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Effect of *in situ* moisture conservation techniques on yield and water use efficiency of pearl millet in Makueni, Kenya

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Abstract

Pearl millet (*Pennisetum glaucum* L.) production in semi-arid areas of Kenya is constrained mainly by moisture deficit. A field study was conducted in Makueni, Kenya during the 2014 short and long rainy seasons to determine the effect of *in situ* moisture conservation techniques on yield and water use efficiency of pearl millet. Treatments comprised of basin technique, tied ridge technique and flat technique as the control. Soil moisture content was monitored and analyzed gravimetrically throughout the growing season at 2 weeks interval. Pearl millet yield parameters (panicle number, panicle weight and grain and stover yields) were assessed at physiological maturity using standard procedures. Harvest index was determined as a ratio of grain yield to total aboveground biomass. Pearl millet water consumption and water use efficiency were estimated using water balance equation. Soil moisture content varied significantly ($p < 0.05$) between the treatments and was consistently highest in tied ridge and lowest in control. Tied ridge technique increased pearl millet grain yields by up to 262kg ha^{-1} and stover yield by a maximum of 638kg ha^{-1}over control. Tied ridge recorded the highest water use of 167.2mm in 2014 short rains and 177.6mm in 2014 long rains. Highest pearl millet water use efficiency of 3.99kg ha^{-1}mm^{-1} was recorded in tied ridge indicating higher resource utilization efficiency of this technique. These results assert the potential use of tied ridge in improving yield and water use efficiency of pearl millet in semi-arid areas.

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Introduction

Pearl millet (*Pennisetum glaucum* L.) productivity in semi-arid areas is primarily limited by low and erratic rainfall (Akram *et al.,* 2012). 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 is often accompanied by large amounts of surface runoff. This runoff can however, be trapped *in situ* and encouraged to infiltrate and become available to crops. One way of doing this is through adoption of *in situ* soil moisture conservation techniques. Such techniques include pot-holing, tied ridging, furrow sowing, earth and stone bunding, pit planting and mulch ripping (Abubaker *et al.,* 2015). These water harvesting techniques increase infiltration and soil water storage and decrease water losses by surface 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 and Deotalu, 2015). By so reducing runoff through increased infiltration and storage of water in the soil profile, the onset and occurrence of severe water stress is delayed thereby buffering the crop against damage caused by water deficits during dry periods (Nyamadzawo *et al*., 2013). 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). Kinama *et al*., (2005) noted that reduced soil evaporative losses under mulches can provide additional 20–25 mm soil moisture for crop transpiration.

The first effect of water deficit on pearl millet growth is reduced leaf and tillers number (Golombek and Al-Ramamneh, 2002; Ayub *et al.,* 2009) and decreased shoot and height growth (Stone *et al.,* 2001; Soler *et al.,* 2007). This lowers pearl millet leaf area index development which compromises light interception, thus leading to less allocation of biomass to stem and grain (Mina *et al.,* 2011; Nagaz *et al.,* 2009; Wang *et al.,* 2006). A considerable reduction also occurs in the pearl millet stomatal conductance, leading to an interruption of CO_2 assimilation. Under such conditions, the water reserves of the plants may be consumed leading to death of pearl millet plants (Sinclair, 2000). Alam (1994) reported that phosphorous deficiency 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 (Premachandra *et al*., 1990). Tanguilig *et al*. (1987) however, observed an increase in uptake of potassium in pearl millet with increasing water stress indicating that K is absorbed preferably to N and P under water-stress conditions.

Technologies which enhance soil moisture contents *in situ* may make more nutrients available to plants and improve the effectiveness of fertilizer, especially in arid and semi-arid small-holder agricultural systems. This study therefore, assessed the effect of *in situ* water conservation techniques on water and nutrient use efficiency of pearl millet in a semi-arid area of Kenya.

Materials and methods

Description of the experimental site

The study was conducted at KARI-Kiboko Research Station located in Makueni County, Kenya during the short and long rainy seasons of 2014. KARI-Kiboko lies along longitudes 37.7235°E and latitudes 2.2172°S at an altitude of 975m above sea level (CIMMYT, 2013). The area falls in agro-ecological zone VI and 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).

Experimental design and trial management

The experiment was laid out in a randomized complete block design with three replications. Treatments comprised of flat technique (control), basin technique and tied ridge. Tied ridges were produced by scooping the soil towards the planting rows forming a 15cm deep furrow between the rows and placing a crosstie every one meter to hold water within the furrows. Basins were made by making ridges at 150cm apart and tied at 250cm interval. This produced 4 broad bed furrows in each plot. Flat technique entailed digging the field conventionally at 10cm depth using a hand hoe (farmers practice).

Pearl millet was planted at a spacing of 75 cm between the rows and 15 cm within the rows by placing 5 seeds per hill which were then thinned at 2 weeks after planting to 3 plants per hill. This gave a plant population of 150,000 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 in holes dug to about 10cm using hand hoes as conventionally practiced.

Di-ammonium phosphate (DAP) was applied as basal at recommended rates of 60kg/ha at planting and top dressed with 180kg/ha CAN at knee-height (ICRISAT, 1992). 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 rust. Birds were noted as the major pests and were controlled by scare-scows and casual guards. Pearl millet panicles were harvested from the 4 central rows on 10th August 2014 for the long rains and 15th February 2015 for the short rains which coincided with the maturity stages.

Soil moisture content determination

Soil samples were taken at 0-15cm and 15-30cm from five randomly distributed points within each plot, thoroughly mixed and immediately sealed in plastic bags.

The samples were weighed and oven dried at 105°C for 48 hrs then expressed as percent soil moisture content (Equation 1.0) (Okalebo *et al.*, 2002).

Gravimetric moisture content (%) =

$$\frac{\text{(wet weight - oven dry weight) (g)}}{\text{Oven dry weight (g)}} \times 100 \quad [1.0]$$

Measurement of rainfall data

Rainfall amount was recorded after every rainfall event using a manual rain gauge installed at the experimental site.

Assessment of yield parameters of pearl millet

Yield parameters data were taken from 4 middle rows leaving out the guard rows which corresponded to $4m^2$ land area. 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°C for 72 hours and expressed in kg ha^{-1} (Equation 2.0).

$$Yield\ (kg/ha) = \frac{Plot\ weight\ (g) * 10{,}000\ m^2}{Plot\ area\ (15) m^2 * 1{,}000} \quad [2.0]$$

Harvest index was determined as a ratio of grain yield to total above ground biomass (Equation 4.0) (Saha *et al.*, 2012).

$$\text{Harvest index (HI)} = \frac{\text{Grainyield (t ha}^{-1})}{\text{Dry aboveground biomass (tha}^{-1})} \quad [3.0]$$

A 1000 grain weight was determined by physical count of 200 dry matter grains randomly sub-sampled from the plot samples and weighed in grams. The weight was then expressed into a 1000 g weight by multiplying by 5 (Saha *et al.*, 2012).

Assessment of crop water use efficiency

Water use efficiency was calculated using the soil water balance equation (Equation 4.0).

$$ET = P + I - D + W_g - R + \Delta S, \quad [4.0]$$

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 (Δ*S*) 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 (Δ*S*) were determined from measurements of soil moisture (gravimetrically) at the beginning and end of each stage of growth (Equation 5.0).

$$\Delta S = (R + I) - (ET + D) \quad [5.0]$$

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).

$$\text{WUE (kg ha}^{-1}\text{ mm}^{-1}) = \frac{\text{Total biomass yield (kg ha}^{-1})}{\text{Evapotranspiration (ET) in mm}} \quad [6.0]$$

Data analysis

The data were subjected to analysis of variance (ANOVA) using Gen Stat statistical package (VSN International 2011). Means were compared using Fischer's protected least significant difference (LSD) test at 5% probability level. Multiple linear regression analysis was performed to determine the response of pearl millet yield to soil moisture conservation.

Results

Soil properties of the site before the experiment

The soil was typically sandy with low soil water holding capacity and was characterized by low soil moisture content prior to the experiment (Table 1.0).

Table 1. Soil physical and chemical properties of the experimental site.

Parameter	Content
Clay (%)	14.32
Silt (%)	10.23
Sand (%)	75.45
Soil water holding capacity (v/v)	22.01
Soil moisture content (%)	8.43

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 20mm per hour, lasting 30 min or less.

The rainfall amount received in the 2014 long rains (157.2mm) were higher than that of the 2014 short rains (99.7mm), but 40% below the long term average. The months of March and November accounted for 40% and 60% of the total rainfall received in the long and short rains respectively.

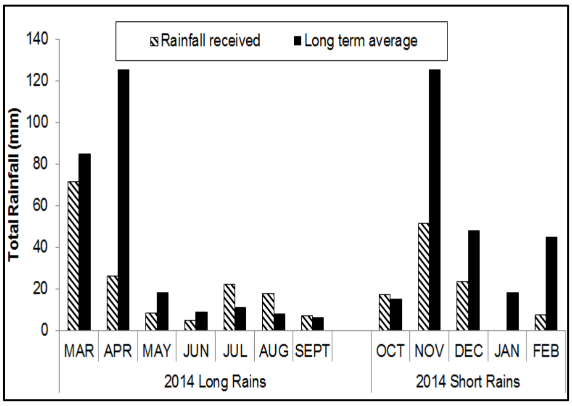

Fig. 1. Mean monthly rainfall of the study area in comparison with the 20 years average.

Soil moisture content as influenced by moisture conservation techniques

Soil moisture content varied significantly ($p<0.05$) between the treatments and increased with soil depth (Fig. 2.0). Moisture content was consistently highest in tied ridge with the values at 0-15 cm soil depth ranging between 32.4mm and 52.4mm in the long rains and 19.9 and 38.9mm during the short rains. Flat technique recorded significantly lower soil moisture content compared to the basin technique regardless of the sampling depth and season.

This moisture content ranged between 22.7mm and 37.8mm in the long rains and 12.0 and 12.4mm during the short rains. There was a sharp increase in soil moisture content across the treatments, ranging between 26.8mm and 48.9mm following rainfall event of 60 DAS in 2014 long rains, and 12.5 and 38.7mm in event of 100 DAS in 2014 short rains.

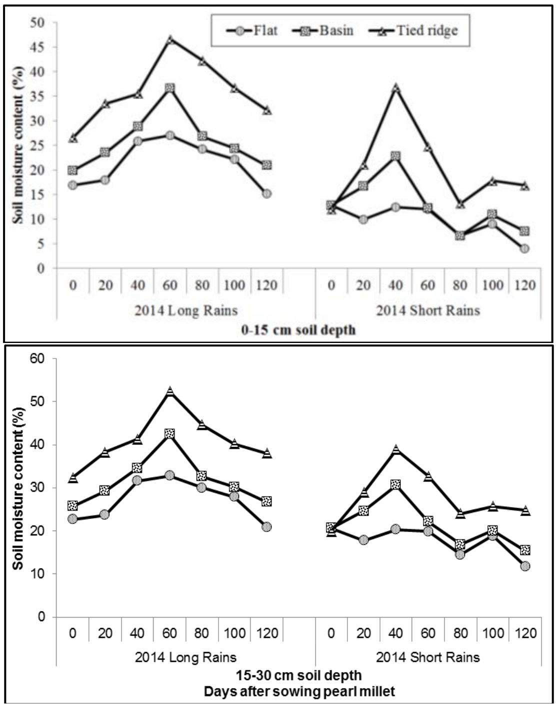

Fig. 2. Soil moisture trend at 0-15 cm and 0-30 cm depths.

Effect of soil moisture conservation techniques on pearl millet yield

Pearl millet stover and grain yields differed significantly ($p < 0.05$) between treatments (Table 2.0). Compared to the flat technique, tied ridge technique increased pearl millet grain yields from 320.5kg ha^{-1} to 482.5kg ha^{-1} in 2014 short ranis and from 376kg ha^{-1} to 638.0kg ha^{-1} in 2014 long ranis, an increase of 162 and 262kg ha^{-1} respectively.

Pearl millet stover yields increased from 672.1kg ha^{-1} in flat technique to 99kg ha^{-1} in tied ridge in 2014 short rains and from 998.2kg ha^{-1} to 1638.2kg ha^{-1} in 2014 long ranis. Basin and flat techniques recorded markedly low grain and stover yields compared to the tied ridge regardless of the seasons.

The 1000 pearl millet grain weight ranged between 52.2g and 55.2g in flat technique and tied ridge technique respectively during the 2014 short rains and 54.4g and 57.6g during the 2014 long rains. Compared to tied ridge technique, flat and basin techniques recorded significantly lower pearl millet grain yield regardless of season indicating that tied ridge provided the highest yield. The harvest indices were generally low, ranging from 0.21 to 0.28 during the 2014 short rains and from 0.27 to 0.33, yet common for pearl millet grown under dry land agriculture (Oluwasemire *et al.,* 2002; de Rouw, 2004).

Table 2. Pearl millet stover and grain yields as influenced by moisture conservation techniques.

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
	Grams				Kg ha^{-1}			
Flat technique	52.2a	54.4a	0.21a	0.27a	320.5a	376.0a	672.1a	998.2a
Tied ridge	55.2b	57.6b	0.28b	0.33b	482.5c	638.0c	998.0c	1638.2c
Basin	52.8a	54.6a	0.23a	0.26a	381.0b	384.2b	954.0b	1002.2b
$LSD_{0.05}$	2.21**	2.46**	0.042*	0.045*	8.95**	32.32**	37.31*	37.71*

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

Effect of moisture conservation techniques on moisture consumption by pearl millet

Tied ridge recorded significantly ($p < 0.05$) higher water use compared to flat and basin techniques regardless of the season (Fig. 3.0). Water use increased from 133.3mm in flat technique to 167.6mm in tied ridge during the 2014 short rains and from 151.2mm to 177.6mm in the 2014 long rains.

There were no significant differences in water consumption between the basin and flat techniques irrespective of the season. Water use was on average higher in 2014 long rains than in 2014 short rains indicating effect of season. In 2014 short rains with only 99.7mm of total rainfall, water use of pearl millet varied from 133.3mm in flat technique to 167.6mm.

With the relatively higher rainfall amount of 157.2mm in 2014 long rains, pearl millet used substantially more water, ranging between 151.2mm in flat technique and 177.6mm in tied ridge technique.

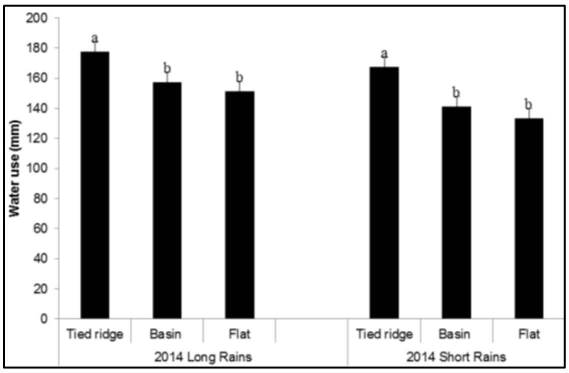

Fig. 3. Pearl millet water use during the experimental period. Vertical bars with different letters indicate significant differences at $p \leq 0.05$.

Water use efficiency of pearl millet under moisture conservation techniques

Highest WUE of pearl millet (3.99kg $ha^{-1}mm^{-1}$) was recorded in tied ridge treatment while the lowest value (3.47kg $ha^{-1}mm^{-1}$) was recorded in flat treatment in the 2014 long rains (Fig. 4.0). A similar observation was made in the 2014 short rains in which the pearl millet WUE ranged between 3.13 and 3.68kg $ha^{-1}mm^{-1}$ in flat and tied ridge treatments, respectively. Basin technique achieved significantly higher water use efficiency of 3.21kg $ha^{-1}mm^{-1}$ in 2014 short rains and 3.51kg $ha^{-1}mm^{-1}$ in 2014 long rains compared to the flat technique.

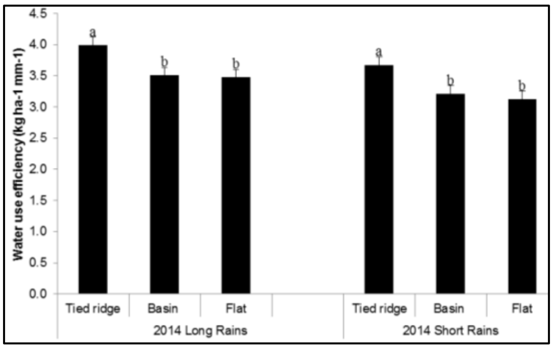

Fig. 4. Water use efficiency of pearl millet during the study period. Vertical bars with different letters denote significant differences at $p \leq 0.05$.

Discussions

Effect of soil moisture conservation techniques on soil moisture contents

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. Consistent results were observed by Abubaker *et al.,* (2015) who 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.

Basin and flat techniques had greater surface area exposed compared to the tied ridges which could have led to higher surface evaporation. This would be in line with the finding by Kinama *et al.*, (2005) who reported that soil evaporation losses account for a very high proportion of water loss in the water balance equation for the semi-arid areas of Kenya. Tied ridge conserved more moisture which enhanced pearl millet canopy development which minimized water 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.

The amount of rain which fell the first 3 weeks after planting did not contribute to any available soil moisture in all the treatments at 0-30cm depths. Kinama, (1997) found that soil moisture content at rainfall onset rarely gets available to plants as this time often find when the soil is bare and exposed to runoff and soil evaporation as very low canopy has developed. This rain might have also infiltrated to the lower soil horizons or evaporated.

The rapid increase in soil moisture content following rainfall events was ascribed to the profile moisture recharge from water infiltration. The availability of moisture at 0-30cm 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 (515mm) and very little amount in short rains (136mm).

Effect of water harvesting techniques on pearl millet yield

Highest grain and stover yield of pearl millet were recorded in 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 stover 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 technique may have also encouraged root proliferation thereby promoting better crop growth in the early season. This is in accordance with the observation by Ali *et al.*, (1998) who demonstrated that tied ridge increases soil moisture content which enhances pearl millet lateral root proliferation. Moisture stress conditions under flat and basin techniques may have however, reduced photosynthesis rate of pearl millet which in turn decreased the production of biomass and its partition among plant organs. Schmidhalter and Studer (1998) argued that adequate soil moisture content increases transpiration efficiency of the crop resulting into an increased yield. The effectiveness of tied-ridge in reducing surface runoff, improving soil water availability, delaying water depletion; all of which contributing to increased yields, have elsewhere been reported by Hayashi *et al.*, (2008).

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 2.0). 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 388kg ha^{-1} when 1.5m tied-ridges were used. 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 112kg ha^{-1} in years of sufficient rainfall (931 mm), 88kg ha^{-1} in years of medium to intermediate rainfall (760 mm) and 474kg ha^{-1} in years of low rainfall (621mm). 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.

Water use and water use efficiency of pearl millet as influenced by in situ moisture conservation

Sufficient moisture conditions in tied ridge technique increased ground cover development and contributed to reduced soil evaporative losses thus increasing pearl millet water use and water use efficiency. Monteith (1994) reported that early development of canopy cover helps the crop to intercept more radiation 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 asserted that highest WUE is achieved at the highest pearl millet 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. Water use increased with progressive increase in soil moisture content 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 was obtained in tied ridge technique which was characterized by higher soil moisture contents. Water stress in flat treatment however, restricted the yield attributes size.

Flat technique significantly lowered the WUE of pearl millet 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. This is in line with the argument by Ibrahim *et al.,* (2015) and Singh *et al.,* (2015) who attributed the decline in pearl millet yield under extremely low soil moisture levels to the higher nutrient concentrations.

Conclusion

The highest pearl millet grain and stover yields occurred with the use of tied-ridge technique. Tied ridges 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 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 available rainfall. The results also showed that seasonal variations play a significant role in pearl millet production. 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 with that of basin and flat techniques.

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