EFFECT OF FERTILIZER MICRODOSING AND *IN SITU* MOISTURE CONSERVATION ON YIELD AND RESOURCE USE EFFICIENCY OF PEARL MILLET IN MAKUENI COUNTY-KENYA

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A thesis submitted in partial fulfillment for the requirements of the degree of Master of Science in Agricultural Resource Management, Department of Plant Science and Crop Protection, Faculty of Agriculture, University of Nairobi.

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DECLARATION

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

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DEDICATION

This thesis is dedicated to the Almighty God who gave and enabled me produce this piece of work, my dear wife Jennifer Mwikali, my children Victor Nyamasyo, Faith Mutheu, Grace Namunyak and John Musyoka Musau, as well as to my late mum Ruth Mutheu Mutiso.

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LIST OF ABBREVIATIONS AND ACRONYMS

AGRA:	Alliance for a Green Revolution in Africa
ANOVA:	Analysis of Variance
ASALs:	Arid and Semi-Arid Lands
CIMMYT:	The International Maize and Wheat Improvement Center
$CuSO_4$:	Copper (II) sulphate
DAP:	Diammonium Phosphate
DAS:	Days after sowing
ET:	Evapotranspiration
FAO:	Food and Agricultural Organization
$FeSO_4$:	Ferrous sulfate
GENSTAT:	General Statistics
GLM:	General Linear Model
H_2O_2:	Hydrogen peroxide
H_2SO_4:	Sulphuric acid
H_3PO_4:	Phosphoric acid
HCl:	Hydrochloric acid
HI:	Harvest Index
ICRISAT:	International Crops Research Institute for the Semi-Arid Tropics
IFAD:	International Fund for Agricultural Development
IFDC:	International Fertilizer Development Center
IPAR:	Intercepted Photosynthetically Active Radiation
$K_2Cr_2O_7$:	Potassium dichromate

KARI:	Kenya Agricultural Research Institute
KCl:	Potassium chloride
KMD:	Kenya Meteorological Department
LA:	Leaf Area
LAI:	Leaf Area Index
LR:	Long Rains
LSD:	Least Significant Difference
LUE:	Light Use Efficiency
mcf:	moisture conversion factor
Na_2SO_4:	Sodium sulfate
NH_4F:	Ammonium Fluoride
NPK:	Nitrogen Phosphorus Potassium
OC:	Organic Carbon
P_2O_5:	Phosphorus pentoxide
PAR:	Photosynthetically Active Radiation
RLD:	Root Length Density
SR:	Short Rains
SSA:	Sub Saharan Africa
UNEP:	United Nations Environmental Program
WU:	Water Use
WUE:	Water Use Efficiency
λ:	Leaf extinction coefficient

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Abstract:

Pearl millet productivity in semi-arid areas of Kenya is constrained mainly by moisture deficit and inherent low soil fertility. A field study was conducted in Makueni, Kenya during the 2014 short and long rains to determine the effect of *in situ* moisture conservation techniques and fertilizer microdozing on growth and yield of pearl millet and to quantify water, light and nutrient use efficiency of pearl millet as affected by fertilizer microdozing and *in situ* moisture conservation techniques. The treatments comprised of three moisture conservation techniques and three levels of fertilizer applications giving nine treatment combinations. Data was collected on soil moisture content, plant height, tiller numbers, root length density, leaf area index (LAI), photosynthetically active radiation (PAR), panicle length and number, 1000 grain weight, harvest index, water use efficiency and nutrient uptake. The data was subjected to Analysis of variance using GENSTAT statistical package (VSN International 2011). Highest plant heights (170.6-182.0 cm) were recorded in tied ridge-recommended rates while panicle length (8.5-10.2 cm) and tillers numbers (7.1-7.2) were recorded in tied ridge-micro dose rates. Maximum LAI ranged between 0.37 and 1.15 in flat-no fertilizer and tied ridge-micro dose respectively. Combination of tied ridge and micro dose fertilizer application increased pearl millet grain yields by 322.5 to 373.9 kg ha^{-1} and Stover yield by 844.9 and 1005 kg ha^{-1}over flat-no fertilizer. Combination of tied ridge and recommended fertilizer rates recorded the highest water use of 140 mm in 2014 short rains and 200 mm in 2014 long rains. Pearl millet water use efficiency ranged between 2.13 and 3.98 kg $ha^{-1}mm^{-1}$ in flat-no fertilizer treatment and tied ridge-micro dose respectively indicating highest resource use efficiency of microdose application. Tied ridge-microdose provided the highest light use efficiency of 1.4 MJ PAR^{-1}. Pearl millet subjected to combined application of tied ridge and micro dose fertilizer recorded the highest nutrient use efficiency of 16.98 kg N grain yield kg^{-1}, 6.4 kg P grain yield kg^{-1}, and 12.45 kg K grain yield kg^{-1}. Overall soil moisture content was highest in tied ridge-no fertilizer (26.2 %) and lowest in flat-recommended fertilizer (17.6 %). Point application of fertilizer in microdose techinique promoted early lateral roots proliferation within the topsoil resulting into better exploitation of water and soil nutrients. These results demonstrate the potential use of integrated tied ridge and fertilizer microdosing in improving resource use efficiency and yield of pearl millet in semi-arid areas.

Keywords: fertilizer microdosing; *in situ* moisture conservation; nutrient uptake; resource use efficiency.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background information

Drought, erratic rainfall and degraded soils remain major limiting factors to growing of crops in most parts of the world (Bruce et al., 2002; Morgan, 2005; Noellemeyer et al., 2006). The problem is most serious in the arid and semi-arid areas that experience high temperatures, very low soil fertility and high population pressures are very high (Bridges and Oldeman, 2001). These ASAL environments cover about 61 million km^2 and represents 46% of the global area (FAO, 2003). Geographical distribution of these areas shows that Africa ranks first with 37% of the continental area being ASALs. In Kenya, these environments constitute 82% of the total land, and supports about 20% of the population (Munyiri et al., 2010).

In situ water harvesting techniques are simple and more affordable technology for the resource poor small holder farmers in sub Saharan Africa (SSA) as compared to irrigation that require large capital investments to capture, store and convey the water into farms (Mudatenguha et al. 2014).These techniques increase the amount of water stored in the soil profile by trapping or holding rainwater where it falls and reduce surface flow (UNEP, 1997). The occurrence of severe water stress is delayed hence buffers the crop against damage as a result of water deficits during dry periods (Nyamadzawo et al., 2013). Such techniques include pot-holing, tied ridging, furrow sowing, earth and stone bunding, pit planting and mulch ripping (Abubaker et al., 2014).

Soil textural class affect the effectiveness of *in situ* water harvesting techniques due to the influence on water holding capacity and drainage characteristics of the soil. Dagg and McCartney (2016) showed that tied ridges produced significantly more pearl millet grain yield than flat planting for vertisols but not on alfisols and andisols. Belay et al. (1998) similarly recorded higher maize grain yield in Ethiopia on tied ridges than flat planting in two soil types (entisols and vertisols), with the effect of the tied ridges generally showing better results in drier seasons and particularly when the ends of the ridges were tied. Mmbaga and Lyamchai (2001) reported that in a season with less than 500mm of rainfall, maize grain yield increased from 0.8 t ha^{-1} on flat planting to 2.3 t ha^{-1} with tied ridges. Rathore et al. (2006) also showed that furrow sowing enhanced the grain yield of pearl millet by 12.5% over the flat sown crop. Similar findings were found by Anchal, (2013) who indicated that ridge and furrow method of sowing had better effect on growth and yield of pearl millet. The effects have majorly been attributed to improved water holding ability of the soil as a result of moisture conservation (Rathore et al., 2006; Bayala et al., 2012).

The effectiveness of these water harvesting techniques in enhancing crop productivity is nevertheless, greatly influenced by the choice of crops (Mudalagiriyappa et al, 2012). Generally, crops with high light and water use efficiency have been shown to enhance grain and biomass yields under moisture deficient conditions (Narayanan et al., 2013). The crop relatively has less water demand and can grow in the areas which are very hot and dry for other crops such as maize and sorghum (Zaongo et al., 1994; Singh and Singh, 1995). The productivity of pearl millet under hot and dry conditions is critically compromised especially when it occurs during panicle initiation or flowering, a situation which can lead to total crop failure (De Rouw and Winkel, 1998).

Use of mineral fertilizer to increase light and water use efficiency of pearl millet under drought conditions has been proposed as an alternative option to increasing the crop yield (Payne, 2000). This is because increased soil fertility promotes quick expansion of leaf area and helps the crop to intercept more radiation (Narayanan et al., 2013). Good rooting of crops increases their ability to exploit a bigger soil volume in extracting water while increased leaf area with long duration increases the plant demand for water (Gajri et al., 1993). The rapid ground cover development under fertilizer application also reduces soil evaporative losses resulting into an increase in water use efficiency (Oluwasemire et al., 2014).

High price of inorganic fertilizer, the limited resource endowment of small-scale farmers and the risk associated with its application in the dry spell prone areas are nevertheless, the most constraining factors for fertilizer use in Kenya (Abdoulaye and Sanders, 2005). An alternative remedy would be to use organic manure and crop residues (Comfort, 2009). The use of organic materials in the Kenyan Arid and Semi-Arid areas for growing of crops is however, a challenge due to steep competition for use as animals feed, fuel and building material (Valbuena et al., 2014). Furthermore, the rates of crop residues reported to achieve the beneficial effects are much higher than what is available in smallholder farms (Akponikpè et al., 2014). The recommended rate of crop residues is around 2,000 kg ha^{-1} $year^{-1}$ in these areas (Rebafka et al., 1994; Valbuena et al., 2014), while the quantity of pearl millet straw in farmer fields is merely around 1,200 kg ha^{-1} (Baidu-Forson, 1995). This implies that the recommended amount of crop residue is not enough for incorporation into the soil or used as mulch, unless inorganic fertilisers are applied substantially to increase straw production and the straw is not used as animal feed, fuel and building material (Bationo et al., 1995; Valbuena et al., 2014).

There is therefore, a need for exploring alternative options to address these constraints and increase food production. Fertilizer microdosing or “micro-fertilization” which involves the application of a small amount of mineral fertilizer in the planting hole at sowing has been recommended under such circumstances (Schlecht and Buerkert, 2013; ICRISAT, 2009). Reports have shown that the application of this technique resulted in increased nutrient use efficiency, increased crop yield and higher economic returns (Bationo and Buerkert, 2001; Tabo et al., 2007). However, few studies have attempted to assess the water and light use efficiency of pearl millet under microdozing technology and *in situ* water harvesting technologies (Camara et al., 2013).

1.2 Statement of research problem

Pearl millet production in semi-arid areas of Kenya is primarily constrained by low, erratic rainfall coupled with low nutrient availability under moisture deficit conditions (Itabari et al., 2004). Consequently, semi-arid areas of Kenya often record an average pearl millet yield of 400 kg ha^{-1} in low input smallholder millet farming systems. The soils in these areas have prevailing light texture and are shallow with low moisture holding capacity (Patil and Sheelavantar, 2001). As a result, rainfall in semi-arid areas produces large amounts of runoff which can easily be trapped *in situ* and encouraged to infiltrate and become available to crops.

Alam (1994) pointed out that lack of phosphorous could be one of the earliest effects of mild to moderate levels of water stress with its uptake decreasing with decreasing soil moisture in pearl millet. A decrease in soil potassium uptake by pearl millet may also occur with increasing moisture stress. Tanguilig et al. (1987) however, observed an increase in uptake of potassium in pearl millet with increasing water stress indicating that K is better absorbed than N and P under water-stress conditions.

Use of mineral fertilizer to improve nutrient and water use efficiency of pearl millet under drought conditions has been proposed as an alternative option to increasing pearl millet yield (Payne, 2000). This is because well fertilized soils enhance rapid leaf area expansion and promote better rooting which increases the capacity of the plant to intercept light and extract water (Narayanan et al., 2013). The rapid ground cover development under fertilizer application reduces soil evaporative losses resulting into increased plant available water (Oluwasemire et al., 2014). The high price of inorganic fertilizer, the limited resource endowment of small-scale farmers and the risk associated with its application in the dry spell prone areas are nevertheless, the most limiting factors for low fertilizer use in Kenya (Abdoulaye and Sanders, 2005). There is therefore, a need for exploring alternative options to address these constraints and increase food production. It is against this backdrop that ICRISAT and its partners developed fertilizer micro-dosing technology to encourage farmers to use mineral fertilizers (ICRISAT, 2009; Tabo et al., 2007; Aune and Bationo, 2008). Limited attention has however, been given to assess the effect of this technology on nutrient, water and light use efficiency of pearl millet (Comfort, 2006). Studies evaluating the effect of fertilizer microdosing on pearl millet growth and yield have besides been conducted under conventional tillage operations with little attention to the potential benefits from the use of *in situ* water harvesting techniques to increase pearl millet light and water use efficiency in the semi-arid areas.

1.3 Justification of research problem

Producing pearl millet under in-situ moisture conservation techniques is essential to improve the radiation and water use efficiency of this crop and optimize its productivity. This would therefore serve as a strategy to achieve effective management of the scarce natural resources and enhance economical returns in the arid and semi-arid regions. Adopting fertilizer microdosing technology in the ASALs of Kenya would increase the on-farm application of mineral fertilizer thereby optimizing fertilizer use, use efficiency, yield and soil water capture. This is because the farmers would be able to meet the fertilizer application cost. Increased pearl millet grain and stover production would further increase the likelihood of meeting food, livestock and fuel needs while having more stover available to be left in fields. Adopting this technology would therefore increase food security and livelihoods of the rural less resource endowed farmers.

1.4 Objectives

1.4.1 Overall objective

To increase productivity and resource use efficiency of pearl millet in semi-arid areas of Kenya through use of affordable fertilizer rates and *in situ* soil moisture conservation techniques.

1.4.2 Specific objectives

i. To assess the effect of different *in situ* moisture conservation techniques (tied ridge, basin and flat) and fertilizer micro-dosing on growth and yield of pearl millet.

ii. To determine the light and water use efficiency of pearl millet under *in situ* moisture conservation techniques and fertilizer microdozing.

iii. To evaluate the effect of *in situ* moisture conservation techniques and fertilizer microdosing on nutrient uptake (NPK) and use efficiency of pearl millet.

1.5 Hypotheses

i. *In situ* moisture conservation techniques and fertilizer microdosing have no effect on growth, grain and stover yield of pearl millet.

ii. *In situ* moisture conservation techniques and fertilizer microdosing have no influence on the light and water use efficiency of pearl millet.

iii. *In situ* moisture conservation techniques and fertilizer micro-dosing have no influence on nutrient uptake (NPK) and use efficiency of pearl millet.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Physiology and production requirement of pearl millet in ASALs

Pearl millet (*Pennisetum glaucum* L.) is an upright bunch grass that tillers from the base and has an extensive root system that provides drought tolerance. It is the fifth most important cereal crop and the most important millet accounting for more than 55% of global millet production. It is a short day C4 plant adapted to hot climate and is the most drought tolerant crop among cereals and millets (Walter et al., 2005). Pearl millet has leaf blades that are 8-40 inches long and 0.5-3.0 inches wide (Newman et al., 2010), while stems are 0.5-1.0 inch in diameter (Adeboye et al., 2016). The crop is deep and profusely rooted, with root penetration rates of between 3.5 and 4.5 cm day^{-1} being reported in sandy soils (Yamoah et al., 2002). The crop has a strategy to maximize carbon fixation as long as water is available. Therefore, stomatal movements adapt in such a way that the transpiration rate is kept as high as possible (Newman et al., 2010).

Pearl millet is grown in over 40 countries, predominantly in Africa (15 million ha/yr) and Asia (14 million ha/yr) as a staple food grain and source of feed, fodder, fuel and construction material in the hottest, driest, semi-arid and arid regions where rainfed agriculture is practiced (Sivakumar and Salaam 1999). The major producing countries are Senegal, Mali, Burkina Faso, Niger, Nigeria, Chad, Sudan and India. Pearl millet is also grown in Oceania and the America, predominantly as a forage and/or mulch component of minimum tillage-based cropping systems (Nema et al., 2008). Global production of pearl millet exceeds 10 million tons a year (National Research Council, 2016). In Kenya, the crop is majorly grown in Eastern part of the country with an average yield of 0.4 ton/ha (Kamau et al., 2016).

Pearl millet is usually grown in soils with depleted fertility, which receives annual rainfall of 150-750 mm, and this makes it a central component of the food security of the rural poor in dry areas (Nema et al., 2012). The grain of pearl millet is superior in nutritive value than sorghum and maize grain, but inferior in feeding value. Pearl millet grain contains about 12.4% moisture, 12.6% protein, 5.0% fat, 67.3% carbohydrates and about 2.7% vitamins (Ibrahim, 2015). Pearl millet grains are eaten cooked like rice or "chapaties" (Sivakumar and Salaam 1999). Besides providing food for human, millet stems are used for a wide range of purposes including construction of hut walls, fences and thatches, and the production of brooms, mats, baskets and sunshades (IFAD, 1999). The protein content of pearl millet is higher than that of maize and has relatively high vitamin A content (Ibrahim, 2015).

Having a well-prepared seedbed before the establishment of pearl millet is critical to avoid weed competition for water and nutrients (Fofana et al., 2008). The seed germinates and emerges fairly quickly, approximately 5 days after planting. At 14 days from planting, the plant initiates a rapid growth phase (Kamau et al., 2016). Pearl millet seed germination and growth is best when soil temperatures are at 20^{o}C or higher and soil moisture is adequate. It grows best at soil pH of 6.0–7.0, but it may also grow in soil pH as high as 8.0 (Bagayoko et al., 2011). Liming is needed only when soil pH is below the recommended target pH of 6.0 (Power et al., 2015). Pearl millet is best-adapted to well-drained soils that do not hold standing water during wet periods (Nema et al., 2008).

Although pearl millet is a fast-growing crop that may outgrow weed competition to some degree, weeds can be a major pest at the slow-growing seedling stage as they compete for light, water, and nutrients. Therefore, good seedbed preparation or pre-plant weed control is important (Hayashi et al., 2008). This activity is normally carried out with a hoe that cuts the soil 2-5 cm under the surface. This not only cuts the roots of the weeds, but also breaks the surface crusts and facilitates water infiltration (Rouw and Rajot, 2004). On the sandy soils of Africa, pearl millet is typically planted either in a dry seedbed or immediately after the first rains (Hayashi et al., 2008). Millet is sown in hills, 10-15 cm deep, and mostly at a spacing of 75 cm x 15 cm with the aid of a hand hoe. DAP fertilizer is normally applied at the recommended rate of 40 kg/ha at planting while topdressing is done at knee height using CAN at a recommended rate of 80kg/ha (ICRISAT, 1992).

Pearl millet development begins at a base temperature of around 12^{o}C, an optimum temperature between 30-35 ^{o}C and a lethal temperature around 45 ^{o}C. The base temperature has been shown to be fairly constant regardless of the stage of development (Ong, 1983). Soil temperatures must reach 12^{o}C for germination to begin. The germination rate increases linearly with temperature to a sharply defined optimum of 33 ^{o}C and then drops sharply as temperatures increase (Ong, 1983). High temperatures (>45 ^{o}C) and soil surface crusting following sowing may also result in poor crop establishment due to seedling death (Soman et al., 1987). In most ASALs, the problem is further complicated by sand blasting and the burying of young seedlings under the sand (ICRISAT, 1992).

Pearl millet develops primary tillers and then secondary tillers from the primary ones (Gascho et al., 2014). Flowering usually begins at 40 to 50 days after emergence, and the plant reaches physiological maturity by 75 to 85 days after emergence. The early flowering enables the crop to complete its maturation cycle with the remaining soil moisture (Seghatoleslami et al., 2008; Sinha, 2005).The leaf area index (LAI) of pearl millet in most fields seldom reaches 1.0 (Sharrett et al., 2015). Even in more intensively managed fields, LAI seldom exceeds 2, and the period during which LAI exceeds this value constitutes only a small portion of the entire growth period (Payne, 2000). The maximum leaf area occurs at the time of 50% flowering, when the majority of the tillers have produced leaves. After flowering, there is a decline in leaf area during which time the leaves begin senescing. At physiological maturity, only the upper 3-4 leaves may be green on the main stem (Meena et al., 2003).

2.2 *In situ* moisture conservation techniques and their effect on crop production

Moisture stress is one of the major limitations in Arid and Semi-Arid areas since the rainfall is highly erratic, unreliable and of little amount (Tian et al., 2003). This problem is mainly faced at the time of seeding of the crop when moisture conditions are usually low. Moisture conservation techniques are thus prerequisite to supply enough water to improve crop yield in the arid and semi-arid lands. These techniques increase infiltration and soil water storage and decrease water losses by runoff and evaporation and thus lead to an increase in the amount of water retained in the soil for subsequent use by crops (Kumar and Rana, 2007; Paslawar et al., 2015). High soil water potential under effective moisture conservation techniques also increases the plant nutrients uptake capacity and the ability of soils to supply nutrients (Shaheen et al., 2012). These techniques also offer mitigation against the adverse erosion effects by stabilizing the soil and enhancing runoff infiltration (Obaid et al., 2014).

Tied-ridging, also known as partitioned furrow technique is one of the *in situ* water harvesting techniques that has gained interest in the ASALs of Africa (Li and Gong 2001). In this technique, lower ridges or cross-ties (15-20 cm high) are made every few metres across the contour furrows, creating mini-basins. In case of light rainfall, the water remains in the mini-basins (Tian et al., 2003). When rainfall is heavy, the water runs off over the cross-ties along the contour because the cross-ties are lower than the ridges and the furrows are built at an angle to the contour (Pacharne et al., 2006). Thus excess water flowing over the ridges (overtopping) is prevented. The cross-ties also reduce the speed of the water flow (Liniger et al., 2011).

Tied-ridging can be used only where rainfall does not exceed the storage capacity of the furrows, otherwise severe erosion may be the result (Obaid et al., 2014). This technique is therefore more successful on coarser soils (more sandy) such as alfisols which are less prone to waterlogging. Soils high in clay contents such as vertisols however, give better overall production yields where broad-bed and furrow techniques are used. Seeds or tubers are placed either near the top of the ridge to avoid water logging or towards the bottom of the basin where rainfall and/or soil moisture are limited.The most appropriate site for planting also depends on the water requirements of the crop (Li and Gong 2001).

Mudalagiriyappa et al. (2012) demonstrated that tied ridging and paired row planting yield significantly higher pearl millet panicle diameter and 1000 grain weight over sowing across the slope. They attributed the higher yield and yield components to vigorous crop growth resulting from increased availability of soil moisture. A study by Akhtar et al. (2010) similarly reported that tied-ridge system enhanced corn emergence, thereby facilitating their rapid growth. This indicates that these techniques influence crop yield due to their effect on attributes of crop productivity. Salas et al. (2009) found that with tied ridge planting systems, on average 40% water was saved as compared to flat planting. In their study, Pramanik et al. (2009) recorded maximum chickpea grain yield under tied ridge planting which was significantly higher by 16.8% over the conventional planting.

Adding mulches in the partitioned furrows in tied ridge systems elongates period of moisture availability to crop by increasing infiltration and releases mineral nutrients. The furrows in between row of crop is also beneficial for improving the drainage system in field during early rainstorms and for decomposing added weed later on. Ridges on the other hand serve as micro-watershed accumulating water in furrow (Salas et al., 2009).

The construction and maintenance of ridges is however, labor intensive, especially on heavy (clayey) soil (Ali, 1998). In order to spread the work out in the first year and make the total labour input sufficiently low, the tied ridges are usually ploughed using an ox-plough or tractor-drawn implement with a reversible blade, and the cross-ties can be made by hand. Ploughing and ridge making only have to be repeated once every four or five years (Justine et al., 2003).

Contour ridges are mainly used in semi-arid areas to harvest water, and in higher rainfall areas for growing potatoes. It involves ploughing, planting and weeding along the contour lines that run along a slope such that the line stays at the same height and does not run uphill or downhill (Pacharne et al., 2006). Studies have shown that contour ridging alone can reduce soil erosion by as much as 50% on moderate slopes and enhance surface water infiltration (Rathore et al., 2006). However, for slopes steeper than 10%, other measures should be combined with this moisture conservation technique to enhance its effectiveness (Pacharne et al., 2006).

Basin planting has also been shown to be more effective in soil moisture conservation than the conventional flat tillage. Rathore et al. (2006) showed that basin sowing enhanced the grain yield of pearl millet by 12.5% over the flat sown crop. Rathore et al. (2006) similarly indicated that basin method of sowing had better effect on growth and yield of pearl millet due to its ability to store runoff and enhance its infiltration. Basins also create micro-depressions which increase the soil surface roughness and therefore slow down runoff initiation and soil and nutrient losses.

Grass barrier strips planted along the contour with fodder grass such as Napier also offer alternative effective soil conservation measures on soils that absorb water quickly and on slopes as steep as 30% (Gachene et al., 2018). This technique enhances soil stability and rain water interception thus protects the soil from erosion and increases water infiltration. Terracing is another moisture conservation technique recommended for farming in sloped land, preferably on hilly or mountainous terrain. Terraced fields decrease erosion and surface runoff, and are effective for growing crops requiring much water, such as rice (Gachene et al., 2018).

2.3 Effect of soil moisture and mineral fertilizer on pearl millet growth and yields

Soil water, nutrient supply and their interaction are of particular importance for crop production in dryland conditions characterized by erratic rainfall, elevated soil evaporation rates and high potential evapotranspiration (Payne et al., 1990; Kinama et al., 2005). Soil moisture in general influences the growth and dry matter production of pearl millet directly as well as indirectly by increasing or decreasing the availability and utilization of nutrient (Sinclair, 2000). Mudalagiriyappa et al., (2012) demonstrated that the interaction effect between soil moisture conservation and nutrient management is necessary to increase the yield of pearl millet. The higher grain and stover yield is attributed to the increased uptake of N and P under sufficient soil moisture conditions. Payne et al. (1992) similarly noted that the interaction of soil water and P supply is of paramount importance to pearl millet growth in Sahelian Africa due to unreliable rainfall and low soil P availability. Plants of higher P levels within the water stressed treatment tended to grow and transpire more rapidly than those of lower P levels, thereby exhausting available water supply more quickly and becoming water stressed earlier (Payne et al., 1992).

The first effect of water deficit on pearl millet growth is reduced leaf number (Golombek and Al-Ramamneh, 2002) and leaf area of every plant (Nagaz et al., 2009) and then yield and dry matter production (Wang et al., 2006). This is accompanied by reduced shoot growth and height to maintain LAI and ensure less allocation of biomass to stem (Soler et al., 2007; Mina et al., 2011). The increase in pearl millet growth and yield associated with increased moisture conditions is therefore mainly due to greater LAI, plant height, number of leaves and tillers per plant (Pandey et al., 2000; Ayub et al., 2009). A considerable reduction also occurs in the pearl millet stomatal conductance, leading to an interruption in CO_2 assimilation. Under such conditions, the water reserves of the plants themselves may be consumed, which can lead to the death of the plants (Sinclair, 2000).

Raised soil nutrient levels seem to exert additive effects on water use efficiency and increasing or optimizing pearl millet yields (Schmidhalter and Studer, 1998; Bindraban et al., 2014; Ibrahim, 2015). Adequately fertilized pearl millet plants may also show higher drought tolerance (Wang et al., 2011). Bindraban et al. (1999) reported that nutrient-limited yields are approximately 1-2 Mg ha^{-1} in the African ASALs, even though the total amount of rainwater would allow yield levels of up to 4-5 Mg ha^{-1}. This indicates that the use of fertilizers is crucial for closing up pearl millet yield gaps (Mueller et al., 2012).

Research in mineral fertilizer strategies for increasing pearl millet yields has generally focused on satisfying plant N and P demands which are the two most limiting nutrients on weakly buffered soils (Bationo et al., 2003; Ibrahim, 2015). According to Fofana et al. (2008), application of phosphorus fertilizer alone is sufficient to steadily and substantially increase grain and straw yields of pear millet on acid sandy soils. Even though several studies support this view, the highest grain yield has been obtained at highest N and P application rates (Manu et al., 1991; Giller et al., 2006;

Twomlow et al., 2011). According to Michels and Bielders (2006), pearl millet yield tripled after addition of phosphorus and increased by a factor of 13.5 when additional nitrogen was applied on eroded sandy soil in the Sahel. This indicates that both N and P are key factors to millet production with P being the most limiting. Bationo and Ntare (2000) also demonstrated that traditional millet cowpea rotation in Sahel does not increase millet yields unless inorganic N and P fertilizers are added and suggested a cropping system that integrates millet-legume rotation and a mixture of N and P fertilization as an appropriate alternative for restoring soil fertility on degraded soils.

Increasing nitrogen fertilization rates causes significant effect in many growth and yield attributes of pearl millet such as plant height, number of tillers (Pathan et al., 2010), number of leaves (Myandoab et al., 2011) and leaf/stem ratio (Piri and Tavassoli, 2012). These results may be due to the effect of nitrogen fertilization in pushing growth of pearl millet and the increments in internode length or/and number of internodes (Shahin et al., 2013).

Applying phosphorus fertilizers increases root density and rooting depth and the amount of water available to plants is increased. This results into enhanced nutrient uptake by pearl millet and therefore growth and biomass accumulation (Ibrahim et al., 2014). The higher pearl millet grain yield associated with DAP has been attributed to the ability of this fertilizer to reduce the soil pH in the immediate vicinity of the roots (the rhizosphere) upon dissolution (Fan and Mackenzie, 1993). The change in rhizosphere pH at the early stage of crop growth increases soil nutrients availability such as extractable P, Ca and Mg close to roots zone (Bagayoko et al., 2000). However, this modification in pH with DAP may not persist for longer period as the pH drops with the transformations of ammonium to nitrate (Khasawneh et al., 1980). The decrease in rhizophere pH can be attributed to the poor pH buffering capacity of the soil due to low soil organic matter content (Hinsinger et al., 2003).

Potassium on the other hand determines the uptake of water by the pearl millet plant roots and the transport of the water to other parts of the plant (Ibrahim et al., 2014). Potash fertilizers are directly involved in the water management of the pearl millet plant since it reduces water loss through transpiration. In sandy soils, water use efficiency for total dry matter production of pearl millet is increased by potassium application (Molden et al., 2010). The importance of K in explaining spatial variability of pearl millet growth has also been pointed out (Voortman et al., 2004). After a two-year continuous millet cropping in a trial with a long-term application of crop residues and mineral fertilizers in Niger, Hafner et al. (1993) observed that potassium deficiency in the soil is a limiting factor for optimal millet production. This suggests that potassium supply through atmospheric deposition and application of crop residues/compost were not sufficient to meet millet potassium requirement for higher grain yield formation.

Long-term experiments have nevertheless, indicated that pearl millet yields may decline following continuous application of only mineral fertilizer (Schlecht et al., 2006). The yield decline may result from many mechanisms such as lowering the base saturation and aggravation of soil acidification, mining of nutrients as higher grain and straw yields remove more nutrients than were added, increased loss of nutrients through leaching and decline in soil organic matter (Bationo et al., 2007). Schlecht et al. (2006) however, showed that combined application of inorganic fertilizer with organic material can neutralize the negative effects of the mineral fertilizers. Balanced use of fertilizers and organic materials should therefore be encouraged to ensure sustainable pearl millet productivity in the intensive cropping system as its lack could lead to significant decline in yields and water use efficiency with lapse of time. Additions of organic materials to soil increases soil water-holding capacity which in turn improves water availability to plants (Fan et al., 2005).

2.4 Fertilizer microdosing and its influence on crop productivity

Fertilizer microdosing or hill placement of mineral fertilizer is a technology jointly developed and field-tested by the University of Hohenheim in Germany, ICRISAT, the International Fertilizer Development Center (IFDC), the UN Food and Agriculture Organization (FAO), and Niger's Institute for National Agricultural Research (NUTMEN/GEMS, 2002; ICRISAT, 2009). This technology involves the application of a small quantity of mineral fertilizer together with seeds of the target crop in the planting hole at sowing or few weeks after planting (Hayashi et al., 2008; Jens et al., 2007; ICRISAT, 2009). It uses about one-twentieth of the amount of fertilizer normally recommended for that crop (Camara et al., 2013). Fertilizer microdosing relies on smaller quantities of placed mineral fertilizers targeting in priority, the most limiting element (Buerkert et al., 2001). This technology thus offers an option which encourages small farmers to make an integrated use of their limited resource to achieve optimal resources use efficiency thereby enhancing food production.

For pearl millet production in most of Sub Saharan African (SSA) soils, small doses of fertilizers, about a full empty soft drink/beer bottle cap or a three-finger pinch per hole of planting are required. This amount equals to 6 gram of fertilizer per planting hole or 30 kg fertilizer per hectare (ICRISAT, 2009). Farmers just prepare small holes before the rain starts when soils are still hard. Later, 6 g fertilizers and seeds are put in the hole when the rain begins and the soils provide enough moist condition, encouraging root growth and the water is captured instead of running off the hard-crusted soil (Jens et al., 2007).

Based on its positive effects in improving crop yields and contributing to the food security of smallholder farmers in West Africa, fertilizer micro-dosing has been considered as a pathway to

Africa's Green Revolution (Twomlow et al., 2010). This technology has therefore, been described by Alliance for a Green Revolution in Africa (AGRA) as a major innovation to benefit a number of smallholder farmers in the Sahelian region of Africa (Bielders and Gérard, 2014). Microdosing has been reported to double crop yields on some African soils which are starved of macronutrients such as N, P, and K (Tabo et al., 2006).

Bationo and Buerkert, (2001) working in Ghana showed that application of 6 g NPK fertilizer per hill can more than double millet yields. Abdou et al. (2012) reported consistently significant increase in pearl millet yield following strategic placement of 4 kg P per hectare as NPK 15-15-15 or DAP (Di-ammonium phosphate) at planting. Similar effects have been previously reported from the application of 4 kg P ha^{-1} as compound NPK fertilizer (Bationo et al., 1989). A similar experiment to investigate the effect of fertilizer microdosing in Ghana showed that microdose fertilizer application at a rate of 62 kg ha^{-1} increased yields of grain and stover of pearl millet by up to 20 tons/ha across wide range of climates and soils (Bationo and Buerkert, 2001).

In Mali, results based on a three-year study using small amount of DAP (3 to 10 kg ha^{-1}) showed that grain yields increased by 42% and 55% for sorghum and millet, respectively (Aune and Bationo, (2008). Bagayoko et al. (2011) also recorded stover yield increases of pearl millet by 250 to 400 kg ha^{-1} on sandy soils and 500 to 2500 kg ha^{-1} on silty clay soils in Mali. Application of 20 kg ha^{-1} P_2O_5 and 30 kg ha^{-1} N in addition to microdose commonly increased grain yields by 140 to 180 kg ha^{-1} and stover yields by 600 to 1500 kg ha^{-1} over that of microdose application only. Tabo et al. (2006) reported that the yields of sorghum increased from 44 to 120% after adoption of fertilizer microdosing in harsh semi-arid climate of Mali, Burkina Faso, and Niger where soils were sandy and low in fertility with 500-800 mm annual rainfall. Rates of fertilizer microdose per hill of planting were 4 g of NPK (15-25-15) in Burkina Faso, 4 g of NPK (17-17-17) in Mali, and

6 g of NPK (15-15-15), 2 g DAP (18-46-0), and 2 g DAP + 1 g Urea (46-0-0) in Niger. A study by Muehlig-Versen et al. (2003) on phosphorus placement on an acid sandy soil in Niger similarly demonstrated that hill application of 3, 5 and 7 kg P ha^{-1} led to 72%, 81% and 88%, respectively of the pearl millet grain yield increase obtained with 13 kg P ha^{-1} broadcast, resulting therefore, in a significant increase in fertilizer-use efficiency.

Bagayoko et al. (2011) working in Botswana indicated that fertilizer microdosing, combined with use of planting pits, substantially improved productivity in rain-fed crops. In this study, yields of sorghum where both methods were applied were about 700 kg per hectare compared with only 200 and 350 kg when rainwater harvesting and microdosing were used alone. Hayashi et al. (2008) also demonstrated that pearl millet farmers could delay inorganic fertilizer application or timing of using the micro-dosing technology from 10 to 60 days after sowing without the reduction of profits and their economic returns relative to the non-fertilizer applied treatment. Fertilizer microdose rate was applied at 6 g of NPK (15-15-15) per millet hill and 2 g of DAP (18-46-0) per millet hill for an on-farm field trial. Fertilizer microdose rates of 4 g of NPK (15-15-15) or equivalent to 62.5 kg ha^{-1} in Burkina Faso and 2 g of DAP (18-46-0) or equivalent to 33.2 kg ha^{-1} at topdressing similarly increased pearl millet production by up to 22 tons/ha (Klaij and Vachaud, 2014).

Although field studies have consistently demonstrated the benefits of fertilizer micro-dosing in increasing crop yields in low input farming systems, there is still little information that elucidates the mechanisms underlying this effect. Elsewhere, a study on a calcareous soil (pH = 8.1) of China demonstrated that microdose application of phosphorus and ammonium improves growth of maize seedling by stimulating root proliferation and rhizosphere acidification (Li et al., 2004). However, the earlier work on phosphorus placement reported by Rebafka et al. (1994) and Buerkert et al.

(2001) which led to the fertilizer micro-dosing recommendation was conducted on an acid sandy soils (pH-KCl = 4.1 - 4.5). Ibrahim et al. (2014) similarly showed that increasing the depth of fertilizer micro-dosing application from 5 to 10 cm results in a marked increase in millet yields. They postulated that the positive effect of fertilizer micro-dosing can probably be attributed to a root-growth stimulating effect of phosphorus fertilization as previously reported by Aune and Bationo (2008) and Schlecht and Buerkert (2013).

Ibrahim (2015) argued that the positive effect of fertilizer micro-dosing in increasing millet yield results from the better exploitation of soil nutrients due to early lateral roots proliferation within the topsoil. This study showed that fertilizer microdosing enhanced the lateral root length density in the topsoil (0-20 cm) by 72% and 40% at respective lateral distances of 25 cm and 50 cm from the centre of the hill compared with broadcast of 200 kg NPK ha^{-1}. There is however, no explicit empirical evidence that explains the root growth dynamics under fertilizer micro-dosing. There is therefore, a need to elucidate the root mechanisms underlying the growth enhancing phenomena of the fertilizer micro-dosing technology.

The sustainability of fertilizer micro-dosing has also become a matter of debate within the scientific community. Buerkert et al. (2001) cautioned that the application of 0.9 g N together with 0.4 g P in NPK to each planting hill since it constitutes only 10 and 20% of millet plant's total N requirements. In addition, Muehlig-Versen et al. (2003) noticed that low rates of phosphorus placement can be easily adopted by the smallholder farmers, but it could not sustain soil's P reserves. Camara et al. (2013) argued that fertilizer micro-dosing does not comply with the agronomic sustainability because it may in the long term cause nutrient depletion of the soil and consequently decrease soil fertility and crop productivity. However, some scientists consider this claim an exaggeration (Schlecht and Buerkert, 2013; Bagayoko et al., 2011; Aune and Coulibaly, 2015). According to these authors, the increase in grain yield reported from micro-dosing ranging from 240 to 300 kg ha^{-1} on sandy soils across a broad range of climatic and soil conditions in West Africa is not high enough to push the alarm on mining effect of fertilizer micro-dosing.

Other researchers have also argued that the increase in yields with fertilizer micro-dosing is always accompanied by an increase in soil nutrients uptake which results in negative nutrient balances (Ibrahim, 2015). This argument is based on the fact that growth parameters (leaf area index, leaf chlorophyll content and root length density) have often been markedly increased with fertilizer micro-dosing at the early stage of millet growth resulting in increased nutrient uptake. The application of fertilizer at microdose rates also needs additional persons at the time of sowing for fertilizer application. The labour demand at sowing period is thus high which can lead to delayed sowing thereby resulting in yield decrease. On-farm research in Niger has however, shown that farmers can delay the application of fertilizer under micro-dosing technology from 10 to 60 days after sowing without significantly reducing the yield and the economic returns (Hayashi et al., 2008).

Whether application of fertilizer at rates that are far less than the recommended rates of 15-20 kg P ha^{-1} and 30 kg N ha^{-1} for pearl millet can substantially raise yields in the absence of manure has also yet to be extensively tested on farmers' fields (Bationo and Mokwunye, 1991; Bationo et al., 1993; Abele and von Oppen, 2000). In arid and semi-arid areas of Kenya this technology has received limited attention due to differences in soils and climatic conditions (Wamuyu, 2012). Comfort (2006) reported that the micro-dosing technology was effective in raising pearl millet yield under low fertility in a semi-arid area of Kenya primarily due to the ability of this technology to increase uptake of nutrients.

2.5 Fertilizer microdosing and pearl millet root growth relationships

Pearl millet yield increase due to fertilizer microdosing results from the better exploitation of soil nutrients which ensures early lateral roots proliferation within the topsoil. Jing et al. (2010) similarly showed that localized application of phosphorus and ammonium fertilizers increase maize yield by stimulating growth and root proliferation as well as rhizosphere acidification. Schlecht et al. (2006) observed high concentration of millet roots in the topsoil with fertilizer microdosing which was ascribed to the crop response to the localized application of nutrients leading to proliferation of roots in patches with high nutrient concentration. It has also been postulated that fertilizer microdosing induces higher crop yields due to its positive effect on root penetration into deeper soil layers. This enhances crop nutrient and water uptake (Aune and Bationo, 2008).

Increase in lateral root length density at early millet growth stage with fertilizer microdosing has been demonstrated to enhance the uptake of native phosphorus due to the high uptake capacity of young roots for this nutrient (Ma et al., 2013; Smit et al., 2013). The effect of fertilizer microdosing in enhancing root proliferation has been shown to have a positive association with pearl millet leaves dry matter, shoot dry matter, leaf area and plant height. Ibrahim, (2015) associated the increase in lateral root proliferation due to fertilizer microdosing and moisture conservation techniques with enhanced NPK uptake and use efficiency. In their study, Smit et al. (2013) showed that timing of microdose fertilizer application influenced pearl millet yield, an observation attributed to the enhanced tapping of rainfall at its onset.

2.6 Light interception and use efficiency and their relevance to crop production

Under optimum growing conditions, the biomass productivity of different crops can be described by the amount of solar radiation intercepted by the green foliage and the efficiency with which such intercepted radiation is converted to plant dry matter. This is in accordance with Monteith, (1977) who demonstrated that for most crop species growing in the absence of biotic and abiotic stress, the amount of dry matter produced is linearly related to the amount of photosynthetically active solar radiation (PAR) intercepted by its green leaf area.

Light interception is primarily determined by the leaf area index and an index of radiation interception, the extinction coefficient (λ) (Sivakumar and Virmani 1984; Lizaso et al., 2003). As LAI increases, more radiation is intercepted per unit ground area resulting in higher assimilation rates (Ewert 2004). A reasonable increase in LAI is however, critical to maintain high photosynthetic rates and yield (Xiaolei and Zhifeng, 2002). If the index is too low, not enough light will be absorbed and if too high, lower leaves will not receive enough light and will thus be a liability (Brintha and Seran, 2009). The canopy extinction coefficient (λ) value is dictated by canopy structure, species and planting pattern (Zarea et al., 2005). Differences in extinction coefficients at constant LAI would result in differences in radiation accumulation and potential biomass accumulation (Lizaso et al., 2003).

Other factors which influence the radiation interception of a crop are the crop development stage, canopy architecture/crop geometry, intensity and the quality of solar radiation intercepted by the canopy and soil moisture or nutrient levels (Plénet et al., 2000; Purcell, 2000; Li et al., 2004). Early development of a canopy cover helps the crop to intercept more radiation, increase root development and apportion more of the water extracted by the roots to transpiration (Liu et al., 2010). Light levels during the late flowering to mid pod formation stages of growth have been found to be more critical than during vegetative and late reproductive periods (Liu et al., 2010). Soil moisture and nutrient levels affect foliage expansion and eventually radiation capture (Stone et al., 2001; Inman-Bamber 2004). Leaf senescence increases under nutrient shortage resulting in a reduction in crop leaf area index and thus light interception (Massignamet al., 2011). This implies that any approach that increases soil moisture and nutrient availability can increase LAI and lengthen the value of leaf area duration, therefore results in a positive effect on the formation of the grain yield.

Canopy architecture/crop geometry has a direct relationship with the interception efficiency of both direct and diffuse irradiance (Valladares and Pearcy, 2000). Light interception decreases exponentially from top to bottom of canopy (Liu et al., 2010). The variation in canopy light availability is also as a result of foliage structural and canopy architectural characteristics (Maddonni et al., 2001; Acreche et al., 2009). Radiation interception also varies with the cropping patterns and systems (Watiki et al., 1993). Kemanian et al., (2004) demonstrated that intercropping cereals with legumes results into higher PAR interception than when produced in their pure stands. This is because of differences that exist in vertical foliage arrangement and canopy architecture of crop varieties. Intercropping legumes and cereals therefore enhances PAR interception compared to sole crops. Moreover, it has been found that LAI patterns follow the patterns of radiation interception (Reddy and Willey, 1981; Sivakumar and Virmani, 1984). Baldé et al. (2011) also found that maize intercropped with pigeon pea or brachiria had higher LAI than sole maize crop.

In addition to the intercepted photosynthetically active radiation (IPAR), light use efficiency (LUE) is important factor in crop development. Monteith (1977) defined light use efficiency as the ratio of accumulated crop mass (dry matter) to cumulative intercepted solar radiation. The slope of the linear relationship between biomass and total intercepted PAR is thus the graphical representation of the light use efficiency of a crop (Sinclair and Muchow, 1999). Light use efficiency is a key factor in the determination of the photosynthetic performance of plants growing in any environment (Ceotto and Castelli, 2002).

Some authors report LUE as a stable parameter for many crops (Hughes et al., 1987; Monteith, 1989), but variability in this parameter has been pointed out (Sinclair and Muchow, 1999). This is because light use efficiency is based on the fact that sunlight intercepted is not utilized with similar efficiency by different crops (Haxeltine and Prentice, 1996). There are therefore, clear differences in light use efficiency between crop species, particularly between those with C3 and those with C4 photosynthetic pathways. In general terms, C4 crops have been shown to have higher LUE compared to C3 crops (Kinama et al., 2011). On the other hand, combining C4 and C3 in the agro forestry system has been shown to lower LUE (Kinama et al., 2011).

Light use efficiency may also vary with cropping systems mainly due to variations in PAR interceptions (Matusso et al., 2014). Nakaji, (2014) pointed out that intercropping produces more biomass than sole cropping due to increased LUE as a result of enhanced PAR interception by the intercrop system. Similarly, Ong and Black, (1992) observed that intercropping pearl millet with groundnuts produced 15% more of PAR radiation interception compared to sole pigeon pea and twice that intercepted by the sole groundnut. Reddy et al. (1980) similarly reported that millet-groundnut intercrop system was 28% more efficient in light use than their monocrops which was attributed to approximately 30% greater LAI of the intercrop than the sole crops. The higher PAR conversion efficiencies of intercrop systems relative to the sole crops may be due to spread of light over greater leaf area and more efficient distribution of light in their canopies during early stages of growth (Addo-Quaye et al., 2011).

Canopy structure is another attribute that has been reported to have effect on LUE, and particularly the spatial distribution of leaf angles which has an important bearing on canopy, light, climate and energy conversion (Frankenberg et al., 2012). Large leaf angles with leaves nearly vertical ensure good PAR penetration when solar angle is high and a high proportion of leaves receive similar photon irradiance (Li et al., 2010). An even distribution of PAR at leaf surfaces is advantageous for canopy photosynthesis and improves light use efficiency over canopies where upper horizontal leaves intercept most solar radiation and lower leaves experience greatly attenuated levels (Nakaji et al., 2014). Small and erect leaves, particularly in top canopy layers, are thus a key feature of an ideal plant type, or 'ideotype' for high-density cropping.

Some researchers have demonstrated that LUE is significantly influenced by elements such as vapor pressure deficit, air temperature and water stress (Kemanian et al., 2004; Muurinen and Peltonen-Sainio, 2006; Ahmad et al., 2008, 2016; Lecoeur and Ney, 2003) and nutrients levels (Rodriguez et al., 2000; Caviglia et al., 2001). Maqsood and Azam, (2007) showed that moisture stress reduces leaf area, dry matter accumulation, seed weight and thus light use efficiency and yield of finger millet. Li et al. (2008a) similarly demonstrated that furrow planting pattern increased the soil moisture levels and resulted into an increase in wheat LUE. Reduction in LUE due to water stress has elsewhere been recorded for grain legumes such as soybeans (Muchow 1985), Faba bean (Green et al., 1985), chickpea (Singh and Sri Rama, 1989), sorghum (Rinaldi and Garofalo, 2011) and winter wheat (Li et al., 2008b). Uhart and Andrade (1995) found that vapor pressure deficit and air temperature function to reduce the leaf photosynthetic rate of a crop thereby lowering LUE. Sridhara and Prasad, (2001) explained the decrease in LUE of sunflower after anthesis with the increase in maintenance respiratory losses due to greater temperatures. Inamullah and Isoda (2005) also found that reduction in the LUE under drought stress is related to the direct photo-damaging effect of water scarcity and higher leaf temperature. This reduction is an adaptive characteristic of soybean to increase thermal dissipation of excess absorbed light energy as heat.

2.7 Pearl millet nutrient uptake and use efficiency under semi-arid conditions

Nutrient uptake by pearl millet is influenced by soil physical and chemical properties, soil water availability, soil organic matter content and plant population (Doumbia et al., 2003). Low pH enhances phosphorus fixation lowering its availability to plants and thus reducing its uptake (Kochian, 2012). This problem is especially common in small-holder farmers' fields within East Africa which are highly weathered and have plant available P below critical levels (Manu et al., 1991). Hammond et al. (2004) argued that semi-arid soils of East Africa are predominantly sandy with very low phosphorus absorption capacity making them more sensitive to loss of P to the environment. Low uptake of phosphorus has been related to its immobility which makes its uptake from the soil to be very slow (Manske et al., 2000; Fitter and Hay, 2002; Hammond et al., 2004; Obersteiner et al., 2013).

Deficiency of phosphorus in pearl millet initiates a series of physiological responses which either enhance the plant's ability to acquire the nutrient from the soil or improve the efficiency with which it is utilized (Hammond and White, 2008). Such responses include the development of lateral roots and root hairs, secretion of organic acids and establishment of symbiotic associations with mycorrhizal fungi that aid P acquisition (Burleigh et al., 2002; Ai et al., 2009; Fang et al. 2009; Yang and Finnegan, 2010). The availability of P is critical in the early developmental stages of pearl millet and its deficiency at this time is a direct constraint to crop production, particularly under agricultural conditions where intensive soil fertilization is not affordable (Valluruet al., 2010).

The amount of nitrogen absorbed by pearl millet generally increases with plant age up to flowering stage when the nitrogen is accumulated into grain dry matter. Nitrogen uptake increases with fertilizer application due to increased concentrations of nitrogen available to crops. Rao et al. (2015) indicated that nitrogen fertilization can increase nitrogen availability from other N pools thus enhancing N uptake and use efficiency. Fageria and Stone, (1999) showed that nitrogen fertilization improves root systems which has special significance in absorption of water and nutrients and thus plays role in enhancing nutrient uptake. Costa et al. (2007) similarly reported overall greater root length and surface area with N fertilization compared to no N application treatment in pearl millet genotypes. In cases of severe nitrogen deficiency, leaf area index and leaf area duration are reduced, which lowers radiation interception and use efficiency (Smit et al., 2013). This reduces the photosynthetic rates and biomass accumulation affecting the nutrient uptake and use efficiency of pearl millet (Sinclair and Ilorie, 1989; Uhart and Andrade 1995).

Potassium deficiency becomes an important nutritional disorder limiting pearl millet crop yields under moisture deficit conditions (Barbieri et al., 2000). Soil moisture enhances potassium movement which increases its uptake and use efficiency (Smit et al., 2013). Greater accumulation of potassium is attributed to higher biomass accumulation in response to application of potassium fertilizer (Plenet et al., 2000). Sharma and Kumari (1996) reported an increase in pearl millet potassium uptake with fertilizer application due to increased growth and grain yields. Controlling potassium losses through soil erosion and adopting appropriate potassium management strategies has been shown to increase pearl millet potassium use efficiency in semi-arid areas.

2.8 Crop water use efficiency and its determinants

The key to raise crop yield in limited water supply conditions lies to a large extent in the increase of usable water and raising the efficiency of water use (Li et al., 2001). Many options to improve water use efficiency are available and the target is to produce more biomass with minimum possible amount of water (Chakraborty et al., 2008; Singh et al., 2015). This conclusion was supported by the finding by Carlson et al. (2013) who showed that maize yields were doubled primarily by N fertilizers whereas transpiration varied by less than 10%. This indicates that when water supply is fixed, any factor that increases yield would increase WUE because evapotranspiration would be little affected by the management.

Water use efficiency is affected by a number of factors like climatic conditions, nature of plant, agronomic practices and edaphic factors (Singh et al., 2015). Of these, soil nutrient status or fertility management has been shown to have the major influence on the WUE as nutrient levels directly affect leaf area duration, leaf growth and senescence (Akponikpé et al., 2014). Adequately fertilized soils promote rapid leaf area expansion, thus increasing transpiration and more rapid ground cover thereby reducing evaporation and increasing water use efficiency (Li et al., 2004). The increase in WUE due to fertilizer application is thus attributed mainly to a larger ratio of transpiration to evapotranspiration as a result of greater leaf area (Schmidhalter and Studer, 1998). Fertilizer application also promotes the absorption of soil moisture and thus has a beneficial role for promoting WUE. Gajri et al. (1993) showed that in deeply wetted coarse-textured soils with low organic matter, N application and early-post seeding irrigation in wheat enhanced profile water use by increasing depth and density of rooting as well as leaf area index and leaf area duration. While better rooting increases capacity of the plant to extract water by increasing the size of the water reservoir, extensive canopy with longer duration increases the plant demand for water.

Increased canopy also increases the transpiration component of evapotranspiration. Thus nitrogen application, apart from increasing evapotranspiration and transpiration/evapotranspiration ratios, also increases water use efficiency.

Sowing time has also an influence on the WUE of a crop. This activity should be done at those times which will avoid probable stress periods during anthesis of the crop, or by manipulating the ratio of early to late season water use. Choosing the optimum dates for sowing is needed to ensure good germination by placing the seed in the optimum moisture zone (Singh et al., 2013). The dates also indicate the right type of climate for the shoot growth and optimum utilization of moisture by the roots under normal rainfall conditions (Singh et al., 2012).

There are also differences in WUE between varieties of the same crop. These variations are due to their genetic build-up which affects both morphological traits controlling the rate of transpiration and water absorption by roots from the soil and the physiological functions responsible for photosynthesis, respiration and translocation of photosynthates to economically harvested plant parts (Singh et al., 2008). Varieties also differ in their adaptation to environment, resistance to pests and diseases and management levels (Singh et al., 2015). Selection of properly adopted crops with good rooting habits, low transpiration rates and improved energy consumption in photosynthesis will thus increase WUE.

Water use efficiency has in addition been shown to vary with cropping systems and patterns. Singh et al. (2013) observed that the total water used in intercropping system was almost the same as for sole crops, but yields were increased, thus water use efficiency was higher than in the sole crops. Planting patterns on the other hand have a direct effect on yield, solar energy capture and evaporation, and thus an indirect effect on water use efficiency (Singh et al., 2015).

Water use efficiency is also influenced by the moisture conservation techniques. This is majorly because water availability, water use and nutrient supply to plants are closely interacting factors influencing plant growth and yield production. It is generally reported that water availability enhances nutrient use efficiency thereby causing greater increase in yield which then increases the crop's WUE (Ritchie, 1983). Huang et al. (2005) observed an increase in pearl millet yield under mulching which they attributed to the reduction in soil evaporative rate and thus improved WUE. *In situ* water harvesting practices also increase soil water availability in the upper portion of the root which improves nutrient uptake (Hatfield et al., 2001).

Water use efficiency has been used to evaluate drought resistance in plants and is a useful criterion in drought selection (Ibrahim et al., 1986; Saleh, 2012). Singh and Singh (1995) similarly found that pearl millet had the highest WUE among maize and sorghum species under severely drought-stressed conditions due to its ability to maintain higher leaf area index. Passioura, (1996) therefore, reached a conclusion that leaf area development is the most important factor controlling the WUE in drought-prone environments. The drought resistance variations among crops may also be explained by the differences in water uptake from deep soil layers which help plants to improve their leaf water status and to maintain transpiration rates and dry matter production (Shaheen et al., 2012).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the experimental site

This study was conducted at KARI-Kiboko Research Station located in Makueni County, Kenya during the short and long rainy seasons of 2014 (Figure 1).

Figure 1: Experimental site

KARI-Kiboko lies along longitudes 37.7235°E and latitudes 2.2172°S at an altitude of 975 m above sea level (CIMMYT, 2013). The agro-ecological zonation of the area is described as Semi-Arid (Sombroek et al., 1982). Kiboko has a bimodal distribution of rainfall, with the long rains occurring from late March to late May and the short rains from mid-October to January. The mean annual rainfall ranges between 545 and 629 mm, with 50.7% and 27.5% of the rain occurring during the long and short rainy seasons respectively (CIMMYT, 2013). Kiboko has an estimated mean annual temperature of 22.6°C, with the mean annual maximum of 28.6°C and mean annual minimum of 16.5°C (Gichuki, 2000). The estimated evapotranspiration of the site area is 1480 mm (Sombroek et al., 1982).

The soils in KARI-Kiboko are classified as Acri-Rhodic Ferrassols and are derived from undifferentiated basement system rocks, predominantly banded gneisses (FAO-ISRIC-ISSS, 1998). These soils are well drained, very deep, dark reddish brown to dark red, friable sandy clay to clay. The top soil is low in organic matter content and overlies a haplic horizon (CIMMYT, 2013).

3.2 Experimental layout and design

The experiment was laid out in a randomized complete block design with three replications in a split plot arrangement. The main plots were the moisture conservation techniques while the fertilizer application rates constituted the sub plots giving nine treatment combinations;

T1 = Flat technique + zero fertilizer

T2 = Basin technique + Zero fertilizer

T3 = Tied ridge + Zero fertilizer

T4 = Basin technique + microdose rate

T5 = Flat technique + recommended rate

T6 = Flat technique + Microdose rate

T7 = Basin technique + recommended rate

T8 = Tied ridge + recommended rate

T9 = Tied ridge + microdose

3.3 Trial management and agronomic activities

Tied ridges were made by scooping the soil towards the planting rows forming a 15 cm deep furrow between the rows and placing a cross-tie every one meter to hold water within the furrows. Basins were made by making ridges at 150 cm apart and tied at 250 cm interval. This produced 4 broad bed furrows in each plot. Flat technique entailed digging the field normally at 10 cm depth using a hoe without any modification (farmers practice).

Pearl millet was planted at a spacing of 75 cm between the rows and 15cm within the rows by placing 5 seeds per hill which were then thinned 2 weeks after planting to 3 plants per hill. This gave a plant population of 266,667 plants per hectare. Planting was done on the furrows for the tied ridge treatments and in the broad beds for the basin treatments. For the flat technique, the pearl millet seeds were placed on holes dug to 10 cm using hand hoes as conventionally practiced. Di-ammonium phosphate (DAP) was applied as basal at recommended rates of 60 kg/ha at planting and top dressed with 180 kg/ha recommended CAN rates at knee-height (ICRISAT, 1992). Microdosing rates were done at one-third the recommended rates (ICRISAT, 2009) which corresponded to 20 kg/ha DAP (2 g DAP $hill^{-1}$) at planting and 60 kg/ha CAN (6 g $hill^{-}1$) at top-dressing. Fertilizer application at recommended rates consisted of scattering fertilizer over the plant rows and then covering with the soil as conventionally done by the farmers. The crops were sprayed with dithane-M 45 (0.2%) from 14 days after planting and progressively at 2 weeks interval till physiological maturity to prevent the rust. Birds were noted as the major pests and were controlled by scare-crows and casual labor force. Pearl millet panicles were harvested from the 4 central rows on 10^{th} August 2014 for the long rains and 15^{th} February 2015 for the short rains which coincided with the maturity stages.

3.4 Measurement of rainfall data

Rainfall amount was recorded immediately after every rainfall event using a manual rain gauge installed at the experimental site. The results obtained were compared with the site weather station and used in computing water use and water use efficiency of pearl millet.

3.5 Characterization of soil chemical and physical properties

3.5.1 Soil sampling and analysis

Soil samples were collected using soil auger from 0–15 and 15-30 cm soil depths. These depths were informed by the fact that pearl millet roots mainly concentrate in the 0-30 cm depth and hardly go beyond 15 cm depth at pre-flowering stage (ICRISAT, 2009). Sampling was done randomly in a zig-zag pattern. The samples were composited in a container and a sub-sample of about 1 kg transported to the laboratory in an ice box. The samples were air dried, passed through a 2 mm sieve and kept at $4^{o}C$ for nutrient analyses.

3.5.2 Determination of pH

Soil pH was analyzed using 1:2.5 ratio of soil to water (Mehlich et al., 1953). Six and a half grams (6.5 g) soil was transferred into a vial followed by 25 ml of distilled water. The suspension was stirred and allowed to stand for 30 minutes after which the pH meter was calibrated using buffer solutions of pH 4 and 7, then pH was measured.

3.5.3 Determination of soil organic carbon

Soil organic carbon content was determined following the Walkley-Black procedure (Keeney and Nelson, 1982). Five grams (5 g) of air-dried soil was transferred into 500 ml Erlenmeyer flask followed by 10 ml of 0.1667 M potassium dichromate ($K_2Cr_2O_7$) solution. The mixture was gently stirred to disperse the soil. Twenty milliliters (20 ml) of concentrated H_2SO_4 (95%) was added to the suspension, shaken gently and allowed to stand for 30 minutes. Distilled water (250 ml) was added followed by 10 ml of concentrated phosphoric acid (H_3PO_4) and 1 ml of diphenylamine indicator. The suspension was titrated with 1.0 M $FeSO_4$ until the color changed to pale green. The percentage organic carbon (OC) was calculated using Equation 1.

$$\%OC = \frac{[M*(V1-V2)]}{S} * 0.39 * mcf \qquad \text{[Equation 1]}$$

Where;

M = molarity of $FeSO_4$ (from blank titration)

V1 = volume of $FeSO_4$ required for the blank,

V2 = volume of $FeSO_4$ required for the soil sample,

S = weight of soil sample in gram

mcf = Moisture conversion factor

0.39 = 3 x 10^{-3} x 100% x 1.3

3 is the equivalent weight of carbon and 1.3 is the compensation for the incomplete combustion of the organic matter in this procedure.

3.5.4 Determination of total nitrogen

The total N was determined by the Kjeldahl digestion method (Keeney and Nelson, 1982). One (1 g) of 0.5mm sieved air-dry soil was transferred into a Kjeldahl digestion flask followed by 2.5 ml of Kjeldahl catalyst (mixture of 1 part selenium powder + 10 parts $CuSO_4$ + 100 parts Na_2SO_4) and heated at 100 ˚C for 2 hours. The content was allowed to cool after which 2 ml of H_2O_2 was added and the mixture heated at 330 ˚C until clear and colorless digest was obtained (approximately 4 hours). The volume of the solution was made up to 75 ml with distilled water. The percent total N was calculated using Equation 2.

$$\%\text{Total N} = \frac{[(\text{a}-\text{b})*75]}{\text{Weight of sample (g)}} * 1000 \qquad \text{[Equation 2]}$$

Where;

a = N content of the soil sample

b = N content of the blank

1000 = coefficient of conversion from ppm N to percent N

75 ml = final diluted volume of digest

3.5.5 Determination of available phosphorus

Soil available phosphorus was determined by double acid extraction (Mehlich et al., 1962). Four grams (4 g) of air-dried soil (2 mm sieved) was transferred into 100 ml flasks followed by 14 ml of 0.03 M NH_4F and 0.025 M HCl. The mixture was shaken for 5 minutes on a mechanical shaker, centrifuged for 5 min at 3000 rpm and filtered through a Whatman No. 42 paper. Five milliliters (5 ml) of the extract was pipetted into a volumetric flask followed by 4 ml of ascorbic acid and thoroughly mixed. The volume of the solution was made up to 25 ml with distilled water and left to stand for an hour to allow for the blue color to develop. Standard series containing 0.1, 2.0, 2.4, 3.6, 4.8 and 6.0 mg l^{-1} P were prepared and treated similarly. The absorbance was measured on the spectrophotometer at 882 nm and the available P calculated using equation 3.

$$\text{P (mg kg}^{-1}\text{ soil)} = \frac{[(\text{a}-\text{b})*14]}{\text{s}} * \text{mcf} \qquad \text{[Equation 3]}$$

Where;

a = mg l^{-1} P in the sample extract

b = mg l^{-1} P in the blank

S = air-dry weight of the soil sample in gram

mcf = moisture factor of conversion

3.6 Soil moisture content determination

Soil moisture content was determined gravimetrically following procedures described by Okalebo et al. (2002). Soil samples were taken at five randomly distributed points within each plot, thoroughly mixed and immediately sealed in plastic bags. The soil samples were weighed using a precision balance, oven dried at 105°C for 48 hrs and expressed as percent soil moisture content using Equation 4.

$$\text{Gravimetric moisture content } (\%) = \frac{(\text{wet weight} - \text{oven dry weight})\ (\text{g})}{\text{Oven dry weight (g)}} * 100 \qquad \text{[Equation 4]}$$

3.7 Crop water use and water use efficiency determination

3.7.1 Assessment of crop water use

Water use efficiency was based on seasonal crop evapotranspiration (ET) and crop yield (Monteith, 1977). Seasonal evapotranspiration (ET) was calculated using the soil water balance equation (Equation 5).

$$\mathrm{ET} = \mathrm{P} + \mathrm{I} - \mathrm{D} + \mathrm{W_g} - \mathrm{R} + \Delta\mathrm{S} \qquad \text{[Equation 5]}$$

where ET is the evapotranspiration (mm); P the total seasonal precipitation (mm); I the amount of irrigation water (mm); D the soil water drainage (mm); Wg the amount of water used by the crop through capillary rise from groundwater (mm); R the surface runoff; and ΔS the change of soil water content from planting to harvest in the measured soil depth (mm).

Change in root zone soil moisture (ΔS) was considered equal to the difference between the input (rainfall, R and Irrigation, I) and output (evapotranspiration, ET, and drainage from the root zone, D). Soil moisture variations in the root zone (ΔS) were determined from measurements of soil moisture (gravimetrically) at the beginning and end of each stage of growth (Equation 6.).

$$\Delta S = (\mathrm{R} + \mathrm{I}) - (\mathrm{ET} + \mathrm{D}) \qquad \text{[Equation 6]}$$

Where ΔS is the change in soil water storage in the root zone; ET is evapotranspiration; R is rainfall and D is the root zone drainage. The drainage below the root zone was not detected during the cropping seasons and therefore considered negligible. Runon and runoff at the study site were assumed to be negligible due to the sandy texture of the soil and to the low slope of less than 2% (Zhang et al., 2007).

3.7.2 Assessment of crop water use efficiency

Water use efficiency was calculated from the water use and total biomass yield using (Equation 7) (Allen et al., 1998). The total biomass was obtained by computing the root biomass and aboveground biomass from a 1 m^2 area in each plot. The ET data was computed from the water balance equation.

$$\mathrm{WUE}\ (\mathrm{kg\ ha}^{-1}\mathrm{mm}^{-1}) = \frac{\text{Total biomass yield (kg ha}^{-1}\text{)}}{\text{Evapotranspiration (ET)in mm}} \qquad \text{[Equation 7]}$$

3.8 Determination of light interception

The light interception of the photosynthetically active radiation was measured from 24 days after sowing and progressively at 14 days interval until harvest in each plot using a Sunfleck Ceptometer (Decagon Devices, Pullman, WA, USA). All measurements were taken on clear cloudless days between 11.30 am and 01:30 pm (local time) to eliminate the effect of solar elevation on PAR interception. For each measurement, one above-canopy reading and five below-canopy readings were taken at an angle of 60^{o} across the crop rows to ensure that more leaf area is exposed to the light sensors.

The PAR intercepted in percentage was calculated using Equation 8 (Goudriaan, 1988).

$$\%\mathrm{PAR} = \frac{(\mathrm{PAR_a} - \mathrm{PAR_b})}{\mathrm{PAR_b}} \mathrm{x}\ 100 \qquad \text{[Equation 8]}$$

Where, $\mathrm{PAR_a}$ = PAR intercepted above the canopy and $\mathrm{PAR_b}$ = PAR below the canopy.

3.9 Determination of light extinction coefficient

Light extinction coefficient (λ) was determined from the LAI and their corresponding PAR with intercept set at zero using Equation 9 (Tesfaye et al., 2006; Goudriaan, 1988).

$$\text{Light extinction coefficient } (\lambda) = \frac{\mathrm{In}(\mathrm{PAR_b})}{\mathrm{PAR_a}}\ \mathrm{x}\ \frac{1}{\mathrm{LAI}} \qquad \text{[Equation 9]}$$

Where; $\mathrm{PAR_b}$ is the PAR values below the canopy, $\mathrm{PAR_a}$ is the PAR values above the canopy, and LAI is the leaf area index.

3.10 Determination of light use efficiency (LUE)

The LUE was determined by fitting a linear curve to the cumulative above-ground dry matter and the cumulative intercepted PAR (Monteith, 1994). The slope of each regression (least square regression) line was taken as the LUE for each treatment. The period of the data used in the regression was up to 75 days after sowing (DAS).This decision was informed by the fact that the data near the maturity stage of pearl millet should be excluded from the LUE calculations because it does not present any physiological importance (Black and Ong, 2000).

3.11 Assessment of growth and yield parameters of pearl millet

Growth parameters data (plant height, number of tillers, LAI, leaf length) were taken from two weeks after planting the pearl millets and progressively at two weeks interval until the crops attained physiological maturity. Data was taken from 4 middle rows leaving out the guard rows which corresponded to 4 m^2 land area. For plant height and number of tillers, 10 plants were randomly selected and their average height and number of tillers recorded. The distance from the base to the tip of 10 randomly selected fresh panicles per plot were measured using a graduated meter rule to determine the panicle length. Panicle diameter was recorded by measuring the panicle width at the middle of the earhead (the widest section) of 10 randomly selected fresh panicles per plot using a tape measure. For millet grain and biomass yield, straw samples and millet panicles from each plot were harvested at physiological maturity, oven-dried at 65^{o}C for 72 hours and expressed in kg ha^{-1}.

3.11.1 Estimation of leaf area index

Leaf area index (LAI) was calculated using Equation 10 (Koocheki et al., 2016). The data was determined from week two after planting pearl millet to physiological maturity.

$$\text{LAI} = \frac{\text{Leaf area } (\text{m}^2)}{\text{Plot area } (\text{m}^2)} \qquad \text{[Equation10]}$$

Leaf area was calculated using Equation 11.

$$\text{Leaf area } (\text{m}^2) = \text{leaf length x leaf width x K} \qquad \text{[Equation 11]}$$

Where; K is a shape factor with the value of 0.5 for partially unfolded leaves and 0.75 for completely unfolded leaves.

3.11.2 Root sampling and determination of root length density

Two millet hills were tagged from each plot and roots were collected at tillering, stem elongation and flowering stages with a 15 x 10 x 10 cm metal frame directly driven under the pearl millet hill. Roots were sampled at 20 cm depth increment with an access tube of 7.5 cm inner diameter following the first sampling depth of 0-20 cm. All root samples were washed to remove debris and died roots. Samples were cut into small pieces of about 1 cm and spread in a 2 cm by 2 cm rectangular grid (Bohm, 1979). Fields within the area occupied by the roots were viewed through the microscope with the center point of the hair-line placed in turn over each grid intersection. The microscope eye-piece containing the hair-line disk was rotated to give the hair-line a random direction and a count was made of the number of intersections between the hair-line and the roots. An intersection was only counted if the hair-line crossed the center line of the root. The root length and root length density were calculated using Equations 12 and 13 respectively (Bohm, 1979).

$$\text{Root length (cm)} = \frac{3.142 \text{ x number of intersections x area of rectangle}}{2 \text{ x total length of straight lines}} \qquad \text{[Equation 12]}$$

$$\text{Root lenth density } (\text{cm cm}^{-3}) = \frac{\text{Root length (cm)}}{\text{Soil volume of corresponding depth } (\text{cm}^3)} \qquad \text{[Equation 13]}$$

3.12 Computation of pearl millet yield

Harvested pearl millet panicle sample (500 g) was oven-dried at 75 ^{o}C for 48 hours and expressed in tons per hectare using Equation 14 (Payne, 2007).

$$\text{Yield (t/ha)} = \frac{\text{Plot weight (g)} * 10{,}000 \text{ m}^2}{\text{Plot area (15)m}^2 * 1{,}000} \qquad \text{[Equation 14]}$$

3.13 Harvest index determination

Harvest index was determined as a ratio of grain yield to total above ground biomass using (Saha et al., 2012).

$$\text{Harvest index (HI)} = \frac{Grainyield(t\ ha^{-1})}{\text{Dry aboveground biomass } (t\ ha^{-1})} \qquad \text{[Equation 15.0]}$$

3.14 Nutrient uptake and use efficiency assessment

Pearl millet aboveground biomass (shoot, stem and panicles) were harvested from 4 central rows of each plot at physiological maturity. The samples were chopped and dried at 65˚C for 72 hours in an air-forced oven for total dry matter weight (DM) and nutrient assessments. Nutrient uptake and use efficiency of pearl millet were calculated using equations 16 and 17 respectively (Maranville et al., 1980).

$$\text{Grain nutrient uptake } (\text{Kgha}^{-1}) = \text{Grain nutrient conc. x grain DM yield} \qquad \text{[Equation 16]}$$

$$\text{Nutrient use efficiency (kg DM yield kg}^{-1}) = \frac{\text{Total drymatter yield}}{\text{Grain nutrient uptake}} \qquad \text{[Equation 17]}$$

3.15 Data analysis

The data were subjected to analysis of variance (ANOVA) using GENSTAT statistical package (VSN International, 2011). Means were separated using Fischer's protected least significant difference (LSD) method at 5% probability level. General linear model regression analyses was performed to establish the interactive relation of pearl millet yield, WUE, nutrient uptake and use efficiency of water and nutrients.

CHAPTER FOUR

4.0 RESULTS

4.1 Baseline soil properties of the experimental site

Table 1.0: Soil physical and chemical properties of the experimental site

Soil properties	Parameter	Concentrations	Critical level	Ratings
Soil physical	Clay (%)	14.32	-	Low
	Silt (%)	10.23	-	Low
	Sand (%)	75.45	-	High
Soil chemical	pH-H_2O (1:2.5)	8.10	5.50-7.80	Optimal
	OC (%)	1.62	≥ 2.40	Low
	Total N (%)	0.11	≥ 0.20	Very low
	Available P (mg kg^{-1})	7.99	≥ 25.00	Optimal
	Exchangeable K (cmol kg^{-1})	1.12	≥ 0.24	Adequate

Table 1.0 presents the soil physical and chemical properties of the experimental site. The soil pH was alkaline and above the adequate level. The soil organic carbon was very low as anticipated under high temperature conditions and in sandy soils where organic matter decomposes rapidly (Feller and Beare, 1997). This was an indication of poor soil structure and low soil water holding capacity. The total nitrogen and the available phosphorus contents were limiting and could not achieve the maximum pearl millet yield. Potassium level was adequate though regular applications of organic and inorganic inputs to replenish the removed nutrients through crop harvest and leaching is necessary.

4.2 Rainfall distribution

Seasonal rainfall and rainfall distribution during this study period were erratic and below the long term average (Fig.1.0). The seasons were characterized by high-intensity rainfall exceeding 20 mm per hour, lasting 30 min or less. The rainfall amount received in the 2014 long rains (157.2 mm) were higher than that of the 2014 short rains (99.7 mm), but 40% below the long term average amounting to 629 mm (ICRISAT, 2009). The months of March and November accounted for 40% and 60% of the total rainfall received in the long and short rains respectively.

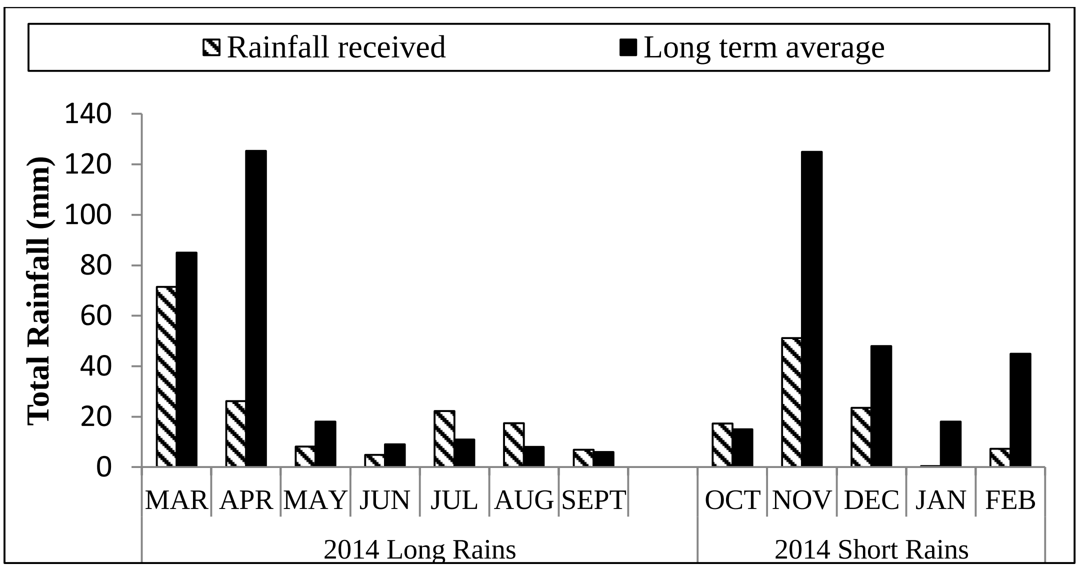
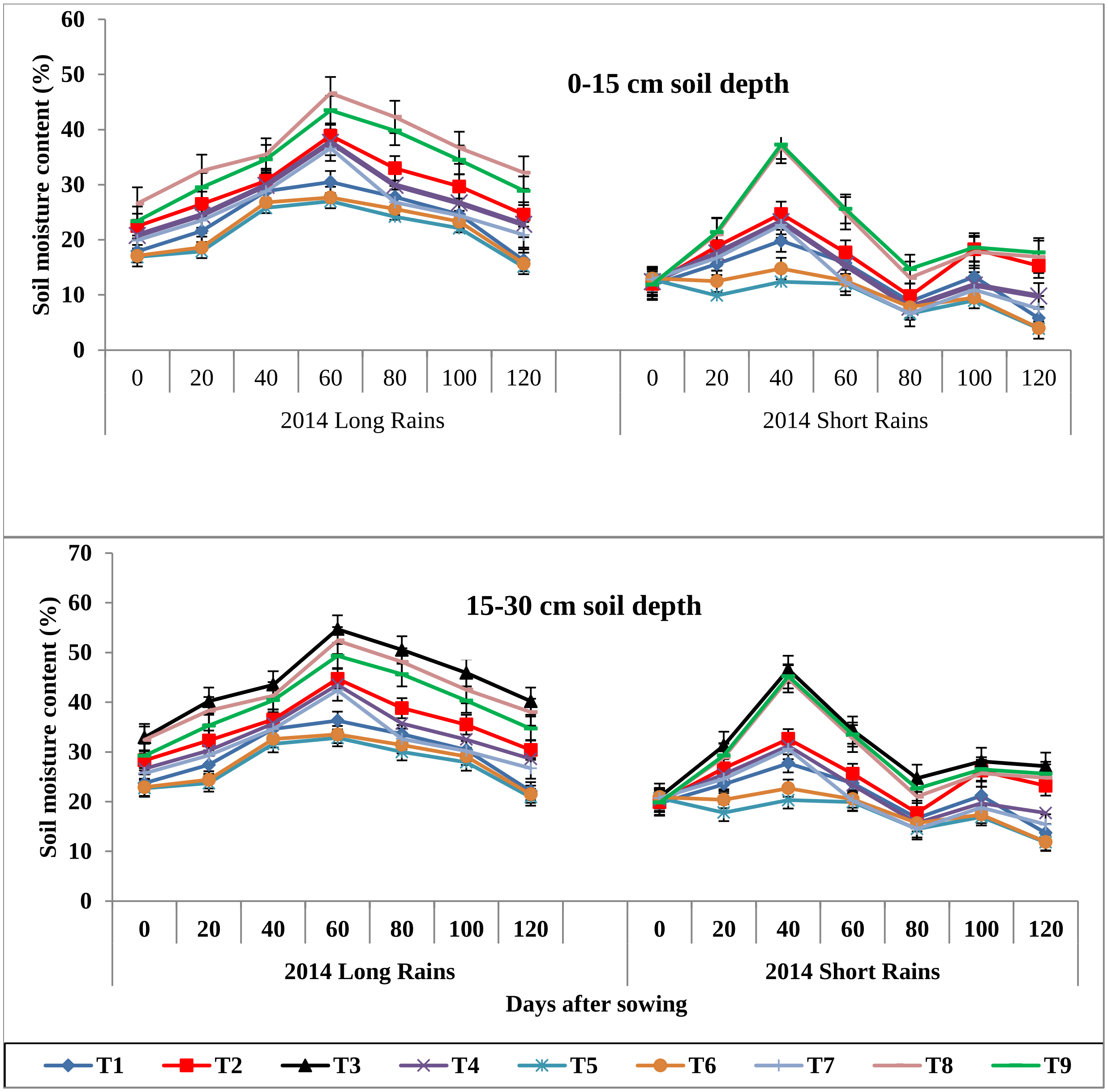


Figure 2.0: Mean monthly rainfall of the study area in comparison with 20 years average

4.3 Changes in Soil moisture content

Soil moisture content varied significantly ($p<0.05$) between the treatments and increased with soil depth (Fig. 2.0).



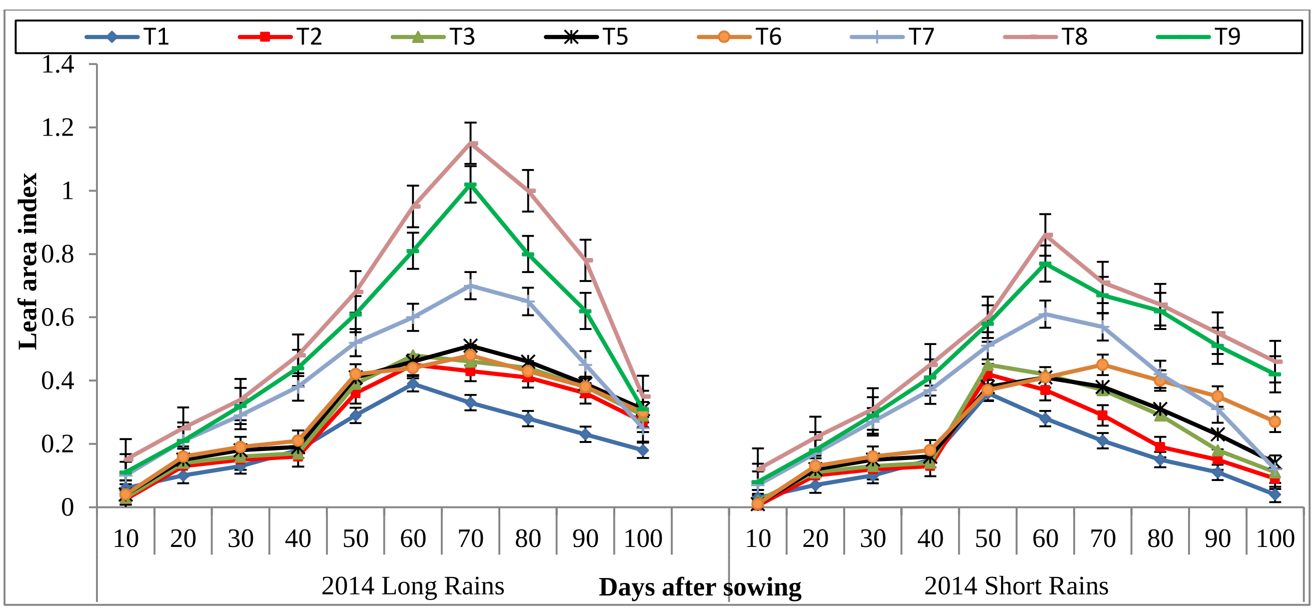
T1=Flat + No fertilizer; T2=Basin + No fertilizer; T3=Tied ridge + No fertilizer; T4=Basin + Microdose; T5=Flat + Recommended; T6= Flat + Microdose; T7=Basin + Recommended; T8=Tied ridge recommended; T9=Tied Ridge + Microdose. Error bars denote standard error of means.

Figure 3.0: Soil moisture trend at 0-15 and 15-30 cm soil depth

Combination of tied ridge and no fertilizer at 0-15 cm depth recorded the highest soil moisture content ranging between 27.1% and 48.9% during the 2014 long rains and 13.0% and 38.7% in the short rains. Combination of tied ridge plus recommended fertilizer rates at 0-15 cm depth ranged between 26.6% and 46.6% during the long rains and 12.0% and 36.8% during the short rains and showed no significant differences compared to the tied ridge plus fertilizer microdose which ranged between 29.2% and 49.3%, and 19.8% and 45.2% in the 2014 long and short rains, respectively. There was a sharp increase of soil moisture content across the treatments, ranging between 27.7% and 48.9% following rainfall event of 60 DAS in 2014 long rains and 12.4% and 38.7% in event of 40 DAS in 2014 short rains at 0-15 cm depth in flat plus recommended fertilizer rates and tied ridge plus control treatments respectively. Across the moisture conservation techniques and fertilizer application rates, soil moisture content generally decreased with increase in fertilizer application rates. Similar results were observed at 15-30 cm depth.

4.4 Pearl millet leaf area index development during the experiment period

The development of LAI in the two seasons was similar, with the 2014 long rain season having a higher peak LAI than the 2014 short rain season (Fig. 3.0).



T1=Flat + No fertilizer; T2=Basin + No fertilizer; T3=Tied ridge + No fertilizer; T4=Basin + Microdose; T5=Flat + Recommended; T6= Flat + Microdose; T7=Basin + Recommended; T8=Tied ridge + recommended; T9=Tied Ridge + Microdose.

Figure 4.0: Leaf area development during the experimental period as affected by fertilizer application and water conservation

Combination of tied ridge and recommended fertilizer application rates (T8) recorded the maximum LAI of 1.15 at 70 DAS in 2014 long rains and 0.86 at 60 DAS in 2014 short rains. The peak LAI recorded under microdose (T9) and recommended fertilizer (T8) application rates in tied ridge treatments showed no significant differences in both the two seasons and were 1.02 and 1.15 and 0.77 and 0.86 in 2014 long and short rains respectively.

Flat and basin treatments recorded significantly lower LAIs with a peak ranging from 0.36 to 0.61 in 2014 short rains and between 0.39 and 0.70 during the 2014 long rains. The minimum peak LAI values across the seasons and moisture conservation techniques (0.36-0.48) were recorded in control treatments at 50 to 60 DAS, the lowest value being that of flat treatment (T1). There was a general decline in the LAIs immediately after the maximum LAIs were reached in the two seasons in all the treatments, the fastest decline being observed under control treatments.

4.5 Leaf extinction coefficient (λ) of pearl millet in response to fertilizer microdosing and *in situ* moisture conservation

Table 2.0: Pearl millet leaf extinction coefficient variations

	Long Rains 2014	Short Rains 2014
Treatment	Leaf extinction coefficient (λ)	
Flat control (T1)	0.52a	0.57a
Basin control (T2)	0.51ab	0.55ab
Tied ridge control (T3)	0.50ab	0.51b
Flat microdose (T6)	0.49b	0.52b
Flat recommended (T5)	0.46c	0.46c
Basin microdose (T4)	0.45cd	0.44cd
Basin recommended (T7)	0.43d	0.42d
Tied ridge microdose (T9)	0.39e	0.41d
Tied ridge Recommeded (T8)	0.34f	0.37e
LSD	0.024*	0.036**
CV (%)	3.20	4.40

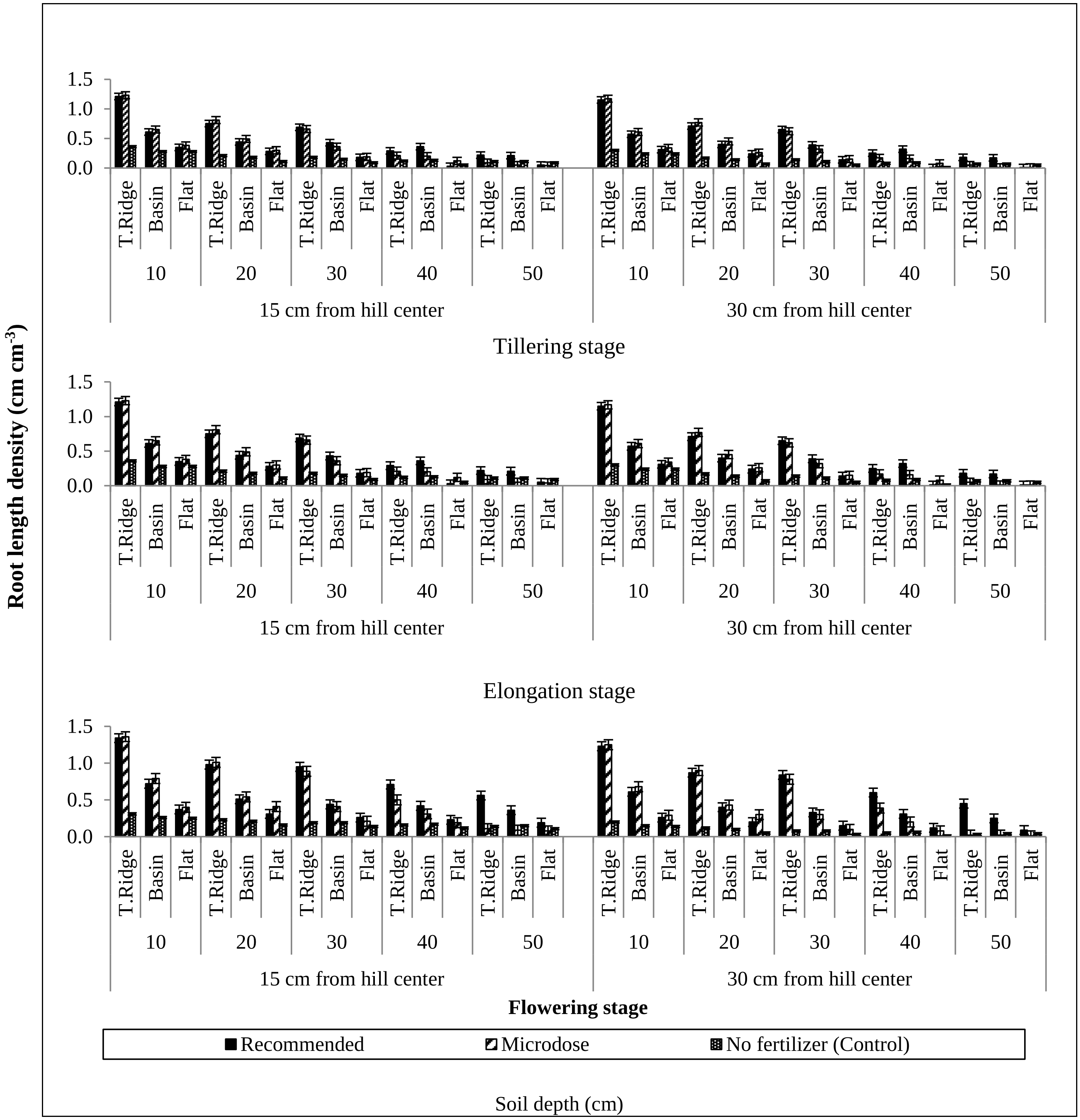
Means with different letters indicate significant differences at $p \leq 0.05$. *, ** indicate significant at $p<0.05$ and $P<0.01$ respectively.

The leaf extinction coefficient decreased with increasing moisture content from 0.52 to 0.34 in 2014 long rains and 0.57 to 0.37 in 2014 short rains in flat control and tied ridge recommended fertilizer application respectively (Table 2.0).

4.6 Changes in Root length density in response to moisture conservation techniques and fertilizer application rates

Regardless of fertilizer application rates and pearl millet growth stages, tied ridge technique recorded remarkably higher root length density ranging between 8 and 45 cm cm^{-3} at flowering stage, 20 and 45 cm cm^{-3} at stem elongation stage, and 43 and 56 cm cm^{-3} at tillering stage in the 0-20 cm soil layer (Fig. 4.0). This was followed by those of basin and flat techniques, respectively. At tillering stage, topsoil (0-20 cm) root length density (RLD) of pearl millet was notably higher for the fertilizer micro-dosing treatments ranging between 10 and 20 cm cm^{-3} but lower in the 21-50 cm cm^{-3} layer ranging between 12 and 15 cm cm^{-3}.

At flowering stage, micro-dosing and recommended fertilizer application rates resulted in similarly higher RLD of 1.01 and 0.98 cm cm^{-3} respectively in the topsoil (20 cm) while at deeper soil layers (21-50 cm), RLD was significantly higher for the techniques subjected to recommended fertilizer application rates. Lateral root length density in the topsoil (0-20 cm) was significantly increased by 50% and 44% with fertilizer micro-dosing treatments at the lateral distances of 15 cm and 30 cm, respectively from the centre of the hill compared to the control (Fig. 4.0).



Error bars indicate standard error of means.

Figure 5.0: Root length density of pearl millet at 25 cm and 50 cm lateral distances from the hill

4.7 Growth of pearl millet as affected by *in situ* moisture conservation and fertilizer microdosing

Pearl millet growth components were significantly ($p<0.05$) affected by water harvesting techniques and fertilizer application rates (Table 3.0).

Table 3.0: Pearl millet growth parameters as affected by different treatments

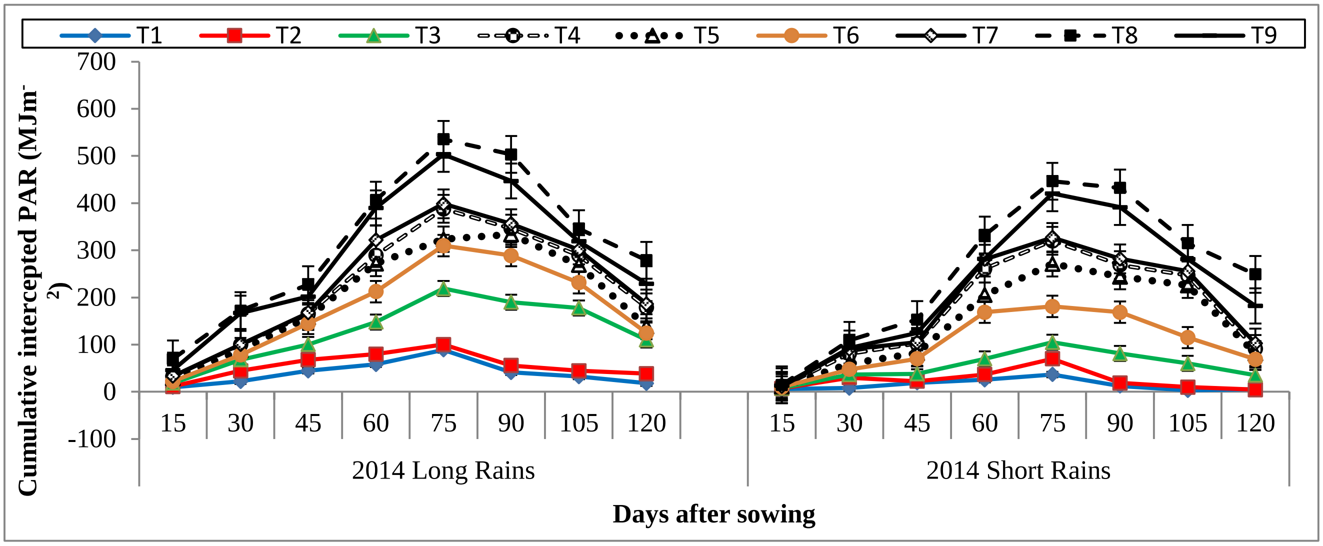
	Parameter	Plant height (cm)		Panicle length(cm)		Panicle diameter (cm)		Tillers No.	
	Season	2014 SR	2014 LR	2014 SR	2014 LR	2014 SR	2014 LR	2014 SR	2014 LR
Flat technique	Control	107.0d	117.2e	4.0d	5.4d	5.5d	6.7e	3.9d	4.0c
	Recommended	133.0b	143.9bc	5.3bc	6.7bc	7.4ab	8.5b	6.6b	6.5ab
	Microdose	134.0b	142.3bc	5.0bcd	6.6bc	7.0bc	7.7cd	5.2b	5.7b
Tied ridge	Control	125.6bc	136.0cd	4.9bcd	6.4c	6.2cd	7.5d	5.0c	6.0ab
	Recommended	170.6a	182.0a	8.5a	10.2a	7.9a	9.4a	7.1a	7.2a
	Microdose	168.7a	177.3a	8.4a	10.3a	7.8ab	9.3a	6.1ab	6.8ab
Basin	Control	115.7cd	125.8de	4.3cd	5.9cd	5.6d	7.2de	4.6c	5.8b
	Recommended	136.2b	149.9b	5.7b	6.7bc	7.6ab	8.8ab	5.5b	7.0ab
	Microdose	133.9b	146.3bc	5.5b	6.6bc	7.0b	8.3bc	5.1bc	6.0b
$LSD_{0.05}$		11.57^{**}	11.47^{**}	1.02^{*}	0.81^{*}	0.83^{*}	0.76^{*}	1.42^{*}	1.47^{*}
CV (%)		5.40	5.80	6.00	7.60	8.20	6.40	15.40	16.50

Means followed by different letters denote significant differences at 5% probability level.*, ** indicate significant levels at $p<0.05$ and $p<0.01$, respectively.

Combination of tied ridge and recommended fertilizer application rates recorded the highest significant plant height of 182 cm in 2014 long rains and 170.6 cm in 2014 short rains. Similar results were recorded for the panicle length (8.5 and 10.3 cm), panicle diameter (7.9 and 9.4 cm) and tillers numbers (7.1 and 7.2), for the 2014 short and long rains respectively. Application of fertilizer either at microdose or recommended rates in tied ridge technique produced non-significant quantity of growth attributes regardless of the season and was 20% to 40% higher than the control treatments.

4.8 Photosynthetically active radiation interception of pearl millet as influenced by *in situ* moisture conservation and fertilizer microdosing

Figure 5.0 shows the fraction of PAR intercepted by pearl millet throughout crop growth.

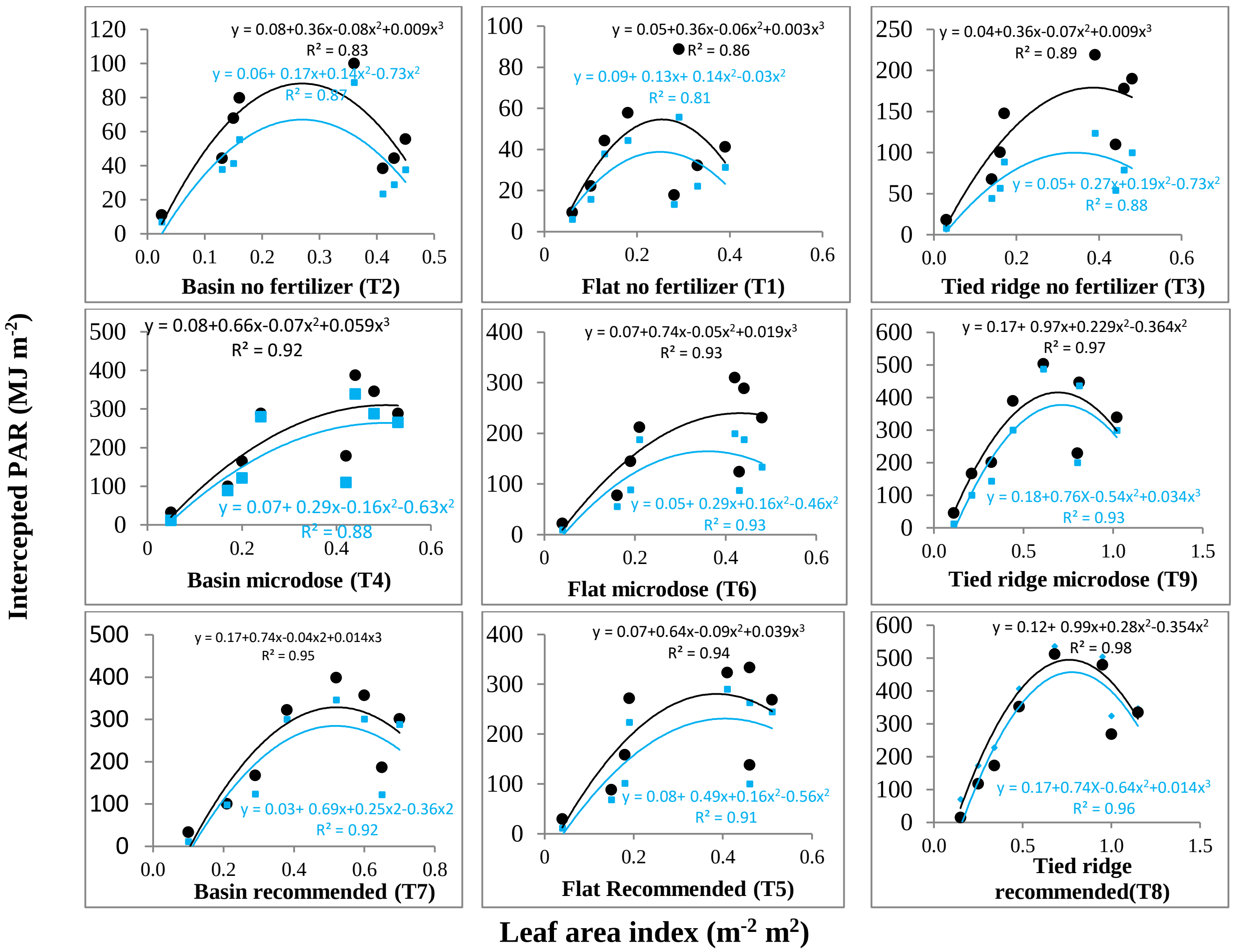


T1=Flat + No fertilizer; T2=Basin + No fertilizer; T3=Tied ridge + No fertilizer; T4=Basin + Microdose; T5=Flat + Recommended; T6= Flat + Microdose; T7=Basin + Recommended; T8=Tied ridge recommended; T9=Tied Ridge + Microdose. Error bars denote standard error of means.

Figure 6.0: PAR intercepted by pearl millet throughout crop growth

There was variability in the PAR intercepted during the growing seasons with the maximum PAR being attained at 75 DAS in both the two seasons. The PARs were remarkably higher in the 2014 long rains season with the maximum value ranging from 88.78 MJ m^{-2} in flat water harvesting technique receiving no fertilizer (T1) to 535.41 MJm^{-2} in tied ridge and recommended fertilizer combination (T8). Regardless of seasons, the PAR interception of the tied ridge microdose and tied ridge recommended fertilizer application rates showed no significant differences indicating higher resource use efficiency of microdose fertilizer application rates. Control treatments recorded the least PAR across the seasons and moisture conservation techniques with the maximum value ranging between 36.78 and 218.98 MJ m^{-2} in flat (T1) and tied ridge techniques (T3), respectively.

4.9 Relationship between PAR and LAI of pearl millet



Key: ● 2014 long rains; ▪ 2014 short rains

Figure 7.0: Relationship between cumulative intercepted PAR and LAIs

The PAR was positively and significantly ($p < 0.01$) correlated with LAI using an exponential model ($0.81 \leq R^2 \leq 0.98$; $0.027 \leq SEE \leq 0.047$) in 2014 long rains, and ($0.81 \leq R^2 \leq 0.96$; 0.026

≤ SEE ≤ 0.057) in 2014 short rains seasons across the moisture conservation techniques (Fig. 6.0).

4.10 Effect of *in situ* moisture conservation and fertilizer microdosing on yield of pearl millet.

Pearl millet stover and grain yields differed significantly ($p<0.05$) between treatments (Table 4.0). Combination of tied ridge and microdose fertilizer application increased pearl millet grain yields from 402.5 kg ha^{-1} in tied ridge control treatment to 594.4 kg ha^{-1} in tied ridge microdose in 2014 short ranis and from 417 kg ha^{-1} to 698.5 kg ha^{-1} in 2014 long ranis, an increase of 191.9 and 281.5 kg ha^{-1} respectively (Table 4.0). Pearl millet stover yields increased from 992 kg ha^{-1} in tied ridge control to 1706.3 kg ha^{-1} in tied ridge microdose in 2014 long rains and from 1038.2 kg ha^{-1} to 1992.1 kg ha^{-1} in 2014 long ranis. No significant yield increase to application of the higher recommended rates of N and P fertilizers was found when compared to microdose application rates. Basin and flat techniques recorded markedly low grain and stover yields compared to the tied ridge with the recommended and control treatments recording the highest and lowest yields respectively.

The difference in 1000 pearl millet grain weight in tied ridge technique was 4.5% to 13.3% for microdose and 9.2% to 15.5% for recommended rates. This value was remarkably lower in flat and basin techniques and was 2.9% to 11.7%, and 2.8% to 10.8%, respectively indicating that tied ridge technique provided the highest yield. The harvest indices were low, ranging from 0.21 to 0.35 during the 2014 short rains and from 0.27 to 0.39, yet common for pearl millet grown under dry land agriculture (Oluwasemire et al. 2002; de Rouw, 2004).

Pearl millet grain and stover yields responded to moisture conservation technique, season, fertilizer application, and to their interactive effects (Table 4.0). Individual ANOVA of the fertilizer application (Appendix 1.0) revealed that grain yields responded to the tied ridge technique receiving microdose fertilizer indicating that this technique was effective in resource utilization.

Table 4.0: Pearl millet stover and grain yields as influenced by *in situ* moisture conservation and fertilizer microdosing in the short and long rains of 2014

Treatment		1000 Grain Weight		Harvest Index (HI)		Grain Yields		Stover Yields	
		2014, SR	2014, LR	2014 SR	2014, LR	2014, SR	2014, LR	2014, SR	2014, LR
		g				Kg ha^{-1}			
Flat technique	Control (T1)	52.2d	54.4e	0.21e	0.27ef	320.5g	376.0e	892.1g	1002.0f
	Recommended rates (T5)	56.1b	62.3b	0.29bc	0.32bcd	539.0c	612.8c	1224.2d	1879.1c
	Microdose rates (T6)	54.2b	58.7cd	0.25de	0.29def	519.5d	600.8c	1188.0d	119.0d
Tied ridge	Control (T3)	55.2c	57.6d	0.28cd	0.33bcd	402.5e	417.0d	992.0e	1038.2e
	Recommended rates (T8)	60.3a	66.5a	0.35a	0.39a	601.0a	701.8a	1737.0a	2007.0a
	Microdose rates (T9)	57.7a	65.3a	0.33ab	0.37ab	594.4a	698.5ab	1706.3a	1992.1a
Basin	Control (T2)	53.7c	54.6e	0.23e	0.26f	381.0f	404.2de	962.0e	1033.2ef
	Recommended rates (T7)	59.9ab	62.5b	0.31bc	0.34bc	581.5b	668.5b	1655.0b	2001.0a
	Microdose rates (T4)	55.8b	61.0bc	0.29bc	0.31bcd	522.2d	616.5c	1560.4c	1942.0b
LSD$_{0.05}$		2.21**	2.46**	0.042*	0.045*	8.95**	32.32**	37.31*	37.71*
	Moisture conservation technique					<0.001		0.004	
	Fertilizer application					0.001		0.006	
	Season					0.02		0.03	
	Moisture conservation* Fertilizer application					<0.001		<0.001	

Means followed by different letters denote significant differences at $p \leq 0.05$. *, ** indicate significant at $p \leq 0.05$ and 0.01 respectively.

4.11 Nutrient uptake of pearl millet as affected by *in situ* moisture conservation and fertilizer microdosing

The highest nitrogen uptake of 85.75 and 103.73 kg ha^{-1} ($p < 0.05$) was obtained with combined application of fertilizer recommended rates and tied ridge in the 2014 short and long rains, respectively (Table 5.0). This was followed by combination of tied ridge and microdose (85.30 and 100.30 kg ha^{-1}), basin plus recommended fertilizer (75.30 and 86.30 kg ha^{-1}) and basin plus microdose (69.23 and 78.35 kg ha^{-1}) during the 2014 short and long rains, respectively.

Table 5.0: Nutrient uptake by pearl millet under different treatments (kg ha^{-1})

		2014 Short rains			2014 Long rains		
		N	P	K	N	P	K
		kg ha^{-1}					
Flat technique	Control	58.10a	42.47a	31.55a	67.65a	45.47a	34.55a
	Recommended rates	74.80c	54.72ab	34.33b	85.80b	65.92bc	40.08b
	Microdose rates	67.35bc	48.80a	35.65b	80.23b	60.00b	35.65a
Tied ridge	Control	75.50c	47.50a	34.60b	86.50b	58.55b	41.00b
	Recommended rates	85.75d	79.62c	36.53b	103.73c	90.62d	42.52b
	Microdose rates	85.30d	77.50c	36.53b	100.30c	88.50d	41.60b
Basin	Control	60.45ab	44.10a	31.63a	69.11a	55.10ab	34.98a
	Recommended rates	75.30c	64.15b	35.25b	86.30b	75.15c	42.52b
	Microdose rates	69.23bc	53.90ab	35.00b	78.35b	62.00bc	41.25b
$LSD_{0.05}$		8.990	13.300	2.464	8.920	13.600	2.600

ANOVA

	N	P	K
	p values		
Moisture conservation technique	0.011	0.033	0.034
Fertilizer application	0.012	0.032	0.031
Season	0.016	0.054	0.021
Moisture conservation* fertilizer	<0.001	0.008	0.013
Moisture conservation* season	0.031	0.014	0.043

Means followed by different letters denote significant differences at $p<0.05$ within the columns.

Control treatments exhibited the least nutrient uptake regardless of the season with that of flat recording the lowest values ranging between 58.10 and 67.65 kg ha^{-1}. Phosphorus uptake showed a consistent trend and ranged between 42.47 and 79.62 kg ha^{-1} during the 2014 short rains and 45.47 and 90.62 kg ha^{-1} during the 2014 long rains. Potassium uptake did not show significant differences between the treatments except for the controls both in the 2014 long rains and 2014 short rains.

4.12 Nutrient use efficiency of pearl millet under *in situ* moisture conservation and fertilizer microdosing

Table 6.0: Nutrient use efficiency (kg DM yield kg^{-1}) of pearl millet under different treatments

		2014 Short rains			2014 Long rains		
		N	P	K	N	P	K
		Kg DM yield kg^{-1}					
Flat technique	Control	10.03a	3.40a	4.86a	11.95a	4.91a	5.90a
	Recommended rates	14.74c	5.12c	7.39b	16.69b	8.21c	9.27b
	Microdose rates	11.57b	5.17c	7.32b	17.24b	6.70b	9.11b
Tied ridge	Control	15.04c	4.66b	7.00b	16.61b	8.20c	10.35b
	Recommended rates	16.86d	6.36d	7.67b	19.27c	10.30d	12.41b
	Microdose rates	16.98d	6.40d	7.72b	19.89c	10.45d	11.45b
Basin	Control	10.90ab	3.64a	5.20a	12.06a	6.40b	9.01b
	Recommended rates	15.36c	5.28c	7.55b	17.62b	8.95c	11.40b
	Microdose rates	15.34c	5.20c	7.44b	17.35b	8.85c	10.55b
$LSD_{0.05}$		0.9790	0.3426	0.4899	1.1880	1.0530	3.1090

ANOVA

	N	P	K
	p value		
Moisture conservation technique	0.021	0.043	0.012
Fertilizer application	<0.001	0.011	<0.001
Season	0.023	0.044	0.023
Moisture conservation* fertilizer	<0.001	0.004	0.003
Moisture conservation* season	0.021	0.067	0.087

Means followed by different letters denote significant differences at p<0.05.

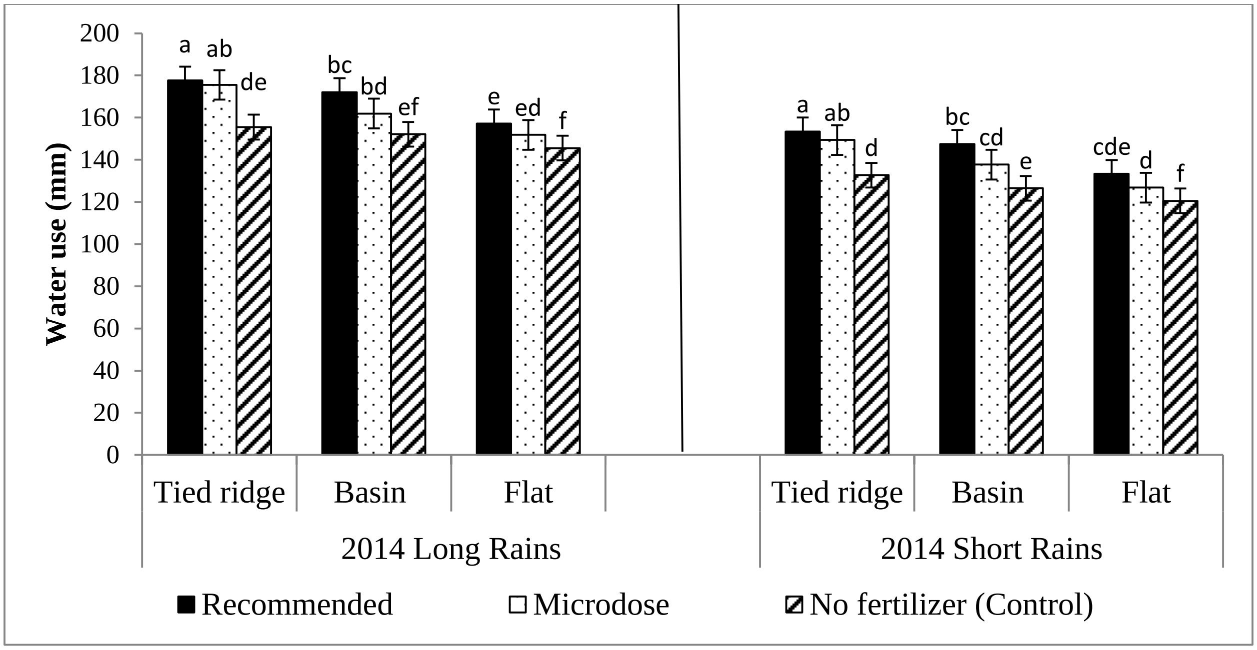
Mean nitrogen use efficiency of pearl millet increased from 15.04 kg DM yield kg^{-1} in tied ridge control to 16.98 kg DM yield kg^{-1} in tied ridge microdose and from 16.61 kg DM yield kg^{-1} to 19.89

kg DM yield kg^{-1} in 2014 short and long rains, respectively (Table 6.0). Combination of tied ridge and recommended fertilizer increased pearl millet nitrogen use efficiency by 1.82 to 2.66 kg DM yield ha^{-1} compared to tied ridge control and by 6.83 to 7.32 kg DM yield ha^{-1} compared to flat controls across the seasons. Pearl millet subjected to combined application of tied ridge and microdose fertilizer had higher phosphorus use efficiency by 3.0 to 5.6 kg DM yield kg^{-1} over flat control across the seasons. Regardless of the season, nitrogen and phosphorus use efficiency of pearl millet in tied ridge microdose and tied ridge recommended fertilizer showed no significant differences indicating similarities in nutrient use efficiency. Potassium use efficiency was markedly higher in tied ridge recommended and microdose treatments, though the differences among treatments were significant only for the controls.

4.13 Water use and water use efficiency of pearl millet as affected by fertilizer microdosing and *in situ* moisture conservation

4.13.1 Pearl millet water use by the different treatments

Regardless of fertilizer application rates and seasons, tied ridge recorded significantly ($p<0.05$) higher water use compared to flat and basin techniques (Fig. 7.0). Water use increased from 155.5 mm in tied ridge control to 177.6 mm in tied ridge recommended fertilizer rates during the 2014 long rains and from 132.7 mm to 153.4 mm in the 2014 short rains. There were however, no significant differences in the water use between the tied ridge microdose and recommended fertilizer applications irrespective of the season. Basin techniques recorded significantly higher water use compared to the flat techniques regardless of fertilizer applications and seasons. The control treatments recorded the lowest water use regardless of the treatments.



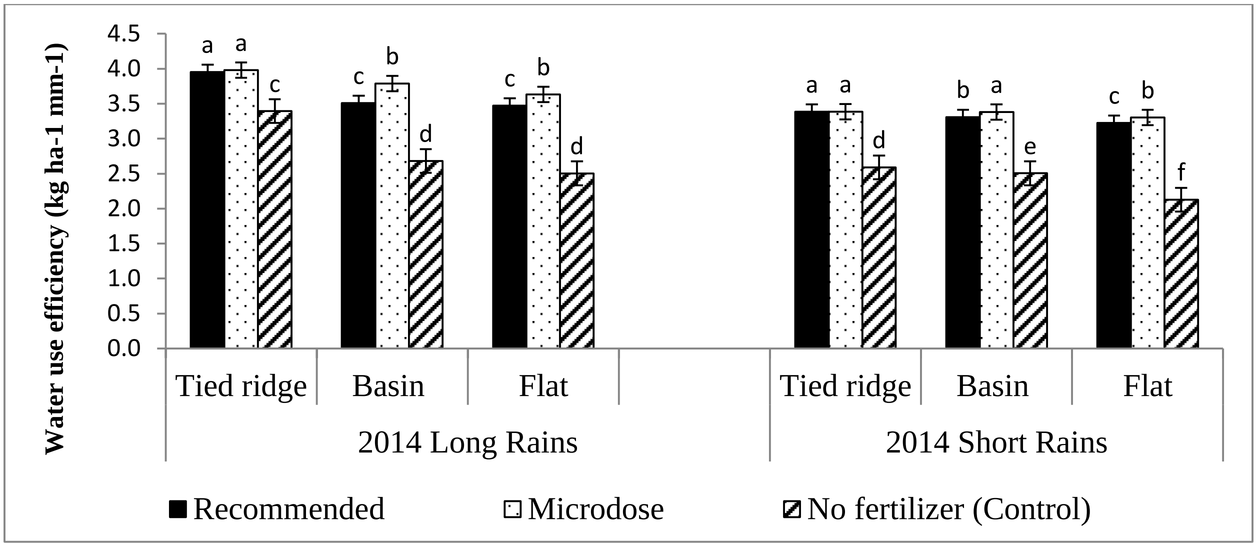
Bars with different letters across the moisture conservation techniques are significantly different.

Figure 8.0: Pearl millet water use during the experimental period

Water use was on average higher in 2014 long rains than in 2014 short rains indicating seasonal effect. In 2014 short rains with only 99.7 mm of total rainfall, water use of pearl millet varied from 120.5 mm in flat control (T1) to 153.4 mm tied ridge recommended treatment (T8). With the relatively higher rainfall amount of 157.2 mm in 2014 long rains, pearl millet used substantially more water, ranging between 145.5 mm in flat control and 177.6 mm in tied ridge recommended fertilizer rates.

4.13.2 Water use efficiency of pearl millet as affected by *in situ* moisture conservation and fertilizer microdosing

Highest WUE of pearl millet (3.98 kg $ha^{-1}mm^{-1}$) was recorded in tied ridge microdose treatment (T9) while the lowest value (2.50 kg $ha^{-1}mm^{-1}$) was recorded in flat-no fertilizer treatment (T1) in the 2014 long rains (Fig. 8.0). A similar observation was made in the 2014 short rains in which the pearl millet WUE ranged from 2.13 to 3.39 kg $ha^{-1}mm^{-1}$ in flat-no fertilizer treatment and tied ridge microdose treatment respectively.



Bars with different letters across the moisture conservation techniques are significantly different.

Figure 9.0: Water use efficiency of pearl millet during the study period

Combination of tied ridge and recommended fertilizer rates recorded remarkably lower water use efficiency of 3.385 to 3.954 kg $ha^{-1}mm^{-1}$ in 2014 short rains and 2.13 to 3.39 kg $ha^{-1}mm^{-1}$ in 2014 long rains compared to the microdose rates indicating higher resource utilization efficiency of microdose application. Flat and basin techniques showed the same trend with the maximum value of WUE being recorded in microdose application rates. These values were statistically higher ($p<0.05$) than those of the recommended and control treatments.

4.14 Effect of fertilizer microdosing and *in situ* moisture conservation on pearl millet light use efficiency

The aboveground biomass of pearl millet was linearly related to the cumulative intercepted PAR (Table 7.0). The slopes of the regressions (b) (LUE) between these variables were 0.95, 0.98, 1.25, 1.34, 1.11, 1.37, 1.45 and 1.62 g MJ PAR^{-1} for T1, T2, T3, T4, T5, T6, T7, T8 and T9, respectively during the 2014 long rains, and 0.78, 0.92, 1.24, 1.07, 1.01, 1.17, 1.35 and 1.41 g MJ PAR $^{-1}$ respectively during the 2014 short rains. This indicates that tied ridge microdose (T9) provided the highest light use efficiency.

Table 7.0: Light use efficiency of pearl millet under different treatments

		2014 Long Rains				2014 short Rains			
		Regression parameter							
Treatment		a	b	c	R^2	a	b	c	R^2
Flat	Control (T1)	-91.28	**0.95**	0.0011	0.86	-79.48	**0.78**	0.0001	0.76
	Recommended rates (T5)	-30.39	**1.17**	0.0001	0.89	-45.69	**1.07**	0.0021	0.82
	Microdose rates (T6)	-97.86	**1.11**	0.0012	0.92	-92.86	**1.01**	0.0022	0.82
Tied ridge	Control (T3)	-35.99	**1.25**	0.002	0.94	-85.99	**1.06**	0.0006	0.84
	Recommended rates (T8)	-103.54	**1.45**	0.0011	0.92	-113.64	**1.35**	0.0031	0.91
	Microdose rates (T9)	-43.92	**1.62**	0.0021	0.93	-53.92	**1.41**	0.0043	0.91
Basin	Control (T2)	-113.4	**0.98**	0.003	0.93	123.4	**0.92**	0.0005	0.89
	Recommended rates (T7)	-36.67	**1.37**	0.002	0.91	-45.37	**1.17**	0.0001	0.81
	Microdose rates (T4)	-101.24	**1.34**	0.005	0.87	-112.24	**1.24**	0.0004	0.83

LUE is given by the slope of the linear regression (b).

Pooling the data from both treatments yielded a seasonal LUE of 1.24 and 1.11g MJ PAR $^{-1}$for 2014 long rains and 2014 short rains respectively indicating that seasons had effect on pearl millet LUE. The slope of these relationships (the LUE) increased significantly by 20-25 % with N and P fertilization. Pearl millet generally stopped showing a linear correlation at 75 DAS in both the growing seasons.

CHAPTER FIVE

5.0 DISCUSSIONS

5.1 Soil moisture content variation during the experimental period

The tied ridge technique consistently showed higher soil moisture content at any stage of sampling. The crossties in this technique enhanced ponding, allowing a greater depth of water to remain on the soil surface after rainfall giving it more time to infiltrate. Abubaker et al. (2014) argued that tied ridges accumulate runoff water and eroded soil particles immediately above the crossties thus retaining more rain water at the lowest point against the surface flow. The basin and flat techniques had a greater surface area exposed compared to the tied ridges which could have led to higher surface evaporation. The absence of significant difference in soil moisture content between tied ridge microdose and tied ridge recommended fertilizer application at any sampling point could be due to the optimal fertilization attained in the two treatments which helped utilize the soil moisture efficiently. The point application of fertilizer at microdose rates therefore increased soil water conservation especially in tied ridge technique by boosting pearl millet growth and thus minimizing the losses due to surface evaporation. Izumi et al. (2009) observed that the greater infiltration and storage of water in soil under tied ridge is attributed to the increased surface area created by the crossties which gives plants ample time to take up the stored water. Consistent results were recorded by Ali, (1998) who showed that fertilization enhances pearl millet canopy development which reduces losses due to soil evaporation while boosting the uptake of water by crops from the deep soil layers.

The amount of rain which fell 3 to 4 weeks after planting did not contribute to any available soil moisture in all the treatments at 0-30 cm depths. This rain might have infiltrated to the lower soil horizons or evaporated. The rapid increase in soil moisture content following rainfall event was ascribed to the profile moisture recharge from water infiltration. The relatively higher soil moisture content in control treatments at any stage of measurement may be related to the reduced water uptake attributed to the low root length density of pearl millet in these treatments. Such roots had comparatively low ability to support sufficient water extraction from the soil layers. The rapid growth of pearl millet in the more fertile plots was however, accompanied by higher moisture consumption during the course of the season which depleted the profile soil moisture content. The availability of moisture at 0-30 cm depth at start of the subsequent season could be attributed to the moisture carryover from the previous season and by the long rains which had started. Statistically higher soil moisture content in 2014 long rains than in short rains was entirely due to abundant rainfall in long rains (515 mm) and very little amount in short rains (136 mm).

5.2 Pearl millet leaf area index as influenced by *in situ* moisture conservation and fertilizer microdosing

The trend of LAI development found in this study is typical of most crops, which increase their LAI until they reach a peak value, beyond which LAI reduces as the crop senesces. The highest (peak) LAI value was recorded in tied ridge technique receiving fertilizer at recommended rates (T8) while the least LAI was recorded in flat control (T1) indicating that leaf area index increased significantly with increasing soil moisture and nutrient contents. The observed reduction in LAI with decrease in soil water content was thus a strategy to reduce water loss by pearl millet and to maintain the soil water uptake at satisfactory levels. This may have been achieved via stomatal conductance and morphological adjustments by pearl millet to meet the demand for transpiration.

Ahmad, (2016) argued that by reducing LAI, transpiration is also reduced therefore absorbed soil water maintains plant vital functions.

Attainment of peak LAI at different times by different treatments suggests that the spatial distribution of LAI was affected by fertilizer application rates and moisture conservation levels in this study. This variability could be explained by changes in the timing of leaf senescence in response to water availability. Low nutrient availability under low moisture levels may have led to an acceleration of leaf senescence to satisfy the nutrient demand of sink organs leading to attainment of peak LAI much earlier in flat and basin water conservation technique treatments. Consistent results were found by Sinclair, (2000) who argued that severe drought conditions considerably reduce the stomatal conductance leading to an interruption in CO_2 assimilation. Under such conditions, the water reserves of the plants themselves may be consumed which can lead to death of the plants. Zahoor et al. (2010) demonstrated that factors such as starch and soluble sugar contents, degradation of chlorophyll, loss of cell wall plastid integrity, drop in photosynthetic rates and/or decline in water status might contribute to shortening the leaf longevity of nutrient and water deficit crops leading to decrease in LAI.

A better LAI distribution was obtained at recommended and microdose fertilizer rates irrespective of the water harvesting techniques suggesting that fertilizer enhanced LAI expansion. Lack of significant differences in the peak LAI of tied ridge microdose (T9) and recommended fertilizer (T8) rates nevertheless, suggests that application of fertilizer at a microdose rates was sufficient to achieve optimal yield under sufficient soil moisture conditions. This is based on the fact that LAI determines leaf photon interception, which highly affects biomass production (Monteith, 1977). High response of LAI to fertilizer application rates suggests deficit of N and P nutrient elements in the soil which could be depicted from the low levels of these nutrients in the initial soil (Table

1.0). A better LAI development in the 2014 long rains than in the 2014 short rains may be a s a result of the higher rainfall amount which was well distributed during the long rains. This may have led to a better nutrient assimilation and acceleration of leaf development.

5.3 Leaf extinction coefficient of pearl millet in response to fertilizer microdosing and moisture conservation

The observed values of leaf extinction coefficient are in agreement with those reported by other authors for pearl millet in tropical Africa (Sridhara and Prasad, 2001; Sivakumar et al. 1984; Sinclair and Muchow, 1999). Higher leaf extinction coefficient observed in flat and basin control treatments was due to low moisture contents and was an indication of few vertical leaves in these treatments. It thus implies that these treatments had uneven distribution of light in the canopy resulting into a reduced radiation interception owing to the foliage rolling. Jeuffroy and Ney, (1997) showed that moisture deficit conditions may modify leaf angle of inclination, spatial distributions and leaf optical properties thus affecting light distribution. A lower leaf extinction coefficient in tied ridge treatments receiving microdose and recommended fertilizer application rates however, led to more even penetration of light into the canopy, and may have therefore ensured more uniform distribution of photosynthesis across the canopy.

5.4 Effect of fertilizer microdosing and *in situ* moisture conservation on pearl millet roots development

Root length density (RLD) (primarily fine fibrous, characterizing pearl millet) was generally concentrated in the topsoil (0-20 cm) and drastically declined within the lower soil depths. This decrease in RLD can be attributed to the progressive decline in nutrient content with depth. The concentration of pearl millet roots in the topsoil with fertilizer micro-dosing was in line with the crop response to the localized application of nutrients leading to roots proliferation in patches with high nutrient concentration. This observation thus corroborates the fact that fertilizer micro-dosing induces higher crop yields due to its positive effect in stimulating lateral root growth within the top soil layers and therefore enhancing crop nutrient and water uptake (Aune and Bationo, 2008). Ma et al. (2013) and Smit et al. (2013) argued that the high lateral root length density during the early stages of crop growth with fertilizer microdosing stimulates uptake of native P due to the high uptake capacity of young roots for this nutrient.

The growth of roots was more extensive under moisture deficit conditions irrespective of the moisture conservation techniques. Smit et al. (2013) found that over 75% of pearl millet roots are concentrated within the 0-30 cm soil depth under optimal water conditions. Root proliferation beyond 30 cm depth was thus a strategy which was meant to overcome the moisture stress. This observation could be explained by the root plasticity exhibited by pearl millet plants resulting into greater partitioning of dry matter to roots. Jordon et al. (1983) linked the greater root volume of pearl millet under moisture deficit conditions to the need to extract the available soil moisture so as to avoid dehydration. In contrast, the mean length of primary laterals was greater in tied ridge technique implying that partitioning of dry matter and development of the lateral roots were greater under this technique. Root length density was greater under fertilizer microdose and recommended rates and was more pronounced under a high soil moisture regime. This suggests that fertilizer promoted root growth of pearl millet to a greater extent, allowing increased extraction of soil moisture. The higher root density of pearl millet under tied ridge was asserted to the higher moisture content recorded in this technique. Soil moisture is necessary for the applied fertilizer to be dissolved and get available in mobile ionic forms (Weerathaworn et al., 1992).

5.5 Effect of *in situ* moisture conservation and fertilizer microdosing on pearl millet growth

Soil moisture conservation techniques and fertilizer applications caused significant effect on pearl millet height, number of tillers, and panicle length and diameter. The tied ridge technique treatments receiving fertilizer either at microdose or recommended rates showed significantly higher growth attributes than those of the basin and flat techniques. The effect on pearl millet height may be due to the impact of nutrients especially nitrogen fertilization in pushing growth of pearl millet and the increments in internode length and/or number of internodes (Shahin et al., 2013). The significantly lower pearl millet height under flat and basin techniques could be a strategy of the crop to maintain its leaf area index and achieve less allocation of biomass to stem under extreme moisture deficit conditions.

The significantly higher tillers production under tied ridge microdose technique could be attributed to the higher soil moisture content (Fig. 2.0) leading to higher available water for pearl millet uptake. Sinclair et al. (2003) found that the finer fibrous root stimulation under fertilizer microdosing enhances soil water and nutrient uptake resulting into increased pearl millet growth. The much higher lateral root proliferation in combination of tied ridge and fertilizer microdosing (Fig 4.0) enhanced nutrient uptake (Table 5.0), therefore, promoting development basal tillers development. Flat and basin techniques were however, characterized by relatively lower soil moisture content at any stage of pearl millet growth which may have slowed pearl millet tillering. This is based on the fact that pearl millet crop develops deep root system as opposed to the shoot development under moisture deficit conditions (Shahin et al., 2003).

5.6 Effect of *in situ* moisture conservation and fertilizer microdosing on pearl millet yield

Highest grain and stover yield of pearl millet were recorded in treatments under tied ridge technique. This technique conserved more moisture which enhanced nutrient uptake by the crop and in turn resulted in assimilation of photosynthates towards sink. This resulted into an increase in growth and yield attributes (plant height, length and diameter of panicles, 1000 grain weight and tillers number) leading to an increase in grain and biomass yield. Haitham et al. (2009) consistently found that pearl millet produced under high water levels grew taller, yielded more and used water more efficiently than pearl millet grown under low water level at different growth stages. The higher soil moisture storage under tied ridge microdose technique also encouraged root proliferation thereby promoting better crop growth in the early season. This was demonstrated in the highest root length density recorded under this technique at the early stage of millet development (Fig. 4.0). The greater root length density (finer fibrous roots) observed in the topsoil could besides improve P mobility and water availability thereby improving the grain yield. The higher leaf area index in tied ridge treatments also enhanced light interception resulting in increased light use efficiency and thus grain and biomass yield. Moisture stressed conditions under flat and basin techniques however, reduced photosynthesis rate of pearl millet and in turn decreased the production of biomass and its partition among plant organs.

Lack of significant differences in the pearl millet stover and grain yields between the microdose and recommended fertilizer application rates under tied ridge technique indicates that application of fertilizer at microdose rate was sufficient to produce high pearl millet yield. This implies that combined fertilizer microdozing and tied ridges can be a strategy to offset the higher rates of fertilizer applications in the semi-arid areas thus cutting down on the production cost. The effect of fertilizer micro-dosing in improving crop yields has been attributed largely to the early crop development (Tabo et al., 2007). This is consistent with the finding in the current study that provides an empirical evidence of the increase in LAI and lateral root development under fertilizer micro-dosing treatments at tillering stage leading to an increased production of photosynthates for enhanced biomass production. Sufficient soil moisture conditions under tied ridge technique may have increased nutrient use efficiency of pearl millet leading to increased biomass production at lower nutrient level. The effectiveness of tied-ridges at or after planting in reducing surface runoff, improving soil water availability, delaying water depletion and increasing yields have similarly been reported (Hayashi et al., 2008).

Regardless of water harvesting technique, control treatments recorded the least yields indicating that fertilizer application had influence on pearl millet stover and grain yields. This observation was corroborated by the linear regression analyses of moisture conservation techniques and fertilizer application rates on pearl millet yields (Table 4.0). Fertilizer application may have enhanced profile water use by increasing depth and density of rooting as well as leaf area index and duration thus contributing to increased stover and grain yield of pearl millet. The fact that ASAL soils are poor in macro and micro nutrients implies that any strategy which increased nutrient uptake would have effect on pearl millet yield (Ikombo, 1984). Schmidhalter and Studer, (1998) argued that adequate application of fertilizers increases transpiration efficiency of the crop resulting into an increased yield.

The high response of pearl millet to microdose fertilizer application rates can be explained by the low inherent fertility of the sandy soils (Table 1.0) which leads to the positive responses following any improved soil fertility management practice. This implies that small additions of N and P fertilizer would increase the soluble phosphate and nitrate and give significant crop response. Fertilizer application therefore provided more conducive conditions for better uptake of nutrients and in turn helped the plants to boost their growth, leading to the development of yield attributes through supply of more photosynthates towards the sink. The current results thus support the earlier reports on micro-dosing regarding the effectiveness of the technology in improving crop yield under low-input millet based system (Bagayoko et al., 2011; Akponikpè et al., 2014; Ibrahim et al., 2014).

The enhanced response of pearl millet yield to sum effect of moisture conservation techniques and fertilizer application rates indicates that raised soil nutrient levels exerted additive effects on pearl millet WUE and therefore yields. Availability of the applied nutrients to pearl millet therefore depended on the soil moisture content. This was shown by the significantly lower yield recorded by treatments under flat and basin techniques than those under tied ridge techniques implying that pearl millet requires sufficient moisture to fully utilize the applied nutrients. Results from farmer-managed trials conducted in Burkina Faso similarly showed higher pearl millet grain yields with the combination of fertilizer and tied-ridges than with either fertilizer or tied-ridges alone (Muehlig-Versen et al., 2003).

Pearl millet grain and stover yields were significantly affected by the cropping seasons. The yields were significantly higher in 2014 long rain season than in the 2014 short rain season (Table 4.0). During the 2014 long rains season, pearl millet grain and stover yields were higher and the differences between the water harvesting techniques were minimal. This observed seasonal yield differences are primarily due to variations in the amount and distribution of rainfall in relation to the potential demand for water (Fig. 1.0). The larger amount and better distribution of rainfall observed during the 2014 long rains growing period led to more moisture in the soil profile which in turn favored early establishment and growth of pearl millet. On the contrary, pearl millet suffered from the severe moisture stress conditions during flowering and grain-filling stages which greatly contributed to vegetative growth and yield decreases during the 2014 short rains. The inter-annual pearl millet yield differences as a result of rainfall variability have elsewhere been reported (Sivakumar and Salaam, 1999; Akponikpé et al., 2008; Ibrahim et al., 2015). From a study conducted in Zimbabwe, Manu et al. (1991) reported pearl millet yield increases from 118 to 388 kg ha^{-1} when 1.5 m long tied-ridges were used and increases to 1071 kg ha^{-1} when 50 kg N ha^{-1} was applied to the tied-ridges in years of limited rainfall. Taonda, (1999) in Burkina Faso, compared the effects of scarifying and tied-ridges on pearl millet grain yield and reported yield increases due to tied ridges of 112 kg ha^{-1} in years of sufficient rainfall (931 mm), 88 kg ha^{-1} in years of medium to intermediate rainfall (760 mm) and 474 kg ha^{-1} in years of low rainfall (621 mm). Kinama et al. (2007) plotted maize yields as a function of seasonal rainfall and found a close correlation between these two parameters.

Earlier research have also reported the residual effect of mineral fertilizer, particularly P in increasing productivity of the subsequent crop and thus contributing to seasonal yield differences (Bationo et al., 1992; Gérard et al., 2001). It is however unlikely that the large differences in yields obtained in the current study could be due to this effect because, for instance, with the small quantity of P applied a minimal residual effect could be expected. Moreover, the yield in the subsequent season (2014 short rains), were relatively smaller.

5.7 Water use and water use efficiency of pearl millet as influenced by fertilizer microdosing and *in situ* moisture conservation

Sufficient moisture conditions in tied ridge technique increased the supply of N and P thereby promoting pearl millet root growth and leaf area expansion. This consequently increased ground cover development and contributed to reduced soil evaporative losses thus increasing pearl millet water use and water use efficiency. Monteith, (1994) argued that early development of canopy cover helps the crop to intercept more radiation, increase root development and apportion more of the water extracted by the roots to transpiration thereby increasing WUE. More water was used by pearl millet in 2014 long rains than in 2014 short rains due to greater rainfall received during the long rainy growing season. The lower WUE during the 2014 short rain season may have resulted from the low pearl millet yields attained during this time. This is probably due to the shorter growing season and less total rainfall amount recorded. This is in accordance with Tiedong et al. (2012) who argued that highest WUE is achieved at the highest yields. The smaller differences in the observed water use among the treatments during the 2014 short rains could be explained by the low moisture content during this time with nearly all the plant-available water being used up by the crop. This is based on the fact that pearl millet requires 300-450 mm of rainfall in a growing season for optimal grain yield to be attained (ICRISAT, 2009). Water use increased with progressive increase in soil moisture content and nitrogen and phosphorus levels, perhaps due to improved growth attributes (plant height, tiller number, panicle length and diameter). This enabled the crop to effectively utilize the available moisture from the soil layers. Hence in this study, higher yield were obtained in tied ridge technique receiving fertilizer at recommended and microdose rates. These treatments were characterized by higher nutrient uptake and soil moisture contents. Nutrient stress in control treatments (no fertilizer) however, restricted the yield attribute size.

Consuming more fertilizer at recommended rates significantly lowered the WUE of pearl millet in treatments under flat and basin techniques probably due to the limited availability of water which deprived pearl millet root growth thereby decreasing moisture extraction. This may have reduced nutrient uptake by the crop leading to accumulation of nitrogen and phosphorus to toxic levels.

Ibrahim et al. (2015) and Singh et al. (2015) similarly reported decline in pearl millet yield attributed to the higher nutrient concentrations under extremely low soil moisture levels.

5.8 Effect of *in situ* moisture conservation and fertilizer microdosing on nutrient uptake by pearl millet

The soil supply of NPK in zero fertilizer (control) treatments regardless of moisture conservation techniques could not satisfy plant nutrient demand. This hindered root development (Fig. 4.0) thereby decreasing the nutrient uptake (Table 5.0). The proportion of incoming radiation intercepted was also relatively low with the no-fertilizer treatment (Fig. 5.0). This further reduced plant growth and leaf area development (Fig. 3.0) which decreased the biomass accumulation. Muchow, (1988) reported that high NPK rates stimulate pearl millet leaf growth resulting into higher nutrient uptake.

Nitrogen and phosphorus uptake was consistently greater under tied ridge across the moisture conservation techniques. This is probably due to the higher moisture content recorded under this technique which enhanced nutrient availability in the soil. This is in accordance with the finding by Benjamin et al. (1997) who showed that water deficit during crop growth may limit nutrient movement in soils thereby reducing nutrient uptake. Pearl millet plants receiving zero fertilizer within the water stressed conditions of flat and basin techniques transpired less rapidly hence reducing the pearl millet leaf numbers and leaf area index. This significantly lowered the pearl millet dry matter production and therefore the nutrient uptake.

Substantial amounts of phosphorus and nitrogen were extracted from the soil in control treatments despite the low fertility and organic matter content of the soil. This is probably due to the high uptake of these nutrients in their native organic and inorganic forms in response to their low supply.

Tied ridge-recommended rate was likely to have taken up more nitrogen and phosphorus than tied ridge microdose because of higher nitrogen and phosphorus concentrations.

The nitrogen, phosphorus and potassium uptake of pearl millet in tied ridge-recommended and tied ridge-microdose rates were similar demonstrating that nutrient application at microdose rate was optimal to satisfy the nutrient demand of pearl millet crop growth. Fertilizer application at microdose rates enhanced branching of pearl millet fibrous root systems thus increasing water absorption. This enhanced nutrient availability which increased nutrient uptake by pearl millet thus increasing growth and biomass accumulation. Ibrahim et al. (2014) observed that pearl millet crops receiving nitrogen and phosphorus at optimal rates attain critical leaf area index and specific leaf nitrogen content and are able to grow at their maximum potential which enhances N and P uptake.

The higher nutrient uptake observed in 2014 long rains as compared to 2014 short rains was due to variations in climatic conditions, longer growth period, and residual effect of nutrient applied in the first season which increased biomass accumulation. The generally higher phosphorus and nitrogen uptake in the current study was most likely due to their deficiency in the soil especially that of P and total N which were only 7.99 ppm and 0.11% respectively (Table 1.0), whereas available potassium was in adequate levels which could have lowered its uptake and use efficiency. Sharma and Kumari (1996) reported that with increased K fertilizer application, pearl millet grew better and had higher yields.

5.9 Nutrient use efficiency of pearl millet as affected by fertilizer microdosing and *in situ* moisture conservation

The higher nutrient use efficiency in treatments subjected to combination of tied ridge and microdose fertilizer rates is attributed to the increase in dry matter accumulation. Tied ridge technique enhanced soil moisture storage which increased nutrient availability and uptake. This increased pearl millet grain yield at lower nutrient application rate. The markedly lower phosphorus and nitrogen use efficiency values at higher recommended fertilizer application rates indicate that the absorbed P and N were not utilized efficiently to induce biomass increases, but were merely accumulated. Shaheen et al. (2011) demonstrated that the efficiency of plants to absorb nutrients and capacity of soil to supply them are reduced under low soil moisture conditions. This implies that the higher nutrient use efficiency in tied ridge plus microdose treatment was greatly due to the higher moisture content recorded under this technique. The beneficial effect of fertilizers in enhancing nutrient use efficiency of pearl millet could be attributed to the rapid early growth of leaves which increased the leaf area index and light interception thus contributing to dry matter accumulation. Microdose fertilizer rate application instigated localized root formation which enhanced nutrient uptake thereby increasing pearl millet growth. The soils under this study had low content of plant available phosphorus and total N (Table 1.0) which is a consequence of the low organic matter content. This implies that small additions of fertilizer phosphate and nitrate increased the soluble phosphate/nitrate giving significant crop response. The higher nitrogen and phosphorus use efficiency achieved at lower microdose fertilizer rates in tied ridge was due to greater biomass yields. Nutrient uptake was greater in 2014 long rains than in 2014 short rains reflecting the overall higher biomass yields of that year. The available potassium was in adequate levels (Table 1.0), which could have lowered its uptake and use efficiency.

5.10 Water use and water use efficiency of pearl millet as influenced by fertilizer microdosing and moisture conservation

Sufficient moisture conditions in tied ridge technique (Fig. 2.0) increased the supply of N and P (Table 5.0) thereby promoting pearl millet root growth (Fig. 4.0) and leaf area expansion (Fig. 3.0). This consequently increased ground cover development and contributed to reduced soil evaporative losses (Kinama et al., 2005) thus increasing pearl millet water use (WU) and water use efficiency (WUE). The low moisture content under flat and basin techniques (Fig. 2.0) however lowered nutrient uptake (Table 5.0). This significantly affected the growth and yield of pearl millet leading to low water use efficiency. While evaluating the factors affecting crop water use efficiency in rainfed Agriculture, Cooper et al. (1998) noted that decreased soil evaporation contributed by *in situ* moisture conservation can enhance water availability to crops thus increasing their water use efficiency. The crossties in tied ridges have been shown to lower the surface area available for soil evaporation (Ibrahim, 2015). This implies that this technique may have conserved more water against evaporation in this study thus contributing to higher water available for evapotranspiration by the pearl millet crop. Kinama et al. (2005) argued that soil evaporation losses play a significant role in crop water use efficiency determination. This therefore suggests that the reduced soil evaporation under tied ridges may have contributed to increased available soil moisture required for dry matter accumulation. Monteith, (1994) argued that early development of canopy cover helps the crop to intercept more radiation, increase root development and apportion more of the water extracted by the roots to transpiration thereby increasing WUE.

More water was used by pearl millet in 2014 long rains than in 2014 short rains (Fig. 7.0) due to greater rainfall received during the long rainy growing season (Fig. 1.0). The lower WUE during the 2014 short rain season may have resulted from the low pearl millet yields attained during this time. This is probably due to the shorter growing season and less total rainfall amount recorded. This is in accordance with Tiedong et al. (2012) who argued that highest WUE is achieved at the highest yields. The smaller differences in the observed water use among the treatments during the 2014 short rains could be explained by the low moisture content during this time. Nearly all the plant-available water was thus used up by the crop.

Water use increased with progressive increase in soil moisture content and nitrogen and phosphorus levels, perhaps due to improved growth attributes (plant height, tiller number, panicle length and diameter) development. This enabled the crop to effectively utilize the available moisture from the soil layers. Hence in this study, higher yield attributes were obtained in tied ridge technique receiving fertilizer at recommended rates and characterized by higher level of soil moisture. Nutrient stress in control treatments (no fertilizer) restricted the yield attributes size.

Fertilizer application at recommended rates significantly lowered the WUE of pearl millet in treatments under flat and basin techniques probably due to the limited availability of water as these techniques were not effective in soil moisture conservation. This hindered pearl millet root growth (Fig 4.0) thereby decreasing soil moisture and nutrient extraction. Singh et al. (2015) showed that moisture deficit lowered nutrient extraction ability of pearl millet due to the low water available to dissolve the chemical fertilizer. Ibrahim et al. (2015) similarly reported a decline in pearl millet yield attributed to the higher nutrient concentrations under extremely low soil moisture levels.

5.11 Effect of *in situ* moisture conservation and fertilizer microdosing on light interception and use efficiency of pearl millet

There were no significant differences in PAR intercepted among the different treatments between 0 and 20 DAS. This observation implies that at the beginning of the pearl millet reproductive stage when LAI was not fully developed, light penetration inside the canopy was nearly uniform. The sharp decrease of PAR in all the treatments after the attainment of peak LAI was due to the increase in leaf extinction coefficient (Table 2.0). This impaired canopy expansion and changed the pearl millet leaf orientation. The decline in the intercepted PAR after the attainment of peak LAI was however, much rapid in the flat and basin no fertilizer application treatments implying that the extended water stress accelerated leaf senescence.

The large PAR variability observed early in the season may be related to the low pearl millet density which was clumped into rows at this stage. This PAR was low probably due to the low LAI development early in the season. Ewert, (2004) observed that as LAI increases, more radiation is intercepted per unit ground area resulting in higher PAR. According to Brintha and Seran, (2009) if the LAI is too low, not enough light will be absorbed and leaves will not receive enough light. Liu et al. (2010) concluded that early development of a canopy cover helps the crop to intercept more radiation, increase root development and apportion more of the water extracted by the roots to transpiration.

The LUE decline was more pronounced after the attainment of peak LAI in all treatments. This was due mainly to pearl millet leaf senescence which was accompanied by reduction in LAI. Liu et al. (2010) found that LAI development during the late flowering stages of pearl millet growth is more critical for PAR interception than during vegetative and late reproductive periods. The decline in pearl millet LAI due to leaf senescence was indicated by the increase in leaf extinction coefficient (λ). It thus implies that pearl millet LUE was majorly affected by the changes in the orientations and geometry of LAI. This was demonstrated by the strong and positive ($p < 0.001$) correlation of PAR with LAI across moisture conservation techniques (Fig. 6.0) indicating that LAIs accounted for more than 81% of the variability in the PARs, and therefore LUE (Table 7.0).

Other studies have demonstrated that canopy architecture has a direct relationship with the interception efficiency of both direct and diffuse irradiance (Valladares and Pearcy, 2000) and that light interception decreases exponentially from top to bottom of a canopy (Liu et al., 2010).

The significantly higher LUE of pearl millet in tied ridge treatments receiving fertilizer at microdose rates (T8) and recommended rates (T9) is attributed to the higher moisture content maintained by tied ridge technique. This enhanced N and P supply resulting in their uptake by pearl millet. This greatly increased canopy leaf area and light interception resulting in greater LUE. Explanation of this phenomenon is based on the fact that nitrogen content of leaves is distributed in a canopy in relation to the light gradient, resulting in optimization of canopy photosynthesis (Valladares and Pearcy, 2000). This observation thus supports previous studies which have demonstrated that LUE increases with increasing leaf N and photosynthesis (Monteith, 1977; Li et al., 2008). The increased LUE of pearl millet in treatments receiving fertilizer either at microdose or recommended rates across the moisture conservation techniques than in zero fertilizer treatments could be related to the increased biomass production. Increased nutrient levels due to fertilizer application resulted in assimilation of photosynthates towards the sink organs leading to more biomass accumulation.

The significantly lower LUE in 2014 short rains than in 2014 long rains is ascribed to the effect of water stress which was more pronounced in the 2014 short rains season leading to progressive reduction in the LUE. This is in accordance with the previous studies which have shown that water stress affects foliage expansion and eventually radiation capture (Stone et al., 2001; Inman-Bamber, (2004). In a long term study to monitor the effects of hedgerow intercropping in rotation with maize and cowpea in a senna/siamea and panicum/grass strip on light use efficiency, Kinama et al. (2011) found that moisture stress subjected to maize by roots of senna extending to the middle maize rows depressed maize growth which contributed to lower PAR interception. Kinama et al. (2011) further observed that the rainfall amounts though well distributed over the seasons constrained photosynthesis and consequently yield and light use efficiency of maize because it was fairly low and below the long term average for the area. It has also been observed that drought and too low nutrient supply might also affect the seasonal LUE (Kinama et al., 2011). This implies that any approach that increases soil moisture and nutrient availability can increase LAI and lengthen the value of leaf area duration resulting in enhanced formation of grain yield which increases the LUE.

CHAPTER SIX

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The highest pearl millet grain and biomass yields occurred with the use of tied-ridge technique. This technique was associated with increased nutrient uptake and enhanced use efficiency of light, nutrient and water. Tied ridge technique stored more rain water immediately above the crossties, retaining it at the lowest point against the surface flow and permitting more time for the water to infiltrate. The increased soil moisture content under tied ridge resulted into enhanced nutrient availability which encouraged nutrient uptake. Point application of fertilizer employed in microdosing caused pearl millet roots to develop lateral roots within the nutrient-rich top soil, boosting nutrient acquisition. A reduction of leaf extinction coefficient in tied ridge-microdose was indicative of vertical leaf orientation leading to more even penetration of light into the canopy, and may have therefore ensured more uniform distribution of photosynthesis across the canopy.

It is thus concluded that the positive effect of fertilizer micro-dosing in increasing pearl millet yield resulted from the better exploitation of limited soil nutrients due to early lateral roots proliferation within the topsoil and to the increased soil moisture contents, coupled with enhanced light interception and use efficiency. The increase in pearl millet water use and water use efficiency under tied ridge technique was mainly caused by the increase in grain yield as a result of higher water storage capacity from the natural rainfall.

The results also showed that seasonal variations play a significant role in pearl millet productivity. This was mainly attributed to not only the amount, but also the distribution and intensity of rainfall.

Significantly low pearl millet yield recorded in 2014 short rains was due to the dry period, but even in this year, a good yield was obtained under tied ridge technique as compared to that of basin and flat techniques. This therefore, indicates that effective *in situ* moisture conservation is important for enhancing pearl millet yields in rainfed agriculture.

There was however, no significant yield increase to application of the higher recommended rates of N and P fertilizers in the two seasons compared to microdose rates in tied ridge technique. This implies that combined tied- ridge and fertilizer microdosing is capable of providing the optimal nutrient requirement for pearl millet growth in semi-arid areas. This strategy can therefore save the small-scale farmers from the costly large amounts of fertilizer applied at recommended rates.

6.2 Recommendations

1. The results of this study suggest that combined application of fertilizer-microdose and tied ridge moisture conservation can potentially increase pearl millet yields in the Kenyan arid and semi-arid environments where the crop is increasingly being grown. This study therefore recommends this practice to be incorporated into smallholder farming systems to increase resilience against droughts.
2. This study did not consider the cost of making the tied ridges which may be expensive to the smallholder farmers, especially if they have to construct new ridges at start of every season and therefore invites further studies.
3. Further experimental work also deserves being conducted to assess the combined effect of fertilizer microdosing and tied ridges on small scale farmers’ income and livelihoods.

4. For microdose to be more effective in raising pearl millet yields and positively impact the water balance on farmers' fields, the technology's current fertilizer combinations should be tried with modest manure applications to raise millet water use and yields.

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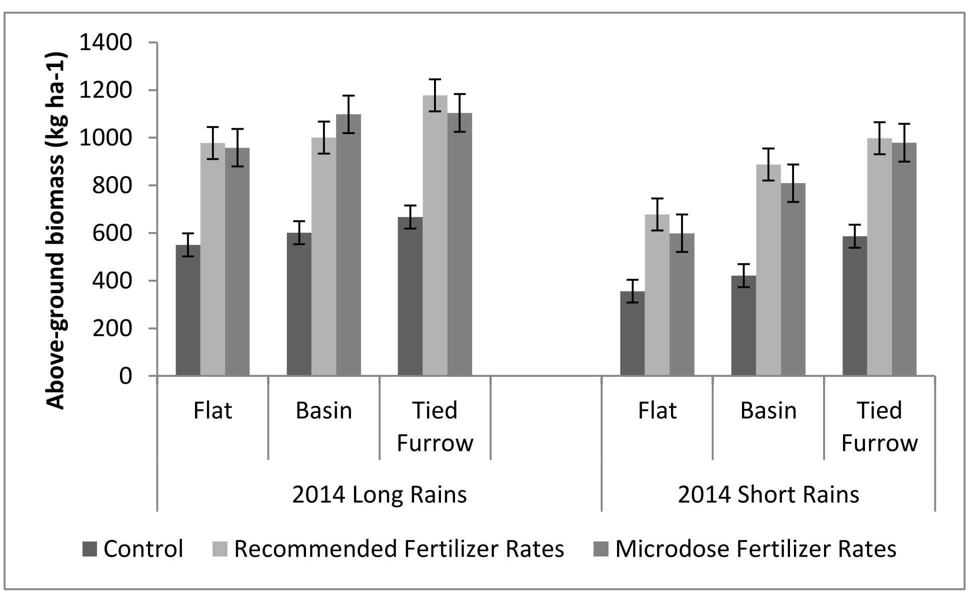
APPENDICES

Appendix 1.0: Moisture conservation techniques effect on pearl millet grain yield

Dependent Variable= Grain Yield				
Independent variables	Coefficients	Standard Error	T	p>│t│
Flat control (T1)	0.000	(base)		
Basin control (T2)	2.087	1.451	1.438	0.002
Tied ridge control (T3)	2.267	1.132	2.003	0.071
Flat microdose (T6)	0.089	1.134	0.078	0.952
Flat recommended (T5)	1.070	1.312	0.816	0.419
Basin microdose (T4)	2.382	1.236	1.926	0.061
Basin recommended (T7)	2.154	1.231	1.750	0.090
Tied ridge microdose (T9)	2.154	1.231	1.750	0.030
Tied ridge Recommeded (T8)	3.003	1.242	2.417	0.020

Appendix 2.0: Effect of fertilizer microdosing and *in situ* moisture conservation on pearl millet biomass yield



Appendix 3.0: ANOVA for panicle diameter 2014 long rains

Variate: Panicle_diameter_cm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	0.2808	0.0936	0.29	
Rep.*Units* stratum					
Treatment	8	27.5589	3.4449	10.77	<.001
Residual	24	7.6767	0.3199		
Total	35	35.5164			

Appendix 4.0: ANOVA for panicle diameter 2014 short rains

Variate: Panicle_diameter_cm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	1.2031	0.4010	1.49	
Rep.*Units* stratum					
Treatment	8	29.2972	3.6622	13.59	<.001
Residual	24	6.4694	0.2696		
Total	35	36.9697			

Appendix 5.0: ANOVA for panicle length 2014 long rains

Variate: Panicle_length_cm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	3.4200	1.1400	3.70	
Rep.*Units* stratum					
Treatment	8	100.2272	12.5284	40.66	<.001
Residual	24	7.3950	0.3081		
Total	35	111.0422			

Appendix 6.0: ANOVA for panicle length 2014 short rains

Variate: Panicle_length_cm

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	3.1942	1.0647	2.20	
Rep.*Units* stratum					
Treatment	8	86.1522	10.7690	22.24	<.001
Residual	24	11.6233	0.4843		
Total	35	100.9697			

Appendix 7.0: ANOVA for pearl millet water use efficiency 2014 short rains

Variate: WUE

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	0.005382	0.001794	1.01	
Rep.*Units* stratum					
Treatment	8	7.399398	0.924925	519.66	<.001
Residual	24	0.042717	0.001780		

Total 35 7.447497

Appendix 8.0: ANOVA for pearl millet water use efficiency 2014 long rains

Variate: WUE_LR

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Rep stratum	3	0.03877	0.01292	0.43	
Rep.*Units* stratum					
Treatment	8	12.66274	1.58284	52.88	<.001
Residual	24	0.71844	0.02993		

Total 35 13.41994