EFFECT OF *IN-SITU* WATER HARVESTING TECHNOLOGIES AND FERTILIZER APPLICATION ON NUTRIENT UPTAKE, USE EFFICIENCY, AND YIELD OF MAIZE AND BEANS IN KATUMANI, MACHAKOS COUNTY, KENYA

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF DEGREE OF MASTER OF SCIENCE IN LAND AND WATER MANAGEMENT

DEPARTMENT OF LAND RESOURCE MANAGEMENT AND AGRICULTURAL TECHNOLOGY, FACULTY OF AGRICULTURE

UNIVERSITY OF NAIROBI

DECLARATION

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

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DEDICATION

To my father, the late Mr. Bernard Mukhebi, my mother Sylvia Nasimiyu, my brothers Maxwell and Brian, for their immense support throughout the entire study, and finally my wife, Grace Mwigi and my beloved daughter Felicity Nabalayo.

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Dio vi benedica tutti (God bless you all)

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LIST OF ACRONYMS AND ABBREVIATIONS

AAS	Atomic Adsorption Spectrophotometer
AE	Agronomic efficiency
ANOVA	Analysis of Variance
ASALs	Arid and semi-arid Lands
CAN	Calcium Ammonium Nitrate
CND	Compositional Nutrient Diagnosis
CVM	Critical Value Method
DAP	Di-Ammonium Phosphate
DRIS	Diagnosis and Recommendation Integrated System
ET_o	Potential/Reference evapotranspiration
FAO	Food Agriculture Organization of the United Nations
ISFM	Integrated Soil Fertility Management
JICA	Japan International Co-operation Agency
KALRO	Kenya Agricultural and Livestock Research Organization
LR	Long rain
LSD	Least Significant Difference
N, P, K	Nitrogen, Phosphorus, Potassium,

NUE	Nitrogen Use Efficiency
PUE	Phosphorus Use Efficiency
PVC	Polyvinyl chloride
^{O}C	Degrees Celsius
RCBD	Randomized Complete Block Design
SOC	Soil Organic Carbon
SLM	Sustainable Land Management
SMC	Soil moisture content
SSA	Sub-Saharan Africa
SR	Short rain
SWB	Soil water balance
TIMPs	Technologies, Innovation and Management Practices
TN	Total Nitrogen
WUE	Water Use Efficiency
WHC	Water Holding Capacity

ABSTRACT

Low crop yields due to erratic rainfall and deteriorating soil fertility in smallholder farmers' fields of Sub-Saharan Africa have prompted a quest for more resource-efficient production practices. *In-situ* water harvesting technologies have been proposed as climate-smart agriculture coping mechanisms to alleviate these problems, however, their full potential has not been realized. A study was undertaken to evaluate selected *in-situ* water harvesting technologies and fertilizer on nutrients uptake, use efficiency, and yield of maize and beans at Kenya Agricultural and Livestock Research Organization (KALRO) in Katumani, Machakos County for two seasons; short rain (SR) 2019 and long rain (LR) 2020. The experiment was laid out in a randomized complete block design with a split-split plot arrangement, replicated three times with *in-situ* rainwater harvesting technologies as the main plots, fertilizer inputs as the split plots, and cropping systems as the split-split plots. *In-situ* rainwater harvesting technologies comprised: Zai pits, Ngolo pits, contour furrows, and conventional tillage. Fertilizer inputs included: Di-ammonium phosphate (DAP) (18:46:0) fertilizer, goat manure, a mixture of DAP + goat manure and control. Cropping systems were: sole maize, sole beans, and maize-bean intercrop. Data was collected on soil nutrient status, soil moisture content, yield, nutrient uptake, and use efficiency. The data were subjected to analysis of variance and mean differences determined at $p \leq 0.05$ significance level using GenStat software 15th Edition. During the SR 2019, soil moisture, maize, and beans yields, nutrient (N and P) uptake and uses efficiency were significantly ($p \leq 0.05$) increased by *in-situ* rainwater harvesting technologies, fertilizer types, and cropping systems. Overall soil moisture content was higher in Zai pits (27.3 cm^3cm^{-3}) followed by contour furrows (22.6 cm^3cm^{-3}), Ngolo pits (20.8 cm^3cm^{-3}) and lowest in conventional tillage (19.1 cm^3cm^{-3}). Ngolo pits recorded higher maize and beans yields of 4.5 and 1.6 t ha^{-1} and above-ground biomass of 7.43 and 1.49 t ha^{-1}, respectively. Application of 100 kg ha^{-1} DAP increased maize and beans grain yield by 44.9 and 62.3%, and 58.2 and 56.2% in maize and beans above-ground biomass; respectively, compared to control. The highest N, P, and K uptake in maize grain were 67.8, 48.2 and 24.9 kg ha^{-1} and 47.2, 14.5, and 64.5 kg ha^{-1} in stover, respectively, recorded under Ngolo pits, whereas the lowest N, P and K contents in grain were 19.5, 25.7, and 9.5 kg ha^{-1} and 19.3, 5.37 and 16.8 kg ha^{-1} in Stover, respectively recorded under conventional tillage treatment. Higher N and P use efficiency of 39.1 and 40.1 kg grain per kg N and P ha^{-1}, respectively, were realized under Ngolo pits treated with 100 kg ha^{-1} DAP fertilizer. In the LR 2020, the application of 100 kg ha^{-1} DAP resulted in a 71.4% and 56% maize grain and biomass increase compared to control. Intercropping maize and beans increased grain yield significantly ($p \leq 0.05$) by 10.3 and 29.4% compared to sole maize and sole beans. N, P and K contents were highest under Ngolo pits following application of 100 kg ha^{-1} DAP. Maize and beans subjected to application of 100 kg ha^{-1} DAP under Ngolo pits recorded the highest N and P use efficiency at 21.1 and 26.4 kg grain kg N and P ha^{-1}. The results of the study show that yield response to *in-situ* water harvesting technologies and fertilizer was influenced by soil moisture availability, N and P uptake, and use efficiency. Ngolo pits in combination with fertilizer performed better compared to conventional tillage under no fertilizer inputs. The results demonstrate the potential of integrating Ngolo pits and DAP fertilizer at the rate of 100 kg ha^{-1} in improving the yield of maize and beans and resource use efficiency in semi-arid areas.

Key words: *In-situ* rainwater harvesting technologies, Ngolo pits, Zai pits, Nutrient uptake, Nutrient use efficiency,

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information

Poor soil fertility and water scarcity continue to be deterrent factors for achieving sustainable agricultural production in semi-arid areas (Rockstrom *et al*., 2010; Yazar and Ali, 2016); owing to erratic and unreliable rainfall, increased diurnal temperature, and high evapotranspiration (Kisaka *et al*., 2015). Soils in the arid and semi-arid lands (ASALs) have low macro and micro nutrients, with shallow and poor structure, hence highly susceptible to wind and water erosion regions (Omoyo *et al*., 2015; Karuku and Mochoge, 2018). The high variability in rainfall patterns, combined with frequent droughts experienced in the semi-arid areas has a great impact on agricultural productivity among the smallholder farmers (Mutekwa, 2009). With such variations, soil moisture becomes a critical factor, and when a deficiency occurs during the critical stages such as flowering and tasseling/silking stages for beans and maize, respectively, it results in a tremendous reduction in yields by up to 75% (Barron *et al.*, 2005; Adamgbe and Ujoh, 2013; Mengistu, 2019).

The reduction in yield from farmers' fields demonstrates the need for appropriate agricultural production technologies, innovations, and management practices (TIMPs) that are climate-smart and geared towards conservation of little water received, improving soil fertility and resilience of farming systems (Ngetich *et al*., 2014; Zougamore *et al*., 2014). This can be achieved through the use of *in-situ* water harvesting technologies, which constitute simpler, more affordable, and adaptable technology for resource-poor smallholder farmers (Mudatenguha *et al*., 2014).

The technologies work by trapping and storing rainwater where it falls, reducing runoff and increasing infiltration rate, resulting in sufficient moisture storage in the soil (Adimassu *et al*., 2014). *In-situ* rainwater harvesting technologies protect crops from failures resulting from water stress during drought periods, reducing drought effects that may occur during the crop growing season (Dile *et al*., 2013; Nyamadzawo *et al*., 2013). Planting pits (Zai pits), furrow-ridges, tied ridges, earth and stone bunds, and mulch ripping are some of the *in-situ* rain water harvesting technology options available for adoption by farmers (Biazin *et al*., 2012; Abubaker *et al*., 2014).

Several studies have found that using *in-situ* rainwater harvesting technologies increases crop yields. In Burkina Faso, for example, sorghum yield increased significantly under Zai pits compared to conventional tillage (Kabore and Reij, 2004). There was higher maize dry matter production in Zai pits compared to conventional tillage (hand-hoeing) in Western Kenya (Muyekho *et al*., 2000). Kimaru *et al*. (2020) working in Tharaka Nithi, Kenya, reported higher sorghum yields in Zai pits compared to conventional tillage.

While conducting a study on the intensive cultivation and environment use among the Matengo in Tanzania, Kato *et al*. (2001), observed that yields in Ngolo pits increased by tenfold when compared to conventional tillage (planting on flat land). Maize planted in Ngolo pits yielded 1.3 times more than conventional tillage in another experiment (Itani, 1998). A similar experiment carried out in the Mt Kilimanjaro region, reported that maize yielded twice more in farms with Ngolo pits compared to farms under conventional tillage, and three times as much in farms with bench terraces. Rathore *et al*. (2006) while working in Rwanda reported that pearl millet sown in contour furrows yielded more than 10 % grain yield when compared to conventional tillage.

Field experiences indicate that *in-situ* water harvesting technologies are inefficient unless supplemented with soil fertility amendments. According to Winterbottom *et al*. (2013), combining *in-situ* water harvesting technologies with fertilizer inputs created synergies that increased water and nutrient use efficiency and thus crop yields. Increased N use efficiency was observed during an experiment, combining Zai pits and organic amendments on degraded soil of sub-Saharan Africa (Fatondji *et al*., 2006; Dile *et al*., 2013). When organic inputs are added to Zai pits, their effectiveness in increasing nutrient use efficiency and yield is improved (Kathuli and Itabari, 2014).

Intercropping cereals and legumes under water harvesting technologies with the application of fertilizer inputs have been reported to increase crop yield even more. According to Biazin *et al*. (2012), the combination of *in-situ* water harvesting technologies, soil amendments, and legume integration into farming systems improves not only soil nutrient status and moisture availability, but also nutrient uptake. Cereals intercropped with legumes, with both organic and inorganic inputs applied concurrently or sequentially, are among the most common integrated cropping systems in sub-Saharan Africa (SSA) (Vanlauwe *et al*., 2012). Yu *et al*. (2016) in India and Brooker *et al*. (2015) reported that inter-cropping cereals and legumes resulted in high overall system productivity, which is attributed to the efficient use of nutrients, moisture, and light interception.

While most studies related to Zai and Ngolo pits as water harvesting technologies have been carried out in West Africa and Tanzania, there is limited information on their interactive effectiveness with different fertilizer rates on influencing nutrient uptake by maize and beans, nutrient use efficiency, and yield in ASALs of Kenya; hence the focus of this study.

1.2 Statement of the problem

Low soil moisture and inadequate soil nutrients are the main hindrances to crop production in arid and semi-arid areas such as Katumani in Eastern Kenya. Low, unreliable, and unpredictable rainfall patterns cause insufficient soil moisture, whereas continuous cropping without soil fertility replenishment causes poor soil fertility. Further, the area has undulating topography with steep elevations, which accelerates soil erosion and water loss through run off. These constraints limit the soil's ability to perform its functions, posing a serious risk to crop production (Pimentel and Burges, 2013).

The soils in the area are shallow, with a light texture, a low water holding capacity, and a low fertility content (Patil and Sheelavantar, 2001). This poses a greater danger to crop production, hence food insecurity. To address these challenges, interventions that aid in capturing and storing water in the soil for crop use must be developed. The large amounts of runoff produced during the rainy season could easily be trapped in *in-situ* harvesting technologies, allowed to percolate into the soil, and made available to crops.

Fertile soils encourage crop vegetative growth and rooting, increasing the soil's capacity to absorb more nutrients and water. As an alternative, the use of inorganic fertilizer and organic amendments to improve crop nutrient use efficiency under drought conditions has been proposed. However, the use of inorganic fertilizer is limited due to its high cost, making it unaffordable to the majority of smallholder farmers.

There is limited information on the effectiveness of *in-situ* water harvesting technologies such as Ngolo pits, Zai pits, and contour furrows in combination with fertilizer amendments and how they affect crop productivity in ASALs, where food production and soil degradation continue to decline despite interventions.

1.3 Justification of the study

With Kenya's ASALs experiencing increasingly low and erratic rainfall, as well as poor soil fertility, there is a quest for technologies and innovative approaches that will collect rain water where it falls and store it for crop production, as well as apply recommended fertilizer rates to improve soil nutrient status. *In-situ* water harvesting technologies and fertilizer applications have been proposed as potential solutions for improving the country's food security status. This is because these technologies work on the principle of increasing water availability to plant roots, allowing room for easier and faster uptake.

Technologies such as Ngolo pits, Zai pits, and contour furrows have been shown to increase soil moisture content, soil fertility status, soil stability, and soil resilience to erosion. These technologies are also simple and less expensive for smallholder farmers, making them economically viable. Application of fertilizer at recommended rates, on the other hand, aids in improving soil fertility and, as a result, crop nutrient uptake and use efficiency. Therefore, incorporating fertilizer inputs into water harvesting technologies in crop production systems would serve as a mechanism for achieving efficient resource management, alleviating soil fertility issues, and improving economic returns in ASALs. Although research has been conducted on water harvesting technologies and soil fertility amendments using both organic and inorganic fertilizer, little attention has been paid to their effects on nutrient uptake, use efficiency and yield of maize and bean.

1.4 Objectives

1.4.1 Overall objective

The main objective of this study was to contribute toward increased crop productivity in semi-arid Kenya through *in-situ* water harvesting technologies and fertilizer application.

1.4.2 Specific Objectives

a) To evaluate the effects of *in-situ* water harvesting technologies, fertilizer application, and cropping systems on soil moisture content and nutrient uptake.

b) To determine the effects of *in-situ* water harvesting technologies, fertilizer application, and cropping systems on nitrogen and phosphorus use efficiency and yield of maize and beans.

c) To identify the limiting nutrients in maize and bean production using Diagnosis and Recommendation Integrated System (DRIS) norms.

1.5 Hypotheses

a) *In-situ* water harvesting technologies, fertilizer application and cropping systems do not influence soil moisture content and nutrient uptake.

b) *In-situ* water harvesting technologies, fertilizer application and cropping systems do not influence nitrogen and phosphorus use efficiency and yield of maize and beans.

c) Nutrient deficiency does not limit maize and beans production.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Overview

Arid and semi-arid lands (ASALs) are characterized by low and unpredictable rainfall, high diurnal temperatures, and soils with inherently poor fertility, which severely limits crop productivity, especially when soil moisture is insufficient (Altieri and Koohafkan, 2008).
The majority of smallholder farmers in these areas rely on crop and livestock production for a living. Unfortunately, these enterprises have been severely affected by changes in weather patterns, which have resulted in crop failure and animal deaths due to drought (Kisaka *et al*., 2015). High rainfall variability in these areas has led to reliance on drought-resistant, tolerant and early maturing crops with high resource use efficiency (Rao *et al*., 2011).

Low yield in rain-fed farming systems could be solved by using soil and water conservation technologies, as well as integrated nutrient management options (Rockstrom *et al*., 2010). Farmers are advised to embrace improved management practices that ensure increased soil moisture conservation through increased infiltration and higher resource use efficiency to cushion crops against failures due to water scarcity and soil nutrient deficiencies (Nyamadzawo *et al*., 2013; Kwena *et al*., 2018).

Smallholder farmers in drought-stricken areas should prioritize technologies that increase infiltration and replenish soil nutrients (Vanlauwe *et al*., 2010; Dile *et al*., 2013). In addition, incorporating fertilizer inputs into cropping systems has proven to be a more effective method of improving soil quality and health (Valnauwe *et al*., 2012). *In-situ* water harvesting technologies and integrated soil fertility management (ISFM) options significantly led to an increase in soil moisture content, according to research conducted in Burkina Faso, Niger, Mali, Rwanda, and Tanzania over the years (Winterbottom *et al*, 2013; Zougmoré *et al*., 2014; Kugedera *et al*., 2018).

2.1.1 Maize production in Kenya

Maize (*Zea mays* L.) is a major staple food grain in Kenya, for more than 95 % of the country's population (Wekesa *et al*., 2003; Riedelsheimer, 2012). Maize is grown for grain, livestock feed, and stover, which is used as a fuel source in some poor homesteads (Gaddameedi *et al*., 2016), as well as for other industrial purposes (Raja *et al*., 2018). It is used as a raw material in thousands of products such as oil, starch, protein, alcoholic beverages, pharmaceuticals, cosmetics, and textiles (Chaoudhary *et al*., 2013).

Maize is grown in over 160 countries around the world due to its adaptability to various agro-climatic conditions, and accounting for 36% of total grain production (FAOSTAT, 2010; FAO, 2012). Maize production in Kenya is divided into smallholder and large-scale farming systems, with the former accounting for roughly 75-80 % of total production (Muui *et al*., 2013; Otieno *et al*., 2020). Despite its adaptability to varying climatic conditions, maize production under subsistence farming is hindered by a lack of access to quality inputs such as seeds, fertilizer, insecticides, quality irrigation water and labor.

Despite the benefits of maize, overall production is low, as evidenced by the large yield gap between on-station and on-farm yields realized by farmers. Maize production has remained below 2 t ha^{-1} over the years, owing primarily to poor soil fertility (Okalebo *et al*., 2007), low and erratic rainfall, insufficient fertilizer use, and limited access to improved farm inputs and varieties (Mugwe *et al*., 2009; Rockstrom *et al*., 2010; Kwena *et al*., 2018). The situation has worsened as a result of frequent drought spells experienced in the ASALs, resulting in poor growth and some cases, total crop failure, and eventually chronic hunger (Omoyo *et al*., 2015). Daryanto *et al*. (2016) reported that approximately 40 % of maize yield in the ASALs has been reduced due to droughts over the years. Other than water stress, biotic factors such as weeds, insect pests and diseases have also impacted negatively maize productivity (Oerke, 2006; Kagoda *et al*., 2015).

2.1.2 Common beans production in Kenya

Common bean (*Phaseolu*s *vulgaris* L.), also known as a dry bean, is one of Kenya's most widely grown pulses, with over 85% of smallholder farmers cultivating it (Rockstrom *et al*., 2010). They are grown for direct consumption because it is a low-cost source of dietary protein for people with low incomes (CIAT, 2013; Margaret *et al*., 2014). Over 200 million people in sub-Saharan Africa (SSA) are estimated to rely on the common bean as a primary source of staple food and the second most important source of calories after maize, accounting for approximately 25% of total calories and 45% of protein intake (Katungi *et al*., 2009).

It is also cultivated for the consumption of its green pods, green leaves, and immature seeds. Smallholder farmers prefer the common bean because of its fast-maturing characteristic, which allows households to obtain cash income for purchasing food and other household needs when other crops have not yet matured (Legesse and Ayenew, 2006). Despite the agronomic, economic, and nutritional benefits of dry beans, their production has been impaired by numerous constraints, such as low soil moisture content as a result of insufficient and erratic rainfall, long dry spells, and delayed onset and/or early cessation of rains and inherent soil fertility (Katungi *et al*., 2009; Jensen *et al*., 2010; Recha *et al*., 2013), resulting in low yields of less than 1t ha^{-1} (CIAT, 2013).

2.*2 In-situ* water harvesting technologies

In-situ rainwater harvesting technologies play an integral role in capturing rain water, storing it in the soil, and availing it for crop use. They also help in mitigating the effects of dry spells, which occur frequently during crop growth stages (Kabore and Reij, 2004; Fatondji *et al*., 2006;

Ayanlade *et al*., 2018). High variability in rainfall, combined with severe drought, has a significant impact on soil and water productivity (Kisaka *et al*., 2015; Mancosu *et al*., 2015). Additionally, high evapotranspiration interferes with plant nutrient and water uptake, resulting in inefficient resource use and yield (Mutekwa, 2009; Rockstrom, 2010).

Drought has been a common phenomenon in Kenya, particularly in the Eastern and North Eastern regions, disrupting crop phenological and physiological performance (Mutua *et al*., 2016), resulting in low yield and food insecurity. To alleviate the problem of moisture stress, interventions aimed at capturing and storing rain water in the soil need to be developed, to supplement insufficient soil moisture in rain-fed agriculture (Oweis and Hachum, 2006).

These interventions comprise soil and water conservation through *ex-situ* and *in-situ* measures. The *ex-situ* technologies are practices in which rain water is collected and stored for productive use, for example, drinking water, agriculture (irrigation), and sanitation. In the *ex-situ* methods, rain water can be collected in open storage systems, but can also be collected from roof tops, soil surfaces, and roads and stored in tanks.

The other mechanisms are the *in-situ* rainwater harvesting technologies, which refer to structures used to collect runoff or flood water from where it falls and store it in the soil for use during crop growing periods (Critchley *et al*., 2013; Kokerai and Kugedera, 2019), making it available to plants and reducing risks of crop failure (Dile *et al*., 2013). Contour furrows, Zai pits, tied ridges, and Ngolo cultivation technologies are some of these technologies (Abubaker *et al*., 2014). They can retain rainwater where it falls, increasing the rate of infiltration and underground recharge and, as a result, mitigating intra-seasonal dry spells that may cause crop failure (Manyatsi *et al*., 2011; Dile *et al*., 2013; Paslawar *et al*., 2015).

2.2.1 Zai pit

The Zai pit system includes three different types of conservation practices: soil conservation, soil water storage, and erosion control. Danjuma and Mohammed (2015) defined Zai as a pit system dug on the farm with a diameter of 20-40 cm and a depth of 10-20 cm to collect water where it falls, allowing time for infiltration and ensuring its availability to crops.

A 'Zai' is a hole dug in the ground that varies in size and dimensions depending on the farmer's ingenuity in different regions. Studies by Danjuma and Mohammed (2015) draw the origin of Zai pits in Burkina Faso and Mali and have spread to many countries including Niger, South Africa, Zimbabwe, Zambia, Ethiopia, and Kenya. In Kenya, Zai pits are known as 'five by nine' pits with dimensions of 0.6 m long, 0.6 m wide, and 0.6 m deep (Kathuli and Itabari, 2015). The 'five by nine' referred to the planting of five maize seeds in dry areas and nine maize seeds in wet areas in pits (Mati, 2006).

This is a water harvesting technology that is appropriate for areas that receive unpredictable rainfall and have low soil fertility (Partey *et al*., 2018). The rainwater that would otherwise be lost through runoff is collected in the pits, where it stays for a long time and is slowly used by crops for various physical, chemical, and biological functions. The high soil moisture in Zai pits mitigates the effects of drought and water scarcity caused by low and unreliable rainfall (Nyamadzaw*o et al.,*2013).

Zai pits have been used in the production of maize and sorghum in Kitui and Makueni (Recha *et al*., 2013; Kathuli and Itabari, 2015) and the coast region (Saha *et al*., 2007). They have also been used as an alternative method for pasture regeneration and restoring degraded rangelands (Kimani *et al*., 2015). Orodho *et al*. (2007) used a different variation of Zai pits called *Tumbukiza* pits in Napier grass production in western Kenya. Before seeds can be planted, a handful of compost manure is mixed into the pits. These types of pits can be re-used for up to three years in a row (Mati, 2006).

Zai pits have also been associated with higher soil moisture content and crop yield. In Ethiopia, Cofie and Amede (2015) reported increased potato and bean yields by 500% and 250%, respectively, as well as an increase in crop water productivity of 300-700% in farms with Zai pits compared to those without pits. In Mali, Malesu *et al*. (2006), found that maize yields under Zai pit increased by a factor of 10 in comparison to conventional tillage. Similar findings were reported by Fatondji *et al*. (2006) in Burkina Faso, where the use of Zai pits increased sorghum production by 500%, owing primarily to higher soil moisture in the pits. Despite the benefits of Zai pits in crop production, this technology is labor-intensive. Kabore and Reij (2004) reported that digging Zai pits in one hectare of land takes about 450 hours and another 250 hours, applying fertilizer, therefore this might be the limiting factor to their adoption and implementation.

2.2.2 Ngolo pit

Ngolo pits (Matengo pits), as they are known in Mbinga highlands in Tanzania, are a remarkable soil and water conservation technology (Kiteme and Ehrensperger, 2015). Ngolo pits have been described as anti-erosion and fertility maintenance technologies on sloppy lands with a slope of 10-60%. The pits are laid out in a grid on sloping land to cover the entire surface. Pits range in size from 1.5 to 2 m in diameter and a depth of 0.3 m. Pits collect runoff water during the rainy season and allow the water to be stored for use during the cropping season. This makes good use of the unpredictability of rainfall and mitigates the effect of drought (Malley *et al*., 2004; Kihila, 2018).

Maize and beans are planted as a sole crop or in intercrop on the ridges, and weeds, are partially controlled and crop residues thrown in the pits to decompose. Among the buried plant residues, the leaves and roots of maize, leaves, and fine stalks of weeds disintegrate into finer debris through decomposition, hence improving the fertility status of the soil through a process called soil maturation.

One of the unique characteristics of the Ngolo pit cultivation system is the arrangement of ridges horizontally and vertically across the slope to intercept water runoff. Rill and gully erosion usually occurs along the path of runoff water but the risk is reduced under the Ngolo system. The pit temporarily traps moving rainwater and soil from ridges in the upper part of the ridges. It also facilitates the infiltration of temporarily stored water into the soil. Because of these reasons, severe erosion is rarely observed on most slopes under the Ngolo pit cultivation system.

When cultivating, the pits are shifted every two years, with new pits dug where the ridge intersected previously. The top and subsoil, as well as dry grasses, are mixed and turned over during the position change. By mixing the residue materials with the deeper soils, darker soils rich in organic matter are formed in deeper layers, providing favorable conditions for crops (Kato *et al.*, 2011). The decomposition of organic matter by bacteria and fungi helps to stabilize soil structure (Ellis-Jones, 2000; Kato, 2001). According to Itani (1998), maize in Ngolo fields yielded 1.3 times more than maize in conventional tillage. Similarly, in an experiment at Mt Kilimanjaro region, farms with Ngolo produced 2.3 times higher maize yield than those under conventional tillage, and 3 times higher than under bench terracing. Despite its labor-intensive nature, Ngolo pits cultivation is an effective method for controlling soil erosion on steep terrain.

2.2.3 Contour furrow

This is an important tillage method for controlling soil erosion and increasing crop yields in sloppy landscapes (Miriti *et al.*, 2012). To promote positive drainage, tillage and planting operations should follow contour lines. Contour furrows increase the roughness of the soil surface, reducing runoff velocity and rainwater ponding in the furrows (Liu *et al.*, 2014).

Furthermore, this technique favors long-term water retention and a high rate of infiltration (Itabari, 2003; Denison *et al*., 2011; Liu *et al*., 2014). Contour furrows and ridges are also important in the recovery of nutrients such as N and P from erosion agents such as water (Ma *et al*., 2010). Faharani *et al*. (2016) reported a 10% reduction in the annual runoff by retaining water in deeper soil layers in contour furrows. Brhane *et al*. (2006) found that contour furrows increased sorghum yield by 62% when compared to conventional tillage. Reduced run-off and soil nutrient retention in the furrows resulted in increased cotton, maize, cowpea, millet, and sorghum yields (Obalum *et al*., 2011).

2.2.4 Conventional tillage

Conventional tillage is a soil-inversion system that alters the natural structure of the soil (Blanco-Congui and Lal, 2008). Typically, it involves ploughing and harrowing with a moldboard or disc-plough for large mechanized farms or ox-plough and hand-hoeing for smallholder farmers, inverting the soil to a depth of 10-20 cm (Powlson *et al*., 2012). In this experiment, hand-hoeing was the conventional tillage system (farmers practice). Conventional tillage improves root penetration, water movement, and aeration by lowering soil resistance (Indoria *et al*., 2017). Soil structure and bulk density are affected by continued disturbance, as are soil pore size, distribution, and aggregation, as well as the loss of soil organic matter content (Karuku *et al*., 2014). It also contributes to soil moisture loss, increased water and wind erosion, and increased fuel consumption.

2.3 Soil fertility amendment options

In smallholder farming systems, one of the impinging factors to crop production is low and inherent soil fertility. Poor agronomic management practices have transformed fertile soils, reducing their ability to provide nutrients to crops (Vanlauwe and Giller, 2006). As a result, improved soil fertility management strategies are required to aid in the restoration of already degraded soils (Kibblewhite *et al.*, 2007).

2.3.1 Inorganic fertilizer application

The main cause of low crop yield is a low fertility status (Tadele, 2017). The application of mineral fertilizers is the easiest way to increase crop production in nutrient-deficient soils, which are common in ASAL soils. The use of inorganic fertilizer appears to be the panacea because it improves soil fertility by supplying nutrients in a form that crops can easily absorb (Okalebo *et al*., 2007). These fertilizers have been designed to provide appropriate and readily available nutrients in the required form, allowing for easier and faster plant root uptake (Timilsena *et al*., 2015).

Soil nutrient levels in most farmlands have decreased due to the absence of inorganic fertilizers, resulting in a decrease in crop production (Ngetich *et al*., 2011) and therefore the agricultural systems necessitate a diverse range of mineral fertilizers to improve soil fertility. Farmers commonly use mineral fertilizers such as Diammonium Phosphate (DAP), urea, and calcium ammonium nitrate (CAN) to increase crop yield due to their high nutrient content and in the form that is readily absorbed and taken up by plant roots, compared to animal manure, which releases nutrients slowly (Adamou *et al*., 2007).

Though beneficial in increasing crop yield, excessive or over-application of mineral fertilizer may cause deterioration in soil properties, resulting in stagnation in crop growth. Excessive use of mineral fertilizers has been associated with increased soil acidity, which raises the toxicity levels of elements such as aluminium, which causes P fixation and renders it unavailable to plants (Misiko *et al*., 2008). Another disadvantage of mineral fertilizer is its high price, which makes it unaffordable to smallholder farmers (Fairhust, 2012).

2.3.2 Integrated organic and inorganic fertilizers

To achieve higher crop productivity to meet current and future food demands, it is imperative to ensure a balanced amount of plant nutrients from organic and inorganic fertilizers at the recommended rates. All nutrient sources should be managed in accordance ISFM approach and the 4 R nutrient stewardship principles, which include using the right nutrient source at the right time, in the right place, and at the recommended rate (Roberts, 2007). The application of combined organic and inorganic fertilizers offers the potential for improving soil fertility and crop yields (Vanlauwe *et al*., 2002). Organic and inorganic fertilizers are the most common materials applied in agricultural management to improve soil fertility and crop productivity (Verman and Sharma, 2007).

However, due to the scarcity of organic amendments and the unaffordability of the inorganic fertilizer, Vanlauwe *et al*. (2002), recommended integrating organic and inorganic fertilizers as the most credible option for meeting growing food demands without increasing dependence on foreign aid. Combining inorganic minerals and organic fertilizers has been effective in promoting crop performance, because of the improved and synchronized nutrient release and in the form readily taken up by plants (Ghosh *et al*., 2010). For instance, combining 5 t ha^{-1} of cattle manure with 40 kg N ha^{-1} increased maize grain yield and fertilizer use efficiency (Sileshi *et al*., 2019). When manure 5 t ha^{-1} was mixed with 30 kg N ha^{-1} mineral fertilizer, maize yields were higher than when a single mineral fertilizer was applied at a rate of 60 kg N ha^{-1} (Mugwe *et al*., 2009). Balemi (2012) similarly reported that yield was significantly influenced by the FYM + NPK fertilizers treatments. Similar findings have been reported by Makinde and Ayoola (2010) who reported that integrating mineral fertilizers with organic manure, resulted in high yields in the degraded soils of Ibadan in Nigeria.

2.4 Influence of *in-situ* water harvesting technologies and fertilizer application on nutrient uptake and use efficiency

Nutrient uptake is the process by which plant roots absorb nutrients from the soil solution and distribute them to the plant's aerial parts (Havlin *et al.,* 2005). Nutrient use efficiency, on the other hand, is a plant's ability to use soil-available nutrients to produce measurable yields (Hati *et al*., 2006). Nutrient uptake is solely determined by the availability of soil moisture, organic matter content as well as the form in which the nutrients are present in the soil (Barker and Pilbeam, 2015).

High soil water potential under effective moisture conservation technologies improves plant nutrient uptake capacity and soil nutrient supply (Shaheen *et al*., 2012). Low pH soils promote P fixation, lowering its availability to plants and, as a result, its uptake (Kochian, 2012). This is a common phenomenon in many smallholder farmlands that are highly degraded and have low soil fertility.

The soil in the semi-arid areas is predominantly sandy with low P absorption capacity, making them more susceptible to erosion losses. Furthermore, crops' low and slow uptake of P has been linked to its immobility and low adsorption (Fernandez and Rubio, 2015). Phosphorus deficiency in plants causes a variety of morphological and physiological responses, and strategies that either improve the plant's ability to acquire nutrients from the soil or increase its efficiency are critical (Richardson *et al*., 2011; Hammond and White, 2008). Such strategies include root foraging, root mining strategies, and internal phosphorus utilization strategies (Richardson *et al*., 2011; Simpson *et al*., 2011).

The root foraging and mining strategies include the formation of lateral roots and root hairs, the secretion of organic acids, and the formation of symbiotic relationships with mycorrhiza fungi, which aid in P acquisition (Lambers *et al*., 2006; Yang and Finnegan, 2010). Phosphorus fertilizer application increases crop root density and rooting depth, which improves water and nutrient uptake from the soil, resulting in increased crop growth and biomass accumulation (Ibrahim *et al*., 2014).

Nitrogen fertilization, on the other hand, has been shown to improve root systems, which aids in the absorption and utilization of water and nutrients from the soil. The amount of nitrogen absorbed by crops increases with plant age, until flowering when the nitrogen is accumulated in grains and biomass. Fertilizer application raises the concentration of N in the soil, resulting in greater uptake. Murthy *et al*. (2015) while working in India, reported increased levels of N, P and K availability in the soil following the application of nitrogen, phosphorus, and potassium fertilizers, and this consequently resulted in higher uptake and use efficiency. In the case of severe N deficiency, plant leaf area is reduced, and this reduces radiation interception and light use efficiency, hence reducing photosynthetic rates and biomass accumulation.

Under moisture stress conditions, potassium (K) deficiency becomes an important nutritional disorder, limiting crop yield (Wang *et al*., 2013). Potassium is transported through diffusion, for which soil moisture is a pre-requisite. Water availability, therefore, promotes K movement, increasing its uptake and utilization (Smit *et al*., 2013). Higher biomass accumulation in response to K fertilizer application is attributed to greater K accumulation (Dotaniya *et al*., 2016). Controlling K losses through soil erosion and adoption has been shown to increase crop productivity and K use efficiency in semi-arid environments. Crop rotations with vigorous, deep-root systems, which are important in mounting the net of bio-pores in the soil profile for root exudates and growth, can improve K availability in soil (Williams and Weil, 2004). Soil moisture, air temperature, and aeration are all affected by *in-situ* water harvesting technologies, which in turn, affects crop nutrient uptake (Onwuka and Mang, 2018). In Burkina Faso, Fatondji (2002) reported that crops under Zai pits had a 43-64, 50-87 and 58-64 % increase in N, P and K uptake, respectively.

2.5 Nutrients limiting crop production in the ASALs

Crop productivity in ASALs has been hampered by soil degradation caused by nutrient mining, soil erosion, and poor land management practices (Barros *et al*., 2014). The nutrient status of the soil determines crop growth and, ultimately, yield. Nitrogen and Phosphorus are two of the most important nutrients that limit yield in ASALs (Sharma *et al*., 2017). Even though both are necessary for crop growth, one nutrient may be more limiting than the other in different soils and environmental conditions.

Nitrogen is most limiting in rain-fed conditions due to its susceptibility to losses in poorly managed soils due to immobilization, volatilization, leaching and run-off (Hopkins *et al*., 2014; Rens *et al.,* 2018). Phosphorus, on the other hand, is severely limited in highly weathered acidic soils due to Magnesium and Calcium fixation in ASALs (Muindi *et al*., 2015). According to Hill *et al*. (2015), the low availability of P results from its adsorption onto soil constituents such as organic matter, clays, and sesquioxides. There is a need therefore to investigate the most limiting nutrients in various geographical areas. The identification of the most yield-limiting nutrient aids in the development of nutrient management strategies to maximize agricultural production and profitability.

2.5.1 Diagnosis and Recommendation Integrated System (DRIS) norms for determining yield-limiting nutrients

Crops require significant amounts of nutrients to achieve the optimal yield, and their balances and standards are required to streamline their application to crops for better performance (Fageria *et al*., 2008). According to Kelling *et al*. (2000), diagnosing plant nutritional anomalies is a critical process that aids in the formulation of fertilizer recommendations.

Nutrients in the diagnostic plant indicate the soil's ability to supply nutrients, indicating the amount present in the soil as well as the amount that must be supplied (Havlin *et al*., 2005). Nutrient concentrations in plant tissues can be used to calculate plant nutritional status (Walworth and Sumner, 1987).

Several approaches to diagnosing plant nutritional disorders have been used in the past, including the Critical Value Method (CVM) (Bates, 1971), and the Diagnosis and Recommendation Integrated System (DRIS) (Walworth and Sumner, 1987), and the Compositional Nutrient Diagnosis (CND). Although CVM is the oldest approach to nutrient diagnosis, it ignores the plant's age and variations, as well as when two or more nutrients are deficient at the same time, and fails to identify the most limiting factor. Beaufils (1973) built DRIS to resolve these limitations. This is based on the principle of nutrient balances (ratios), which are thought to be more efficient in nutrient diagnosis. It assesses the nutritional status of the plant by comparing leaf concentration ratios (norms) from a high-yielding subpopulation, identifying imbalances, deficiencies, and excesses, and then ranking them (Walworth and Sumner., 1987). Previous research by Beaufils (1973) and Sumner (1979) demonstrated that DRIS could reduce the effects of tissue age, leaf position, and cultivars on the accuracy of deficient nutrients as well as predict the most limiting nutrient.

The DRIS reference criteria and indices provide a measure of nutrient balance and rank the order of nutrient limitation from most to least limiting (Walworth *et al*., 1986; Nziguheba *et al*., 2009). It is also used to comprehend and establish soil cut-off values (soil test values). The indices and standards are derived from total plant tissue nutrient concentrations and corresponding yields, which represent field variability. In calculating DRIS norms, dual ratios rather than nutrient concentration levels minimize the effect of dilution, accumulation, and nutrient interaction (Beaufils, 1973), predicting one or more limiting nutrients. This can lead to incorrect diagnosis in cases where nutrients do not limit crop performance. For any nutrient, the optimal DRIS index is zero, with a negative index indicating deficiency and a positive index indicating sufficiency (Jones, 1981).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the study site

The study was conducted at the Kenya Agriculture and Livestock Research Organization (KALRO) Katumani Research Center (Fig 1), at coordinates (01° 35' S and 37º14' E); lying at an altitude of 1575 meters above sea level (Kutu, 2012). The area is characterized as agro-climatic zone IV (Jaetzold *et al*., 2006), receiving a bimodal rainfall, with the first season occurring from March to May, locally called long rains (LR) and the second season occurring from October to January, called short rains (SR) with peaks in April and November, respectively (Jaetzold *et al*., 2006; Recha *et al*., 2012). The short rains tend to be more reliable for crop production than the long rains (Recha *et al*., 2012; Kwena *et al*., 2018).

The average daily minimum and maximum temperatures are 13.7 and 24.6 ^{0} C, respectively, with an annual rainfall of 450-600 mm (Jaetzold *et al*., 2006). The mean potential evaporation ranges from 1820 to 1840 mm with estimated evapotranspiration (ET_o) of 1239 mm per year (Gicheru, 1996).

The dominant soil in the study area is Ferralo-chromic Luvisols (WRB 2015), having low inherent soil fertility of 5-10g kg^{-1} organic carbon and 0.7-0.9 g kg^{-1} nitrogen, with a slightly acidic reaction (pH 5.7-6.9 in water), poor structure with high sand content and moderate clay content (Karuma *et al*., 2014), and exhibiting high bulk density (Karuku, 2018; Karuku and Mochoge, 2018). The area is suitable for Katumani maize (*Zea mays*) and beans (*Phaseolus vulgaris*) variety, millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor*), green grams (*Vigna radiata*), pigeon peas (*Cajanus cajan*) cowpea (*Vigna unguiculata*), and mangoes (*Mangifera indica*).

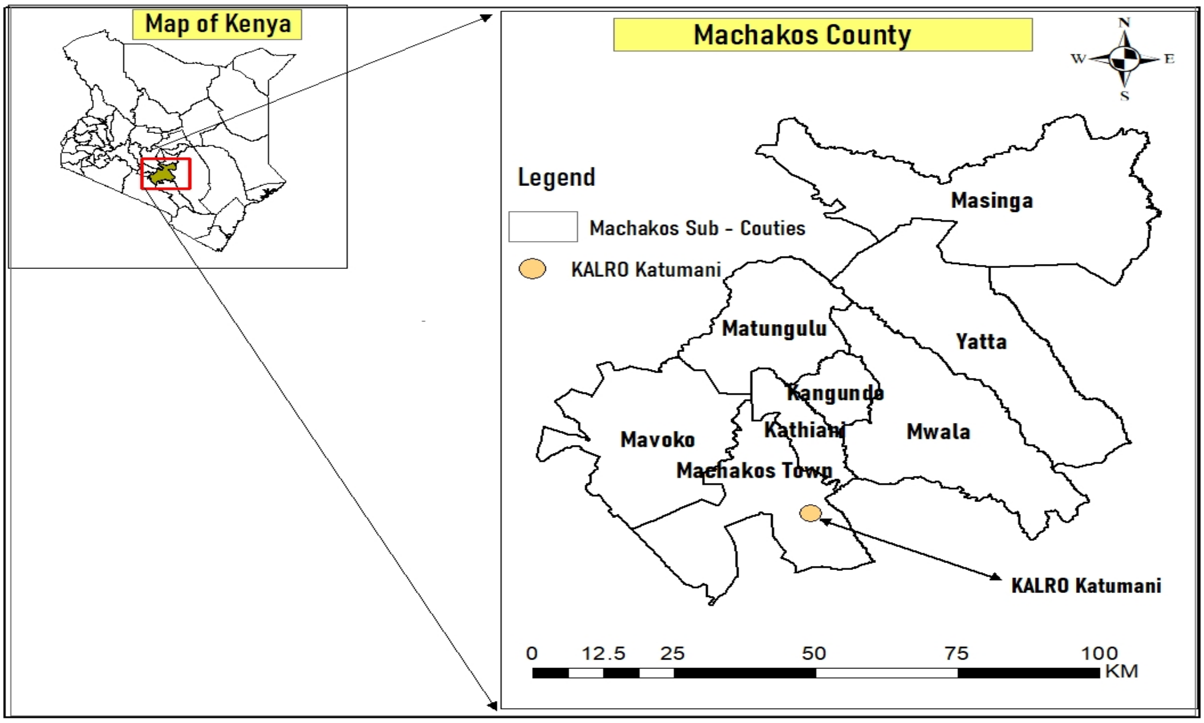

Figure 3. 1*: Map of the study area. Source: Generated from ARC-GIS Software*

3.2 Experimental design, layout, and treatments

The experiment was laid out in a randomized complete block design (RCBD) with a split-split plot arrangement replicated three times. The *in-situ* water harvesting technologies were the main plots and measured 8 m × 11 m; comprising Zai pits, Ngolo pits, contour furrows and hand-hoeing (conventional tillage). Split plots measuring 8 m × 2 m consisted of fertilizer treatments (control with no inputs, Di-ammonium Phosphate (18:46:0) (N: P: K) at 100 kg ha^{-1}, 5 t ha^{-1} goat manure and a mixture of DAP + goat manure at the half- rate (50 kg ha^{-1} + 2.5 t ha^{-1}). The split-spit plots measuring 2 m × 2 m were the cropping systems; sole maize, sole beans and maize-bean intercrop. The test crops were maize (Katumani KDV4 variety) and beans (KATB1 variety). These two varieties were selected due to their good adaptability, early maturation and yields highly under semi-arid conditions. Treatment combinations are summarized in Table 3.1.

Table 3. 1: Summary of Experimental Treatments

Treatment	Technologies (main plots)	Fertilizer application (split plots)	Cropping systems (split-split plots)
T1	Zai pits	100kg ha^{-1} DAP (FF)	Maize
T2		100kg ha^{-1} DAP (FF)	Beans
T3		100kg ha^{-1} DAP (FF)	Maize + beans
T4		50kg ha^{-1}DAP+2.5 t ha^{-1} manure (HF+HM)	Maize
T5		50kg ha^{-1}DAP+2.5 t ha^{-1} manure (HF+HM)	Beans
T6		50kg ha^{-1}DAP+2.5 t ha^{-1} manure (HF+HM)	Maize + beans
T7		5 t ha^{-1} manure (FM)	Maize
T8		5 t ha^{-1} manure (FM)	Beans
T9		5 t ha^{-1} manure (FM)	Maize + beans
T10		Control	Maize
T11		Control	Beans
T12		Control	Maize + beans
T13	Ngolo pits	100kg ha^{-1} DAP (FF)	Maize
T14		100kg ha^{-1} DAP (FF)	Beans
T15		100kg ha^{-1} DAP (FF)	Maize + beans
T16		50kg ha^{-1}DAP+2.5 t ha^{-1} manure (HF+HM)	Maize
T17		50kg ha^{-1}DAP+2.5 t ha^{-1} manure (HF+HM)	Beans
T18		50kg ha^{-1}DAP+2.5 t ha^{-1} manure (HF+HM)	Maize + beans
T19		5 t ha^{-1} manure (FM)	Maize
T20		5 t ha^{-1} manure (FM)	Beans
T21		5 t ha^{-1} manure (FM)	Maize + beans
T22		Control	Maize
T23		Control	Beans
T24		Control	Maize + beans
T25	Contour Furrows	100kg ha^{-1} DAP (FF)	Maize
T26		100kg ha^{-1} DAP (FF)	Beans
T27		100kg ha^{-1} DAP (FF)	Maize + beans
T28		50kg ha^{-1}DAP+2.5 t ha^{-1} manure (HF+HM)	Maize
T29		50kg ha^{-1}DAP+2.5 t ha^{-1} manure (HF+HM)	Beans
T30		50kg ha^{-1}DAP+2.5 t ha^{-1} manure (HF+HM)	Maize + beans
T31		5 t ha^{-1} manure (FM)	Maize
T32		5 t ha^{-1} manure (FM)	Beans
T33		5 t ha^{-1} manure (FM)	Maize + beans
T34		Control	Maize
T35		Control	Beans
T36		Control	Maize + beans
T37	Conventional tillage	100kg ha^{-1} DAP (FF)	Maize
T38		100kg ha^{-1} DAP (FF)	Beans
T39		100kg ha^{-1} DAP (FF)	Maize + beans
T40		50kg ha^{-1}DAP+2.5 t ha^{-1} manure (HF+HM)	Maize
T41		50kg ha^{-1}DAP+2.5 t ha^{-1} manure (HF+HM)	Beans
T42		50kg ha^{-1}DAP+2.5 t ha^{-1} manure (HF+HM)	Maize + beans
T43		5 t ha^{-1} manure (FM)	Maize
T44		5 t ha^{-1} manure (FM)	Beans
T45		5 t ha^{-1} manure (FM)	Maize + beans
T46		Control	Maize
T47		Control	Beans
T48		Control	Maize + beans

3.3 Agronomic practices on the experimental plots

The land was manually prepared using a hand hoe in September before the onset of the rains in preparation for the installation of the water harvesting structures namely; Zai pits, Ngolo pits and contour furrows. The conventional tillage used in this study was hand-hoeing (farmers' practice). **Contour furrows** were prepared by digging 0.3 m deep trenches and planting on the ridges.

Zai pits were constructed by digging the top soil to a depth of 30 cm with a hand hoe. The first 0-15 cm soil was piled on one side, and that from 15-30 cm was piled on the lower side of the pits to trap water in case of a runoff, leaving a pit (Zai) at the center (plate 1). The top 0-15 cm dug-out soil was then mixed with the fertilizer and manure treatments and returned to half-fill the pit before planting, to maintain the original fertility status. Planting was done inside the pits.

Plate 1*: Maize and beans under Zai pits*

Photo: Kelvin Wafula, taken on 11/11/2019

Ngolo pits: During the construction of Ngolo pits, dried pigeon peas residues were collected, cut into smaller pieces and then spread on the 4 sides of squares measuring 2 m × 2 m. Soil from the centre of the square was dug using a hand hoe. The soil dug from the center was heaped evenly on the plant residues, leaving a pit at the center (Ngolo) as described by Kato *et al*. (2001) (plate 2).

Maize and beans seeds were planted on the heaped soils while the Ngolo pits were left bare to collect and hold water during the rainy season.

Plate 2*: Maize and bean planted under Ngolo pits*

Photo: Kelvin Wafula, taken on 11/11/2019

3.4 Installation of access tubes

During the SR 2019, one access pipe was manually inserted in the middle of each plot for soil moisture measurement. The polyvinyl chloride (PVC) pipes were 130 cm long and 5cm in diameter, with a watertight lid at the bottom. The tubes were placed in the center of the plots with Zai pits and conventional tillage, whereas in Ngolo pits and contour furrows, the pipes were placed on top of the ridges. To facilitate and expedite intimate contact between the tubes and the soil, the slurry method of re-filling was used.

The access tubes were implanted after a slurry made of fine soil and water was poured into the bottom of the hole, displacing and pushing the slurry up the hole, forcing out the air, and filling voids between the access tubes and the hole wall. A protrusion of 30cm above the soil surface was left to cover the tubes and prevent runoff from entering the pipes.

Planting for SR 2019 took place on 19th October 2019, and LR 2020 on 12th April 2020. Before planting, the different fertilizer application rates corresponding to the treatments being studied (DAP fertilizer at 100 kg ha^{-1}, goat manure at 5 t ha^{-1}, and a mixture of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure, were spot-applied in the different respective plots.

In the sole crop plots, two maize and two bean seeds were sown per hill, with 75 cm between the rows and 30 cm within the rows for maize and 45 cm between rows, and 15 cm within the rows for beans. Single rows of beans were planted between maize rows in the intercrop system. In an intercrop, the inter-row spacing between bean seeds was 25 cm. Two weeks after emergence (WAE), maize and bean crops were thinned to one plant per hill. All plots were weeded with a hand hoe at the same time. The crops were weeded again at four WAE and top dressed with Calcium Ammonium Nitrate (CAN) fertilizer at a rate of 200 kg ha^{-1}. To manage leaf-eating insects, Duduthrin (active ingredient: Lambdacyhalothrin 17.5g/L) was routinely sprayed, while aphids were controlled by using Thunder (active ingredient: Imidacloprid 100g/L + Beta-cyfluthrin 45g/L) and Marshal (active ingredient: 35 percent Carbosulfan). During the growing season, pesticides were sprayed four times at 14-day intervals.

Beans and maize were harvested at physiological maturity at 2 and 4 months, respectively.

3.5 Data collection

3.5.1 Climate data

Rainfall (mm), maximum and minimum air temperature (°C), relative humidity, sunshine hours, solar radiation, and wind speed (ms^{-1}) at 2 m above ground for the study period was obtained from the meteorological weather station located at the KALRO-Katumani meteorological station.

3.5.2 Soil and manure chemical analysis

Initial soil characterization involved the collection of five (5) soil samples from the experimental site using a 600 cm^3 soil auger in a transect at a depth of 0-30 cm. The collected soils were thoroughly mixed in a bucket to form a composite sample, and then a representative soil sample was placed in small brown packing khaki bags; size ½ and taken to the laboratory for analysis.

Another 1 kg sample of goat manure was collected from a manure pit by subsampling and placed in a khaki bag for chemical analysis. The samples were first air-dried, crushed and then passed through a 2 mm mesh sieve for physical and chemical analyses.

Another set of soil samples was collected during harvest for the two cropping seasons, when crops reached physiological maturity (2 months for beans) and (4 months for maize). Soil samples were collected from inside the Zai pits, on top of the ridges in Ngolo pits, on top of the ridges in the contour furrows, and at the center of the plot under conventional tillage.

Total nitrogen (TN) was determined by the micro-Kjeldahl method (Bremner, 1996) and organic carbon by using Walkley and Black wet oxidation procedure described by Ryan *et al.* (2001), available phosphorus content was determined calorimetrically following procedures outlined by Murphy and Riley (1962) using a UV–vis spectrophotometer while potassium was determined using a flame photometer. Soil pH (H_2O) was measured in a 1:2.5 soil water ratio using a glass electrode pH meter, following the procedure outlined by Okalebo *et al*. (2002). Iron, zinc and copper were determined through Atomic Absorption Spectrophotometer (AAS).

3.5.3 Determination of soil moisture content

Total available water was measured at 4, 8, 12, and 16 weeks after planting (WAP), which represented the growth stages of maize, namely, initiation, development, tasselling/silking, and harvest, using a Neutron 503DR Hydro probe. For calibration, soil samples were collected near the two calibration pipes located at the outer ends of the experimental plots to a depth of 100 cm. Soils were dug at an interval of 20 cm using a soil auger, and placed in khaki bags labelled with the respective depths. The samples were weighed to determine the wet weight before being oven-dried at 70 °C for 48 hours to a constant weight. Soil moisture content in these samples was determined gravimetrically, and labelled as calibrated moisture content.

The neutron counts were calibrated using the gravimetric water content (g/100 g soil) by plotting a graph of neutron count ratio against gravimetric water content (Equ 1) and the probe counts converted into gravimetric readings.

$$y = mx \times c \qquad (1)$$

Where;

y = gravimetric water content, m = the gradient, x = neutron counts and c = y-intercept.

.

The gravimetric water content was converted into volumetric water content by multiplying with the bulk density as in Equ 2.

$$\theta = \omega\rho b \div \rho w \qquad (2)$$

Where;

ϴ = volumetric water content, ω = gravimetric water content, ρb = soil bulk density, ρw = density of water.

3.5.4 Plant tissue sampling and analysis

Beans and maize were harvested upon attaining physiological maturity; 75 and 120 days after planting, respectively. The sampling area consisted of the central 2 rows with 25 cm boarders excluded from each end, giving a harvestable area of 2.25 m^2. Ten and five randomly selected and tagged beans and maize plants, respectively were cut at the base of the soil with a machete, pods and cobs separated from stover. The collected plant samples were threshed manually and their respective grain weights were recorded using a weighing balance with (± 0.05g precision). Three maize Stover and five bean straws from the harvested batch were chopped into 2 cm long pieces. About 500 g sub-samples of maize Stover and bean straws were placed in separate khaki bags. Similarly, a sub-sample of maize and bean grains was also put in ¼ khaki bags. The grain and Stover samples were dried in the oven at 70°C for 24 hours to a constant weight. The samples were ground using a Willey Mill and passed through a 2 mm sieve for analysis of N, P, and K contents.

The sub-samples were digested using a block digester with sulfuric acid at 110^0C for six hours. TN was determined by the micro-Kjeldahl method (Bremner,1996), and available phosphorus content was determined calorimetrically following procedures outlined by Murphy and Riley (1962) using a UV–vis spectrophotometer while potassium was determined using a flame photometer.

3.5.5 Nutrient uptake

The N, P and K content in grains and stover were calculated using Equ 3.

$$Nutrient\ uptake\ (kg\ ha-1) = nutrient\ concentration\ \times total\ dry\ matter\ yield \quad (3)$$

3.5.6 Nutrient use efficiency

Nutrient use efficiency was computed using the formula as described by Brentrup and Palliere (2010) (Equ.4).

$$\text{Nutrient use effiiciency} = \frac{Yield\ in\ fetilized\ plots - yield\ in\ control\ plots}{the\ amount\ of\ fertilzer\ applied} \qquad (4)$$

Where the amount of fertilizer supplied was estimated as the sum of elements (N and P) in the soil at planting time added to that applied through fertilizers.

3.5.7 Determination of grain and biomass yields

Maize and beans grain and biomass yield in megagrams per hectare (t ha^{-1}) (Equ. 5 and 6).

$$Grain\ yield\ (kg\ ha - 1) = \frac{\text{Grain dry yield (kg)} \times 10{,}000\ \text{m}^2}{\text{total area of the plots}} \qquad (5)$$

$$Biomass\ yield\ (kg\ ha - 1) = \frac{\text{total above ground biomass (kg)} \times 10{,}000\ \text{m}^2}{\text{total area of the plots}} \qquad (6)$$

3.5.8 DRIS norms and indices computation

3.5.8.1 Maize leaf sampling and analysis

Maize leaf samples were taken between tasselling and silking stages (60 days after emergence) in all treatments for both seasons. From the maize plots, the leaf opposite and below the ear was removed for nutrient analysis. The samples were washed with distilled water to remove contaminants, oven-dried at 70 ^{0}C, then ground and digested using H_2SO_4 and $HClO_4$. Total Nitrogen was determined by the micro-Kjeldahl method (Bremner, 1996), and available phosphorus content was determined calorimetrically following procedures outlined by Murphy and Riley (1962) using a UV–vis spectrophotometer and potassium determined by flame photometer.

All the 192 collected samples were divided into high-yielding population plants > 2.9 t ha^{-1}. DRIS norms were calculated for the high-yielding population because the high-yield usually results from balanced nutrients in plants.

3.5.8.2 Computation of DRIS norms and indices

Based on the nutrient concentrations in the leaves, the Diagnosis and Recommended Integrated System (DRIS) was applied to generate nutrient norms and indices.

DRIS uses a system of dual nutrient ratios and standard deviation and ranks them according to their importance in limiting crop yields. Each of the three tested nutrients; N, P and K were expressed as means and variance (variance for low yielding / high yielding population) was calculated in the two subpopulations (high and low yielding) for each nutrient using the equation as described by Walworth and Sumner (1987). The forms of expression for each pair of nutrients were N/P, P/K, N/K, K/N, P/N, and, K/P, and the ones having the highest variance ratio were selected for use in the DRIS calculation. The concentrations of N, P, and K in dry leaf tissue samples and the corresponding yield were used to establish DRIS norms (reference values) which consist of means and standard deviation of dual ratios between nutrients obtained from a crop reference population.

The yield data were subdivided into two sub-populations i.e., high-yielding and low-yielding populations (Walworth and Sumner, 1987). The dividing line for grain yields for separating the population into high and low-yielders was obtained based on the calculations following the third (3rd) quartile procedure (Walworth and Sumner, 1987). The 3rd quartile is the N/4th value, when the values are arranged in descending order, where N is the number of observations (experimental plots). In this study, the total experimental plots (N) were 144; therefore, the third quartile value was 144/4 = 36th value. This value is the dividing line for demarking the high and low-yielding populations. DRIS norms, mean, variance, standard deviation and coefficient of variation (CV) for all the nutrient ratios were calculated separately for the high and low yielding sub populations (Equ. 7).

$$\text{norm for nitrogen/phosphorus} = \frac{\mathrm{N/P}}{\mathrm{n}} \tag{7 a}$$

$$\text{norm for nitrogen/potassium} = \frac{\text{N/K}}{\text{n}} \tag{7 b}$$

$$\text{norm for phosphorus/potassium} = \frac{\text{P/K}}{\text{n}} \tag{7 c}$$

Where, NPK is the nitrogen, phosphorus and potassium concentration in percentage (%), respectively, and n is the number of observations in the sufficient populations.

DRIS indices are quantitative evaluations of the relative degree of imbalance among the nutrients under study and were calculated (Equ 8 and 9).

$$N\ Index = \left[\frac{f(N/P)+f(N/K)}{2}\right] \tag{8 a}$$

$$P\ Index = \left[\frac{f(N/P)+f(P/K)}{2}\right] \tag{8 b}$$

$$K\ Index = \left[\frac{f(P/K)+f(N/K)}{2}\right] \tag{8 c}$$

Where, when N / P ≥ n/p

$$f(N/P) = \left[\frac{N\ /\ P}{n\ /\ p} - 1\right]\frac{1000}{CV} \tag{9 a}$$

or when the actual value of N/P < n/p

$$f(N/P) = \left[1 - \frac{n\ /\ p}{N\ /\ P}\right]\frac{1000}{CV} \tag{9b}$$

N/P is the value of the ratio of the two elements in the tissues of the plant being diagnosed (test data), n/p is the optimum value (mean of the high yielders) or norms for that ratio and CV is the coefficient of variation associated with the norms. Values for the functions, such as f(N/K), f(P/K), etc., are calculated in the same way as f(N/P), using appropriate norms and CVs.

The DRIS expresses results of plant nutritional diagnosis through indices, which represent, on a continuous numeric scale, the effects of each nutrient on the nutritional balance of the plant. These indices are expressed by positive (+) and negative (-) signs which indicate that the referred nutrient is in excess or deficient, respectively. The closer to zero (0) the indices are for all the nutrients, the closer it is for the plant to an adequate nutritional balance (Walworth and

Sumner, 1987). The DRIS indices developed for N, P and K for each treatment were arranged in ascending order, which indicates their order of requirement. The highest index is the one, which is more negative, which indicates that a particular nutrient is more deficient or more required to other nutrients used in the diagnostic index.

3.6 Statistical analysis

All the collected data were subjected to analysis of variance (ANOVA) using GenStat package 15th version and means separated using Fisher's Least Significant Difference (LSD) at 5% significance level (Gomez and Gomez, 1984). DRIS norms and indices were developed based on the ear leaves nutrient concentrations and ranking of limiting nutrients performed following the procedure described by (Walworth and Sumner (1987).

CHAPTER FOUR

4.0 RESULTS

4.1 Characterization of soil at the experimental site

Soil-chemical and physical analyses of the experimental site are presented in Table 4.1. The soil was coarse-textured, exhibiting high sand content of 71%, moderate clay at 23%, with low silt content of 6%, hence a sandy clay loam (SCL) textural class, with a pH value of 6.5. Total soil organic carbon and TN were 1.2 and 0.1 %, respectively and thus low according to Landon (2014). The data indicated high exchangeable potassium at 1.7 cmol/kg, iron at 64.1 ppm and copper at 14.7 ppm. Zinc content in the soil was high at 12.5 ppm, while phosphorus level was low at 23.4 ppm. The soil had a bulk density of 1.3 gcm^{-3}.

Table 4. 1: Soil properties of the experimental site in Katumani, Machakos County

Soil properties	Parameters	Soil characterization	Critical level	Ratings
Physical	Bulk density	1.3		
	Sand %	71		
	Silt %	6		
	Clay %	23		
	Textural class	SCL		
Chemical	pH (H_2O)	6.5	5.5-7.8	slightly acidic
	Organic carbon (OC) (%)	1.2	≥ 2.4	Low
	Total Nitrogen (TN) (%)	0.1	≥ 0.5	Low
	Phosphorus (P) (ppm)	23.4	≥ 25	Low
	Potassium (K) (cmol/kg)	1.7	≥ 5	Low
	Zinc (Zn) (ppm)	12.5	≥ 5	High
	Iron (Fe) (ppm)	64.1	≥ 10	High
	Copper (Cu) (ppm)	14.7	≥ 1	High

Legend: SCL: Sandy clay loam

4.2 Characterization of goat manure used in the experiment

Before commencement of the experiment, goat manure was analyzed for pH, TN, total organic carbon, available P and exchangeable cations (K, Ca, Mg, Zn and Fe) using procedures outlined by Okalebo *et al*. (2002). The results are presented in Table 4.2.

The pH of manure used in the two cropping seasons was slightly alkaline (pH >7.0), with manure applied during the SR 2019 having a higher pH value of 8.3 compared to the one used during the LR 2020, which had a pH of 7.9. The % TN content in manure was 2.1% in both seasons, while organic carbon was 6.4 % in SR 2019 and 7.4 % in LR 2020. Phosphorus levels were 785 and 730 ppm, while potassium was 17.5 and 14.7 cmol/kg, in manure used in the SR 2019 and LR 2020, respectively.

Table 4. 2: Chemical composition of goat manure used in the experimental site in Katumani, Machakos county

	SR 2019	LR 2020
Parameters	Levels	
pH (H_2O)	8.3	7.9
Organic carbon (OC) (%)	6.4	7.4
Total Nitrogen (TN) (%)	2.1	2.1
Phosphorus (P) (ppm)	785	730.
Potassium (K) (cmol/kg)	17.5	14.7
Calcium (Ca) (cmol/kg)	15.4	18.5
Magnesium (Mg) (cmol/kg)	8.5	6.9
Zinc (Zn) (ppm)	30.3	41.2
Iron (Fe) (ppm)	160.8	164.4

Legend: SR- Short rain season; LR- Long rain season

4.3 Weather conditions during the study period in Katumani, Machakos County

The monthly climatic data during maize growing seasons are shown in Table 4.3.

In SR 2019, the highest effective rainfall was reported at 142.5, 137.7 and 142 mm dec^{-1} in November, December, and January, respectively, representing crop initiation, development, and tasseling/silking stages. The maturation stage saw a rainfall reduction to 52.7 mm dec^{-1} in February. March recorded the highest minimum and maximum temperatures of 15.7 and 26.2 ^{0}C, respectively. The monthly mean % relative humidity (RH) at the site was 79, recorded in December and April, while the highest monthly solar radiation and wind speed were 557.6 MJm^2 day^{-1} and 3.6 ms^{-1}, recorded in January and February, respectively.

The aridity indices in the SR 2019 ranged between 0.4 and 1.8, with the highest recorded in October to December, coinciding with crop initiation and vegetative stages, respectively, while the lowest aridity index (AI) was observed in February, at the maize maturation stage.

Lower effective rainfall values were recorded in the LR 2020, at the crop vegetative, development and tasseling/silking; 7.6, 15.9, 1.8 and 0.7 mmdec^{-1}; in May, June, July and August, respectively. The AI ranged between 0.0 and 1.8, with the lowest AI observed in July, and August, at the crop maturation stage. On the other hand, the highest AI value of 1.8 was observed in April, at the crop initiation stage.

Table 4. 3: Climatic data observed during the study period in Katumani, Machakos County

Season	Months	Eff. Rain (mm/dec)	T_{max} ^{0}C	T_{min}	RH (%)	Radiation Mj m2/day	WS m/s	SH	ET_o mm/day	AI
SR 2019	October	135.4	24.3	14.8	69	410.8	3.09	8.6	3.57	1.8
	November	142.5	24.7	15.0	73	501.7	3.09	8.1	4.10	1.8
	December	137.7	24.2	14.8	79	469.4	3.09	8.6	3.98	1.7
	January	142.0	24.8	15.2	77	557.6	3.09	10.5	4.49	1.6
	February	52.5	25.9	14.6	72	541.2	3.60	10.4	4.76	0.4
	March	127.7	26.2	15.7	71	584.2	3.09	9.3	5.12	1.1
LR 2020	April	152.4	25.3	14.9	79	449.2	3.09	7.9	5.03	1.8
	May	7.6	24.8	14.2	72	498.8	2.57	7.7	3.82	0.1
	June	15.9	23.9	11.7	71	388.7	2.57	7.7	3.59	0.2
	July	1.8	23.0	10.9	69	296.7	3.09	6.0	3.31	0.0
	August	0.7	24.3	11.1	68	393.0	2.57	4.9	3.42	0.0
	September	9.1	24.3	11.9	64	448.9	2.57	7.5	4.99	0.0

Legend: SR- short rains, LR- long rain season T_{max}*- maximum temperature,* T_{min} *-minimum temperature, RH-Relative humidity;* ET_o*-reference evapotranspiration, SH-sunshine hours, WS-wind speed, AI-aridity index.*

4.4 Soil moisture content as affected by *in-situ* water harvesting technologies, fertilizer inputs, and cropping systems.

Table 4.4 show the effects of *in-situ* water harvesting technologies, fertilizer inputs, cropping systems and depth on soil moisture content (SMC) recorded at different weeks after planting (WAP). *In-situ* water harvesting technologies resulted in significant differences in soil moisture content (SMC) in the SR 2019 ($p < 0.001$) and the LR 2020 ($p < 0.001$) (Table 4.4). In the SR 2019, higher moisture levels were observed in Zai pits (22.28 cm^3 cm^{-3}), and contour furrows (20.14 cm^3 cm^{-3}), while the lowest moisture level was obtained from conventional tillage

(17.31 cm^3 cm^{-3}). There were no significant effects on soil moisture content due to the fertilizer inputs ($p = 0.912$) and the cropping systems ($p = 0.864$) (Table 4.4). However, there were significant ($p = 0.002$) interactions of time × cropping systems, time × *in-situ* water harvesting technologies ($p < 0.001$), time × depth ($p < 0.001$), and time × *in-situ* water harvesting technologies × depth ($p < 0.001$).

In the LR 2020, there were significant interactions between time × *in-situ* water harvesting technologies ($p < 0.001$), time × depth ($p < 0.001$), and time × *in-situ* water harvesting technologies × depth ($p = 0.042$) and time × fertilizer inputs × depth ($p = 0.042$). Soil moisture by *in-situ* water harvesting technologies during the LR 2020 was higher in Ngolo pits (14.98 cm^3 cm^{-3}), followed by Zai pits (13.66 cm^3 cm^{-3}), contour furrows (13.56), and lowest in conventional tillage (13.14 cm^3 cm^{-3}).

The soil moisture content decreased over time (WAP) during the two growing seasons ($p < 0.001$). Across the profile, the soil moisture was higher in the 40-60 cm depth than in the 20-40 cm and 0-20 cm depths and varied among the *in-situ* water harvesting technologies in the two seasons ($p < 0.001$). When the soil moisture content for each water harvesting technology was averaged, a significant difference was found ($p < 0.001$) (Table 4.4). Soil moisture content was not affected by fertilizer inputs ($p = 0.541$) and cropping systems ($p = 0.434$).

Table 4. 4: Soil moisture content (cm^3 cm^{-3}) as affected by in-situ water harvesting technologies, fertilizer inputs, cropping systems and depth in Katumani, Machakos County

Treatments	Soil moisture cm^{3}cm^{-3}		
	SR 2019	LR 2020	Mean
Water harvesting technologies (T**)**			
Zai pits	22.28	13.66	17.97
Ngolo pits	18.62	14.98	16.80
Contour furrows	20.14	13.56	16.85
Conventional tillage	17.31	13.14	15.23
Mean	19.59	13.84	16.71
Fertilizer inputs (I)			
Full rate of DAP Fertilizer	18.88	13.94	16.41
Half rate of DAP + half manure	18.67	13.85	16.26
Full rate of manure	18.62	12.71	15.67
Control	18.29	13.86	16.08
Cropping systems (CS)			
Sole beans	18.72	13.46	16.09
Sole maize	18.53	13.86	16.20
Maize + Beans (intercrop)	18.81	13.89	16.35
Depth			
0-20 cm	17.71	11.65	14.68
20-40 cm	18.53	14.29	16.41
40-60 cm	20.58	15.59	18.09
Significance levels			
Time (weeks after planting)	<0.001	<0.001	<0.001
Technologies	<0.001	<0.001	<0.001
Fertilizer inputs	0.912	0.310	0.541
Cropping systems	0.864	0.838	0.434
Depth	<0.001	<0.001	<0.001
Technologies × Depth	<0.001	<0.001	<0.001
Time × Technologies	<0.001	<0.001	<0.001
Cropping systems × Depth	0.002	0.014	0.003
Time × Depth	<0.001	<0.001	<0.001
Time × Technologies × Depth	<0.001	0.042	0.023

4.5 Effect of *in-situ* water harvesting technologies, fertilizer inputs, and cropping systems on selected soil nutrients

4.5.1 Total Nitrogen

Table 4.5 presents selected soil nutrient contents at the end of the experiment in the SR 2019 and LR 2020 seasons, respectively.

At the end of the SR 2019, *in-situ* water harvesting technologies significantly ($p = 0.004$) increased the total nitrogen (TN) levels in the soil, with the highest TN of 0.15% recorded in Ngolo pits compared to 0.12% in Zai pits, 0.11% in contour furrows and least of 0.10 % under conventional tillage.

Total Nitrogen (TN) content increased significantly ($p < 0.001$) with fertilizer inputs. The lowest TN value of 0.08 % was recorded from control plots, and increased to 0.12 % in plots treated with 100 kg ha^{-1} DAP, a mixture of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure, and 5 t ha^{-1} manure. No significant difference ($p = 0.243$) in TN was observed under the cropping systems.

The trend in TN results at the end of the LR 2020, was similar to that observed in the SR 2019 season. Total nitrogen differed significantly ($p = 0.025$) among the *in-situ* water harvesting technologies, with the highest TN content of 0.09 % being recorded from plots under Ngolo pits and the least TN of 0.06 % obtained under conventional tillage. On the other hand, application of 100 kg ha^{-1} DAP, a mixture of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure and 5 t ha^{-1} manure, increased soil TN significantly ($p < 0.001$) compared to control, which recorded the least TN content of 0.06 %.

About the cropping systems, sole beans and maize-bean intercropped recorded significantly ($p = 0.037$) higher TN content compared to sole maize but this was dependent on the cropping system × fertilizer inputs interaction (I × CS). Maize-bean intercropped treated with 100 kg ha^{-1} DAP fertilizer resulted in 0.11% TN, higher than plots treated with 50 kg ha^{-1} DAP + 2.5 t ha^{-}

^{1} manure, 5 t ha^{-1} manure and control in sole maize. Control plots under sole maize recorded the least TN of 0.06 %.

Table 4. 5: Soil fertility status under *in-situ* water harvesting technologies, fertilizer inputs and cropping systems in Katumani, Machakos County

Treatments	SR 2019			LR 2020		
	N (%)	P (ppm)	K (cmol/kg)	N (%)	P (ppm)	K (cmol/kg)
Water harvesting technologies (T)						
Ngolo pits	0.15^{a}	27.81^{a}	0.44^{a}	0.09^{a}	32.28^{a}	0.46^{a}
Zai pits	0.12^{b}	20.56^{b}	0.45^{a}	0.08^{a}	23.11^{a}	0.49^{a}
Contour furrows	0.11^{bc}	19.94^{b}	0.47^{a}	0.07^{ab}	29.83^{a}	0.44^{a}
Conventional tillage	0.10^{c}	18.33^{c}	0.41^{a}	0.06^{b}	23.25^{a}	0.41^{a}
LSD ≤ 5%	0.013	1.038	0.052	0.016	16.564	0.125
Fertilizer inputs (I)						
FF	0.12^{a}	21.25^{b}	0.44^{b}	0.08^{a}	31.25^{a}	0.49^{a}
HF+HM	0.12^{a}	24.44^{a}	0.48a	0.07^{a}	29.58^{a}	0.48^{a}
FM	0.12^{a}	21.75^{ab}	0.43b	0.07^{a}	27.50^{a}	0.45^{a}
CTRL	0.08^{b}	19.19^{b}	0.41^{c}	0.06^{b}	20.14^{a}	0.37^{b}
LSD ≤ 5%	0.01	2.082	0.021	0.005	9.382	0.061
Cropping systems (CS)						
Sole maize	0.11^{a}	19.77^{b}	0.40^{c}	0.06^{a}	26.10^{a}	0.45^{a}
Sole beans	0.11^{a}	22.35^{a}	0.45^{b}	0.07^{a}	26.69^{a}	0.45^{a}
Intercrop	0.12^{a}	22.85^{a}	0.48^{a}	0.07^{a}	28.56^{a}	0.46^{a}
LSD ≤ 5%	0.004	1.658	0.019	0.004	4.758	0.043
Summary p-values						
T	0.004	<0.001	0.173	0.025	0.476	0.540
I	<0.001	<0.001	<0.001	<0.001	0.100	0.001
CS	0.243	<0.001	<0.001	0.294	0.562	0.831
T × I	0.199	0.160	<0.001	0.081	0.455	0.419
T × CS	0.485	<0.001	<0.001	0.197	0.488	0.512
I × CS	0.502	0.010	<0.001	0.037	0.447	0.164
T ×I × CS	0.632	<0.001	<0.001	0.452	0.317	0.551

*Legend: FF-full rate (100 kg ha^{-1} DAP fertilizer), HF+HM- half-rate DAP + half-rate goat manure (50 kg ha^{-1}+2.5 t ha^{-1}), FM- full-rate goat manure (5 t ha^{-1}), CTRL-control. *Means followed by the different letters down the column differ significantly at $p \leq 0.05$*

4.5.2 Available soil phosphorus

In the SR 2019, available phosphorus (P) was significantly ($p < 0.001$) influenced by *in-situ* water harvesting technologies, fertilizer treatments and cropping systems and their interactions

(T × I × CS). The value ranged between 18.3 ppm and 27.8 ppm in the order of conventional tillage < contour furrows < Zai pits < Ngolo pits (Table 4.5). The fertilizer treatments significantly ($p < 0.001$) increased available P content under cropping systems. The application of 50 kg ha^{-1} DAP+ 2.5 t ha^{-1} resulted in a 21.5 % increase in the soil available P content compared to control.

Cropping systems significantly ($p < 0.001$) influenced available P content, with the highest values of 22.4 and 22.9 ppm, recorded in sole beans and maize-bean intercrop plots, respectively, and the lowest value of 19.8 ppm recorded in plots with sole maize.

The interactive effect of water harvesting technologies and cropping systems (T × CS), fertilizer inputs and cropping systems (I × CS), and water harvesting technologies, fertilizer inputs, and cropping systems (T × I × CS) significantly ($p < 0.001$) influenced soil available P content (Table 4.5). Ngolo pits with 50 kg ha^{-1} DAP + 2.5 ha^{-1}, under maize-bean intercrop recorded a P content of 25.4 ppm, while the lowest P content of 19.1 ppm was obtained from control plots. The results produced under Zai pits, contour furrows and conventional tillage with fertilizer application followed a similar trend as reported for Ngolo pits.

In the LR 2020, available P was not significantly ($p > 0.05$) affected by *in-situ* water harvesting technologies, fertilizer inputs or cropping systems.

4.5.3 Exchangeable potassium

In the SR 2019, fertilizer treatments significantly ($p < 0.001$) affected the exchangeable K content. The highest value of 0.48 cmol (+)/kg was obtained following the application of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure, and the lowest of 0.41 cmol (+)/kg was obtained from the control plots. *In-situ* water harvesting technologies did not significantly ($p = 0.173$) affect the exchangeable potassium content.

Cropping systems increased K content in the soil significantly ($p < 0.001$) from 0.40 Cmol (+)/kg in plots with sole maize to 0.48 cmol (+)/kg in plots with maize-bean intercrop.
The interactive effects of water harvesting technologies, fertilizer inputs, and cropping system (T × I × CS) significantly ($p < 0.001$) affected exchangeable potassium content in the soil. The highest value was recorded under Ngolo pits with maize and beans intercropped following application of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure, while the lowest was obtained under conventional tillage without fertilizer input.

In the LR 2020, exchangeable K content in the soil varied significantly ($p < 0.001$) between the different fertilizer inputs. For instance, control plots recorded the lowest K content at 0.37 mol (+)/kg, whereas, plots treated with 100 kg ha^{-1} had the highest K content at 0.49 cmol (+)/kg, though this was insignificant when compared to plots treated with a mixture of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure and 5 t ha^{-1} manure.

4.6 Effect of *in-situ* water harvesting, fertilizer inputs and cropping systems on maize grain N, P and K uptake

In the SR 2019, the influence of *in-situ* water harvesting technologies on N uptake was statistically significant ($p < 0.001$) with maize under Ngolo pits having a higher average N uptake of 67.7 kg ha^{-1}, than those under Zai pits, contour furrows and conventional tillage which had an average N uptake of 43.1, 38.9 and 19.5 kg ha^{-1}, respectively.

Fertilizer treatments significantly ($p < 0.001$) influenced maize N uptake, with the highest grain N content of 55.4 kg ha^{-1}, being obtained in plots with 100 kg ha^{-1} of DAP fertilizer and the lowest of 24.2 kg ha^{-1} obtained from control plots. Application of 5 t ha^{-1} manure resulted in a 35.9% increase in N uptake compared to control.

Similarly, cropping systems, had a significant ($p < 0.001$) influence on N uptake. The highest grain N content of 45.8 kg ha^{-1} was recorded from intercropped systems, while maize under the sole system gave the least N content of 38.8 kg ha^{-1}. The highest grain P content of 48.2 kg ha^{-1} was recorded from maize grown under Ngolo pits followed by 14.0 kg ha^{-1} in Zai pits, 35.2 kg ha^{-1} in contour furrows and the lowest of 25.7 kg ha^{-1} under conventional tillage.

Table 4. 6: Nutrient uptake in maize grain as affected by *in-situ* water harvesting technologies, fertilizer inputs and cropping systems in Katumani, Machakos County

Treatments	SR 2019			LR 2020		
	Grains uptake (Kgha^{-1})			Grains uptake (Kgha^{-1})		
	N	P	K	N	P	K
Water harvesting technologies (T)						
Ngolo pits	67.7^{a}	48.2^{a}	24.9^{a}	23.2^{a}	20.1^{a}	12.1^{a}
Zai pits	43.1^{b}	40.7^{ab}	16.2^{b}	15.9^{a}	19.0^{a}	10.9^{a}
Contour furrows	38.9^{b}	35.2^{b}	12.5^{b}	11.2^{a}	11.7^{a}	10.0^{a}
Conventional tillage	19.5^{c}	25.7^{c}	9.5^{c}	11.2^{a}	11.3^{a}	7.4^{a}
LSD ≤ 5%	11.003	10.62	3.527	11.878	7.374	5.119
Fertilizer inputs (I)						
FF	55.4^{a}	42.5^{a}	20.9^{a}	20.9^{a}	19.9^{a}	13.3^{a}
HF+HM	51.7^{a}	37.1^{a}	18.5^{b}	18.3^{ab}	17.6^{a}	10.4^{a}
FM	37.8^{b}	29.9^{b}	12.5^{c}	14.3^{b}	15.6^{a}	7.6^{ab}
CTRL	24.2^{c}	19.9^{b}	9.5^{d}	8.0^{c}	9.1^{b}	4.3^{b}
LSD ≤ 5%	10.307	11.13	2.076	4.394	4.953	4.729
Cropping systems (CS)						
Sole maize	38.8^{b}	43.2^{b}	14.2^{b}	14.5^{a}	15.1^{a}	12.2^{a}
Maize-bean intercrop	45.8^{a}	56.5^{a}	16.6^{a}	16.2^{a}	16.0^{a}	12.8^{a}
LSD ≤ 5%	3.64	4.92	0.711	2.371	1.603	0.945
Summary p-values						
T	<0.001	<0.001	<0.001	0.136	0.058	0.079
I	<0.001	<0.001	<0.001	<0.001	0.001	0.034
CS	<0.001	<0.001	<0.001	0.155	0.238	0.122
T × I	0.196	0.084	0.008	0.019	0.260	0.312
T × CS	0.473	0.469	0.056	0.243	0.038	0.541
I × CS	0.364	0.200	0.728	0.870	0.719	0.119
T ×I × CS	0.264	0.633	0.124	0.979	0.742	0.674

*Legend: FF-full rate (100 kg ha^{-1}DAP fertilizer), HF+HM- half-rate DAP + half-rate goat manure (50 kg ha^{-1}+2.5 t ha^{-1}), FM- full-rate goat manure (5 t ha^{-1}), CTRL-control. *Means followed by the different letters down the column differ significantly at $p \leq 0.05$.*

Similarly, fertilizer inputs significantly influenced grain P uptake, with the highest P content of 42.5 kg ha^{-1}, obtained from plots treated with 100 kg ha^{-1} DAP fertilizer. The lowest P uptake of 19.9 kg ha^{-1} was recorded from control plots. and 5.4 kg ha^{-1}. Grain P content was significantly ($p < 0.001$) affected by cropping systems, with plots under maize-bean intercropping systems recording 20 % higher P, compared to those under the sole maize system. Maize crops grown under Ngolo pits recorded the highest K content of 24.9 kg ha^{-1}, while those under conventional tillage had the lowest K content of 9.5 kg ha^{-1}. Grain K content under Zai pits and contour furrows was not statistically different, however, there was a 6.7 and 3.1 kg ha^{-1} increase, respectively, compared to grain K content in maize under conventional tillage. Fertilizer application significantly ($p < 0.001$) influenced grain K content, which ranged between 9.5 and 20.9 kg ha^{-1}, with the lowest being obtained from control plots and the highest obtained from plots treated with 100 kg ha^{-1} DAP fertilizer. K under fertilizer treatment followed the trend of DAP > mixture of DAP + manure > manure > control.

Concerning cropping systems, the amount of K in maize grains was 14.6 % higher ($p < 0.001$) in the intercropping system, compared to maize under the sole system. Statistically, a significant ($p \leq 0.05$) interactive effect of water harvesting technologies and fertilizers inputs (T × I) on K content was observed. The combined use of Ngolo pits with DAP fertilizer at 100 kg ha^{-1} gave the highest K content of 23.4 kg ha^{-1} whereas the lowest K content of 10.7 kg ha^{-1} was obtained from conventional tillage without fertilizer inputs.

In the LR 2020, the uptake of N, P, and K was not influenced by the *in-situ* water harvesting technologies ($p = 0.058$) (Table 4.6). A significant ($p = 0.001$) influence of fertilizer inputs on the uptake of N, P, and K was observed. The application of 100 kg ha^{-1} DAP fertilizer, increased grain N uptake increased by 61.7 % compared to control. Similar observations were made with grain P content, where the highest P content of 19.9 kg ha^{-1} was recorded in plots treated with 100 kg ha^{-1} DAP, while those under control had the lowest P content of 9.1 kg ha^{-1}. Concerning

K uptake, plots treated with 100 kg ha^{-1} DAP recorded the highest K content of 13.3 kg ha^{-1}, while those under control had the lowest K content of 4.3 kg ha^{-1}.

4.7 Effect of *in-situ* water harvesting, fertilizer inputs, and cropping systems on maize stover N, P, and K uptake

Table 4.7 presents the results of N, P, and K content in maize stover.

In the SR 2019, *in-situ* water harvesting technologies significantly ($p < 0.001$) influenced Stover N, P, and K uptake. Maize under Ngolo pits recorded the highest stover N content of 47.2 kg ha^{-1}, while those under conventional tillage recorded the least N of 19.3 kg ha^{-1}. Stover N content under Zai pits and contour furrows was 58.5 and 36.7 %, respectively, higher compared to stover N obtained under conventional tillage.

Fertilizer inputs had a significant ($p < 0.001$) influence on maize stover content, with the highest value of 46.4 kg ha^{-1}, obtained from plots treated with 100 kg ha^{-1} of DAP fertilizer, whereas control recorded the lowest stover N content of 22.5 kg ha$^{-1.}$ plots. Application of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure and 5 t ha^{-1}, increased N content by 44.7 and 33.6 % compared to control.

The interaction effect of *in-situ* water harvesting technologies, fertilizers inputs, and, cropping systems (T × I × CS) increased stover N content significantly ($p < 0.001$). The combined use of Ngolo pits with DAP fertilizer at 100 kg ha^{-1} with a maize-bean intercropping system gave the highest Stover N uptake of 49.4 kg ha^{-1} whereas the lowest stover N content of 23.7 kg ha^{-1}, was obtained from conventional tillage without fertilizer inputs control and sole maize.

Table 4. 7: Nutrient uptake in maize stover as affected by i*n-situ* water harvesting technologies, fertilizer inputs and cropping systems in Katumani, Machakos County

Treatments	SR 2019			LR 2020		
	Stover uptake (Kg ha^{-1})			Stover uptake (Kg ha^{-1})		
	N	P	K	N	P	K
Water harvesting technologies (T)						
Ngolo pits	47.2^{a}	14.5^{a}	64.1^{a}	15.8^{a}	12.8^{a}	21.2^{a}
Zai pits	46.6^{ab}	12.6^{a}	61.8^{ab}	15.0^{a}	11.0^{a}	19.4^{b}
Contour furrows	30.5^{b}	7.4^{b}	52.7^{b}	11.8^{ab}	9.3^{a}	19.0^{a}
Conventional tillage	19.3^{c}	5.37^{b}	16.8^{c}	10.8^{b}	8.4^{a}	7.2^{ab}
LSD ≤ 5%	12.9	2.962	17.46	2.143	4.462	7.712
Fertilizer inputs (I)						
FF	46.4^{a}	11.9^{a}	50.3^{a}	15.1^{a}	12.4^{a}	11.0^{a}
HF+HM	40.7^{ab}	10.9^{a}	46.1^{b}	13.3^{ab}	10.9^{ab}	9.8^{b}
FM	33.9^{b}	7.0^{c}	43.6^{b}	12.5^{b}	8.9^{b}	7.0^{b}
CTRL	22.5^{c}	5.4^{d}	25.4^{c}	9.3^{c}	5.3^{c}	5.1^{c}
LSD ≤ 5%	11.94	1.688	9.47	1.491	1.227	1.089
Cropping systems (CS)						
Sole maize	45.2^{a}	9.7^{a}	57.5^{a}	13.1^{a}	11.8^{a}	9.4^{a}
Maize-bean intercrop	41.6^{a}	7.8^{b}	55.2^{a}	12.6^{a}	11.0^{a}	10.9^{a}
LSD ≤ 5%	9.01	0.99	6.2	0.882	0.75	0.99
Summary p-values						
T	<0.001	<0.001	0.001	0.024	0.213	0.057
I	<0.001	<0.001	<0.001	0.003	0.023	0.014
CS	0.415	<0.001	0.472	0.141	0.111	0.215
T × I	0.002	<0.001	<0.001	0.089	0.234	0.119
T × CS	0.076	<0.001	0.030	0.441	0.067	0.089
I × CS	0.732	0.002	0.002	0.223	0.818	0.746
T ×I × CS	<0.001	0.006	0.002	0.832	0.289	0.444

*Legend: FF-full rate (100 kg ha^{-1}DAP fertilizer), HF+HM- half-rate DAP + half-rate goat manure (50 kg ha^{-1}+2.5 t ha^{-1}), FM- full rate goat manure (5 t ha^{-1}), CTRL-control. *Means followed by the different letter down the column differ significantly at $p \leq 0.05$.*

Maize Stover under Ngolo pits recorded the highest P content of 14.5 kg ha^{-1} and 12.6 kg ha^{-1}, while those under conventional tillage had the lowest stover P content of 5.4 kg ha^{-1} (Table 4.7). Stover P uptake was significantly ($p < 0.001$) affected by fertilizer inputs. The highest P content 11.9 kg ha^{-1}, was obtained from plots treated with 100 kg ha^{-1} DAP fertilizer, while the lowest P content 5.4 kg ha^{-1}, was obtained from control. P content in stover increased by 23% in plots treated with 5 t ha^{-1} manure, compared to the control plots. Stover P content was significantly ($p < 0.001$) affected by cropping systems. Plots under maize-bean intercropping systems recorded higher P content by 19% P compared to those under sole maize.

Interactive effects of *in-situ* water harvesting technologies, fertilizer inputs and, cropping systems (T × I × CS) were significant ($p = 0.006$) in influencing Stover P content. The combination of Ngolo pits with 100 kg ha^{-1} DAP fertilizer and intercropping maize and beans resulted in 15.2 kg ha^{-1}; higher P compared to 5.3 kg ha^{-1} obtained from control. A similar trend was observed in Zai pits, contour furrows and conventional tillage.

The highest Stover K content of 64.1 kg ha^{-1} was recorded from maize grown in Ngolo pits, while those under conventional tillage had the lowest K content of 16.8 kg ha^{-1}. Stover K content under Zai pits and contour furrows were 45 and 35.9 kg ha^{-1} higher, respectively, compared to maize under conventional tillage.

The K content in stover ranged between 25.4 and 50.3 kg ha^{-1}, with the lowest being obtained from control plots and the highest obtained from plots treated with 100 kg ha^{-1} DAP fertilizer. A Mixture of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure and 5 t ha^{-1} applied alone increased stover K content by 20.7 and 18.2 kg ha^{-1} compared to the control.

The interaction of *in-situ* water harvesting technologies and cropping systems (T × CS), fertilizer input and cropping systems (I × CS), and *in-situ* water harvesting technologies, fertilizer inputs, and cropping systems (T × I × CS) influenced stover K content significantly ($p = 0.002$). Plots with maize and beans intercropped under Ngolo pits, treated with 100 kg ha^{-1} DAP fertilizer gave the highest K content of 52.3 kg ha^{-1}, whereas maize grown under control recorded the lowest K content at 21.3 kg ha^{-1}. In Zai pits, contour furrows and conventional tillage, a similar trend in stover K content was observed.

In the LR 2020, *in-situ* water harvesting technologies significantly ($p \leq 0.05$) influenced stover N content. Maize stover under Ngolo pits and Zai pits recorded 31.6 and 28 % higher stover N contents, respectively, compared to those under conventional tillage (Table 4.7). Stover N uptake varied significantly ($p = 0.003$) with fertilizer inputs. The highest N content of 15.1 kg ha^{-1} was obtained from plots treated with 100 kg ha^{-1} DAP fertilizer, whereas, those under control recorded the lowest N content of 9.3 kg ha^{-1}. There was a 4 and 3.2 kg ha^{-1} N increase following application of a mixture of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure and 5 t ha^{-1} manure alone, compared to control, respectively.

Fertilizer inputs had a significant ($p = 0.023$) influence on maize stover P content. Plots treated with 100 kg^{-1} DAP fertilizer recorded the higher P content of 12.4 kg ha^{-1} and the lowest of 5.3 kg ha^{-1} obtained from the control plots. A mixture of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure and 5 t ha^{-1} manure applied alone resulted in a 5.6 and 3.6 kg ha^{-1} P increase, respectively compared to the control.

The K content was significantly ($p = 0.014$) influenced by fertilizer inputs (Table 4.7). The lowest K content of 5.1 kg ha^{-1} was obtained from control plots, while plots treated with 100 kg ha^{-1} DAP recorded the highest grain K content of 11 kg ha^{-1}. A mixture of 50 kg ha^{-1} DAP+ 2.5 t ha^{-1} manure and 5 t ha^{-1} manure applied alone increased K content by 47.9 and 27.1%, respectively compared to the control.

4.8 The N and P agronomic use efficiency of maize

Data on the use efficiency of N and P in maize crops are presented in Table 4.8.

In the SR 2019, the agronomic use efficiency of N and P was significantly ($p = 0.024$) influenced by *in-situ* rainwater harvesting technologies. Maize crops grown under Ngolo pits recorded the highest N use efficiency value of 30.2 kg grain per kg N ha^{-1}, while those under conventional tillage yielded the lowest value at 12.4 kg grain per kg N ha^{-1}.

Concerning fertilizer inputs, a significantly ($p < 0.001$) higher N use efficiency value of 39.1 kg grain per kg N ha^{-1} was obtained from maize plots treated with 100 kg ha^{-1} DAP fertilizer, followed by 23.9 kg grain per kg N ha^{-1} from plots with 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure, and the least N use efficiency value of 16.6 kg grain per kg N ha^{-1} obtained from plots treated with 5 t ha^{-1}. Cropping systems did not significantly ($p = 0.613$) affect the N use efficiency.

The phosphorus use efficiency values ranged from 16.9 to 38.3 kg grain per kg P ha^{-1}, with maize under Ngolo pits recording the highest N use efficiency, whereas, significantly ($p = 0.014$) lower N use efficiency was observed in maize under conventional tillage. Maize grown under Zai pits and contour furrows efficiently used the applied P and produced 17.3 and 15.7 kg grain per kg P ha^{-1}, respectively, more than maize under conventional tillage.

The use efficiency of P increased significantly ($p < 0.001$) following the application of fertilizer. Maize treated with 100 kg ha^{-1} DAP and the mixture of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure efficiently utilized the applied P and recorded the highest yield of 40.1 and 35.9 kg grain per kg P ha^{-1}, respectively. The lowest use efficiency of P was reported in maize plots treated with 5 t ha^{-1}, producing only 23.3 kg grain per kg P ha^{-1}.
There was no significant ($p = 0.845$) difference in P use efficiency between the cropping systems.

In the LR 2020, *in-situ* water harvesting technologies did not significantly ($p > 0.05$) affect the N and P uses efficiency. However, their use efficiency was significantly ($p \leq 0.05$) increased with fertilizer inputs. Maize in plots treated with 5 t ha^{-1} manure, had the lowest use efficiency, yielding only 13.2 kg grain per kg N ha^{-1}, whereas those treated with 100 kg ha^{-1} DAP fertilizer had a higher N use efficiency and yielded 22.9 kg per kg N ha^{-1}. On the other hand, plots with 5 t ha^{-1} recorded 10.9 kg grain per kg P ha^{-1}, while plots treated with 100 kg ha^{-1} DAP fertilizer and plots treated with a mixture of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure produced 24.4 and 17.9 kg grain per kg P ha^{-1}. The cropping system did not significantly ($p > 0.05$) affect the use efficiency of N and P.

Table 4. 8: Nitrogen and phosphorus use efficiency in maize cropping system under i*n-situ* water harvesting technologies, fertilizer inputs and cropping systems in Katumani, Machakos County

	SR 2019		LR 2020	
Treatments	NUE	PUE	NUE	PUE
Water harvesting technologies (T)				
Ngolo pits	30.16^{a}	38.27^{a}	21.11^{a}	26.42^{a}
Zai pits	24.39^{a}	34.18^{a}	12.04^{a}	14.55^{a}
Contour furrows	25.89^{a}	32.60^{a}	10.80^{a}	12.05^{a}
Conventional tillage	12.44^{b}	16.92^{b}	10.04^{a}	13.14^{a}
LSD ≤ 5%	10.14	12.8	8.708	13.056
Fertilizer inputs (I)				
FF	39.09^{a}	40.05^{a}	22.97^{a}	24.47^{a}
HF+HM	23.93^{b}	35.90^{a}	15.39^{b}	17.98^{a}
FM	16.64^{c}	23.28^{b}	13.20^{c}	10.92^{b}
Control	-	-	-	-
LSD ≤ 5%	6.55	8.84	4.941	7.006
Cropping system (CS)				
Sole maize	22.5^{a}	29.4^{a}	13.28^{a}	16.86^{a}
Maize-bean intercrop	23.9^{a}	30.1^{a}	14.43^{a}	17.72^{a}
LSD 5%	5.72	7.39	2.464	3.182
Summary p-values				
T	0.024	0.014	0.100	0.131
I	<0.001	<0.001	<0.001	0.008
CS	0.613	0.845	0.347	0.585
T × CS	0.214	0.230	0.150	0.524
T × I	0.345	0.368	0.406	0.365
I × CS	0.705	0.916	0.639	0.817
T × I × CS	0.894	0.968	0.579	0.856

*Legend: FF-DAP fertilizer (100 kg ha^{-1}), FM- goat manure (5 t ha^{-1}), HF+HM- half-rate of DAP + half-rate goat manure (50kg ha^{-1}+2.5 t ha^{-1}), CTRL-control. NUE-Nitrogen use efficiency, PUE- Phosphorus use efficiency *Means followed by the different letters down the column differ significantly at $p \leq 0.05$.*

4.9 The N and P agronomic use efficiency of beans

The effect of *in-situ* rainwater harvesting technologies, fertilizer application, and cropping systems on nitrogen and phosphorus use efficiency by bean crops are presented in Table 4.9. The N use efficiency by beans varied significantly ($p = 0.026$) within the *in-situ* water harvesting technologies, with yields ranging from 6.8 to 16.7 kg grain per kg N ha^{-1}. The lowest N use efficiency value of 6.8 kg grain per kg N ha^{-1} was recorded under conventional tillage, whereas beans under Ngolo pits recorded the highest N use efficiency value of 16.7 kg grain per kg N ha^{-1}.

Fertilizer inputs had a significant ($p < 0.001$) impact on the beans N use efficiency. The lowest use efficiency on N was observed in bean plots treated with 5 t ha^{-1}, yielding 8.8 kg grain per kg N ha^{-1}, whereas plots treated with 100 kg ha^{-1} DAP had the highest N use efficiency, yielding 15.8 kg grain per kg N ha^{-1}. No significant difference in N use efficiency was observed in the cropping systems.

The three-way interaction between *in-situ* water harvesting technologies, and fertilizer input cropping systems was significant (T × I × CS) significantly ($p = 0.053$) influenced N use efficiency. Maize and beans intercropped under Ngolo pits treated with 100 kg ha^{-1} DAP fertilizer utilized efficiently the applied N and yielded 16.4 kg ha^{-1}, compared to 9.2 kg ha^{-1} in sole maize plots treated with 5 t ha^{-1} manure.

The use efficiency of phosphorus by beans varied significantly ($p = 0.023$) across water harvesting technologies, with values ranging from 8.9 to 20.1 kg grain per kg P ha^{-1}. Beans grown in Ngolo pits had the highest P use efficiency value, compared to those under conventional tillage. The beans P use efficiency values under Zai pits, contour furrows, and conventional tillage did not differ significantly. The use efficiency of phosphorus increased significantly ($p < 0.001$) with the application of different fertilizer inputs. The highest P use efficiency by beans was recorded following application of 100 kg ha^{-1} DAP fertilizer, yielding 22.2 kg grain per kg P ha^{-1}, while those treated with 5 t ha^{-1} recorded the lowest use efficiency value and produced 12.7 kg grain per kg P ha^{-1}.

Table 4. 9: Beans nitrogen and phosphorus use efficiency as affected by *in-situ* water harvesting technologies, fertilizer inputs, and cropping systems in Katumani, Machakos County

Treatments	SR 2019	
	NUE	PUE
Water harvesting technologies (T)		
Ngolo pits	16.73^{a}	20.06^{a}
Zai pits	11.59^{ab}	14.25^{ab}
Contour furrows	11.52^{ab}	13.94^{ab}
Conventional tillage	6.77^{b}	8.89^{b}
LSD ≤ 5%	5.512	8.021
Fertilizer inputs (I)		
FF	15.84^{a}	22.21^{a}
HF+HM	12.31^{b}	17.96^{b}
FM	8.81^{c}	12.68^{c}
Control	-	-
LSD ≤ 5%	2.544	3.54
Cropping system (CS)		
Sole beans	11.09^{a}	13.39^{a}
Maize-bean intercrop	12.22^{a}	15.18^{a}
LSD ≤ 5%	1.792	2.723
Summary p-values		
T	0.026	0.023
I	<0.001	<0.001
CS	0.203	0.187
T×CS	0.003	0.020
T×I	0.005	0.052
I×CS	0.942	0.002
T×I×CS	0.053	0.045

*Legend: FF-DAP fertilizer (100 kg ha^{-1}), FM- goat manure (5 t ha^{-1}), HF+HM- a half-rate of DAP + half-rate goat manure (50kg ha^{-1}+2.5 t ha^{-1}), CTRL-control. NUE-Nitrogen use efficiency, PUE- Phosphorus use efficiency *Means followed by the different letters down the column differ significantly at P≤0.05*

The interactive effects of water harvesting technologies, fertilizer inputs, and cropping systems (T × I × CS) were significant ($p \leq 0.05$) in influencing P use efficiency. The P use efficiency in the maize-bean intercropping system under Ngolo pits treated with 100 kg ha-1 of DAP fertilizer increased by 24.4, 23.2, and 21.9 kg grain per kg ha-1, respectively, compared to Zai pits, contour furrows, and conventional tillage, all treated with 5 t ha-1 of manure.

No bean yield data were recorded in the LR 2020 due to poor rainfall distribution and prolonged drier conditions in the growing season that coincided with the beans flowering stage, and led to total beans failure.

4.10 Maize grains and Stover yields

The interactive effect of water harvesting technologies, fertilizer inputs and cropping systems on maize yield is shown in Table 4.10.

In the SR 2019, water harvesting technologies significantly ($p < 0.001$) improved maize grain yield, with the highest yield of 4.5 t ha^{-1} obtained in Ngolo pits and the lowest of 1.4 t ha^{-1} from conventional tillage with intermediate yields of 3.2 t ha^{-1} in Zai pits and 2.5 t ha^{-1} in contour furrows.

Application of fertilizers resulted in a significant ($p < 0.001$) maize grain yield increase as follows; 1.7 t ha^{-1} for 100 kg ha^{-1} DAP, 1.5 t ha^{-1} in plots with 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure; half recommended rate, while 5 t ha^{-1} of manure gave 0.5 t ha^{-1} above the control plots. Significant differences ($p < 0.001$) in maize grain yield were observed between cropping systems, with intercrop yielding 3.2 t ha^{-1} compared to sole maize which yielded 2.9 t ha^{-1}.

Trends in maize Stover production were similar to those of grain yields, with Ngolo pits recording significantly ($p = 0.006$) higher Stover of 7.4 t ha^{-1}, followed by 5.9 t ha^{-1} in Zai pits, 4.39 t ha^{-1} in contour furrows and lowest of 3.2 t ha^{-1} in conventional tillage. DAP fertilizer applied at a rate of 100 kg ha^{-1} yielded the highest Stover of 7.2 t ha^{-1} compared to the other inputs, with control plots yielding the lowest Stover of 3.0 t ha^{-1}, intermediate of 5.7 and 5.1 t ha^{-1} in 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure and manure at 5 t ha^{-1} rate, respectively. The yield of maize did not differ significantly across cropping systems.

Table 4. 10: Maize grain and stover yields as affected by *in-situ* water harvesting technologies, fertilizer inputs and cropping systems in Katumani, Machakos County

Treatments	SR 2019		LR 2020	
	Stover	Grains	Stover	Grains
		t ha^{-1}		
Water harvesting technologies (T)				
Ngolo pits	7.43^{a}	4.52^{a}	4.21^{a}	1.55^{a}
Zai pits	5.98^{ab}	3.23^{b}	2.65^{a}	1.06^{a}
Contour furrows	4.39^{bc}	2.53^{b}	3.47^{a}	0.88^{a}
Conventional tillage	3.16^{c}	1.42^{c}	2.24^{a}	0.61^{a}
LSD ≤ 5%	1.827	0.574	2.5824	1.048
Fertilizer inputs (I)				
FF	7.20^{a}	3.67^{a}	4.81^{a}	1.54^{a}
HF+HM	5.66^{b}	3.49^{a}	3.49^{b}	1.25^{a}
FM	5.09^{b}	2.53^{b}	2.51^{c}	0.87^{b}
Control	3.01^{c}	2.02^{c}	1.74^{d}	0.44^{c}
LSD ≤ 5%	0.681	0.323	0.522	0.353
Cropping system (CS)				
Sole maize	5.36^{a}	2.88^{b}	2.97^{b}	0.97^{a}
Maize-bean intercrop	5.12^{a}	3.21^{a}	3.31^{a}	1.08^{a}
LSD ≤ 5%	0.339	0.132	0.234	0.146
Summary of p-values				
T	0.006	<0.001	0.134	0.234
I	<0.001	<0.001	<0.001	<0.001
CS	<0.001	<0.001	0.024	0.124
T×CS	0.685	0.330	0.151	0.500
T×I	0.008	0.058	0.090	0.050
I×CS	0.659	0.659	0.017	0.045
T×I×CS	0.439	0.467	0.477	0.997

*Legend: FF-DAP fertilizer at full rate (100 Kg ha^{-1}), FM- goat manure at full rate (5 t ha^{-1}), HF+HM- half DAP +half-goat manure (50 kg ha^{-1} + 2.5 t ha^{-1}), CTRL-control. *Means followed by the different letters down the column differ significantly at $p \leq 0.05$.*

The interactions between in-situ water harvesting technologies and fertilizer inputs (T × I) were found to be significant (p = 0.008). The application of 100 kg ha-1 DAP fertilizer in maize crops under Ngolo pits produced the highest Stover yield of 11.7 t ha-1, while control treatments with conventional tillage produced the lowest Stover yield of 3.0 t ha-1. There was no significant difference in maize grain yield among the *in-situ* water harvesting technologies in the LR 2020; however, the highest grain yield of 1.6 t ha^{-1} was obtained from Ngolo pits and the lowest grain yield of 0.6 t ha^{-1} from conventional tillage.

Maize plots treated with 100 kg ha^{-1} DAP fertilizer yielded a significantly ($p \leq 0.05$) higher grain yield of 1.5 t ha^{-1}, whereas control plots yielded the lowest grain yield of 0.4 t ha^{-1}. Maize grain yield gradually increased as fertilizer rates were increased, following the trend of 100 kg ha^{-1} DAP > 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure > 5 t ha^{-1} manure > control. Although intercropping maize and beans did not result in a significant increase in maize grain yield, there was a 10.3 % increase in grain yield in the intercrop system when compared to sole maize.

There was a significant interaction between water harvesting technologies × fertilizer inputs × cropping systems (T × I × CS). Plots under maize-bean intercrop treated with 100 kg ha^{-1} DAP fertilizer yielded 1.5 t ha^{-1} more grain than control plots with sole maize. Similarly, applying 100 kg ha^{-1} DAP in Ngolo pits increased maize grain yield by 26.7 % when compared to conventional tillage with no fertilizer input.

There was no significant difference in maize Stover under *in-situ* water harvesting technologies, however, maize crops under Ngolo pits produced the highest Stover of 4.2 t ha^{-1} and the lowest of 2.2 t ha^{-1} in conventional tillage.

Maize Stover yield was 4.8 t ha^{-1} in plots treated with 100 kg ha^{-1} DAP fertilizer, which was significantly ($p < 0.001$) different from 3.5 t ha^{-1} in plots treated with 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure, 2.5 t ha^{-1} in plots treated with 5 t ha^{-1} manure, and 1.7 t ha^{-1} in control plots.

There was a significant ($p = 0.024$) difference in maize Stover yield between cropping systems, with maize-bean intercrop yielding 3.31 t ha^{-1} compared to 2.9 t ha^{-1} in sole maize plots. The interaction between fertilizer and cropping system (I × CS) significantly ($p = 0.017$) increased maize Stover yield. Plots under maize-bean intercrop treated with 100 kg ha^{-1} produced a higher Stover of 4.1 t ha^{-1}, compared to 2.5 t ha^{-1} obtained from sole maize plots without fertilizer input.

4.11 Bean grain and biomass yields

Table 4.11 shows beans grains and biomass yields during the experimental period.

Bean grain yield differed significantly ($p = 0.038$) between *in-situ* water harvesting technologies in the SR 2019, with beans under Ngolo plots yielding 1.6 t ha^{-1}, and the lowest yield of 0.4 t ha^{-1} obtained under conventional tillage.

Fertilizer inputs increased bean grain yields significantly ($p < 0.001$) from 0.7 t ha^{-1} in control plots to 1.9 t ha^{-1} in plots treated with 100 kg ha^{-1} DAP fertilizer. Similarly, plots treated with 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure increased beans grain yield by 23% compared to plots treated with 5 t ha^{-1} manure. In plots with bean-maize intercrop, grain yield was significantly ($p < 0.001$) highest at 1.3 t ha^{-1}, whereas those plots under sole beans recorded the lowest grain yield of 1.2 t ha^{-1}.

The interactions between in-situ water harvesting technologies and cropping systems (T × CS) ($p = 0.002$), fertilizer inputs and cropping systems (I × CS) ($p = 0.02$), and in-situ water harvesting technologies, fertilizer inputs and, cropping systems (T × I × CS) ($p = 0.032$), influenced beans grain yield significantly. Intercropping beans and maize in Ngolo pits, with 100 kg ha-1 DAP fertilizer produced the highest grain yield of 2.8 t ha-1, while sole beans under conventional tillage, with no fertilizer input yielded the lowest grain yield of 0.1 t ha^{-1}.

In Zai pits and contour furrows, a similar trend was observed, with the application of 100 kg ha-1 DAP fertilizer applied in the intercropped system, recording the highest grain yield.

In-situ water harvesting technologies did not significantly affect beans biomass yield, however, the highest biomass of 1.5 t ha^{-1} was obtained in Ngolo pits and lowest of 0.6 t ha^{-1} in conventional tillage.

Bean biomass yield differed significantly ($p < 0.001$) following the application of different fertilizer inputs. Beans plots treated with100 kg ha^{-1} DAP fertilizer yielded the highest biomass of 1.37 t ha^{-1} while control plots yielded the lowest biomass of 0.6 t ha^{-1}. The application of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure resulted in a 26% higher biomass yield compared to plots treated with 5 t ha^{-1} manure. There was a significant ($p < 0.001$) difference in bean biomass across the cropping systems, with maize-bean intercrop yielding 1.1 t ha^{-1} higher compared to 0.9 t ha^{-1} obtained from plots with sole beans.

In the LR 2020, *in-situ* water harvesting technologies had no significant effect on bean biomass; however, Ngolo plots yielded the highest biomass yield of 0.7 t ha^{-1}, while conventional tillage yielded the lowest at 0.2 t ha^{-1}.

A significantly higher ($p < 0.001$) bean biomass yield of 0.5 t ha^{-1} was obtained in plots treated with 100 kg ha^{-1} DAP, whereas control plots recorded the lowest biomass yield of 0.2 t ha^{-1}. Application of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} manure resulted in a 25 and 48 % increase in bean biomass yield compared to plots treated with 5 t ha^{-1} and control, respectively.

There was a significant ($p = 0.017$) interaction between water harvesting technologies × cropping system, with maize-beans intercropping under Ngolo pits producing more biomass than the other treatment combinations. No bean yield data were recorded in the LR 2020 due to poor rainfall distribution and prolonged drier conditions in the growing season that coincided with the beans flowering stage, and led to total beans failure.

Table 4. 11: Bean grains and biomass yields as affected by *in-situ* water harvesting technologies, fertilizer inputs and cropping systems in Katumani, Machakos County

Treatments	SR 2019		LR 2020
	Biomass	Grains	Biomass
		t ha^{-1}	
Water harvesting technologies (T)			
Ngolo pits	1.49^{a}	1.64^{a}	0.66^{a}
Zai pits	0.95^{a}	1.38^{ab}	0.49^{ab}
Contour furrows	0.95^{a}	1.40^{ab}	0.36^{ab}
Conventional tillage	0.56^{a}	0.44^{b}	0.33^{ab}
LSD ≤ 5%	0.687	0.788	0.364
Fertilizer inputs (I)			
FF	1.37^{a}	1.91^{a}	0.54^{a}
HF+ HM	1.13^{a}	1.26^{b}	0.44^{b}
FM	0.84^{b}	0.97^{c}	0.33^{c}
Control	0.60^{b}	0.72^{d}	0.24^{d}
LSD ≤ 5%	0.207	0.184	0.068
Cropping system (CS)			
Sole beans	0.85^{b}	1.15^{b}	0.34^{a}
Bean-maize intercrop	1.12^{a}	1.28^{a}	0.29^{a}
LSD ≤ 5%	0.105	0.06	0.035
Summary of p-values			
T	0.081	0.038	0.026
I	<0.001	<0.001	<0.001
CS	<0.001	<0.001	0.214
T×CS	0.429	0.002	0.017
T×I	0.731	0.296	0.096
I×CS	0.556	0.020	0.455
T×I×CS	0.640	0.032	0.450

*Legend: FF-DAP fertilizer at full rate (100 Kg ha^{-1}), FM- goat manure at full rate (5 t ha^{-1}), HF+HM- half DAP +half goat manure (50 kg ha^{-1} + 2.5 t ha^{-1}), CTRL-control. *Means followed by the different letters down the column differ significantly at p ≤ 0.05.*

4.12 Maize leaf nutrient concentrations

The maize leaf nutrient concentrations used to compute DRIS norms are shown in Table 4.12. It was noted that in the SR 2019, nitrogen content in the ear leaves ranged from 0.9 to 2.0 % with an overall mean of 1.5 %, with leaves collected in plots treated with 100 kg ha^{-1} under Ngolo pits recording the highest concentration of N and lowest in control plots.

Phosphorus concentrations in ear leaves ranged from 0.2 % in control under conventional tillage to 0.4% obtained in Ngolo pits with 100 kg ha^{-1} DAP fertilizer. P concentrations were higher in fertilizer treatments than control treatments, regardless of water harvesting technologies. Potassium concentrations in the ear leaves ranged from 1.4 % recorded in control under conventional tillage to 2.6 % recorded in Ngolo pits + 100 kg ha^{-1} DAP fertilizer.

A similar trend in N, P, and K concentration in ear leaves was recorded in the LR 2020. The highest nitrogen concentration ranged from 0.3 % to 0.5 %. Phosphorus concentrations ranged from 0.07 to 0.12 % while K concentrations ranged from 0.6 to 1.1 %.

Table 4. 12: Nutrient concentrations in maize crop in Katumani, Machakos County in the SR 2019 and LR 2020

	SR 2019				LR 2020		
		% N	% P	% K	% N	% P	% K
Ngolo pits	FF	2.0	0.4	2.1	0.5	0.1	1.1
	HF+HM	1.8	0.3	1.7	0.5	0.1	0.6
	FM	1.9	0.3	1.8	0.4	0.1	0.6
	CTRL	1.7	0.3	1.7	0.2	0.1	0.5
Zai pits	FF	1.9	0.3	2.2	0.4	0.1	1.3
	HF+HM	1.9	0.3	2.0	0.4	0.1	1.3
	FM	1.9	0.3	1.7	0.4	0.1	1.2
	CTRL	0.9	0.3	1.0	0.4	0.1	0.5
Contours furrows	FF	1.5	0.3	1.9	0.4	0.1	1.2
	HF+HM	1.3	0.2	1.9	0.4	0.1	0.9
	FM	1.3	0.2	1.9	0.4	0.1	0.6
	CTRL	1.1	0.2	1.7	0.4	0.1	0.5
Conventional tillage	FF	1.1	0.3	1.7	0.4	0.1	1.2
	HF+HM	1.1	0.3	1.7	0.4	0.1	1.1
	FM	1.1	0.2	1.6	0.3	0.1	0.7
	CTRL	0.9	0.2	1.4	0.3	0.1	0.6
Mean		1.52	0.24	1.52	0.40	0.10	0.81
CV (%)		21.2	0.00	0.00	6.60	5.00	2.30
Standard deviation (SD)		0.57	0.014	0.29	0.19	0.03	0.39

Legend: FF-DAP fertilizer at full rate (100 Kg ha^{-1}), FM- goat manure at full rate (5 t ha^{-1}), HF+HM- half DAP +half goat manure (50 kg ha^{-1} + 2.5 t ha^{-1}), CTRL-control, CV-coefficient of variation.

4.13 DRIS Norms

Table 4.13 shows mean values, coefficient of variation (CV) standard deviation (SD) and variance (δ^2) ratio of the low-yielding and high-yielding (V_{low}/V_{high}) for maize in the experimental site. A total of 6 nutrient ratio expressions for low and high-yielding populations, were calculated. Binary nutrient ratio combinations of all the three nutrients were calculated, and summary statistics were evaluated for each of the resulting nutrient ratio expressions. Low yielding populations showed high values of standard deviation and coefficient of variation as compared with high yielding populations.

Table 4. 13: Nutrient ratio expressions (DRIS norms) in maize crop in Katumani, Machakos County in the SR 2019 and LR 2020

		High-yielding population						Low yielding population					
Treatments / Ratios		N/P	N/K	P/N	P/K	K/N	K/P	N/P	N/K	P/N	P/K	K/N	K/P
Ngolo pits	FF	5.96	1.23	0.17	0.20	0.90	5.15	8.35	1.79	0.18	0.21	2.24	7.00
	HF+HM	5.22	0.95	0.18	0.17	1.13	6.30	7.83	1.79	0.22	0.12	1.35	8.05
	FM	6.25	1.07	0.18	0.17	1.02	5.80	7.04	1.75	0.26	0.13	1.46	5.74
	CTRL	6.93	1.00	0.16	0.15	1.03	6.87	5.85	1.52	0.29	0.12	1.28	8.75
Zai pits	FF	5.26	0.88	0.21	0.116	1.35	6.46	7.68	1.44	0.27	0.13	2.46	7.42
	HF+HM	5.22	0.95	0.19	0.20	0.97	5.06	7.50	1.47	0.12	0.12	2.40	8.10
	FM	5.79	1.04	0.18	0.116	1.09	6.09	7.10	1.40	0.10	0.13	2.61	7.81
	CTRL	2.97	0.84	0.54	0.28	1.95	3.58	5.14	1.27	0.09	0.11	2.36	9.41
Contours furrows	FF	4.56	0.88	0.09	0.07	1.15	6.12	6.03	1.85	0.23	0.14	2.89	7.39
	HF+HM	7.29	0.89	0.18	0.13	1.31	7.83	5.56	1.85	0.23	0.12	2.00	8.10
	FM	4.08	1.09	0.08	0.08	0.92	7.18	5.44	1.39	0.13	0.12	1.86	8.42
	CTRL	4.56	0.79	0.24	0.17	1.39	5.84	4.81	1.35	0.11	0.11	3.27	9.41
Conventional tillage	FF	3.57	0.50	0.29	0.14	2.27	7.56	7.81	1.94	0.15	0.13	1.61	8.00
	HF+HM	2.04	0.22	0.59	0.12	2.88	8.74	8.23	1.75	0.15	0.11	1.18	8.72
	FM	6.51	0.74	0.17	0.12	1.42	8.68	6.56	1.28	0.10	0.11	0.88	8.82
	CTRL	2.07	0.41	0.93	0.36	2.43	4.78	3.01	1.25	0.09	0.11	0.97	9.38
Mean		4.89	0.84	0.27	0.16	1.45	6.38	6.50	1.57	0.35	0.16	2.25	8.26
CV (%)		22.5	18.1	10.0	23.70	10.4	20.10	30.8	15.3	27.8	23.7	36.9	23.2
Standard deviation (SD)		3.64	0.37	0.29	0.10	1.13	1.31	2.87	0.55	0.33	0.12	1.98	4.85
Variance (Var)		13.25	0.14	0.084	0.01	1.28	1.72	8.24	0.31	0.11	0.01	3.92	23.53

Legend: FF-DAP fertilizer at full rate (100 Kg ha^{-1}*), FM- goat manure at full rate (5 t ha*$^{-1}$*), HF+HM- half DAP +half goat manure (50 kg ha*$^{-1}$ *+ 2.5 t ha*$^{-1}$*), CTRL-control, CV-coefficient of variation.*

4.14 DRIS indices

Table 4.14 presents the DRIS indices for maize for the high-yielding population which gave grain yield higher than 2.5 t ha^{-1}. A total of twenty-four (24) treatment combinations presented yielded higher than 2.5 t ha^{-1}, forming the high yield subpopulations.

Table 4. 14: DRIS Indices for various nutrients in the selected high-yielding population

		Leaf concentration			DRIS indices			Orde of Importance
		N%	P%	K%	N	P	K	
Ngolo pits	FF	2.0	0.4	2.1	-4.8	-3.1	-8.2	K>N>P
	HF+HM	1.8	0.3	1.7	-6.2	-5.4	-7.4	K>N>P
	FM	1.9	0.3	1.8	-6.7	-17.4	-6.2	P>N>K
	CTRL	1.7	0.3	1.7	-11.0	-36.7	-8.8	P>N>K
Zai pits	FF	1.9	0.3	2.2	-5.3	-4.4	-10.8	K>N>P
	HF+HM	1.9	0.3	2.0	-5.4	-4.1	-11.4	K>N>P
	FM	1.9	0.3	1.7	-7.4	-4.7	-11.3	K>N>P
	CTRL	0.9	0.3	1.0	-9.6	-5.4	-8.6	N>K>P
Contours furrows	FF	1.5	0.3	1.9	-7.7	-10.7	-7.3	P>N>K
	HF+HM	1.3	0.2	1.9	-11.4	-11.8	-14.6	K>N>P
	FM	1.3	0.2	1.9	-11.4	-5.4	-11.2	N>K>P
	CTRL	1.1	0.2	1.7	-14.6	-11.5	-9.0	N>P>K
Conventional tillage	FF	1.1	0.3	1.7	-6.5	-12.3	-6.0	P>N>K
	HF+HM	1.1	0.3	1.7	-11.3	-11.2	-16.8	K>N>P
	FM	1.1	0.2	1.6	-11.5	-11.1	-23.5	K>N>P
	CTRL	0.9	0.2	1.4	-14.3	-4.9	-18.0	K>N>P

Legend: FF-DAP fertilizer (100 kg ha^{-1}), FM-goat manure (5 t ha^{-1}), HF+HM- half DAP + half- rate goat manure (50 kg ha^{-1} +2.5 t ha^{-1}), CTRL-control.

The calculated N, P and K with DRIS indices on maize at the study site, indicated that in the control, DRIS indices showed that N, P and K were required throughout the growth period. At the 100 kg ha^{-1} level, K and N alternated as being the most required nutrients. For the two treatments in which 50 kg ha^{-1} + 2.5 t ha^{-1} were applied, K was still the most limiting element. Addition of fertilizer slightly improved the soil nutrient status, but not to a point warranting sufficiency. A similar trend was observed in the P and K indices. Different order of importance was presented depending on the treatment's combinations; however, it was noted that all the three diagnosed nutrients (N, P, and K) were limited in the study area.

CHAPTER FIVE

5.0 DISCUSSION

5.1 Initial soil characterization

The soils in the study area are coarse textured, with a high sand content of 71 %, moderate clay content at 23 %, and low silt content of 6 %; a sandy-clay loam textural class, implying a high-water percolation and low water holding capacity. As a result of the high soil water percolation, maize and beans would fail in the event of insufficient moisture. According to Bationo *et al.* (2012), soils in sub-Saharan Africa with ≥ 35 % sand content have a low water-holding capacity and are thus susceptible to nutrient leaching by percolating water.

The initial TN and organic carbon were low based on a rating by Landon (2014), and thus, could be a constraint to crop growth and yields (King *et al.*, 2020). Organic matter, through gradual decay and mineralization, is an important source of soil N for crop growth. The low amount of TN in the soil could be a result of low soil organic matter, which was attributed to the lack of residue plough back. In the area, crop residues are fed to livestock and not returned to the soil (Valbuena *et al.*, 2015). The initial available phosphorus content of was low at 23.4 ppm, compared with the threshold value of 25 ppm, as reported by Fairhurst (2012). This means that crops (maize and beans) could not experience poor root development, stunted growth, or delayed maturity. The soil had a pH of 6.5 which is within the 6.0-7.2 optimal pH range for maize and beans production (Mallarino, 2011).

The initial exchangeable potassium (K) concentration was low at 1.7 cmol/kg, implying low consumption, in which plants take up less K than is required for physiological processes (Roy *et al.*, 2006). Potassium is essential for crop growth and yields because it is important for maintaining turgor pressure, and accumulating and transporting metabolic products in plants, especially in water-stressed conditions (Bationo *et al.*, 2012). The initial Iron and Copper were also high at 64.1 and 14.7 ppm according to ratings by Landon (2014) of > 10 and > 1 ppm, respectively. Iron and Copper are important micronutrients in plants for they play critical functions in some protein complexes involved in photosynthesis and respiration (Jain *et al*., 2014). Iron deficiency results in interveinal chlorosis (Tagliavini and Rombola, 2001), while the formation of small necrotic spots may form, especially on the leaf margins when copper is limited (Yamasaki e*t al*., 2008). This subsequently decreases chlorophyll content which undoubtedly affects the photosynthetic efficiency, hence lowering yields (Slattery *et al*., 2017). Initial zinc content was low in the study site according to Landon *et al*. (2014). Zinc deficiency causes interveinal chlorosis, which in turn leads to the disruption of normal enzyme activity including that of key photosynthetic enzymes (Sharma *et al*., 2020).

5.2 Weather conditions during the study period

In semi-arid areas, effective rainfall represents the total amount of rainwater that directly meets crop water needs and is used in crop production. It necessitates soil water recharge and allows a crop to meet evapotranspiration requirements (Karuku *et al*., 2014). Effective rainfall is mainly influenced by the soil type, cropping patterns, crop characteristics, rainfall and ground water (Adnan and Khan, 2009; Arthar, 2020). Therefore, uneven distribution of rainfall reduces effective rainfall.

In the SR 2019, higher effective rainfall values were recorded in November, December, and January, corresponding to the crop initiation, development, and tasseling/silking, respectively, yielding higher amounts of soil water recharge relative to the atmospheric demand (Table 4.3). High rainfall meant higher recharge of the soil, thus increasing the available water, increasing plant water and nutrient uptake and productivity (Benjamin *et al*., 2007). Rainfall decreased during the maturation stage, which was necessary because this stage requires relatively dry and warm weather to achieve the required moisture content in the grains; otherwise, the grains would rot. The decrease in rainfall during the 2020 long rain season implied that crop yields would be lower because uptake of water and nutrients by roots would be difficult. After all, water is held at higher tension, requiring more energy expended in water uptake that could be used to produce yield.

Aridity index (AI) is a numerical indicator of the relative degree of water deficiency present at a given location (Bannayan *et al*., 2010; Mustafa *et al*., 2018). The highest aridity indices reported in the SR 2019 (Table 4.3), indicated a degree of wetness as a result of soil water recharge from rainfall. However, during the LR 2020, the aridity indices reported, particularly during crop vegetative, tasseling, and silking, were low, indicating the severity of aridity and its potential impact on economic yield. Low aridity indices at the tasseling, silking, and maturation stages revealed a lack of humidity due to a lack of moisture recharge, implying that crop water requirements were not met significantly during the growing period. Mbayaki and Karuku (2021) working in the same area with sweet potatoes reported similar findings.

5.3 Soil moisture content as affected by *in-situ* water harvesting technologies, fertilizer inputs and cropping systems between season and depth

Rainfall distribution during the crop growing period significantly influences moisture content in the soil. The two-cropping season received a relatively low amount of rainfall; however, the SR 2019 received a higher rainfall amount than the LR 2020 (Table 4.3). This observed difference in the rainfall amounts during the SR 2019 and LR 2020 could have contributed to the observed soil moisture variation in the two cropping seasons (Mujdeci *et al*., 2010, Karuma *et al*., 2014). The Zai, contour furrows, and Ngolo pits had higher soil moisture than the conventional tillage due to the pits and furrows formation which served as rainwater collecting troughs, allowing for a greater depth of water to remain on the soil surface, giving it more time to infiltrate. Breaking the surface crust and digging pits could have highly favored rain water harvesting, infiltration, and reduced run off probably due to the earthen bunds formed downslope of the pits (Fatondji *et al*., 2006; Kimaru *et al*., 2018).

Adeyemo *et al*. (2019) in their study on two contrasting degraded Alfisols of southwestern Nigeria found that Zai pits retained significantly higher moisture than conventional tillage (hand hoeing). Similar observations were made by Kausar *et al*. (2020) in Pothwar Plateau of Pakistan who found that Zai pits collected runoff and eroded soil particles immediately after raining, retaining more rain water at the lowest point against the surface flow. In Burkina Faso, Zougmoré *et al*. (2014) reported higher soil moisture content in sorghum fields under Zai pits than in conventional tillage.

In the Mbinga highlands of Tanzania, Allan (1965) reported higher soil moisture content in Ngolo pits compared to conventional tillage, alluding to maize stalks buried during the construction of the pits. The dry grass/stalks buried under the ridges had the same effect as green manure (Itani, 1998; Moritsuka *et al*., 2000) and helped in providing internal drainage of water both vertically and horizontally. One of the unique characteristics of the Ngolo cultivation system is the arrangement of ridges horizontally and vertically across the slope to intercept water runoff. Rill and gully erosion usually occurs along the path of runoff water but the risk is reduced under the Ngolo system (Allan, 1995; Kato, 2001).

Cropping systems recorded inconsistencies in the soil moisture content in the two seasons, which could be attributed to varying crop requirements and climate conditions (Giller *et al*., 2009). Soil water extraction by crops is determined not only by soil water content, evaporative demand, and soil physical properties but also by the crop's physiological status (Passioura and Angus, 2010; Karuma *et al*., 2014), which may explain the non-significant effects observed.

A general increase in soil moisture content with depth was noticed where the upper 0-20 cm, a depth which hosts most of the crop roots had the least moisture compared to the deeper depths (20-40 and 40-60 cm) at all the sampling times. The low soil moisture in the upper profile might have been caused primarily by plant uptake, transpiration, and evaporation (Passioura and Angus, 2010; Karuma *et al*., 2014). The increase in moisture with increasing depth could be attributed to more percolation into the lower levels of the profile (Tromp-van *et al*., 2006; Yu *et al*., 2015).

The higher soil moisture content at 4 WAP compared to 8 and 10 WAP in all treatments could be explained by the fact that crops were still in their early stages and had not yet been fully established, hence low demand. Similarly, the fact that crop vegetative growth was quite vigorous could have led to higher water uptake.

Soil moisture is the primary limiting factor to crop production and therefore, technologies that conserve moisture are vital for increasing yields and mitigating the devastating effects of drought in arid and semi-arid areas (McVay *et al*., 2006; Binyam and Desale, 2015).

The results of this study show that combining soil amendments with Ngolo pits and Zai pits helps to promote moisture retention and limit water loss through evaporation and run off.

5.4 Soil nutrient status at the end of the SR 2019 and LR 2020 cropping seasons

There was a significant increase in TN content during the two cropping systems, under water harvesting technologies, fertilizer inputs and cropping systems. The highest TN content obtained under Ngolo pits compared to Zai pits, contour furrows and conventional tillage (Table 4.5), could be attributed to the decomposition of buried pigeon peas residues at the beginning of the experiment, in addition to the DAP fertilizer and goat manure applied during planting, which was not the case in the other technologies. An active microbial population in contact with the residue is the most important requirement for crop residue decay.

Under moist conditions, these soil microbes (bacteria, fungi, and actinomycetes) are most active and thrive. Crop residues and animal manure decomposition can both significantly increase soil TN (Abbasi *et al*., 2014). Among the buried plant residues, the leaves and stalks are decomposed and disintegrated into finer debris during the cropping year, suggesting increased fertility levels. This coincides with findings by Itani (1998), who reported increased soil N levels in Ngolo pits as a result of residue decomposition.

High TN contents in DAP fertilized plots and a mixture of DAP and manure plots could be attributed to the faster dissolution and release of nutrients, compared to manure which releases N slowly. This could be because chemical fertilizer offers nutrients in a soil soluble form and thereby make them instantly available for plant uptake. The inorganic fertilizer was immediately available for the plants and it may also have helped in the increased mineralization process of the organic manure, as microbes use the fertilizer as a source of energy (Karuku and Mochoge, 2018; Karuku 2019). Farm yard manure is reported to be a good source of nutrients such as P and K and also enhances the availability of secondary micronutrients (Bodruzzaman *et al*., 2010; Aziz *et al*., 2018). These findings are consistent with those of Ademba *et al*. (2015) who reported increased TN in maize plots following the application of DAP fertilizer.

The significantly higher TN recorded in sole beans and intercrop compared to sole maize could be attributed to N_2 fixation and accumulation in legume residues. This finding is consistent with the observations made by Kerma *et al.* (2018) who reported that grain legumes grown in poorly fertile soil contributed to more TN in the soil. The significant change in soil available P during the two seasons could be explained by the solubility of DAP fertilizer and manure decomposition under Ngolo pits and Zai pits. As alluded by Ali *et al*. (2010), the presence of sufficient moisture in the soil beneath the pits may have aided in the dissolution of plant nutrients from complex solid substances in the soil to ionic inorganic forms that are accessible to plants for easy uptake. These results are in close agreement with the previous result by Haynes and Mokolobate (2001), that application of the organic amendment to soil was beneficial and could increase soil available P by up to 115%. Adeleye *et al*. (2010), similarly reported that mixing mineral fertilizer and poultry manure increased soil N, P, K than the application of inorganic fertilizer or poultry manure alone.

Manure contains both N and P as well as other nutrients, but in less soluble forms than organic fertilizers. This could be the reason for low nutrient status in plots where manure was applied alone as compared to plots where DAP fertilizer was applied alone or a mixture of DAP + manure. Latati *et al*. (2016) reported that P availability increased significantly in the rhizosphere especially in intercropping under P deficient soil conditions.

5.5 Nutrient uptake by plants grown under water harvesting technologies, fertilizer application, and cropping systems

Nitrogen uptake by maize and beans was significantly higher under Ngolo pits and Zai pits techniques by 71.2 and 54.7 %, respectively, compared to those under conventional tillage (Table 4.7, 4.8, and 4.9). This could probably be due to the availability of soil moisture and better root growth that favored nutrient uptake. Soil water content influences nutrient movement from the soil, to the roots and the aboveground part of the plants (Li *et al*., 2009; Benjamin *et al*., 2017). These findings are in agreement with those of Fatondji (2002) who reported that Zai pits improved nitrogen uptake by the sorghum in the range of 43-64 % compared to conventional tillage.

It is worth noting that nutrient uptake is influenced mainly by climatic conditions, the number of available nutrients in the soil and the form in which they are present in the soil. It was observed in the study that nitrogen uptake in maize grain and stover increased significantly by 56.3 and 51.4 %, respectively, following the application of 100 kg ha^{-1} DAP fertilizer alone and a mixture of DAP + manure at half rate (50 kg ha^{-1} + 2.5 t ha^{-1}) compared to control. This could be because manure conserved moisture and released slowly nutrients in the soil, while nitrogen in DAP was available for rapid plant use, facilitating root development, early growth, and increased nitrogen uptake. These findings corroborate with the result of Serme (2015) who indicated increased N uptake by sorghum with the addition of manure and mineral fertilizer over control. Similarly, Akande *et al*. (2005) found that combining organic and inorganic inputs increased soil nutrient release, water retention capacity, and crop growth and yield.

The increased nitrogen uptake under the combined use of water harvesting technologies and fertilizer inputs might have been attributed to the conserved soil moisture which could have helped in dissolving the soil nutrients from the applied DAP fertilizer, making them easily available for plant uptake. During dry the season, soils become dry and therefore, plants experience difficulty absorbing nutrients, because most nutrients are in elemental forms rather than ionic forms, resulting in low uptake and hence nutrient levels may be lower than normal (Jones *et al*., 2011; Liu *et al*., 2013; Innocent, 2014;). This could explain why there was higher nutrient uptake in the 2019 short rains as compared to 2020 long rains (Table 4.6 and 4.7).

Phosphorus and potassium uptake in maize grain was higher in Ngolo pits, Zai pits and contour furrows than in conventional tillage. The increase in P and K under water harvesting technologies could be explained by the enhancement of soil moisture content which led to crop growth. Phosphorus and potassium are transported through diffusion, for which moisture is a pre-requisite. Soil moisture affects K diffusivity in the soil as well as root growth. This, in turn, is the apparent reason for the increasing rate of K uptake as soil moisture content increases (Kuchenbuch *et al.*, 1986). Outtara (1994) reported a positive correlation between soil moisture and P and K uptake due to improved soil moisture status and which increased P availability. Similar results have been presented by Zeng and Brown (2000) who reported higher K uptake in maize due to increased soil moisture.

Higher phosphorus uptake values in grain and stover were recorded under 100 kg ha^{-1} DAP fertilizer and a mixture of 50 kg ha^{-1} + 2.5 t ha^{-1} manure treatments. This may be attributed to increased absorption of P by plants due to better root growth and additional supply through manure. Hellal *et al.* (2013) observed that phosphorus enriched with farm yard manure was effective in increasing P availability and uptake as well as increasing maize dry matter.

Despite the low organic matter content of the soil, significant amounts of nitrogen and phosphorus were extracted from the control treatments. Crops that receive nitrogen and phosphorus fertilizer as recommended can grow to their full potential, which increases N and P uptake (Ibrahim *et al.*, 2014). According to Vanalauwe *et al.* (2012) and Mahmood *et al.* (2017), the addition of organic and inorganic materials improves soil chemical, physical, and biological properties, which improves nutrient availability, retention, and uptake. The uptake of nitrogen, phosphorus, and potassium by maize under Ngolo and Zai pits combined with 100 kg ha^{-1} alone and a mixture of 50 kg ha^{-1} DAP + 2.5 t ha^{-1} were similarly demonstrated that the nutrient application rate was optimal to satisfy the nutrient demand of maize crop growth.

Nonetheless, N, P, and K uptake varied with cropping season, with the higher uptake recorded in the 2019 short rain season compared to the 2020 long rain season, which could be attributed to rainfall amounts (Table 4.3). Water is critical in determining a plant's ability to absorb nutrients from the soil (Su *et al.*, 2014). As evidenced by the 2019 SR, water, played an important role in solubilizing P and thus making it available for uptake. These findings are consistent with the findings of Ademba *et al*. (2014), who reported that N, P, and K uptake varied seasonally due to variations in rainfall patterns. Thus, weather conditions have a significant impact on a plant's ability to absorb nutrients, with low uptake occurring during seasons with insufficient rainfall (Sigunga *et al*., 2002; Ibrahim *et al*., 2011).

5.6 Nutrient use efficiency as influenced by *in-situ* water harvesting technologies, fertilizer input, and cropping systems

The higher N and P use efficiencies of maize and beans denoted by yields under Ngolo and Zai pits than in conventional tillage (Table 4.8 and 4.9) is an indication that there was better utilization of nutrients and water. For instance, crops under Ngolo and Zai pits benefited from the available water and nutrients at the root zone, which could have improved nutrient uptake and enhanced utilization.

A study carried out by Shaheen *et al*. (2012) in Pothwar plateau in Punjab and Rehman *et al*. (2013) in the Tista floodplain in Bangladesh, reported that the efficiency of plants to absorb nutrients and the capacity of the soil to supply them are reduced under low soil moisture condition, and therefore in agreement with this study's findings.

The beneficial effect of fertilizers in enhancing nutrient use efficiency of maize and beans could be attributed to the rapid early growth, which contributed to dry matter accumulation and hence higher use efficiency (Kugedera *et al*., 2019). For instance, DAP fertilizer applied at 100 kg ha^{-1} or a mixture of 50 kg ha^{-1} + 2.5 t ha^{-1} significantly influenced N and P use efficiency, probably due to the availability of nutrients in forms easily absorbed by crops (Ademba *et al*., 2014). This is in agreement with findings by Fatondji (2002) who reported that a combination of organic amendments and mineral fertilizer increased grain phosphorus use efficiency by 2 times compared to control treatments.

5.7 Maize and bean yields under *in-situ* water harvesting technologies, fertilizer and cropping systems

Maize and beans yield significantly increased under Ngolo pits, Zai pits and contour furrows, respectively compared to conventional tillage (Table 4.10 and 4.11). This could have been due to the better soil moisture conservation and the availability of nutrients in the vicinity of maize rooting systems under the *in-situ* water harvesting technologies in comparison to conventional tillage. The observed increases in maize grain yield following the use of water harvesting technologies are in agreement with the findings of Mudatenguha *et al*. (2014) while working in Rwanda, who reported a 50 % increase in maize grain yield in Zai pits compared to conventional tillage. Kugedera *et al*. (2018), indicated similar findings, with a 59% increase in sorghum yields under Zai pits compared to those under conventional tillage.

Higher yields in Ngolo pits compared to other technologies could be attributed to relatively higher soil fertility possibly resulting from the decomposed pigeon peas residue that was used during the construction of Ngolo pits. These findings confirm those of Mari (2009) and Rutatora *et al*. (2001), who reported higher maize yield under Ngolo pits compared to those under conventional tillage. In their results, the use of Ngolo pits resulted in 2.3 times higher maize yield compared to bench terraces and conventional tillage in an experiment conducted at the Mt. Kilimanjaro area.

DAP fertilizer applied at 100 kg ha^{-1} and a mixture of DAP + manure at 50 kg ha^{-1} +2.5 t ha^{-1}, increased maize grain yields by 44.9 and 42.1 % and stover grain yields by 58.2 and 46.8 %, respectively, while application of 5 t ha^{-1} manure increased grain and stover yield by 20.2 and 40.9 %, respectively compared to the control. This could be attributed to the improved fertility status of the soil as a result of the added fertilizer inputs, as alluded by Patel *et al*. (2013). Inorganic fertilizer provides immediate nutrients required for plant roots for uptake, while organic manure releases nutrients slowly. This implies that cropping systems should incorporate both organic and inorganic fertilizer inputs, even in small amounts to achieve optimal yields (Vanlauwe *et al*., 2011).

This study demonstrated that intercropping systems outperformed monocropping systems in terms of productivity. This occurred even though intercrops had the lowest amount of soil moisture when compared to corresponding mono-crops. As a result, even in intercropped systems with relatively high plant populations, water constraints appeared to be minimal. Furthermore, intercrop systems had the highest economic yield and biomass production, implying that intercropping is more efficient than mono-crops in utilizing soil water. The findings of this study revealed that complementarity and synergy between crops in an intercropping system were more visible than the competition. This is contrary to the findings of Belel *et al*. (2014), who reported reduced yields in the intercropping systems, attributing this to competition for moisture, nutrients, and solar radiation.

These findings are consistent with those of Kermah *et al*. (2018) and Brooker *et al*. (2015) who reported that intercrops have higher water, nutrient and biomass conversion compared to mono-cropping. Intercrops may thus be more productive than monocrops. Improved intercrop productivity is explained by increased acquisition and utilization of growth resources such as nutrients, moisture, and light interception (Yu *et al*., 2016), resulting in increased soil nitrogen content through fixation by legumes (Mucheru-Muna *et al*., 2010).

Yields received in the SR 2019 were significantly higher than yields in LR 2020. The observed seasonal yield differences were primarily caused by variations in rainfall distribution to potential crop water demand. The higher and better distribution of rainfall received in the SR 2019 compared to the LR 2020, resulted in more soil moisture in the soil profile, which favored early maize and bean establishment and growth. Crop yields were greatly impacted by severe soil moisture stress conditions that occurred during the vegetative, flowering, and grain filling stages during the LR 2020.

These findings are consistent with those of Barron *et al*. (2003) and Jaetzold *et al*. (2006), who found that short periods of water stress during the critical growth stage of a crop had a significant impact on crop growth and yields. According to Ibrahim *et al*. (2011), meteorological parameters such as rainfall are the most important factors influencing crop yields, and thus the onset, availability, and distribution of rain in the cropping season are very important.

Overall, the findings of this study indicate that intercropping under Ngolo pits with 100 kg ha^{-1} DAP fertilizer application may be a good option for intensifying crop production. This enables scarce resources such as water and nutrients to be captured and utilized fully to increase crop productivity per unit area.

5.8 DRIS Norms and indices

Maize yields and nutrient concentrations in the two-season experiment indicated that N, P and K were all limiting maize production in the study site, even in the plots with recommended rates of DAP fertilizer and goat manure. The nutrient indices generated through the DRIS approach reflected the different water harvesting technologies and fertilizer inputs in nutrient management. The N leaf concentrations at tasseling in the study were lower than the critical value of 3% reported by Okalebo *et al*. (2002). This probably explains the insufficiency of N exhibited by the DRIS norms. In the experiment, P concentrations were also lowest and were below the critical range of 0.2 - 0.3 % (Reuter and Robinson, 1997). The yields revealed that the limiting nutrients for good crop growth were N, P, and K, in that order, implying that the soil was inherently low in N and P status and that an external supply of N and P fertilizers was required to support plant growth and yield. This is consistent with the low OC, TN, and available P contents recorded in the soil of the experimental site.

Negative DRIS indexes of N, P, and K were more common in treatments where no fertilizer was applied (control). However, despite recording relatively lower indices, the application rates of 100 kg ha^{-1} DAP fertilizer and 5 t ha^{-1} manure were insufficient to overcome nutrient limitations, indicating that higher rates of fertilizer were required. Similar findings were reported by Balemi and Negisho (2012) and Youssef *et al*. (2013), who stated that N and P were the major limiting nutrients in maize production. The DRIS indices from this study demonstrated greater diversity than those presented by Elwali *et al*. (1985), which were lower than those reported in the current study. This disparity could be attributed to the region from which the samples were collected.

Furthermore, depending on soil properties, this situation may imply that regionality may influence the values of DRIS norms to some extent. These findings are consistent with those of Walworth *et al* (1986).

When nutrients are in a state of imbalance, negative DRIS index values indicate that they are undersupplied, while positive DRIS index values indicate that they are oversupplied. According to DRIS indices obtained from this study, deficiencies for each nutrient for maize production were identified as N > P > K for the two seasons.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Based on the objectives and the results obtained in this study, the following conclusions were drawn;

- The soil moisture content varied significantly in the *in-situ* water harvesting technologies and seasons. An average for the two seasons shows that Zai pits and Ngolo pits conserved the highest moisture content. The capacity of these two technologies to conserve water increased with increasing moisture stress, making them better options for moisture conservation under rain fed conditions. A significant finding in this study is that, during the LR 2020, soil moisture in the *in-situ* water harvesting technologies was significant, even when the rainfall amount was very low, demonstrating their effectiveness in semi-arid areas.
- Nutrients (N, P, and K) uptake by maize and beans were high under *in-situ* water harvesting technologies, with the highest uptake recorded in Ngolo pits. Similarly, the highest N and P utilization efficiency was recorded in Ngolo pits. These results suggest that Ngolo pits can be regarded as climate-smart technologies geared towards improved crop production in arid and semi-arid areas.
- The higher yield in treatments with sole maize compared to sole beans in the LR 2020, when rainfall was low and unevenly distributed, suggests that the maize crop may be a better option for farmers in the study area.
- Application of DAP fertilizer and goat manure at recommended rates increased maize and beans yields. It was worth noting however, that yields from plots with 100 kg ha^{-1} DAP did not differ significantly from yields from plots with 50 kg DAP ha^{-1} + 2.5 t ha^{-}

^{1}). Farmers can therefore, opt to apply mineral fertilizers in combination with manure at a reduced cost, but get optimal yield.

- Although there were inconsistencies in the yields, the synergy that existed between *in-situ* water harvesting technologies, fertilizer application, and cropping systems was observed. Ngolo pits with DAP fertilizer gave the best yields ad led to higher nitrogen and phosphorus uptake and use efficiency.
- For optimal production, farmers are therefore advised to combine the two parameters. Considering the inherent soil fertility of soils in the ASALs and soil water stress, the farmers must combine inorganic and organic fertilizers with appropriate water harvesting technologies to increase crop yields.
- Based on the soil nutrient analysis, and the leaf nutrient concentrations determined using the DRIS norms, the three major nutrients (N, P, and K) were all limited in the soil.

6.2 Recommendations

6.2.1 recommendations from the results

- Farmers may use maize-bean intercrop with 100 kg ha^{-1} DAP fertilizer under Ngolo pits during the season when rainfall is adequate and reliable, as this combination was the most productive in the study area. However, during the dry season, farmers may consider growing maize monocrop with DAP fertilizer in Ngolo pits.

6.2.2 Recommendations for further research

- Further studies should be carried out to determine the economic implications of the selected *in-situ* water harvesting technologies.
- Need for studies to evaluate the long-term effects of the technologies especially Ngolo pits on soil's physical and chemical properties.

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8.0 APPENDICES

Appendix 1: Analysis of variance for soil moisture in SR 2019

4 weeks after planting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	46.36	23.18	0.47	
Blocks.Techniques stratum					
Techniques	3	3953.95	1317.98	26.91	<.001
Residual	6	293.84	48.97	0.84	
Blocks.Techniques.Input stratum					
Input	3	96.82	32.27	0.55	0.650
Techniques.Input	9	1175.81	130.65	2.25	0.055
Residual	24	1395.95	58.16	1.13	
Blocks.Techniques.Input.Crop stratum					
Crop	2	62.18	31.09	0.60	0.551
Techniques.Crop	6	424.96	70.83	1.37	0.239
Input.Crop	6	149.70	24.95	0.48	0.818
Techniques.Input.Crop	18	1347.82	74.88	1.45	0.139
Residual	64	3302.72	51.61	0.89	
Blocks.Techniques.Input.Crop.*Units* stratum					
Depth	1	498.88	498.88	8.61	0.004
Techniques.Depth	3	195.36	65.12	1.12	0.343
Input.Depth	3	337.08	112.36	1.94	0.128
Crop.Depth	2	352.29	176.14	3.04	0.052
Techniques.Input.Depth	9	613.73	68.19	1.18	0.318
Techniques.Crop.Depth	6	108.56	18.09	0.31	0.929
Input.Crop.Depth	6	280.24	46.71	0.81	0.568
Techniques.Input.Crop.Depth	18	994.99	55.28	0.95	0.518
Residual	96	5561.56	57.93		
Total	287	21192.81			

8 weeks after planting

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	100.801	50.401	0.89	
Blocks.Techniques stratum					
Techniques	3	1933.319	644.440	11.32	0.007
Residual	6	341.496	56.916	4.28	
Blocks.Techniques.Input stratum					
Input	3	91.120	30.373	2.28	0.105
Techniques.Input	9	120.982	13.442	1.01	0.459
Residual	24	319.180	13.299	1.28	
Blocks.Techniques.Input.Crop stratum					
Crop	2	97.625	48.812	4.71	0.012
Techniques.Crop	6	36.964	6.161	0.59	0.733
Input.Crop	6	48.176	8.029	0.78	0.592
Techniques.Input.Crop	18	222.747	12.375	1.20	0.292
Residual	64	662.731	10.355	1.53	
Blocks.Techniques.Input.Crop.*Units* stratum					
Depth	1	2095.294	2095.294	310.05	<.001
Techniques.Depth	3	63.222	21.074	3.12	0.030
Input.Depth	3	31.036	10.345	1.53	0.211
Crop.Depth	2	31.368	15.684	2.32	0.104
Techniques.Input.Depth	9	77.593	8.621	1.28	0.260
Techniques.Crop.Depth	6	25.173	4.196	0.62	0.713
Input.Crop.Depth	6	38.770	6.462	0.96	0.459
Techniques.Input.Crop.Depth	18	154.615	8.590	1.27	0.224
Residual	96	648.756	6.758		
Total	287	7140.969			

Appendix 2: Analysis of variance for soil nutrients in SR 2019

Total N

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	0.0087347	0.0043674	8.60	
Blocks.Technique stratum					
Technique	3	0.0215576	0.0071859	14.14	0.004
Residual	6	0.0030486	0.0005081	1.13	
Blocks.Technique.Input stratum					
Input	3	0.0320076	0.0106692	23.67	<.001
Technique.Input	9	0.0061507	0.0006834	1.52	0.199
Residual	24	0.0108167	0.0004507	3.80	
Blocks.Technique.Input.crop stratum					
crop	2	0.0003431	0.0001715	1.44	0.243
Technique.crop	6	0.0006569	0.0001095	0.92	0.485
Input.crop	6	0.0006403	0.0001067	0.90	0.502
Technique.Input.crop	18	0.0018264	0.0001015	0.85	0.632
Residual	64	0.0076000	0.0001188		
Total	143	0.0933826			

Available P

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	26.39	13.19	4.07	
Blocks.Technique stratum					
Technique	3	1907.91	635.97	196.24	<.001

Residual	6	19.44	3.24	0.18	
Blocks.Technique.Input stratum					
Input	3	504.30	168.10	9.18	<.001
Technique.Input	9	270.12	30.01	1.64	0.160
Residual	24	439.50	18.31	1.11	
Blocks.Technique.Input.crop stratum					
crop	2	262.89	131.44	7.95	<.001
Technique.crop	6	1246.11	207.69	12.56	<.001
Input.crop	6	306.39	51.06	3.09	0.010
Technique.Input.crop	18	1515.28	84.18	5.09	<.001
Residual	64	1058.00	16.53		
Total	143	7556.33			

Exchangeable K

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	0.014492	0.007246	0.90	
Blocks.Technique stratum					
Technique	3	0.056282	0.018761	2.34	0.173
Residual	6	0.048160	0.008027	4.40	
Blocks.Technique.Input stratum					
Input	3	0.080596	0.026865	14.71	<.001
Technique.Input	9	0.309531	0.034392	18.84	<.001
Residual	24	0.043821	0.001826	0.79	
Blocks.Technique.Input.crop stratum					
crop	2	0.147038	0.073519	31.70	<.001
Technique.crop	6	0.075304	0.012551	5.41	<.001
Input.crop	6	0.123964	0.020661	8.91	<.001
Technique.Input.crop	18	0.299354	0.016631	7.17	<.001
Residual	64	0.148437	0.002319		
Total	143	1.346977			

Appendix 3: Analysis of variance for nutrients uptake in SR 2019

Nitrogen

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	615.3	307.6	2.84	
Blocks.Technologies stratum					
Technologies	3	36778.3	12259.4	113.07	<.001
Residual	6	650.5	108.4	0.32	
Blocks.Technologies.Input stratum					
Input	3	15587.2	5195.7	15.25	<.001
Technologies.Input	9	3133.2	348.1	1.02	0.451
Residual	24	8175.6	340.6	2.57	
Blocks.Technologies.Input.Crop stratum					
Crop	1	920.7	920.7	6.93	0.013
Technologies.Crop	3	70.6	23.5	0.18	0.911
Input.Crop	3	367.9	122.6	0.92	0.441
Technologies.Input.Crop	9	1454.7	161.6	1.22	0.319
Residual	32	4248.8	132.8		
Total	95	72002.8			

Phosphorus

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.

Blocks stratum	2	887.0	443.5	1.26	
Blocks.Technologies stratum					
Technologies	3	44871.1	14957.0	42.33	<.001
Residual	6	2120.1	353.3	0.78	
Blocks.Technologies.Input stratum					
Input	3	24298.3	8099.4	17.77	<.001
Technologies.Input	9	5620.7	624.5	1.37	0.255
Residual	24	10936.3	455.7	1.95	
Blocks.Technologies.Input.Crop stratum					
Crop	1	5722.3	5722.3	24.49	<.001
Technologies.Crop	3	653.3	217.8	0.93	0.437
Input.Crop	3	586.9	195.6	0.84	0.484
Technologies.Input.Crop	9	2320.2	257.8	1.10	0.388
Residual	32	7478.3	233.7		
Total	95	105494.6			

Potassium

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	26.451	13.226	0.53	
Blocks.Technologies stratum					
Technologies	3	4014.494	1338.165	53.68	<.001
Residual	6	149.569	24.928	2.05	
Blocks.Technologies.Input stratum					
Input	3	2007.188	669.063	55.09	<.001
Technologies.Input	9	368.013	40.890	3.37	0.008
Residual	24	291.496	12.146	4.15	
Blocks.Technologies.Input.Crop stratum					
Crop	1	139.934	139.934	47.85	<.001
Technologies.Crop	3	24.578	8.193	2.80	0.056
Input.Crop	3	3.840	1.280	0.44	0.728
Technologies.Input.Crop	9	45.410	5.046	1.73	0.124
Residual	32	93.579	2.924		
Total	95	7164.553			

Appendix 4: Analysis of variance for maize nutrients use efficiency in SR 2019

Nitrogen

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	252.1	126.0	0.78	
Blocks.Technologies stratum					
Technologies	3	2806.7	935.6	5.78	0.033
Residual	6	971.1	161.8	1.55	
Blocks.Technologies.Input stratum					
Input	2	13223.3	6611.7	63.37	<.001
Technologies.Input	6	1016.0	169.3	1.62	0.205
Residual	16	1669.4	104.3	0.93	
Blocks.Technologies.Input.Crop stratum					
Crop	1	11.9	11.9	0.11	0.747
Technologies.Crop	3	263.0	87.7	0.78	0.515
Input.Crop	2	39.8	19.9	0.18	0.838
Technologies.Input.Crop	6	98.9	16.5	0.15	0.988
Residual	24	2686.0	111.9		

Total	71	23038.1			

Phosphorus

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	1127.4	563.7	2.29	
Blocks.Technologies stratum					
Technologies	3	6315.7	2105.2	8.54	0.014
Residual	6	1478.3	246.4	1.18	
Blocks.Technologies.Input stratum					
Input	2	9965.6	4982.8	23.86	<.001
Technologies.Input	6	1923.8	320.6	1.54	0.230
Residual	16	3341.6	208.9	0.90	
Blocks.Technologies.Input.Crop stratum					
Crop	1	9.1	9.1	0.04	0.845
Technologies.Crop	3	763.7	254.6	1.10	0.368
Input.Crop	2	40.9	20.4	0.09	0.916
Technologies.Input.Crop	6	297.9	49.6	0.21	0.968
Residual	24	5544.6	231.0		
Total	71	30808.5			

Appendix 5: Analysis of variance for beans nutrients use efficiency in SR 2019

Nitrogen

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	428.33	214.16	4.69	
Blocks.Technologies stratum					
Technologies	3	893.22	297.74	6.52	0.026
Residual	6	274.06	45.68	2.64	
Blocks.Technologies.Input stratum					
Input	2	4098.19	2049.09	118.54	<.001
Technologies.Input	6	506.80	84.47	4.89	0.005
Residual	16	276.57	17.29	1.27	
Blocks.Technologies.Input.Crop stratum					
Crop	1	23.21	23.21	1.71	0.203
Technologies.Crop	3	250.92	83.64	6.17	0.003
Input.Crop	2	1.62	0.81	0.06	0.942
Technologies.Input.Crop	6	168.74	28.12	2.07	0.094
Residual	24	325.50	13.56		
Total	71	7247.16			

Phosphorus

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	809.09	404.55	4.18	
Blocks.Technologies stratum					
Technologies	3	1127.51	375.84	3.89	0.074
Residual	6	580.22	96.70	2.89	
Blocks.Technologies.Input stratum					
Input	2	2899.22	1449.61	43.31	<.001
Technologies.Input	6	544.53	90.76	2.71	0.052
Residual	16	535.48	33.47	1.07	
Blocks.Technologies.Input.Crop stratum					
Crop	1	57.88	57.88	1.85	0.187
Technologies.Crop	3	372.47	124.16	3.96	0.020

Input.Crop	2	1.55	0.77	0.02	0.976
Technologies.Input.Crop	6	269.29	44.88	1.43	0.244
Residual	24	752.11	31.34		
Total	71	7949.36			

Appendix 6: Analysis of variance for maize yields in SR 2019

Grain yield

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	1.2421	0.6211	0.94	
Blocks.Technologies stratum					
Technologies	3	121.2191	40.4064	61.14	<.001
Residual	6	3.9654	0.6609	2.25	
Blocks.Technologies.Input stratum					
Input	3	44.0615	14.6872	49.98	<.001
Technologies.Input	9	5.8663	0.6518	2.22	0.058
Residual	24	7.0523	0.2938	2.92	
Blocks.Technologies.Input.Crop stratum					
Crop	1	4.3223	4.3223	42.96	<.001
Technologies.Crop	3	0.3585	0.1195	1.19	0.330
Input.Crop	3	0.1626	0.0542	0.54	0.659
Technologies.Input.Crop	9	0.8972	0.0997	0.99	0.467
Residual	32	3.2199	0.1006		
Total	95	192.3670			

Stover yield

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	11.5219	5.7609	0.86	
Blocks.Technologies stratum					
Technologies	3	249.4729	83.1576	12.42	0.006
Residual	6	40.1568	6.6928	5.12	
Blocks.Technologies.Input stratum					
Input	3	216.0156	72.0052	55.11	<.001
Technologies.Input	9	39.5903	4.3989	3.37	0.008
Residual	24	31.3571	1.3065	1.97	
Blocks.Technologies.Input.Crop stratum					
Crop	1	1.3193	1.3193	1.99	0.168
Technologies.Crop	3	0.9958	0.3319	0.50	0.685
Input.Crop	3	1.0747	0.3582	0.54	0.659
Technologies.Input.Crop	9	6.1489	0.6832	1.03	0.439
Residual	32	21.2489	0.6640		
Total	95	618.9021			

Appendix 7: Analysis of variance for beans yields in SR 2019

Grain yield

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	2.37698	1.18849	0.95	
Block.Technologies stratum					
Technologies	3	20.21500	6.73833	5.41	0.038
Residual	6	7.47533	1.24589	13.11	
Block.Technologies.Input stratum					
Input	3	18.96236	6.32079	66.51	<.001
Technologies.Input	9	3.63612	0.40401	4.25	0.002

Residual	24	2.28093	0.09504	4.62	
Block.Technologies.Input.Crop stratum					
Crop	1	0.36760	0.36760	17.85	<.001
Technologies.Crop	3	0.07943	0.02648	1.29	0.296
Input.Crop	3	0.23415	0.07805	3.79	0.020
Technologies.Input.Crop	9	0.44835	0.04982	2.42	0.032
Residual	32	0.65895	0.02059		
Total	95	56.73520			

Biomass yield

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	1.50969	0.75485	0.80	
Block.Technologies stratum					
Technologies	3	10.49517	3.49839	3.70	0.081
Residual	6	5.67533	0.94589	7.82	
Block.Technologies.Input stratum					
Input	3	8.18089	2.72696	22.53	<.001
Technologies.Input	9	1.14887	0.12765	1.05	0.429
Residual	24	2.90478	0.12103	1.91	
Block.Technologies.Input.Crop stratum					
Crop	1	1.69188	1.69188	26.69	<.001
Technologies.Crop	3	0.08239	0.02746	0.43	0.731
Input.Crop	3	0.13392	0.04464	0.70	0.556
Technologies.Input.Crop	9	0.44250	0.04917	0.78	0.640
Residual	32	2.02825	0.06338		
Total	95	34.29368			

Appendix 8: Analysis of variance for soil nutrients in LR 2020

Total N

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	0.00145972	0.00072986	1.01	
Blocks.Technique stratum					
Technique	3	0.01439444	0.00479815	6.62	0.025
Residual	6	0.00435139	0.00072523	5.70	
Blocks.Technique.Input stratum					
Input	3	0.00553889	0.00184630	14.50	<.001
Technique.Input	9	0.00232222	0.00025802	2.03	0.081
Residual	24	0.00305556	0.00012731	1.72	
Blocks.Technique.Input.crop stratum					
crop	2	0.00018472	0.00009236	1.25	0.294
Technique.crop	6	0.00065972	0.00010995	1.49	0.197
Input.crop	6	0.00106528	0.00017755	2.40	0.037
Technique.Input.crop	18	0.00135694	0.00007539	1.02	0.452
Residual	64	0.00473333	0.00007396		
Total	143	0.03912222			

Available P

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	2325.3	1162.7	1.41	
Blocks.Technique stratum					
Technique	3	2340.5	780.2	0.95	0.476
Residual	6	4949.3	824.9	2.22	

Blocks.Technique.Input stratum					
Input	3	2592.2	864.1	2.32	0.100
Technique.Input	9	3401.0	377.9	1.02	0.455
Residual	24	8926.1	371.9	2.73	
Blocks.Technique.Input.crop stratum					
crop	2	158.4	79.2	0.58	0.562
Technique.crop	6	750.2	125.0	0.92	0.488
Input.crop	6	800.0	133.3	0.98	0.447
Technique.Input.crop	18	2852.1	158.4	1.16	0.317
Residual	64	8714.0	136.2		
Total	143	37809.0			

Exchangeable K

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	0.23451	0.11725	2.48	
Blocks.Technique stratum					
Technique	3	0.11247	0.03749	0.79	0.540
Residual	6	0.28319	0.04720	2.96	
Blocks.Technique.Input stratum					
Input	3	0.35482	0.11827	7.41	0.001
Technique.Input	9	0.15357	0.01706	1.07	0.419
Residual	24	0.38286	0.01595	1.43	
Blocks.Technique.Input.crop stratum					
crop	2	0.00413	0.00206	0.19	0.831
Technique.crop	6	0.05897	0.00983	0.88	0.512
Input.crop	6	0.10616	0.01769	1.59	0.164
Technique.Input.crop	18	0.18556	0.01031	0.93	0.551
Residual	64	0.71178	0.01112		
Total	143	2.58802			

Appendix 9: Analysis of variance for nutrients uptake in LR 2020

Nitrogen

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	32.33	16.17	0.06	
Blocks.Technologies stratum					
Technologies	3	2200.68	733.56	2.61	0.147
Residual	6	1688.88	281.48	4.57	
Blocks.Technologies.Input stratum					
Input	3	3908.02	1302.67	21.17	<.001
Technologies.Input	9	1349.85	149.98	2.44	0.039
Residual	24	1477.01	61.54	1.71	
Blocks.Technologies.Input.Crop stratum					
Crop	1	140.89	140.89	3.91	0.057
Technologies.Crop	3	139.72	46.57	1.29	0.294
Input.Crop	3	40.44	13.48	0.37	0.772
Technologies.Input.Crop	9	54.54	6.06	0.17	0.996
Residual	32	1153.06	36.03		
Total	95	12185.42			

Phosphorus

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.

Blocks stratum	2	633.37	316.69	2.23	
Blocks.Technologies stratum					
Technologies	3	1029.18	343.06	2.41	0.165
Residual	6	853.17	142.20	1.54	
Blocks.Technologies.Input stratum					
Input	3	3098.74	1032.91	11.17	<.001
Technologies.Input	9	852.23	94.69	1.02	0.449
Residual	24	2218.75	92.45	5.46	
Blocks.Technologies.Input.Crop stratum					
Crop	1	48.82	48.82	2.88	0.099
Technologies.Crop	3	95.19	31.73	1.88	0.154
Input.Crop	3	23.22	7.74	0.46	0.714
Technologies.Input.Crop	9	57.14	6.35	0.38	0.939
Residual	32	541.49	16.92		
Total	95	9451.30			

Appendix 10: Analysis of variance for maize nutrients use efficiency LR 2020

Nitrogen

Source of variation	d.f.				F pr.
Blocks stratum	2	37.43	18.72	0.15	
Blocks.Technologies stratum					
Technologies	3	1140.62	380.21	3.11	0.110
Residual	6	733.02	122.17	1.81	
Blocks.Technologies.Input stratum					
Input	2	2989.41	1494.70	22.20	<.001
Technologies.Input	6	821.24	136.87	2.03	0.120
Residual	16	1077.49	67.34	2.50	
Blocks.Technologies.Input.Crop stratum					
Crop	1	14.35	14.35	0.53	0.473
Technologies.Crop	3	61.93	20.64	0.77	0.525
Input.Crop	2	40.04	20.02	0.74	0.487
Technologies.Input.Crop	6	205.52	34.25	1.27	0.308
Residual	24	647.45	26.98		
Total	71	7768.51			

Phosphorus

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	98.99	49.50	0.19	
Blocks.Technologies stratum					
Technologies	3	2153.68	717.89	2.80	0.131
Residual	6	1537.37	256.23	1.95	
Blocks.Technologies.Input stratum					
Input	2	1758.47	879.24	6.71	0.008
Technologies.Input	6	701.39	116.90	0.89	0.524
Residual	16	2097.29	131.08	3.06	
Blocks.Technologies.Input.Crop stratum					
Crop	1	13.13	13.13	0.31	0.585
Technologies.Crop	3	142.29	47.43	1.11	0.365
Input.Crop	2	17.48	8.74	0.20	0.817
Technologies.Input.Crop	6	108.77	18.13	0.42	0.856

Residual	24	1027.06	42.79		
Total	71	9655.93			

Appendix 11: Analysis of variance for maize yields LR 20209

Grain yield

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	0.2916	0.1458	0.07	
Blocks.Technologies stratum					
Technologies	3	12.2521	4.0840	1.88	0.234
Residual	6	13.0278	2.1713	6.67	
Blocks.Technologies.Input stratum					
Input	3	16.4667	5.4889	16.86	<.001
Technologies.Input	9	5.2989	0.5888	1.81	0.119
Residual	24	7.8153	0.3256	2.63	
Blocks.Technologies.Input.Crop stratum					
Crop	1	0.3097	0.3097	2.50	0.124
Technologies.Crop	3	0.2966	0.0989	0.80	0.504
Input.Crop	3	0.1025	0.0342	0.28	0.843
Technologies.Input.Crop	9	0.1713	0.0190	0.15	0.997
Residual	32	3.9669	0.1240		
Total	95	59.9996			

Stover yield

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Blocks stratum	2	18.7820	9.3910	1.41	
Blocks.Technologies stratum					
Technologies	3	55.2923	18.4308	2.76	0.134
Residual	6	40.0398	6.6733	8.70	
Blocks.Technologies.Input stratum					
Input	3	126.6541	42.2180	55.01	<.001
Technologies.Input	9	13.5782	1.5087	1.97	0.090
Residual	24	18.4196	0.7675	2.43	
Blocks.Technologies.Input.Crop stratum					
Crop	1	2.6531	2.6531	8.39	0.007
Technologies.Crop	3	1.7922	0.5974	1.89	0.151
Input.Crop	3	3.7131	1.2377	3.91	0.017
Technologies.Input.Crop	9	2.7826	0.3092	0.98	0.477
Residual	32	10.1209	0.3163		
Total	95	293.827			

Appendix 12: Analysis of variance for beans yields LR 2020

Biomass yield

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Block stratum	2	0.117662	0.058831	0.42	
Block.Technologies stratum					
Technologies	3	2.734790	0.911597	6.51	0.026
Residual	6	0.840658	0.140110	10.87	
Block.Technologies.Input stratum					
Input	3	1.302871	0.434290	33.68	<.001
Technologies.Input	9	0.223947	0.024883	1.93	0.096
Residual	24	0.309455	0.012894	1.81	
Block.Technologies.Input.Crop stratum					

Crop	1	0.253382	0.253382	35.47	<.001
Technologies.Crop	3	0.084112	0.028037	3.93	0.017
Input.Crop	3	0.019153	0.006384	0.89	0.455
Technologies.Input.Crop	9	0.065150	0.007239	1.01	0.450
Residual	32	0.228582	0.007143		
Total	95	6.179761			