59^{a}	5.66^{a}	0.5648	200.2^{a}	318.3^{a}	0.0067	1.36^{a}	0.58^{a}	0.0109	8.46^{a}	37.47d	0.0632
ZNO	0.37^{a}	0.19^{bc}	0.0005	5.40^{a}	5.36^{a}	0.4557	249.8^{a}	303.3^{a}	0.2257	1.33^{a}	0.43^{a}	0.1047	12.75^{a}	14.54^{ad}	0.1387
SED	0.0483	0.0112		0.1071	0.1313		18.4474	16.658		0.1729	0.1897		2.0173	5.6397	
P value	0.4011	0.0214		0.812	0.1511		0.2677	0.0097		0.8296	0.0974		0.0971	0.0005	

Beg=Beginning of experiment SR2018, End=End of experiment LR2019, *=significant at $p<0.05$ between SR2018 & LR2019 seasons, CMF30=Conventional + Cattle Manure + 30 kg N ha^{-1}, CNO= Conventional with no inputs, CM60= Conventional + Manure, CF60=Conventional+ 60 kg N ha^{-1}, ZNO=*zai* with no inputs, ZMF30=*zai*+ Cattle manure+ 30 kg N ha^{-1}, ZM60=*zai* + Manure, ZF60=*zai*+ 60 kg N ha^{-1}
Means followed by a different letter are not significantly different ($p<0.05$).

The treatments did not record any significant (*p*=0.1313) effect on soil pH at the end of the study period (Table 4.1). However, the pH rating for treatments with sole manure increased while those with fertilizer (60 kg N ha^{-1}) reduced in both *zai* and conventional tillage systems (Table 4.1). The treatments significantly (*p*=0.0097) increased the electrical conductivity at the end of the LR2019 season (Table 4.1). Under the conventional tillage treatments, electrical conductivity significantly (*p*=0.0415, *p*=0.0180, *p*=0.0037, respectively, t-test *p*) increased in conventional with manure and mineral fertilizer, conventional without inputs and conventional with sole mineral fertilizer treatments at the end of LR2019 season. Under the *zai* pit tillage treatments electrical conductivity significantly (*p*=0.0067, *p*=0.0175, *p*=0.0010, respectively t-test *p*) increased in *zai* with manure and fertilizer, *zai* with sole manure and *zai* with mineral fertilizer treatments at the end of LR2019 (Table 4.1). Compared to the control, electrical conductivity increased significantly (*p*=0.0010, *p*=0.0167, *p*=0.0392, respectively, t-test *p*) in conventional with manure and fertilizer, *zai* with sole mineral fertilizer and *zai* with sole manure treatments at the end of the two cropping seasons (Table 4.1).

Soil organic carbon (SOC) significantly (*p*=0.0015, *p*=0.0109, *p*=0.0146, respectively, t-test *p*) reduced in conventional without inputs, *zai* with manure and mineral fertilizer and *zai* with mineral fertilizer treatments at the end of the LR2019 season. There was a reduction in the soil organic carbon percentages in all the treatments with conventional without fertility input recording the highest decrease -70.09% (Table 4.1). Available phosphorous was significantly (*p*=0.0005) influenced by *zai* pit planting and ISFM technologies at the end of LR2019 season. The total percentages of available phosphorous increased at the end of the two cropping seasons with the highest increase recorded in *zai* with mineral fertilizer by 500.98% with the lowest increase recorded in *zai* without fertility input by 14.04%. Available phosphorous increased significantly (p=0.0258, p=0.0114, p=0.0266 respectively) in z*ai* with sole manure, *zai* with sole mineral fertilizer and conventional planting with sole manure treatments at the end of LR2019 season (Table 4.1).

From the results obtained there was an indication that the use of *zai* pits and addition of fertility inputs influenced the chemical properties of soil. Manure and mineral fertilizer application significantly reduced total nitrogen at the end of the LR2019 season. This could be because the application of this fertility inputs makes nitrogen readily available for plant uptake hence the reduction of total nitrogen in the soil. The reduction of nitrogen could also be attributed to loss through volatilization, nitrous oxide emission, leaching, erosion and oxidation of nitrogen as reported by Pal *et al.* (2020). These results were concurred with Pasley *et al*. (2019) who noted that an increase in nitrogen fertilizer application increased nitrogen uptake by crops reducing its availability in the soil. Similarly, Omara *et al*. (2019) also reported that the efficiency of nitrogen uptake by crops was accelerated by manure and fertilizer application. However, other studies recorded a significant increase in total nitrogen in the soil. For instance, Bedada *et al*. (2014) noted that combining compost and nitrogen phosphorous (NP) fertilizer increased total nitrogen 0-10 cm compared to the control experiment and nitrogen phosphorous (NP) fertilizer alone treatments. Similarly, Mattuso *et al*. (2014), Yegon *et al*. (2016), Kihara *et al*. (2016) and Liu *et al*. (2020) also reported that the addition of manure and mineral fertilizer increased total nitrogen in the soil.

There was no significant effect on soil pH at the end of the two cropping seasons. However, the soil pH rating slightly increased in treatments that had sole mineral fertilizer and increased in treatments that had sole cattle manure in both conventional and zai tillage systems. This was in line with what other researches had recorded that cattle manure has the ability to restore soil fertility in small holder farms because it increases soil pH (Zingore *et al*., 2008; Mugwe *et al*., 2009). The increase in the rating of soil pH could be associated with the application of cattle manure which has calcium carbonate and bicarbonates as well as the organic anions present in manure which neutralizes the H+ ions (Butterfly *et al*., 2012). The decrease in soil pH rating as a result of mineral fertilizer application could be due to the acidifying effect of the mineral fertilizer and the increase of electrical conductivity (Han *et al.,* 2016). Mucheru-Muna *et al*. (2014) also recorded a significant increase of soil pH in sole application of organic manure and reduction of soil pH with sole application of mineral fertilizer. Elsewhere, Bedada *et al.* (2014) had also recorded that a decrease in soil pH in treatments that had sole application of mineral fertilizer at $p<0.001$ after 6 years of consecutive treatments.

The application of sole manure increased the electrical conductivity of soil. This could be associated with the high amounts of dissolved salts in manure. Soil electrical conductivity increases resulting from manure application is related to the high amounts of dissolved salts that is beneficial in supplying a pool of nutrients and ions into the soil. Similarly, Carmo *et al*. (2016a), Carmo *et al*. (2016b) and Miller *et al*. (2016) have also reported that electrical conductivity increased with manure application.

Conversely, organic carbon reduced in all the treatments at the end of LR2019 season. This could be due to the slow changes in organic carbon in compacted, poorly drained soils and clayey soils compared to sloping and coarse-textured soils. Tillage also speeds up soil the loss of soil organic carbon by intensifying the mineralization process and other losses through erosion. This is because mixing of soils with litter favours bacteria and promotes the rapid breakdown process of organic carbon. Tillage induced erosion of soils is also the cause of severe loss of soil organic carbon more especially in upland landscapes. Liu *et al*. (2003), Blanco-Canqui *et al*. (2013) and Corsi *et al*. (2013) also reported similar results which indicated that soil organic carbon declined significantly in the first five years of cultivation. Long-term experiments are required to detect changes in organic carbon in the soil because it responds slowly to changes in agricultural management. This means that the changes may require a long period of time to be detected and quantify the effect of the management activities (Haddaway *et al.*, 2015). A similar study on the changes of soil organic carbon in an established plantation in northern China recorded an initial decrease in soil carbon (Lei *et al.*, 2019). This could be attributed to the loss of carbon through decomposition which outweighed gains of carbon from litter.

Available phosphorous increased in treatments that had sole manure in *zai* and conventional tillage systems an indication that manure could be associated with the increase in phosphorous in the soil. The current trend of results is similar with findings of Ali *et al*. (2019) who noted that the application of manure as an amendment in agricultural soils improved the soil physiochemical properties and cycling of nutrients through enhancing enzyme as well as the soil microbial activities leading to improved phosphorous bioavailability for crop uptake. Buckley and Makortoff (2004) reported that manure contains about 45% to 90% of inorganic orthophosphates a form in which phosphorous is readily available for uptake by plants which makes it a rich supplier of phosphorous into the soil. Mucheru-Muna *et al.* (2014) also noted that the compost treatments significantly increased soil available phosphorous content.

4.3 Effects of *Zai* Pit in Combination with Selected ISFM Technologies on Sorghum Yields

The highest sorghum grain and stover yields (4.38 t ha^{-1} and 12.71 t ha^{-1}), respectively were recorded during the short rains (SR2018) season while the lowest grain (0.06 t ha^{-1}) and stover (1.29 t ha^{-1}) yields were recorded during the long rains (LR2019) season (Table 4.2). Variation of grain and stover yields due to seasons, tillage systems (*zai* and conventional) and the different fertility inputs were observed during the two cropping seasons. During the SR2018 season, sorghum grain yields were significantly (p<0.001) influenced by *zai* pits and ISFM technologies (Table 4.2). Sorghum grain yields were significantly (p<.0001) higher in *zai* treatments when compared to the conventional treatments during the SR2018. During the LR2019 the grain and stover yield were also significantly (p=0.0005, p=0.0007, respectively) higher in *zai* treatments compared to their conventional counterparts.

Table 4.2: Sorghum grain and stover yield during the SR2018 and LR2019 seasons at Kabati, Kitui County

Treatments	**Grain yield ($t\ ha^{-1}$)**		**Stover yield ($t\ ha^{-1}$)**	
	SR2018	**LR2019**	**SR2018**	**LR2019**
Conventional + Fertilizer	2.54^{b}	0.24^{a}	6.35^{c}	2.18^{bcd}
Conventional + Manure	2.88^{b}	0.10^{a}	7.34^{c}	1.49^{cd}
Conventional + Manure + Fertilizer	3.13^{b}	0.06^{a}	5.95^{c}	1.85^{cd}
Conventional + No inputs	2.06^{b}	0.11^{a}	6.75^{c}	1.29^{d}
Zai +Fertilizer	4.38^{a}	0.28^{a}	7.81^{bc}	3.62^{a}
Zai +Manure	3.86^{a}	0.18^{a}	10.37^{ab}	2.98^{ab}
Zai + Manure + Fertilizer	4.37^{a}	0.20^{a}	12.71^{a}	2.33^{bc}
Zai +No inputs	3.06^{b}	0.14^{a}	6.74^{c}	1.97^{cd}
P	<.0001	0.1209	0.0005	0.0007
SED $_{(0.05)}$	0.2908	0.0547	0.8613	0.2926

SED=Standard Error of Difference, SR=Short Rains, LR=Long Rains

Means followed by a different letter are significantly different ($p<0.05$)

The SR2018 season recorded averagely higher grain yield compared to LR2019 season. Averagely the *zai* tillage system had higher grain and stover yield compared to their conventional counterparts in both SR2018 and LR2019 seasons. However, during the LR2019 season the grain yields in both conventional and *zai* treatments were lower due to the prolonged dry spell during the season.

In SR2018 season, grain yield was highest in *zai* with sole fertilizer (4.38 $t\ ha^{-1}$) and lowest in conventional without inputs (2.06 $t\ ha^{-1}$) treatments. In LR2019 season, the highest grain yield was recorded in *zai* planting with fertilizer (0.28 $t\ ha^{-1}$) and the lowest grain yield recorded in conventional with manure and mineral fertilizer treatments (0.06 $t\ ha^{-1}$) (Table 4.2). During the two cropping (SR2018 and LR2019) seasons stover yield ranged between 5.95 t ha^{-1} to 12.71 t ha^{-1} and 1.29 t ha^{-1} to 3.62 t ha^{-1}, respectively (Table 4.2).

During the SR2018 season, significant higher grain yields were recorded in *zai* with sole fertilizer, *zai* planting with sole manure and *zai* with manure and fertilizer (p=0.0027, p=0.0036, p=0.0116, respectively) compared to conventional with fertilizer, conventional with sole manure and conventional with manure and mineral fertilizer. During the same season, stover yields were significantly (p=0.0009) higher in *zai* planting with manure and fertilizer as compared to conventional planting with manure and mineral fertilizer. During the LR2019 season, significantly higher stover yields (p=0.0498, p=0.0390, respectively) were recorded in *zai* planting with mineral fertilizer and *zai* with sole manure as compared to conventional with sole fertilizer and conventional with sole manure (Table 4.2).

On average, the LR2019 season recorded lower grain and stover yields compared to the SR2018 season. This could be associated with the dry spells and prolonged meteorological drought that was experienced in the planting (LR2019) season where the cumulative rainfall declined (Figure 4.1) affecting the growth and production of sorghum. Rockstrom (2010), Ibrahim *et al*. (2011) and Nyakudya and Stroosnijder (2011) also reported similar results that low yields experienced were because of water stress which is often experienced by the smallholder farmers in the ASAL regions.

Zai pits as a water harvesting technique increased the grain yields in SR2018 and this could be because they are able to retain moisture in the soil and improve the efficiency of nutrient uptake. These results were similar with Amede *et al*. (2011) and Wouterse (2017) who noted that the *zai* pit technology was an intervention used by smallholder farmers to increase agricultural productivity through improving precipitation capture, reduction of runoff, increase infiltration and evaporation of water from the soil. The current trend of results also corroborated by Kathuli and Itabari (2014) who highlighted that the use of *zai* pits significantly increased sorghum grain yield. Similarly, Mazvimavi and Twomlow (2008) noted higher yields in pitting technology when comparing to the conventional tillage system.

During the SR2018 season, grain yields were significantly higher in *zai* with full-rate fertilizer when compared with *zai* without fertility input an indication that mineral fertilizer significantly increased the grain yields. This could be because mineral fertilizer improves soil properties by increasing the availability of soil nutrients and promotes the growth of crops. During the same season grain yields were significantly higher in *zai* with manure and *zai* with manure and mineral fertilizer comparing to the control. This could also be associated to the ability of the combination to enhance the release of nutrients and uptake by crops. Tittonel *et al.* (2008), Kihara *et al*. (2017) and Mi *et al*. (2018) also attributed the grain yield increase to the combined use of inorganic fertilizer and manure. Mattuso *et al*. (2014) linked the significant increase in grain yield to the ability of the combination to enhance the nutrient release and uptake. Amede *et al.* (2011) also reported that *zai* pits and a combination of fertilizer additions increased the yield of potatoes by 500% to 2000% and bean yield by 250%.

The application of sole manure or in combination with inorganic fertilizer increased crop yield and this could be associated with the increase in the nutrients supplied into the soil as well as the ability of the combination to enhance release of nutrients hence increase in nutrient availability.

This was similar with Mucheru-Muna *et al.* (2014) and Chen *et al*. (2018) who reported that the application of sole organics or in combination with fertilizers led to improved crop yield compared to the sole mineral fertilizers. Elsewhere, Chivenge *et al*. (2011) also reported an increase in maize yield in treatments that had a combination of organic resources and fertilizers (114%) and sole organic resources (60%). Biazin *et al*. (2012), Dunjana *et al*. (2012) and Kar *et al*. (2013) also noted that rainwater harvesting in combination with the use of both inorganic and organic inputs increases the nutrients in the soil improving crop productivity.

4.4 Economic Feasibility of *Zai* Pit Utilization Combined with Selected Integrated Soil Fertility Management on Sorghum Production in Kitui County

Labour costs varied significantly among the treatments with the *zai* tillage system recording higher labour costs incurred during the SR2018 compared to the conventional tillage system. During the same season, *zai* planting with mineral fertilizer treatment recorded the highest labour costs (1153.35 USD ha^{-1}) and the lowest labour costs were recorded in conventional planting without fertility input (145.85 USD ha^{-1}) (Table 4.3).

Table 4.3: Economic analysis of the different treatments during the SR2018 and LR2019 seasons

Treatment	Labour cost SR2018 USD/Ha	Labour cost LR2019 USD/Ha	Total cost SR2018	Total cost LR2019	Total benefit SR2018	Total benefit LR2019	Net benefit SR2018	Net benefit LR2019	Return to Labour SR2018	Return to Labour LR2019	BCR SR2018	BCR LR2019
CF60	228.71^{c}	230.06^{a}	271.27^{d}	271.27^{a}	1993.65^{b}	188.15^{a}	1722.38^{bc}	-83.12^{ab}	7.47^{d}	-0.37^{ab}	6.34^{d}	-0.31^{a}
CM60	150.00^{e}	144.22^{c}	172.48^{f}	172.48^{de}	2234.89^{b}	73.63^{a}	2062.39^{abc}	-98.86^{ab}	14.30^{bcd}	-0.69^{b}	11.96^{abc}	-0.57^{a}
CMF30	207.83^{d}	212.10^{b}	246.4^{e}	246.4^{b}	2616.67^{b}	43.14^{a}	2369.83^{ab}	-203.69^{b}	11.16^{cd}	-0.96^{b}	9.59^{cd}	-0.82^{a}
CNO	145.85^{e}	145.02^{c}	145.02^{g}	145.02^{f}	2242.86^{b}	84.11^{a}	2097.84^{abc}	-60.78^{ab}	14.45^{bcd}	-0.42^{ab}	14.45^{abc}	-0.42^{a}
ZF60	1153.35^{a}	150.57^{c}	1194.55^{a}	191.79^{c}	3596.78^{a}	221.66^{a}	2402.23^{ab}	29.88^{a}	15.92^{abc}	0.21^{a}	12.51^{abc}	0.16^{a}
ZM60	1118.56^{b}	115.78^{d}	1167.93^{a}	157.78^{ef}	3815.14^{a}	140.18^{a}	2647.21^{a}	-17.60^{a}	22.82^{a}	-0.15^{ab}	17.09^{a}	-0.11^{a}
ZMF30	1149.92^{a}	147.14^{c}	1189.36^{a}	186.59^{cd}	3980.85^{a}	156.93^{a}	2791.48^{a}	-29.66^{ab}	19.20^{ab}	-0.20^{ab}	15.23^{ab}	-0.16^{a}
ZNO	1118.36^{b}	115.65^{d}	1118.36^{c}	115.65^{g}	2399.68^{b}	112.24^{a}	1281.31^{c}	-3.41^{a}	11.09^{cd}	-0.01^{ab}	11.09^{bcd}	-0.01^{a}
P	<.0001	<.0001	<.0001	<.0001	<.0001	0.1202	0.0049	0.0393	0.0001	0.0956	0.0036	0.1115
SED $_{(0.05)}$	3.809	3.2578	6.0487	6.0916	226.7482	42.9366	227.866	42.8921	1.5772	0.2532	1.5147	0.2229

CMF30=Conventional + Cattle Manure+30 kg N ha^{-1}, CNO= Conventional with no inputs, CM60=Conventional+Manure, CF60=Conventional+ 60 kg N ha^{-1}, ZNO=*zai* with no inputs, ZMF30=*zai*+ Cattle manure+ 30 kg N ha^{-1}, ZM60=*zai* + Manure, ZF60=*zai*+ 60 kg N ha^{-1} BCR=Benefit Cost Ratio, SR= Short Rains, LR=Long Rains

Means followed by a different letter are not significantly different (p<0.05)

(SED) Standard Error of Difference

Total costs were significantly (p<0.0001) influenced by the treatments in both cropping seasons. Generally, total costs were higher in *zai* planting compared to conventional planting with the same treatments during the SR2018 season. The highest total costs during the SR2018 were recorded in *zai* with sole fertilizer (1194.55 USD ha^{-1}) and the lowest recorded in conventional without input (145.02 USD ha^{-1}). During the LR2019 season, the total costs were higher in conventional treatments compared with the *zai* tillage system. The highest total cost recorded in the season was recorded in conventional with fertilizer (271.27 USD ha^{-1}) and the lowest recorded in *zai* without input (115.65 USD ha^{-1}). The total benefits were significantly (p<0.0001) influenced by the treatments during the SR2018 season (Table 4.3).

The three economic tools i.e., the net benefits, return to labour and benefit cost ratio (BCR) were significantly (p=0.0049, p=0.0001, p=0.0036, respectively) influenced by *zai* pits and ISFM technologies during the SR2018 season. The highest net benefit during the SR2018 season was recorded in *zai* planting with manure and mineral fertilizer (2791.48 USD ha^{-1}) and the lowest recorded in *zai* without input (1281.31 USD ha^{-1}) in the same season (Table 4.3). During the SR2018 season, return to labour was significantly higher (p=0.0269, p=0.0252, p=0.0379, respectively) in *zai* with fertilizer, *zai* with manure and *zai* with manure and fertilizer as compared to conventional with fertilizer, conventional with manure and conventional with manure and fertilizer.

In the LR2019 season the most of the treatments recorded a negative change in the net benefits (Table 4.3). The highest net benefit was recorded in *zai* with fertilizer (29.88 USD ha^{-1}) and the lowest recorded in conventional with manure and fertilizer (-203.69 USD ha^{-1}). During the SR2018 season, the highest return to labour was recorded in *zai* with sole manure treatment

(22.82 USD ha^{-1}) and the lowest recorded in conventional with fertilizer treatment (7.47 USD ha^{-1}). In the LR2019 season the highest return to labour was recorded in *zai* with fertilizer treatment (0.21 USD ha^{-1}) and the lowest in conventional with manure and fertilizer (-0.96 USD ha^{-1}). BCR was highest in *zai* with sole manure (17.09 USD ha^{-1}) and lowest in conventional with fertilizer (6.34 USD ha^{-1}). In LR2019 the BCR was highest (Table 4.3) in *zai* with fertilizer (0.16 USD ha^{-1}) and lowest in conventional with manure and fertilizer (-0.82 USD ha^{-1}).

There was a significant effect on the economic parameters in the two cropping seasons, with SR2018 performing better than the LR2019 season. This could be because the LR2019 recorded lower grain yields due to the prolonged dry spell. Ray *et al.* (2018) noted that drought causes significant reduction in yields and economic returns in both irrigated and rainfed crops because of the reduction of water and moisture available for crop growth. The SR2018 season had higher benefits in treatments that had a combination of manure and fertilizer in both conventional and zai tillage systems compared to the control. This was an indication that the combined application of organics and inorganics fertilizers was economically viable to the small-holder farmers. Hobbs *et al*. (2011) and Kebede *et al.* (2020) attributed the high net benefits with soil fertility amendments and water conservation techniques used in crop production. This generally explains the higher net benefit results in the SR2018 season that averagely, the combined use of cattle manure and fertilizer recorded higher net benefits than the rates recommended for fertilizer application (Olarinde *et al*., 2012; Girma *et al*., 2020).

The net benefits, return to labour and BCR were higher in *zai* treatments compared to conventional treatments with similar fertility inputs. This could be associated with the water conservation and fertility technologies in the *zai* treatments which increased the overall net benefits. Hobbs *et al.* (2011) reported that *zai* pits has been used as an intervention to increase productivity by improving water availability and nutrient efficiency. Higher net benefits, return to labour and BCR were recorded in treatments that had combined manure and fertilizer in both *zai* and conventional planting. This could be due to the increased supply of nutrients hence high productivity. Similar results have also been reported by Mutegi *et al*. (2012) who revealed that averagely, the combined use of organics and mineral fertilizers recorded higher net benefit and Benefit Cost Ratio when compared with sole fertilizers application. Kearney *et al*. (2012), Ojiem *et al*. (2014), Matusso *et al*. (2014) and Thimmaiah *et al*. (2016) noted that greater net benefits were recorded in a combined application of inorganics and fertilizers when compared to the application of sole inorganics and sole fertilizer.

During the SR2018 season, BCR was greater than one in all the treatments compared with the LR2019 season whereby the BCR was less than one in all the treatments. When the Benefit Cost Ratio (BCR) is greater than one, it indicates that the technologies can be beneficial as Shively and Galopin (2012) reported. Higher BCR was recorded in *zai* planting with manure and *zai* with manure and mineral fertilizer compared to their conventional counterparts in the two cropping seasons. This could be a consideration because its more economical and a feasible alternative available for nutrient supplementation compared to the higher costs of fertilizers (Mucheru-Muna *et al.*, 2007).

CHAPTER FIVE: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of the Findings

From the findings, *zai* pits and the integrated soil fertility management technologies had a very minimal effect on the soil chemical properties. Soil total nitrogen and organic carbon reduced at the end of the LR2019 season. Application of both sole cattle manure increased soil pH in both conventional and *zai* pit planting. This was an indication that cattle manure played a role in increasing soil pH. Conversely, application of sole fertilizer reduced soil pH at the end of LR2019 season in both *zai* and conventional planting. Electrical conductivity and available phosphorous increased in all the treatments at the end of the two cropping seasons. Available phosphorus and electrical conductivity of the soil increased significantly in treatments that sole application of manure. The organic matter present in manure increased the phosphorous content and the electrical conductivity in the soil.

On average, sorghum yields were higher in *zai* tillage system compared to conventional tillage system in the two cropping seasons. The LR2019 season recorded lower yields than the SR2018 season due to the prolonged meteorological drought that was experienced during the season. Lower stover yields were also recorded in conventional planting in the two planting seasons. On assessing the economic feasibility of *zai* planting with the selected ISFM technologies, *zai* planting generally recorded higher labour costs compared to conventional planting which recorded lower labour costs in the SR2018 season. This was attributed to the higher costs of installing *zai* pits. The lowest labour costs were recorded in conventional planting without fertility inputs. Generally, total costs were higher in *zai* planting compared to conventional planting with the same treatments during the SR2018 season. The total benefits were significantly higher in *zai* treatments compared to their conventional counterparts with the same fertility inputs.

The three economic tools i.e., the net benefits, return to labour and Benefit Cost Ratio (BCR) were significantly influenced by *zai* pits and ISFM technologies during the SR2018 season. During the SR2018 the highest net benefit was recorded in *zai* planting with manure and mineral fertilizer and the lowest recorded in *zai* without input in the same season. During the SR2018 season, return to labour was significantly higher in *zai* with fertilizer, *zai* with manure and *zai* with manure and fertilizer as compared to their conventional counterparts with the same fertility inputs. During the LR2019 season the highest return to labour was recorded in *zai* with fertilizer treatment and the lowest in conventional with manure and fertilizer. BCR was highest in *zai* with sole manure and lowest in conventional with fertilizer during SR2018 seasons. In LR2019 the BCR was highest in *zai* with fertilizer and lowest in conventional with manure and fertilizer.

5.2 Conclusion

Cattle manure an amendment used to improve soil fertility increased soil pH in both *zai* pit and conventional planting. The use of sole mineral fertilizer decreased soil pH in both tillage systems. Total nitrogen content significantly decreased in all the treatments at the end of the two cropping systems. There was a reduction in the soil organic carbon in all the treatments at the end of the two seasons but the changes were not significant. The available phosphorous content also increased significantly in treatments that had sole manure application in both *zai* and conventional planting.

Averagely the *zai* tillage system had higher grain and stover yield compared to their conventional counterparts in both SR2018 and LR2019 seasons. The SR2018 season recorded higher grain yield compared to LR2019 season due to the prolonged dry spell during the season. During the two cropping seasons, labour costs and total costs were higher in *zai* treatments with *zai* with sole fertilizer recording the highest labour and total costs. The total benefits were also higher in *zai* treatments in both cropping seasons compared to their conventional counterparts.

The three economic tools i.e., the net benefits, return to labour and benefit cost ratio (BCR) were significantly influenced by *zai* pits and ISFM technologies during the SR2018 season. *Zai* planting was the best in enhancing sorghum grain yields and economic returns compared to conventional planting that had lower yields hence lower economic returns. Application of cattle manure and mineral fertilizer is essential as it improves productivity through enhancing soil fertility and hence improved productivity and better economic returns.

5.3 Recommendations

From the results of this study, it is recommended that;

i. To enhance crop yields, *Zai* pits should be used with a combined application of both organic resources and inorganic soil fertility inputs to supplement nutrient deficiencies due to the limited purchasing power of the farmers for improved crop production

ii. Farmers should also be trained on the importance of using *zai* pit as a soil and water conservation technique in ASALs to improve crop production.

5.4 Further Research

This study was limited to the use of *Zai pits* and integrated soil fertility management for sorghum production at Kabati in Kitui County for two cropping seasons. Further research should consider how the data collected for the two cropping seasons (SR2018 and LR2019) seasons can be enhanced through crop modelling to enable more generalized statements on the impact of *Zai* pits and ISFM on sorghum yields. Further, more soil and water conservation technologies should also be considered as well as their effects and sustainability on small holder farmers in the ASAL regions of Kenya.

REFERENCES

Adamtey, N., Musyoka, M. W., Zundel, C., Cobo, J. G., Karanja, E., Fiaboe, K. K., Muriuki, A., Mucheru-Muna, M., Vanlauwe, B., Berset, E., Messmer, M. M., Gattinger, A., Bhullar, G. S., Cadisch, G., Fliessbach, A., Mäder, P., Niggli, U., & Foster, D. (2016). Productivity, profitability and partial nutrient balance in maize-based conventional and organic farming systems in Kenya. *Agriculture, Ecosystems & Environment*, *235*, 61-79. https://doi.org/10.1016/j.agee.2016.10.001

Adimassu, Z., & Kessler, A. (2016). Factors affecting farmers' coping and adaptation strategies to perceived trends of declining rainfall and crop productivity in the central Rift valley of Ethiopia. *Environmental Systems Research*, *5*(1), 1-16.

Agehara, S. & Warncke, D. D. (2015). Soil moisture and temperature effects on nitrogen release from organic nitrogen sources. *Soil Science Society of America Journal*, *69*(6), 1844-1855.

Ali, A., & Erenstein, O. (2017). Assessing farmer use of climate change adaptation practices and impacts on food security and poverty in Pakistan. *Climate Risk Management*, *16*, 183-194.

Ali, S., Liu, Y., Ishaq, M., Shah, T., Ilyas, A., & Din, I. U. (2017). Climate change and its impact on the yield of major food crops: Evidence from Pakistan. *Foods*, *6*(6), 39.

Ali, W., Nadeem, M., Ashiq, W., Zaeem, M., Gilani, S. S. M., Rajabi-Khamseh, S.,Kavanagh, V., Thomas, R., & Cheema, M. (2019). The effects of organic and inorganic phosphorus amendments on the biochemical attributes and active microbial population of agriculture podzols following silage corn cultivation in boreal climate. *Scientific reports*, *9*(1), 1-17

Amede, T., Menza, M., & Awlachew, S. B. (2011). Zai improves nutrient and water productivity in the ethiopian Highlands. *Experimental Agriculture*, *47*(S1), 7-20. https://doi.org/10.1017/s0014479710000803

Amelework, B. A., Shimelis, H. A., Laing, M. D., Ayele, D. G., Tongoona, P. & Mengistu, F. (2016). Sorghum production systems and constraints, and coping strategies under drought-prone agro-ecologies of Ethiopia. *South African Journal of Plant and Soil*, *33*(3), 207-217.

Aniah, P., Kaunza-Nu-Dem, M. K., & Ayembilla, J. A. (2019). Smallholder farmers' livelihood adaptation to climate variability and ecological changes in the savanna agro ecological zone of Ghana. *Heliyon*, *5*(4), e01492.

Assefa, Y., Staggenborg, S. A. & Prasad, V. P. (2010). Grain sorghum water requirement and responses to drought stress: A review. *Crop Management*, *9*(1), 1-11.

Ayal, D. Y., & Leal Filho, W. (2017). Farmers' perceptions of climate variability and its adverse impacts on crop and livestock production in Ethiopia. *Journal of Arid Environments*, *140*, 20-28.

Ayande, A., Radeny, M., Morton, J.F., & Muchaba, T. (2018). Rainfall variability and drought Characteristics in Two Agro-Climatic Zones: An Assessment of Climate Change Challenges in Africa. Science of the Total Environment, 630, 728-737.

Banwart, S. (2011). Save our soils. *Nature*, *474*(7350), 151-152. https://doi.org/10.1038/474151a

Bashagaluke, J. B., Logah, V., Opoku, A., Sarkodie-Addo, J. & Quansah, C. (2018). Soil nutrient loss through erosion: Impact of different cropping systems and soil amendments in Ghana. *PloS one*, *13*(12), e0208250.

Bationo, A., Mokwunye, U., Vlek, P. G., Kaola, S., & Shapiro, B. I. (2003). Soil fertility management for sustainable land use in West African Sudano-Sahelian zone. In *Soil fertility management in Africa: A regional perspective* (pp. 253-292). Nairobi, Kenya: Academic Science Publishers.

Bationo, A., Kihara, J., Waswa, B., Ouattara, B., & Vanlauwe, B. (2005). Technologies for sustainable management of sandy Sahelian soils. *Management of tropical sandy soils for sustainable agriculture. Proceedings*, 414-429.

Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., & Kimetu, J. (2007). Soil organic carbon dynamics, functions and management in west African agro-ecosystems. *Agricultural Systems*, *94*(1), 13-25. https://doi.org/10.1016/j.agsy.2005.08.011

Bayu, T. (2020). Review on contribution of integrated soil fertility management for climate change mitigation and agricultural sustainability. *Cogent Environmental Science*, *6*(1), 1823631.

Bedada, W., Karltun, E., Lemenih, M., & Tolera, M. (2014). Long-term addition of compost and NP fertilizer increases crop yield and improves soil quality in experiments on smallholder farms. *Agriculture, Ecosystems & Environment*, *195*, 193-201. https://doi.org/10.1016/j.agee.2014.06.017

Bedada, W., Lemenih, M., & Karltun, E. (2016). Soil nutrient build-up, input interaction effects and plot level N and P balances under long-term addition of compost and NP fertilizer. *Agriculture, Ecosystems & Environment*, *218*, 220-231. https://doi.org/10.1016/j.agee.2015.11.024

Biazin, B., Sterk, G., Temesgen, M., Abdulkedir, A., & Stroosnijder, L. (2012). Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa – A review. *Physics and Chemistry of the Earth, Parts A/B/C*, *47-48*, 139-151. https://doi.org/10.1016/j.pce.2011.08.015

Blanco-Canqui, H., Shapiro, C. A., Wortmann, C. S., Drijber, R. A., Mamo, M., Shaver, T. M., & Ferguson, R. B. (2013). Soil organic carbon: The value to soil properties. *Journal of Soil and Water Conservation*, *68*(5), 129A-134A. https://doi.org/10.2489/jswc.68.5.129a

Bremner, J. M. (1960). Determination of nitrogen in soil by the Kjeldahl method. *The Journal of Agricultural Science*, *55*(1), 11-33.

Bryan, E., Ringler, C., Okoba, B., Roncoli, C., Silvestri, S., & Herrero, M. (2013). Adapting agriculture to climate change in Kenya: Household strategies and determinants. *Journal of environmental management*, *114*, 26-35.

Buckley, K., & Makorto, M. (2004). Phosphorus in Livestock Manures. In Advanced Silage Corn Management; *Agriculture and Agri-Food* Canada: Brandon, MB, Canada.

Butterly, C. R., Baldock, J. A., & Tang, C. (2012). The contribution of crop residues to changes in soil pH under field conditions. *Plant and Soil*, *366*(1-2), 185-198. https://doi.org/10.1007/s11104-012-1422-1

Canning, D., Raja, S., & Yazbeck, A.S. (2015) Africa's demographic transition: dividend or disaster? The World Bank, Washington, DC

Carmo, D. L., Lima, L. B., & Silva, C. A. (2016). Soil fertility and electrical conductivity are affected by organic waste rates and nutrient inputs. *Revista Brasileira de Ciência do Solo*, *40*(0). https://doi.org/10.1590/18069657rbcs20150152

Carmo, D. L., Silva, C. A., Lima, J. M., & Pinheiro, G. L. (2016). Electrical conductivity and chemical composition of soil solution: Comparison of solution samplers in tropical soils.

Revista Brasileira de Ciência do Solo, *40*(0). https://doi.org/10.1590/18069657rbcs20140795

Castaldelli, G., Colombani, N., Soana, E., Vincenzi, F., Fano, E. A. & Mastrocicco, M. (2019). Reactive nitrogen losses via denitrification assessed in saturated agricultural soils. *Geoderma*, *337*, 91-98.

Chen, H., Deng, A., Zhang, W., Li, W., Qiao, Y., Yang, T., Zheng, C., Cao, C., & Chen, F. (2018). Long-term inorganic plus organic fertilization increases yield and yield stability of winter wheat. *The Crop Journal*, *6*(6), 589-599. https://doi.org/10.1016/j.cj.2018.06.002

Chepng'etich, E., Nyamwaro, S. O., Bett, E. K., & Kizito, K. (2015). Factors That Influence Technical Efficiency of Sorghum Production: A Case of Small Holder Sorghum Producers in Lower Eastern Kenya. *Advances in Agriculture*, *2015*, 1-11. https://doi.org/10.1155/2015/861919

Chivenge, P., Vanlauwe, B., & Six, J. (2011). Does the combined application of organic and mineral nutrient sources influence maize productivity? A meta-analysis. *Plant and Soil*, *342*(1-2), 1-30. https://doi.org/10.1007/s11104-010-0626-5

Chivenge, P., Vanlauwe, B., Gentile, R., Wangechi, H., Mugendi, D., Van Kessel, C., & Six, J. (2009). Organic and mineral input management to enhance crop productivity in central Kenya. *Agronomy Journal*, *101*(5), 1266-1275. https://doi.org/10.2134/agronj2008.0188x

Corsi, S., Friedrich, T., Kassam, A., Pisante, M., & Sà, J. D. M. (2012). *Soil organic carbon accumulation and greenhouse gas emission reductions from conservation agriculture: a literature review*. Food and Agriculture Organization of the United Nations (FAO).

Cregger, M. A., McDowell, N. G., Pangle, R. E., Pockman, W. T. & Classen, A. T. (2014). The impact of precipitation change on nitrogen cycling in a semi-arid ecosystem. *Functional ecology*, *28*(6), 1534-1544.

Dai, X., Ouyang, Z., Li, Y. & Wang, H. (2013). Variation in yield gap induced by nitrogen, phosphorus and potassium fertilizer in North China Plain. *PLoS One*, *8*(12), e82147.

Danjuma, M. N., & Mohammed, S. (2015). *Zai* pit System: A catalyst for restoration in the dry lands. *Agriculture and vertinary science*, *8*(2), 1-4.

Danso-Abbeam, G., Dagunga, G., & Ehiakpor, D. S. (2020). Rural non-farm income diversification: implications on smallholder farmers' welfare and agricultural technology adoption in Ghana. *Heliyon*, *6*(11), e05393.

Dolschak, K., Gartner, K. & Berger, T. W. (2019). The impact of rising temperatures on water balance and phenology of European beech (Fagus sylvatica L.) stands. *Modeling earth systems and environment*, *5*(4), 1347-1363.

Duncan, D. S. (2016). Linking Soil Microbiology and Environmental Conditions to Variability in Nitrous Oxide Production in Bioenergy Systems. The University of Wisconsin-Madison

Dunjana, N., Nyamugafata, P., Shumba, A., Nyamangara, J., & Zingore, S. (2012). Effects of cattle manure on selected soil physical properties of smallholder farms on two soils of Murewa, Zimbabwe. *Soil Use and Management*, *28*(2), 221-228. https://doi.org/10.1111/j.1475-2743.2012.00394.x

Ejigu, W., Selassie, Y. G., Elias, E., & Damte, M. (2021). Integrated fertilizer application improves soil properties and maize (Zea mays L.) yield on Nitisols in Northwestern Ethiopia. *Heliyon*, *7*(2), e06074.

Ekwuea, E. I., Anya, T. D., & Chakansinghc, A. (2018). A Wet Sieving Apparatus for Determining Aggregate Stability of Soils. *Assoc. Prof*, *46*, 35-40.

Ershadi, S. Z., Dias, G., Heidari, M. D. & Pelletier, N. (2020). Improving nitrogen use efficiency in crop-livestock systems: A review of mitigation technologies and management strategies, and their potential applicability for egg supply chains. *Journal of Cleaner Production*, *265*, 121671.

Fairhurst, T. (2012). Introduction. *Africa Soil Health Consortium: Handbook for integrated soil fertility management*, 1-4. https://doi.org/10.1079/9781780642857.0001

Food and Agriculture Organisation. (2015). *World reference base for soil resources 2014 International soil classification system for naming soils and creating legends for soil maps Update 2015 WORLD SOIL RESOURCES REPORTS*.

Food and Agriculture Organization. (2010). *The Hague conference on Agriculture, Food security and climate change. Climate smart agriculture: policies, practices and financing for food security, adaptation and mitigation*. Rome, Italy: FAO.

Funk, C., Sathyan, A. R., Winker, P., & Breuer, L. (2020). Changing climate-Changing livelihood: smallholder's perceptions and adaption strategies. *Journal of environmental management*, *259*, 109702.

Gebru, G. W., Ichoku, H. E., & Phil-Eze, P. O. (2020). Determinants of smallholder farmers' adoption of adaptation strategies to climate change in Eastern Tigray National Regional State of Ethiopia. *Heliyon*, *6*(7), e04356.

Gemeda, D. O. & Sima, A. D. (2015). The impacts of climate change on African continent and the way forward. *Journal of Ecology and the Natural environment*, *7*(10), 256-262.

Gichangi, A., Maina, M. P., Lelgut, D. K., Kinyua, M. G., Macharia, E., Kamwaga, J., & Luvonga, J. (2006). Cassava-Grain Legume Intercrop:its feasibility and implications on Household Food Security in Kenya. In *10th KARI Biennial Scientific Conference*. Nairobi, Kenya: Kenya Agricultural Research Institute (KARI).

Gicheru, P. (2012). An overview of soil fertility management, maintenance, and productivity in Kenya. *Archives of Agronomy and Soil Science*, *58*(sup1), S22-S32. https://doi.org/10.1080/03650340.2012.693599

Girma, T., Beyene, S., Lemaga, B., & Temesgen, B. B. (2020). Integrated application of organic and blended mineral fertilizers improves potato productivity and income for smallholder farmers in acidic soils. *Environment and Natural Resources Research*.

Global Hunger Index (2011) *The Challenge of Hunger: Taming Price Spikes and Excessive Food Price Volatility*,

Government of Kenya (2010). *Economic Review of Agriculture*. Ministry of Agriculture, Nairobi, Kenya

Groppo, J. D., Lins, S. R., Camargo, P. B., Assad, E. D., Pinto, H. S., Martins, S. C., Salgado, P. R., Evangelista, B., Vasconcellos, E., Sano, E. E., Pavão, E., Luna, R., & Martinelli, L. A. (2015). Changes in soil carbon, nitrogen, and phosphorus due to land-use changes in Brazil. *Biogeosciences*, *12*(15), 4765-4780. https://doi.org/10.5194/bg-12-4765-2015

Haddaway, N. R., Hedlund, K., Jackson, L. E., Kätterer, T., Lugato, E., Thomsen, I. K., & Söderström, B. (2015). What are the effects of agricultural management on soil organic carbon in boreo-temperate systems?. *Environmental Evidence*, *4*(1), 1-29

Haileselassie, B., Stomph, T. J. & Hoffland, E. (2011). Teff (Eragrostis tef) production constraints on Vertisols in Ethiopia: farmers' perceptions and evaluation of low soil zinc as yield-limiting factor. *Soil Science and Plant Nutrition*, *57*(4), 587-596.

Hamoud, Y. A., Guo, X., Wang, Z., Shaghaleh, H., Chen, S., Hassan, A. & Bakour, A. (2019). Effects of irrigation regime and soil clay content and their interaction on the biological yield, nitrogen uptake and nitrogen-use efficiency of rice grown in southern China. *Agricultural Water Management*, *213*, 934-946.

Han, S. H., An, J. Y., Hwang, J., Kim, S. B., & Park, B. B. (2016). The effects of organic manure and chemical fertilizer on the growth and nutrient concentrations of yellow poplar (Liriodendron tulipiferaLin.) in a nursery system. *Forest Science and Technology*, *12*(3), 137-143. https://doi.org/10.1080/21580103.2015.1135827

Hatfield, J. L., Antle, J., Garrett, K. A., Izaurralde, R. C., Mader, T., Marshall, E., & Ziska, L. (2020). Indicators of climate change in agricultural systems. *Climatic Change*, *163*(4), 1719-1732. https://doi.org/10.1007/s10584-018-2222-2

Hatibu, N., Mutabazi, K., Senkondo, E., & Msangi, A. (2006). Economics of rainwater harvesting for crop enterprises in semi-arid areas of East Africa. *Agricultural Water Management*, *80*(1-3), 74-86. https://doi.org/10.1016/j.agwat.2005.07.005

Hellmuth, M. E., Osgood, D. E., Hess, U., Moorhead, A., & Bhojwani, H. (2009). Index insurance and climate risk: Prospects for development and disaster management. International Research Institute for Climate and Society (IRI).

Hobbs, P.R., Sayre, K., & Gupta, R. (2011). The role of conservation agriculture in sustainable agriculture. Philosophical transactions of the Royal Society of London. Series B. *Biological Sciences*, 363, 1491

Huang, S., Peng, X., Huang, Q., & Zhang, W. (2015). Soil aggregation and organic carbon fractions affected by long-term fertilization in a red soil of subtropical China. *Geoderma*, *154*(3-4), 364-369. https://doi.org/10.1016/j.geoderma.2009.11.009\

Huho, J. M., & Mugalavai, E. M. (2010). The effects of droughts on food security in Kenya. *The International Journal of Climate Change: Impacts and Responses*, *2*(2), 61-72. https://doi.org/10.18848/1835-7156/cgp/v02i02/37312

Ibrahim, A.A., Ati, F.O., & Adebayo, A.A. (2011). Effect of Climate on the Growth and Yield of Sorghum (Sorghum bicolor) in Wailo, Ganjuwa Local Government Area, Bauchi State. *Research Journal of Environmental and Earth Sciences*, 3, 469-472.

Jaetzold, R., Schmidt, H., Hornetz, B. & Shisanya, C. (2007). Farm management handbooks of Kenya, Vol. II: Natural Conditions and Farm Management Information, Part C East Kenya, Subpart C1 Eastern Province. Nairobi, Kenya, Ministry of Agriculture and GTZ

Jaramillo, S., Graterol, E. & Pulver, E. (2020). Sustainable transformation of rainfed to irrigated agriculture through water harvesting and smart crop management practices. *Frontiers in Sustainable Food Systems*, *4*, 437086.

Joshi, P. K., Jha, A. K., Wani, S. P., & Sreedevi, T. K. (2009). Scaling-out community watershed management for multiple benefits in rainfed areas. *Rainfed agriculture: unlocking the potential*, 276-291. https://doi.org/10.1079/9781845933890.0276

Jupp, A. R., Beijer, S., Narain, G. C., Schipper, W. & Slootweg, J. C. (2021). Phosphorus recovery and recycling–closing the loop. *Chemical Society Reviews*, *50*(1), 87-101.

Kaluli, J. W., Ng'ang'a, K., Home, P. G., Gathenya, J. M., Muriuki, A. W., & Kihurani, A. W. (2013). Effect of rainwater harvesting and drip irrigation on crop performance in arid and semi-arid environment. *Journal of Agriculture, Science and technology*, *14*(2).

Kalungu, J. W., Filho, W. L., Mbuge, D. O., & Cheruiyot, H. K. (2015). Assessing the impact of Rainwater HarvestingRainwater harvesting technology as adaptation strategy for rural communities in Makueni County, KenyaMakueni County. *Handbook of Climate Change Adaptation*, 1615-1634. https://doi.org/10.1007/978-3-642-38670-1_23

Kar, R., Bindroo, B. B., Ghosh, M. K., & Majumder, S. K. (2013). Carbon credit in soil under a long-term fertilizer experiment on mulberry. *Nature and science*, *11*(3).

Karanja, D. C., Kamau, L., Muthoni, A., Kariuki, C. W., Kavoi, J., Ochieng, A. &Wafula, W. J. (2009). *Improving food security and income of farmers in ASALs through commercialization of Gadam sorghum project*. Unpublished report, Machakos Kenya.

Karanja, D. R., Kisilu, R. K., Kathuli, P., Mutisya, D. L., Njaimwe, A. N., Keya, G. & Ouda, J. (2014). Enhancing Sorghum production in semi-arid Kenya. Retrieved from Kalro.org/Sorghum-training-manual

Kathuli, P., & Itabari, J. (2014). In-situ soil moisture conservation: Utilisation and management of rainwater for crop production. *International Journal of Agricultural Resources, Governance and Ecology*, *10*(3), 295. https://doi.org/10.1504/ijarge.2014.064009

Kavoi, J., Kisilu, R., Kamau, G, Wafula, J., Njangungi N., & Nganga, T. (2013). Gadam sorghum production and marketing through a public private partnership in Eastern Kenya, KARI Nairobi, Kenya - 39pp

Kearney, S., Fonte, S. J., Salomon, A., Six, J., & Scow, K. M. (2012). Forty percent revenue increase by combining organic and mineral nutrient amendments in Ugandan smallholder market vegetable production. *Agronomy for Sustainable Development*, *32*(4), 831-839. https://doi.org/10.1007/s13593-012-0097-6

Kebede, E. (2020). Grain legumes production and productivity in Ethiopian smallholder agricultural system, contribution to livelihoods and the way forward. *Cogent Food & Agriculture*, *6*(1), 1722353.

Kenya Ministry of Agriculture [MoA]. (2012). *Traditional High Value Crops Program*. Journal of the Agricultural Industry in Africa. Agricultural Review Online.

Kiboi, M., Ngetich, K., Diels, J., Mucheru-Muna, M., Mugwe, J., & Mugendi, D. (2017). Minimum tillage, tied ridging and mulching for better maize yield and yield stability in the central Highlands of Kenya. *Soil and Tillage Research*, *170*, 157-166. https://doi.org/10.1016/j.still.2017.04.001

Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V. Njoroge, N., Palm, C., & Huising, J. (2016). Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. *Agriculture, Ecosystems & Environment*, *229*, 1-12. doi:10.1016/j.agee.2016.05.012

Kihara, J., Sileshi, G. W., Nziguheba, G., Kinyua, M., Zingore, S., & Sommer, R. (2017). Application of secondary nutrients and micronutrients increases crop yields in sub-Saharan Africa. *Agronomy for Sustainable Development*, *37*(4). doi:10.1007/s13593-017-0431-0

Kimaru, S. W. (2017). *Zai Pits and integrated soil fertility management enhances crop yields in the drier parts of Tharaka Nithi County, Kenya* (Doctoral dissertation, Kenyatta University, Nairobi, Kenya). Retrieved from http://www.ku.ac.ke/erepository

Kimaru-Muchai, S. W., Ngetich, F. K., Baaru, M., & Mucheru-Muna, M. W. (2020). Adoption and utilisation of Zai pit for improved farm productivity in drier upper Eastern Kenya. *Journal of Agriculture and Rural Development in the Tropics and Subtropics (JARTS)*, *121*(1), 13-22.

Kogo, B. K., Kumar, L., & Koech, R. (2021). Climate change and variability in Kenya: a review of impacts on agriculture and food security. *Environment, Development and Sustainability*, *23*(1), 23-43.

Kumar, R., Kumar, R. & Prakash, O. (2019). Chapter-5 the Impact of Chemical Fertilizers on Our Environment and Ecosystem. *Chief Ed*, *35*, 69.

Lahmar, R., Bationo, B. A., Lamso, N. D., Guero, Y., & Tittonell, P. (2012). Tailoring conservation agriculture technologies to West Africa semi-arid zones: building on traditional local practices for soil restoration. *Field crops research*, *132*, 158-16

Lamb, J. A., Fernandez, F. G. & Kaiser, D. E. (2014). Understanding nitrogen in soils. *University of Minnesota Extension,(Revised)*, 1-5.

Lee, S. & Kim, R. (2012). Rainwater Harvesting. In: Meyers, R.A. (eds) Encyclopedia of Sustainability Science and Technology. Springer, New York, NY. https://doi.org/10.1007/978-1-4419-0851-3_332

Lei, Z., Yu, D., Zhou, F., Zhang, Y., Yu, D., Zhou, Y., & Han, Y. (2019). Changes in soil organic carbon and its influencing factors in the growth of Pinus sylvestris var. mongolica plantation in Horqin Sandy Land, Northeast China. *Scientific reports*, *9*(1), 1-12.

Leonard, L. N., Duffy, C., & Butt, G. (2010)." *Data-intensive hydrologic modeling, A cloud strategy for integrating PIHM, GIS and web services" annual fall proceedings* In *AGU Fall Meeting Abstracts* (Vol. 2010, pp. H53H-08).

Lesk, C., Rowhani, P., & Ramankutty, N. (2016). Influence of extreme weather disasters on global crop production. *Nature*, *529*(7584), 84-87. https://doi.org/10.1038/nature16467

Liang, X.Z., Wu, Y., Chambers, R.G., Schmoldt, D.L., Gao, W., Liu, C., Liu, Y.A., Sun, C. & Kennedy, J.A. (2017). Determining climate effects on US total agricultural productivity. In *Proceedings of the National Academy of Sciences doi* (Vol. 10).

Liang, X., & Van Dijk, M. P. (2011). Economic and financial analysis on rainwater harvesting for agricultural irrigation in the rural areas of Beijing. *Resources, Conservation and Recycling*, *55*(11), 1100-1108. https://doi.org/10.1016/j.resconrec.2011.06.009

Liu X.B., Han X.Z., Herbert S.J., & Xing B. (2003). Dynamics of soil organic carbon under different agricultural management systems in the black soil of China. *Community Soil Sci.* Plant Anal., 34: 973–984

Liu, L., Li, C., Zhu, S., Xu, Y., Li, H., Zheng, X., & Shi, R. (2020). Combined application of organic and inorganic nitrogen fertilizers affects soil prokaryotic communities' compositions. *Agronomy*, *10*(1), 132. https://doi.org/10.3390/agronomy10010132

Lokuruka, M. N. (2020). Food and nutrition security in east Africa (Kenya, Uganda and Tanzania): Status, challenges and prospects. *Food security in Africa*.

Macharia, J. M., Mugwe, J. N., & Mucheru-Muna, M. (2012). *Factors influencing levels of knowledge in soil fertility management in the central highlands of Kenya* [Conference session]. Third RUFORUM Biennial Meeting 24 - 28 September 2012, Entebbe, Uganda.

Manda, J., Alene, A. D., Gardebroek, C., Kassie, M., & Tembo, G. (2016). Adoption and impacts of sustainable agricultural practices on maize yields and incomes: Evidence from rural Zambia. *Journal of Agricultural Economics*, *67*(1), 130-153. https://doi.org/10.1111/1477-9552.12127

Mati, B. M. (2006). *Overview of water and soil nutrient management under smallholder rain-fed agriculture in East Africa*. Colombo, Sri Lanka: International Water Management Institute.

Matsumoto, T., Cifuentes, O., & Mas, T. (2013). Characterization of soil properties in relation to maize productivity in Andosols of the western Highland of Guatemala. *Soil Science and Plant Nutrition*, *59*(2), 195-207. https://doi.org/10.1080/00380768.2012.760430

Matusso,, J., Mugwe,, J., & Mucheru-Muna, M. (2014). Effects of different maize (Zea mays L.) soybean (Glycine Max (L.) Merrill) intercropping patterns on soil mineral-N, N-uptake and soil properties. *African Journal of Agricultural Research*, *9*(1), 42-55. https://doi.org/10.5897/ajar2013.7178

Mavhura, E., Manatsa, D., & Mushore, T. (2015). Adaptation to drought in arid and semi-arid environments: Case of the Zambezi Valley, Zimbabwe. *Journal of Disaster Risk Studies*, *7*(1). https://doi.org/10.4102/jamba.v7i1.144

Mazvimavi, K., & Towmlow, S. (2008). Socio economic Factors Influencing Adoption of Conservation Farming by Vulnerable Households in Zimbabwe. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Bulawayo, Zimbabwe, Pp 40.

Mbakaya D. S, Okalebo J. R, Muricho M., Lumasayi, S. (2010). Effects of liming and inorganic fertilizers on maize yield in Kakamega North and Ugunja districts, western Kenya. In:

Wasilwa et al (Eds) 12**th** KARI Biennial Scientific Conference. 8 – 12 November, 2010, Nairobi, Kenya pp 123-129

Mbingo, J. M. (2013). Response of maize to potassium and phosphorus fertilizers combinations on acidic soils of western Kenya. Msc. Thesis, University of Eldoret

Mganga, K. Z., Musimba, N. K. R., & Nyariki, D. M. (2015). Combining sustainable land management technologies to combat land degradation and improve rural livelihoods in semi-arid lands in Kenya. *Environmental management*, *56*(6), 1538-1548.

Mi, W., Sun, Y., Xia, S., Zhao, H., Mi, W., Brookes, P. C., Liu, Y., & Wu, L. (2018). Effect of inorganic fertilizers with organic amendments on soil chemical properties and rice yield in a low-productivity Paddy soil. *Geoderma, 320,* 23-29. https://doi.org/10.1016/j.geoderma.2018.01.016

Miller, J., Beasley, B., Drury, C., Larney, F., & Hao, X. (2016). Surface soil salinity and soluble salts after 15 applications of composted or stockpiled manure with straw or wood chips. *Compost Science & Utilization*, *25*(1), 36-47. https://doi.org/10.1080/1065657x.2016.1176968

Ministry of Agriculture (2012). Crops Extension Pocket Handbook Vol. 1 - Field Crops. Kilimo House, Nairobi, Kenya

Mohamadi, M. A., & Kavian, A. (2015). Effects of rainfall patterns on runoff and soil erosion in field plots. *International Soil and Water Conservation Research*, *3*(4), 273-281. https://doi.org/10.1016/j.iswcr.2015.10.001

Morris, T. F., Murrell, T. S., Beegle, D. B., Camberato, J. J., Ferguson, R. B., Grove, J. & Yang, H. (2018). Strengths and limitations of nitrogen rate recommendations for corn and opportunities for improvement. *Agronomy Journal*, *110*(1), 1-37.

Motis, T., D, C. & Lingbeek, B. (2013). *Zai* Pit System. Technical Note #78, ECHO.

Motsara, M. R. (2008). *Guide to laboratory establishment for plant nutrient analysis*. Rome: Food and Agriculture Organization of the United Nations.

Muchai, S. K., Ngetich, F. K., Baaru, M., & Mucheru-Muna, M. W. (2020). Adoption and utilisation of Zai pits for improved farm productivity in drier upper Eastern Kenya. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, *121*(1), 13-22.

Mucheru-Muna, M. W., Ada, M. A., Mugwe, J. N., Mairura, F. S., Mugi-Ngenga, E., Zingore, S., & Mutegi, J. K. (2021). Socio-economic predictors, soil fertility knowledge domains and strategies for sustainable maize intensification in Embu County, Kenya. *Heliyon*, *7*(2), e06345. doi:10.1016/j.heliyon.2021.e06345

Mucheru-Muna, M., Mugendi, D., Kung'u, J., Mugwe, J., & Bationo, A. (2007). Effects of organic and mineral fertilizer inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya. *Agroforestry Systems*, *69*(3), 189-197. https://doi.org/10.1007/s10457-006-9027-4

Mucheru-Muna, M., Mugendi, D., Pypers, P., Mugwe, J., Kung'u, J., Vanlauwe, B., & Merckx, R. (2014). Enhancing maize productivity and profitability using organic inputs and mineral fertilizer in central Kenya small-hold farms. *Experimental Agriculture*, *50*(2), 250-269. https://doi.org/10.1017/s0014479713000525

Mucheru-Muna, M., Pypers, P., Mugendi, D., Kung'u, J., Mugwe, J., Merckx, R., & Vanlauwe, B. (2010). A staggered maize–legume intercrop arrangement robustly increases crop yields and economic returns in the Highlands of central Kenya. *Field Crops Research*, *115*(2), 132-139. https://doi.org/10.1016/j.fcr.2009.10.013

Mugalavai, E. M., Kipkorir, E. C., Raes, D., & Rao, M. S. (2008). Analysis of rainfall onset, cessation and length of growing season for western Kenya. *Agricultural and Forest Meteorology*, *148*(6-7), 1123-1135. https://doi.org/10.1016/j.agrformet.2008.02.013

Mugwe, J., Mugendi, D., Mucheru-Muna, M., Merckx, R., Chianu, J., & Vanlauwe, B. (2009). Determinants of the decision to adopt integrated soil fertility management practices by smallholder farmers in the central Highlands of Kenya. *Experimental Agriculture*, *45*(1), 61-75. https://doi.org/10.1017/s0014479708007072

Mugwe, J., Mugendi, D., Mucheru-Muna, M., Odee, D., & Mairura, F. (2009). Effect of selected organic materials and inorganic fertilizer on the soil fertility of a humic Nitisol in the central Highlands of Kenya. *Soil Use and Management*, *25*(4), 434-440. https://doi.org/10.1111/j.1475-2743.2009.00244.x

Muriuki, J. P. (2009). An evaluation of organic and inorganic inputs for soil nutrient replenishment in Mukuuni and Murugi, Central Kenya. *MSc Thesis*, Kenyatta University.

Mutegi, E. M., Kung'u, J. B., Mucheru-Muna, M., Pieter, P., & Mugendi, D. N. (2012). Complementary effects of organic and mineral fertilizers on maize production in the smallholder farms of Meru south district, Kenya. *Agricultural Sciences*, *03*(02), 221-229. https://doi.org/10.4236/as.2012.32026

Mutie, F. M., Rono, P. C., Kathambi, V., Hu, G. W. & Wang, Q. F. (2020). Conservation of wild food plants and their potential for combatting food insecurity in Kenya as exemplified by the drylands of Kitui County. *Plants*, *9*(8), 1017.

Muui, C., Muasya, R. M., & KIrubi, D. T. (2013). Baseline survey on factors affecting sorghum production and use in eastern Kenya. *African Journal of Food, Agriculture, Nutrition and Development*, *13*(01), 7339-7342. https://doi.org/10.18697/ajfand.56.11545.

Mwadalu, R., & Mwangi, M. (2013). The potential role of sorghum in enhancing food security in semi-arid eastern Kenya: A review. *Journal of Applied Biosciences*, *71*(1), 5786. https://doi.org/10.4314/jab.v71i1.98826

Mwangi, P. (2020). A climate-smart agriculture approach using double digging, Zai pits and Aquacrop model in rain-fed sorghum cultivation at Wiyumiririe location of Laikipia County, Kenya. *Africa Journal of Physical Sciences ISSN: 2313-3317*, *4*.

Naik, A., Teggelli, R.G., Ahamed, Z., & Patil, D.H. (2016). Yield gap analysis of sorghum through front line demonstrations in Kalaburagi region of northern Karnataka. *Research in Environment and Life Sciences 9*(5):597-598

Ndeke, A. M., Mugwe, J. N., Mogaka, H., Nyabuga, G., Kiboi, M., Ngetich, F., & Mugendi, D. (2021). Gender-specific determinants of Zai technology use intensity for improved soil water management in the drylands of Upper Eastern Kenya. *Heliyon*, e07217.

Nezomba, H. (2016). Exploring mechanisms to restore fertility of degraded lixisols for enhanced crop productivity under Smallholder Farmer Management Systems.

Nezomba, H., Mtambanengwe, F., Chikowo, R., & Mapfumo, P. (2014). Sequencing integrated soil fertility management options for sustainable crop intensification by different categories of smallholder farmers in Zimbabwe. *Experimental Agriculture*, *51*(1), 17-41. https://doi.org/10.1017/s0014479714000131

Ngetich, F. K., Shisanya, C. A., Mugwe, J., Mucheru-Muna, M., & Mugendi, D. N. (2012). *The potential of organic and inorganic nutrient sources in sub-Saharan African crop farming systems*.

Ngetich, F. K., Shisanya, C. A., Mugwe, J., Mucheru-Muna, M., & Mugendi, D. N. (2012). *The potential of organic and inorganic nutrient sources in sub-Saharan African crop farming systems*.

Njeru, P. N., Maina, I., Lekasi, J. K., Kimani, S. K., Esilaba, A. O., Mugwe, J., & Mucheru-Muna, M. (2016). Climate smart agriculture adaptation strategies for rain-fed agriculture in drought-prone areas of Central Kenya. *International Journal of Agricultural Resources, Governance and Ecology*, *12*(2), 113-124.

Njeru, P. N., Maina, I., Miruka, M., Amboga, J.S., Gitari, J., Rono, B., Mahasi, M., & Murithi, F. (2011). Soil fertility characterization of small holder farms under group and individual management in Central Kenya. Proceedings on held at Maputo, Mozambique on 10th to 13th October. Afri. Crop Sci. Conf. Prod. 10:1-4

Norman, J. S. & Friesen, M. L. (2017). Complex N acquisition by soil diazotrophs: how the ability to release exoenzymes affects N fixation by terrestrial free-living diazotrophs. *The ISME journal*, *11*(2), 315-326.

Nyakudya, I., & Stroosnijder, L. (2011). Water management options based on rainfall analysis for rainfed maize (Zea mays L.) production in Rushinga district, Zimbabwe. *Agricultural Water Management*, *98*(10), 1649-1659. https://doi.org/10.1016/j.agwat.2011.06.002

Nyang'au, J. O., Mohamed, J. H., Mango, N., Makate, C., & Wangeci, A. N. (2021). Smallholder farmers' perception of climate change and adoption of climate smart agriculture practices in Masaba South Sub-county, Kisii, Kenya. *Heliyon, 7*(4), e06789. doi:10.1016/j.heliyon.2021.e06789

Obanyi, S., Muya, E., Ngutu, M., & Bulle, H. (2009). *Characterization of farming systems in mountain and oasis areas of northern Kenya*. Kenya Agricultural and Research Institute, Nairobi, Kenya.

Ogada, M. J., Rao, E. J., Radeny, M., Recha, J. W., & Solomon, D. (2020). Climate-smart agriculture, household income and asset accumulation among smallholder farmers in the Nyando basin of Kenya. *World Development Perspectives*, *18*, 100203.

Ojiem, J., Franke, A., Vanlauwe, B., De Ridder, N., & Giller, K. (2014). Benefits of legume–maize rotations: Assessing the impact of diversity on the productivity of smallholders in western Kenya. *Field Crops Research*, *168*, 75-85. https://doi.org/10.1016/j.fcr.2014.08.004

Olarinde, L.O, Oduol, J.B., & Binam, J.N. (2012). Impact of the adoption of soil and water conservation practices on crop production: Baseline evidence of the Sub-saharan Africa Challenge programme forum for agricultural research in Africa (FARA), Sub-Saharan Africa Challenge 12. *Journal of Agriculture and Environmental Science*, 12 (3), 293-305.

Omara, P., Aula, L., & Raun, W. R. (2019). Nitrogen Uptake Efficiency and Total Soil Nitrogen Accumulation in Long-Term Beef Manure and Inorganic Fertilizer Application. *International Journal of Agronomy*, *2019*, 1-6. doi:10.1155/2019/9594369

Omoyo, N. N., Wakhungu, J., & Oteng'i, S. (2015). Effects of climate variability on maize yield in the arid and semi-arid lands of lower eastern Kenya. *Agriculture & Food Security, 4*(1). https://doi.org/10.1186/s40066-015-0028-2

Ondiko, J. H., Ochieng', R., & Karanja, A. M. (2018). Rainfall Variability Coping Strategies for Improved Food Security: A Case Study of Baringo South, Baringo County, Kenya. *The International Journal of Humanities & Social Studies*.

Opala, P. A., Okalebo, J. R., & Othieno, C. (2013). Comparison of effects of phosphorus sources on soil acidity, available phosphorus and maize yields at two sites in western Kenya. *Archives of Agronomy and Soil Science*, *59*(3), 327-339. https://doi.org/10.1080/03650340.2011.627681

Opiyo, F., Wasonga, O., Nyangito, M., Schilling, J., & Munang, R. (2015). Drought Adaptation and Coping Strategies Among the Turkana Pastoralists of Northern Kenya. *International Journal of Disaster Risk Science*, *6*(3), 295-309. https://doi.org/10.1007/s13753-015-0063-4

Ouda, S., & Zohry, A. E. H. (2020). Water scarcity leads to food insecurity. In *Deficit Irrigation* (pp. 1-13). Springer, Cham.

Oweis, T., & Hachum, A. (2009). Water harvesting for improved rainfed agriculture in the dry environments. *Rainfed agriculture: unlocking the potential*, 164-181. https://doi.org/10.1079/9781845933890.0164

Oweis, T., Prinz, D., & Hachum, A. (2012). Rainwater Harvesting for Agriculture in the Dry Areas. Doi:10.1201/b12351

Pachauri, R. K., & Meyer, L. A. (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Pal, A., Adhikary, R., Barman, S., & Maitra, S. (2020). Nitrogen transformation and losses in soil: A cost-effective review study for farmer. *International Journal of Chemical Studies, 8*(3), 2623-2626. doi:10.22271/chemi.2020.v8.i3al.9609

Pasley, H. R., Cairns, J. E., Camberato, J. J., & Vyn, T. J. (2019). Nitrogen fertilizer rate increases plant uptake and soil availability of essential nutrients in continuous maize production in Kenya and Zimbabwe. *Nutrient Cycling in Agroecosystems*, *115*(3), 373-389. doi:10.1007/s10705-019-10016-1

Patle, G. T., Kumar, M., & Khanna, M. (2020). Climate-smart water technologies for sustainable agriculture: A review. *Journal of Water and Climate Change*, *11*(4), 1455-1466.

Rafique, E., Mahmood-ul-Hassan, M., Rashid, A. & Chaudhary, M. F. (2012). Nutrient balances as affected by integrated nutrient and crop residue management in cotton-wheat system in Aridisols. I. Nitrogen. *Journal of plant nutrition*, *35*(4), 591-616.

Raimi, A., Adeleke, R., & Roopnarain, A. (2017). Soil fertility challenges and Bio-fertiliser as a viable alternative for increasing smallholder farmer crop productivity in sub-Saharan Africa. *Cogent Food & Agriculture*, *3*(1). DOI:10.1080/23311932.2017.1400933

Ray, R. L., Fares, A., & Risch, E. (2018). Effects of drought on crop production and cropping areas in Texas. *Agricultural & Environmental Letters*, *3*(1), 170037. https://doi.org/10.2134/ael2017.11.0037

Recha, C. W., Makokha, G. L. & Shisanya, C. A. (2017). Climate variability and causes: from the perspective of the Tharaka people of eastern Kenya. *Geoscience Letters*, *4*(1), 1-8.

Rockström, J., Karlberg, L., Wani, S. P., Barron, J., Hatibu, N., Oweis, T., Bruggeman, A., Farahani, J., & Qiang, Z. (2010). undefined. *Agricultural Water Management*, *97*(4), 543-550. https://doi.org/10.1016/j.agwat.2009.09.009

Roobroeck, D., van Asten, P. J., Jama, B., Harawa, R., & Vanlauwe, B. (2015). Integrated Soil Fertility Management: Contributions of framework and practices to climate-smart agriculture. *CSA Practice Brief* .DOI:10.13140/RG.2.1.1695.2400

Rosegrant, M. W., Mandy, E., Gary, Y., Burton, I., Huq, S., & Rowena, V. S. (2008). *Climate change and agriculture: Threats and opportunities*. Eschborn, Germany.

Sainju, U. M., Senwo, Z. N., Nyakatawa, E. Z., Tazisong, I. A., & Reddy, K. C. (2008). undefined. *Agriculture, Ecosystems & Environment*, *127*(3-4), 234-240. https://doi.org/10.1016/j.agee.2008.04.006

Sarkar, S., Skalicky, M., Hossain, A., Brestic, M., Saha, S., Garai, S., & Brahmachari, K. (2020). Management of crop residues for improving input use efficiency and agricultural sustainability. *Sustainability*, *12*(23), 9808.

Satyanarayana, V., Vara Prasad, P. V., Murthy, V. R., & Boote, K. J. (2002). undefined. *Journal of Plant Nutrition*, *25*(10), 2081-2090. https://doi.org/10.1081/pln-120014062

Sawadogo, H. (2011). Using soil and water conservation techniques to rehabilitate degraded lands in northwestern Burkina Faso. *International Journal of Agricultural Sustainability*, *9*(1), 120-128. Doi:10.3763/ijas.2010.0552.

Schjoerring, J. K., Cakmak, I. & White, P. J. (2019). Plant nutrition and soil fertility: synergies for acquiring global green growth and sustainable development. *Plant and Soil*, *434*(1), 1-6.

Schröder, J. J. (2014). The position of mineral nitrogen fertilizer in efficient use of nitrogen and land: a review. *Natural resources*, *5*(15), 936.

Schröder, J. J., Smit, A. L., Cordell, D. and Rosemarin, A. (2011). Improved phosphorus use efficiency in agriculture: a key requirement for its sustainable use. *Chemosphere*, *84*(6), 822-831

Sharma, B., Molden, D. & Cook, S. (2015). *Water use efficiency in agriculture: Measurement, current situation and trends* (No. 612-2016-40604).

Shively, G., & Galopin, M. (2013). An overview of benefit-cost analysis. *Accessed online at http://www. agecon. purdue. edu/staff/shively/COURSES/AGEC406/reviews/bca. htm*.

Silva, J.A., & Uchida, R. (2000). Plant nutrient management in Hawaii's soils, approaches for tropical and sub-tropical agriculture. College of tropical agriculture and human resources, university of Hawaii at Manoa

Skidmore, E. L., & Powers, D. H. (1982). Dry soil-aggregate stability: Energy-based index. *Soil Science Society of America Journal*, *46*(6), 1274-1279.

Smaling, E. M. A., Nandwa, S. M. & Janssen, B. H. (1997). Soil fertility is at stake. In replenishing soil fertility in Africa: An investment in natural resource capital, 47–61. (Eds R. J. Buresh, P. A. Sanchez, and F. Calhoun). Soil Science

Smith, J. U., Fischer, A., Hallett, P. D., Homans, H. Y., Smith, P., Abdul-Salam, Y., & Phimister, E. (2015). Sustainable use of organic resources for bioenergy, food and water provision in rural Sub-Saharan Africa. *Renewable and Sustainable Energy Reviews*, *50*, 903-917.

Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., & Zimmermann, M. (2013). The Knowns, known unknowns and unknowns of sequestration of soil organic carbon. *Agriculture, Ecosystems & Environment*, *164*, 80-99.

Tabu, J., Otwelo, J., Koskei, P., & Makokha, P. (2013). Hazard analysis of Arid and semi-Arid (ASAL) regions of Kenya. *East African journal of public health.*, *10*(410-5).

Thimmaiah, M., Kumar, M. D., Nandish, M. S., & Veeranna, H. K. (2016). Effect of integrated nutrient management on growth, yield and economics of rain-fed finger millet. *Green farming*, *7*(4), 875-879.

Tittonell, P., Shepherd, K., Vanlauwe, B., & Giller, K. (2008). Unraveling the effects of soil and crop management on maize productivity in small holder agricultural systems of western Kenya—An application of classification and regression tree analysis. *Agriculture, Ecosystems & Environment*, *123*(1-3), 137-150. Doi:10.1016/j.agee.2007.05.005

Troy, T.J., C. Kipgen, & Pal., I. (2015). The impacts of climate extremes and irrigation on US crop yields. Environment Research Letters 10:054013. doi:10.1088/1748-9326/10/5/054013

Tumushabe, J. T. (2018). Climate change, food security and sustainable development in Africa. In *The Palgrave handbook of African politics, governance and development* (pp. 853-868). Palgrave Macmillan, New York.

U. S Grain Council. (2010). Sorghum. Retrieved from http://www.grains.org/tags/sorghum

Ulrich, A., Speranza, C. I., Roden, P., Kiteme, B., Wiesmann, U., & Nüsser, M. (2012). Small-scale farming in semi-arid areas: Livelihood dynamics between 1997 and 2010 in Laikipia, Kenya. *Journal of Rural Studies*, *28*(3), 241-251.

Vanlauwe, B., Bationo, A., Chianu, J., Giller, K., Merckx, R., Mokwunye, U., Ohiokpehai, O., Pypers, P., Tabo, R., Shepherd, K., Smaling, E., Woomer, P., & Sanginga, N. (2010). undefined. *Outlook on Agriculture*, *39*(1), 17-24. https://doi.org/10.5367/000000010791169998

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., & Zingore, S. (2015). Integrated soil fertility management in sub-Saharan Africa: Unravelling local adaptation. *SOIL*, *1*(1), 491-508. https://doi.org/10.5194/soil-1-491-2015

Vanlauwe B., Hungriab, M., Kanampiua, F., & Giller, K. E. (2019). The role of legumes in the sustainable intensification of African smallholder agriculture: Lessons learnt and challenges for the future. *Agriculture, Ecosystems and Environment*.

Vicente-Serrano, S. M., Gouveia, C., Camarero, J. J., Begueria, S., Trigo, R., Lopez-Moreno, J. I., Azorin-Molina, C., Pasho, E., Lorenzo-Lacruz, J., Revuelto, J., Moran-Tejeda, E., & Sanchez-Lorenzo, A. (2012). Response of vegetation to drought time-scales across global land biomes. *Proceedings of the National Academy of Sciences*, *110*(1), 52-57. https://doi.org/10.1073/pnas.1207068110

Wang, Z. H. & Li, S. X. (2019). Nitrate N loss by leaching and surface runoff in agricultural land: A global issue (a review). *Advances in agronomy*, *156*, 159-217.

Wani, S. P., Sreedevi, T. K., Rockström, J., & Ramakrishna, Y. S. (2009). undefined. *Rainfed agriculture: unlocking the potential*, 1-35. https://doi.org/10.1079/9781845933890.0001

Wawire, A. W., Csorba, Á., Tóth, J. A., Michéli, E., Szalai, M., Mutuma, E., & Kovács, E. (2021). Soil fertility management among smallholder farmers in Mount Kenya East region. *Heliyon*, *7*(3), e06488.

Wildemeersch, J. C., Garba, M., Sabiou, M., Sleutel, S., & Cornelis, W. (2015). The effect of water and soil conservation (WSC) on the soil chemical, biological, and physical quality of a Plinthosol in Niger. *Land Degradation & Development*, *26*(7), 773-783. https://doi.org/10.1002/ldr.2416

Wouterse, F. (2017). Empowerment, climate change adaptation, and agricultural production: Evidence from Niger. *Climatic Change*, *145*(3-4), 367-382. https://doi.org/10.1007/s10584-017-2096-8

Yegon, R., Mtakwa, P., Mrema, G., & Ngetich, F. (2016). Planting pits' effects on soil nutrients in a sorghum and pigeon pea rotation in semi-arid areas of eastern Kenya. *International Journal of Plant & Soil Science*, *13*(5), 1-10. https://doi.org/10.9734/ijpss/2016/30127

Zhang, X., Zhu, A., Xin, X., Yang, W., Zhang, J., & Ding, S. (2018). undefined. *Field Crops Research*, *221*, 157-165. https://doi.org/10.1016/j.fcr.2018.02.025

Zhou, H., Fang, H., Mooney, S. J., & Peng, X. (2016). Effects of long-term inorganic and organic fertilizations on the soil micro and macro structures of rice paddies. *Geoderma*, *266*, 66-74. https://doi.org/10.1016/j.geoderma.2015.12.007

Zhu, G., Wang, S., Zhou, L., Wang, Y., Zhao, S., Xia, C. & Qu, J. (2015). Ubiquitous anaerobic ammonium oxidation in inland waters of China: an overlooked nitrous oxide mitigation process. *Scientific reports*, *5*(1), 1-10.

Zingore, S., Murwira, H., Delve, R., & Giller, K. (2008). Influence of nutrient management strategies on variability of soil fertility, crop yields and nutrient balances on small holder farms in Zimbabwe. *Agriculture, Ecosystems & Environment*, *119*(1-2), 112-126. Doi:10.1016/j.agee.2006.06.019

Zougmoré, R., Zida, Z., & Kambou, N. (2003). Role of nutrient amendments in the success of half-moon soil and water conservation practice in semiarid Burkina Faso. *Soil and Tillage Research*, *71*(2), 143-149. Doi:10.1016/s0167-1987(03)00050-3

Zougmoré, R., Mando, A., & Stroosnijder, L. (2011). Benefits of Integrated Soil Fertility and Water Management in Semi-arid West Africa: An Example Study in Burkina Faso. *Innovations as Key to the Green Revolution in Africa*, 215-225. Doi:10.1007/978-90-481-2543-2_20

Zougmoré, R., Jalloh, A., & Tioro, A. (2014). Climate-smart soil water and nutrient management options in semiarid West Africa: a review of evidence and analysis of stone bunds and *Zai* techniques. *Agriculture & Food Security*, *3*(1), 16. Doi:10.1186/2048-7010-3-16

APPENDICES

Appendix 1. Steps of laboratory analysis of the soil chemical properties

Total Nitrogen

Kjeldahl method

The apparatus needed include; distillation unit and Kjeldahl digestion, burettes, conical flasks. Reagents included; $CuSO_4.H_2O$, H_2SO_4, Potassium Sulphate, 35% NaOH, 0.1M NaOH, 0.1M HCl, Salicylic and Devarda alloy

Procedure: Weigh 1g of the soil sample and put in a Kjeldahl flask, add 1.5g of K_2SO_4 0.7g of copper sulphate, 1.5g of K_2SO_4 &30 ml of H_2SO_4, Heat lightly until frothing stops, Boil until you get a clear solution and digest for 30 minutes. Cool, transfer into in to a distilling., Put 20ml of (0.1M HCl) into a conical flask, Add 2 drops of methyl red indicator, Cool with tap water through the condenser, In the distilling flask add 30 ml of 35% NaOH and do not mix, Distil ammonia by heating for 30 minutes, Remove and rinse the outlet tube wit distilled water. The excess acid in the distillate should be titrated

Available phosphorous

Bray's Method; The apparatus required include: a spectrophotometer, pipette, beakers/flasks. The reagents: Bray's Extract (0.03M NH4F in 0.025M HCL), Molybdate reagent, Stannous chloride solution (stock solution), Stannous chloride solution

Procedure

Preparation of the standard curve, Extraction: weigh 5g of the soil sample, Add 50 ml of the Bray's Extractant No. 1 to the sample and shake it for about 5 minutes and filter, color development: measure 5ml of the filtered soil extract with a bulb pipette to 25ml measuring flask. Add 5 ml of the molybdate reagent using, add 20 ml of distilled water to dilute, shake and add 1 ml of the dilute $SnCl_2$ solution, add 25 ml of distilled water and shake, Set the spectrophotometer at 660 nm at 0 and read the blue color after 10 minutes with and without the soil.

Soil pH

The apparatus include: a pH meter ranging 0–14 pH, beakers, pipette and a glass rod.

reagents: Buffer solutions and Calcium chloride solution (0.01M)

The procedure is: Use two buffer solutions (neutral pH 7.0 and range of soil) calibrate the pH meter. Place the buffer solutions into the beakers and place the electrode to measure the pH. Weigh 10g of soil and put it in a beaker and add 20ml of CaCL2 solution. Let the soil absorb CaCL2 solution and then stir using a glass rod for 10 seconds. pH recording on the calibrated pH meter after stirring for 30 minutes.

Electrical conductivity

The apparatus required: an EC meter, Erlenmeyer flasks, pipettes beakers, filter paper.

Reagents required; potassium chloride solution,

Procedure: Weigh 40g of soil into a 250-ml Erlenmeyer flask, add 80ml of distilled H2O, shake for one hour and filter. Ensure you clean the conductivity electrode with distilled and rinse with standard KCl solution. Put KCl into a beaker and dip the electrode in the solution. Adjustment should be made to the conductivity meter to read 1.412 mS/cm and should be corrected to 25 °C. Dip the electrode it into the soil extract and record

Organic carbon

Loss of weight on ignition

Required apparatus include: oven, a sieve, a beaker and a muffle furnace.

Procedure: Weigh 5g of sieved soil into a beaker. Place the beaker in a drying oven and set at 105 °C for 4 hours. Remove the beaker from the drying oven, cool and weigh a place in a muffle furnace and add temperature to 400°C for 4 hours. Remove, cool and weigh to the nearest 0.01g.

Appendix 2. Sample Partial Budget for Economic Returns Analysis

Benefits	**Value (US Dollars)**	**Costs**	**Value (US Dollars)**
Additional income		Reduced income	
Additional yield		Labor	
Costs reduced		Costs added	
		Additional labor	
Total costs reduced		Total costs added	
Total income added and costs reduced		Total income reduced and costs added	
Change in net income			

Appendix 3: Research Authorization Letter from Graduate School

(8)

KENYATTA UNIVERSITY
GRADUATE SCHOOL

E-mail: dean-graduate@ku.ac.ke

Website: www.ku.ac.ke

P.O. Box 43844, 00100
NAIROBI, KENYA
Tel. 020-8704150

Our Ref: N50/33084/2015

DATE: 14th October, 2019

Director General,
National Commission for Science, Technology
and Innovation
P.O. Box 30623-00100
NAIROBI

Dear Sir/Madam,

RE: RESEARCH AUTHORIZATION FOR MS. GETARE EDNAH KERUBO – REG. NO. N50/33084/15

I write to introduce Ms. Getare Ednah Kerubo who is a Postgraduate Student of this University. She is registered for M.Env.Science degree programme in the **Department of Environmental Science & Education.**

Ms. Getare intends to conduct research for a M.Env.Sc. thesis Proposal entitled, **"Sorghum Production using Zai Pits and Soil Fertility Management in Kitui County."**

Any assistance given will be highly appreciated.

Yours faithfully,

for

PROF. ELISHIBA KIMANI
DEAN, GRADUATE SCHOOL

EO/cww

Appendix 4: Research License

REPUBLIC OF KENYA

NATIONAL COMMISSION FOR SCIENCE, TECHNOLOGY & INNOVATION

Ref No: 848163

Date of Issue: 25/November/2020

RESEARCH LICENSE

This is to Certify that Ms.. Ednah Kerubo Getare of Kenyatta University, has been licensed to conduct research in Kitui on the topic: Sorghum production using of Zai pits and soil fertility management in Kitui County for the period ending : 25/November/2021.

License No: NACOSTI/P/20/7604

848163

Applicant Identification Number

Director General

NATIONAL COMMISSION FOR SCIENCE,TECHNOLOGY & INNOVATION

Verification QR Code