African Journal of Rural Development, Vol. 10 (1): pp. 31- 45 ISSN 2415-2838

Integration of Tied Ridges and Fertilizer Use Enhance Water and Nitrogen Use Efficiencies for maize production in Semi-Arid Lands

ALWANG'A.K. S., NJOROGE, R., OTHIENO, C. and NGETICH, W.
Department of Soil Science, School of Agriculture & Biotechnology, University of Eldoret
P.O.BOX. 1125 – 30100, Eldoret, Kenya
*Corresponding author: susankelly2015@gmail.com

ABSTRACT

Low maize (*Zea mays* L.) production in arid and semi-arid lands (ASALs) has been attributed to inadequate soil moisture and declining soil fertility. This could be improved through enhanced water use efficiency (WUE) and nutrient use efficiency (NUE). During the short rain (SR) seasons of 2013 and 2014, a study was conducted at Kenya Agricultural and Livestock Research Organization (KALRO) – Katumani Research Station to monitor WUE, NUE and grain yield in maize production. A 2*2*4 factorial trial of cropping seasons, soil moisture conservation (tied versus untied ridging) and fertilizer types (control, CAN, FYM, CAN + FYM) were set up in a Randomized Complete Block Design (RCBD). Interaction between tied ridged and FYM application had the largest WUE at 3.23 kg mm^{-1} ha^{-1}. Plots with FYM had the highest yield (222.9 kg ha^{-1}), which was 14% higher than CAN + FYM (165.8 kg ha^{-1}), 26% higher than CAN alone (128.8 kg ha^{-1}) and 28% higher than Control (127.4 kg ha^{-1}). On average, maize yields were 21% higher in 2013 than in 2014 SR. Application of FYM in tied ridges resulted in larger yields (294kg ha^{-1}) compared to untied ridges (152kg ha^{-1}). FYM (5.12 kg $grain^{-1}$ kg N^{-1}) and CAN (4.72 kg $grain^{-1}$ kg N^{-1}) plots under tied ridges had the largest NUE. Application of FYM in combination with CAN and tied ridges seemed to be the best bet for increased maize yields through enhancing both NUE and WUE.

Keywords: arid and semi-arid lands, Kenya, maize yield, short rains (SR), soil moisture, untied ridges

RÉSUMÉ

La faible production de maïs (Zea mays L.) dans les zones arides et semi-arides (ASALs) est attribuée à un déficit hydrique du sol et à la baisse de la fertilité de ce dernier. Des améliorations sont envisageables grâce à un renforcement concomitant de l'efficacité de l'utilisation de l'eau (EUE) et de l'efficacité de l'utilisation des nutriments (EUN). Pendant les saisons de petites pluies (short rains, SR) de 2013 et 2014, une étude a été conduite à la station de recherche du Kenya Agricultural and Livestock Research Organization (KALRO) – Katumani pour évaluer l'EUE, l'EUN et le rendement grainier en maïs. Un dispositif factoriel 2 × 2 × 4 a été mis en place selon un plan en blocs complets randomisés (RCBD), combinant deux campagnes culturales (deux saisons de petites pluies), deux techniques de conservation de l'humidité du sol (billons retenus, *tied ridging* vs. billons non retenus), et quatre types de fertilisants (témoin, CAN, fumier de ferme — FYM —, et combinaison CAN + FYM).

Cite as: Alwanga, A. K. S., Njoroge, R., Othieno, C. and Ngetich, W. 2025. Integration of Tied Ridges and Fertilizer Use Enhance Water and Nitrogen Use Efficiencies for maize production in Semi-Arid Lands. African Journal of Rural Development 10 (1):31-45.

L'interaction entre l'usage de billons retenus et l'application de fumier de ferme a abouti à la plus forte EUE (3,23 kg mm^-1 ha^-1). Les parcelles traitées au fumier de ferme ont affiché le rendement le plus élevé (222,9 kg ha^-1), soit 14 % supérieur à la combinaison CAN + FYM (165,8 kg ha^-1), 26 % plus élevé que le CAN seul (128,8 kg ha^-1) et 28 % supérieur au témoin (127,4 kg ha^-1). Sur l'ensemble, les rendements en maïs ont été supérieurs de 21 % en 2013 par rapport à 2014. L'application de fumier de ferme avec billons retenus a permis d'obtenir un rendement moyen de 294 kg ha^-1, contre 152 kg ha^-1 pour des billons non retenus. Les parcelles traitées au fumier de ferme (5,12 kg grain^-1 kg N^-1) et au CAN (4,72 kg grain^-1 kg N^-1) sous billons retenus ont présenté l'EUN la plus élevée. L'association du fumier (FYM) et du CAN, couplée à la pratique des billons retenus, apparaît ainsi prometteuse pour optimiser simultanément l'EUN et l'EUE, et accroître considérablement la production de maïs dans ces zones semi-arides.

Mots-clés : zones arides et semi-arides, Kenya, rendement en maïs, petites pluies (SR), humidité du sol, billons non retenus

INTRODUCTION

Agricultural production in Sub-Saharan Africa (SSA) relies on rain-fed agriculture (Mutuku *et al.*, 2020). Over 95% of smallholder agricultural land in SSA and approximately 70% of Kenya's marketable produce is obtained from rain-fed farming. In Kenya, over 80% of land is classified under arid and semi-arid lands (ASALS) based on the relatively low amounts of annual rainfall received. Kenyan economy is dependent on agriculture with maize contributing significantly to food security and the national economy (Wandaka, 2016). However, in Machakos County, maize production is barely 1t ha^{-1} per season from farmers, compared to over 2.0 t ha^{-1} obtained from research stations and in commercial farms (Kwena *et al.*, 2018). The low yield is primarily caused by scarce and erratic rainfall, poor agricultural water management practices and degraded soil quality (Recha *et al.*, 2016). Practices that increase water retention and soil fertility increase yields, and are therefore required.

Water is a critical factor in influencing crop production and its scarcity contributes to decline in agricultural productivity hence the need to improve crop production with minimal water consumption (Rahman *et al*., 2017). Furthermore, soils in the ASALS are inherently low in essential plant nutrients, particularly nitrogen (N) and phosphorus (P) (Kwena *et al*., 2017). Nitrogen is a vital plant nutrient and a major yield determining factor required for maize production. Nitrogen requirements for dryland areas highly depends on the conserved soil moisture (Felziasl *et al.*, 2016). Soil water conservation and soil available nitrogen contents are crucial for increasing maize yield. Availability of adequate soil water and nutrient contents can regulate root growth, delay leaf senescence, and promote grain filling and yield (Wu *et al*., 2022). Enhanced water use efficiency (WUE) and Nutrient use efficiency (specifically nitrogen) are, therefore, crucial in arid and semi-arid regions for sustainable agricultural productivity to be attained in a context of limited water availability and soil degradation (Afreh *et al*., 2018).

In an area where rainfall is low and poorly distributed, higher food production thus food security can be achieved by increasing crop WUE (Wadzanayi and Stroosnijer, 2014).Therefore WUE assessment is crucial in addressing effectiveness of water utilization in agricultural production (Koech and Langat, 2018). Appropriate agronomic practices in ASALs can enhance WUE to sustain crop production and minimize crop failure (Sharma *et al.*, 2015).

To increase nitrogen use efficiency (NUE) by maize, a clear understanding of NUE mechanisms, such as utilization of appropriate N fertilizer sources, application rate, time, soil and water management and cropping system is required (Qiu *et al*., 2015).In practice NUE can be improved through proper soil and water management practices (Qiu *et al*., 2015). Nitrogen use efficiency optimization, under different agro ecological conditions, is a management strategy for increasing crop production and reducing both N losses and farmers' input costs (Habbib *et al*., 2016).

Another vital factor affecting soil properties and crop yield is soil tillage. It affects the sustainable use of soil resources through its influence on soil properties (Alam *et al*., 2014). Soil tillage influences N dynamics in the soil by affecting soil aeration, microbial activities, organic matter (OM) decomposition and nutrient availability (Wasaya *et al*., 2017). On the other hand inappropriate tillage may cause a variety of detrimental outcomes, for example, soil structure destruction, accelerated erosion, loss of organic matter and fertility, disruption in cycles of water, organic carbon, (Alam *et al*., 2014).

Tied ridges and other soil and water conservation practices coupled with soil fertility practices can curb soil moisture stress and improve crop productivity (Zhao *et al*., 2018). When ridges are tied, rectangular pools are created between ridges which increase water surface retention capacity and reduce water runoff, resulting in improved soil moisture content and, as a result, enhance crop development and yields (Mak-Mensah *et al*., 2021). However, the beneficial effects of tillage systems such as tied-ridging on crop yield vary due to differences in amount and distribution of rainfall, soil type, slope, landscape position, crop type and time of ridging (Bekele and Chemeda, 2022). Tied ridging is effective in areas receiving low to medium rainfall, freely drained soils and gentle slopes. Severe storms can lead to ridge overtopping, ridge failure, waterlogging and total loss of crop (Bekele and Chemeda, 2022). On heavy (clayey) soils, it is difficult to construct and maintain tied ridges while in coarse-textured soils, regardless of seasonal rainfall amount, maize crop may not benefit from tied ridging. Maize crop is likely to benefit from tied ridging when in fine-textured soils and for seasonal rainfall between 500-900 mm (drought or dry years). Furthermore, in normal or wet years, tied-ridging is likely to lead to waterlogging in fine but not coarse-textured soils (Bekele and Chemeda, 2022). This study thus assessed the interaction effect of tied ridging and fertilizer use on NUE and WUE of maize grown in two short rainy seasons in a semi-arid environment.

MATERIALS AND METHODS

Study area. The study was conducted at KALRO–Katumani, National Dry Land Farming Research Centre (1º35'S and 37º14'E), which is a gently sloppy (1%slope) area. Machakos County falls under the upper midland 4 (UM 4) agro ecological zone, described as the sunflower-maize zone (Jaetzold *et al*., 2007). It is a hot and dry region receiving bimodal (two-season) type of rainfall, with long rains spread from mid-March to May (MAM) with a peak in April while short rains begin from mid–October, peaking in November and ending in December (OND) (Jaetzold *et al*., 2007). A dry spell between June and September separates the two rainfall seasons. Rainfall data for 25 years (1990 – 2014) were obtained from KARI Katumani in Machakos County having a long-term mean of 730.1mm (Huho, 2017). Katumani station receives about 309.9mm and 298mm of rain during the MAM and OND seasons respectively (Huho, 2017). Even though the short rains receive less amount of rainfall, they are more reliable because the rains more evenly distributed; hence more important for crop production (Jaetzold *et al*., 2007, Kwena *et al*., 2017). Temperature and evaporation rates are generally high with February and September being the hottest months of the year. Minimum mean annual temperatures vary from 14˚C to 22˚C while maximum mean annual temperatures vary from 26°C to 30°C (Jaetzold *et al*., 2007). Evaporation rates (ETo) are high and exceed the amount of rainfall (r) except in November. Mean potential evaporation ranges between 1820 and 1840 mm per year, whilst evapotranspiration is estimated to be 1239 mm giving an r/ETo ratio of 0.57 (Kwena *et al*., 2017). Chromic Luvisols, (WRB, 2015) dominate this region. Soil samples taken from the experimental site for characterization (Table 1) showed that the soil had a sandy clay loam texture at the 0 – 20cm depth surface with a dark red to reddish-brown hue (Sharma *et al*., 2015). It was moderately acidic (pH 5.6) with low organic carbon (0.5 – 1.5%) and low phosphorous (< 10mg P kg^{-1}). It also had low nitrogen (<0.25%), exchangeable potassium and magnesium at 0.74 and 1.84 $cmol_c$ kg^{-1}, respectively. The levels of exchangeable calcium ions (3.34 cmolc kg^{-1}) were moderate (Table 1).

Table 1. Physicochemical properties of soils from the study site at 0-20cm depth

	Measured values	Reference values	Interpretation
pH (1:2.5 soil water)	**5.60**	5. 0 – 6.0	Moderately acidic
*P (mg kg^{-1})	**4.05**	< 10	Low
Organic carbon (%)	**0.78**	0.5 – 1.5	Low
Total N (%)	**0.18**	0.12 – 0.25	low-moderate
K ($cmol_c$ kg^{-1})	**0.74**	0.2 – 1.5	Moderate
Ca ($cmol_c$ kg^{-1})	**3.34**	2 – 10	Moderate
Mg ($cmol_c$ kg^{-1})	**1.84**	1 – 3	Moderate
Texture			
% sand	56		
% clay	32		
% silt	12		
Textural class	Sandy clay loam		
Soil type (WRB,2015)	Chromic Luvisols		

*All analytical procedures for the measured parameters were adopted from Okalebo *et al*., 2002

Field Trial design. Field trials conducted at KALRO Katumani, Machakos County were of 2*2*4 factorial laid in Randomized Complete Block Design (RCBD). The trial factors comprised two cropping seasons (SR 2013 and SR 2014), two moisture conservation techniques (tied and untied ridges) and four fertilizer sources. The fertilizer sources were; Control, where no fertilizer was used (W0F0 and W1F0 plots), sole application of farmyard manure (FYM) (W0F1 and W1F1 plots), sole application of Calcium Ammonium Nitrate (CAN) (W0F2 and W1F2 plots) and combined use of CAN and FYM in the W0F3 and W1F3 plots. Both soil conservation techniques and fertilizer sources were replicated four times totaling 64 plots. Each plot measured 5.4m×3.6m with a 1m strip while a 3m strip separated the blocks. Prior to application, FYM was analyzed for total N, available P and exchangeable cations (Ca, Mg, K) following the procedures outlined by Okalebo *et al.*(2002). It contained 1.26%N, 7.4% Organic carbon and 78.5 P

Establishment and maintenance of the field trials. Preset trial plots were prepared manually and a medium tilth established. Tied ridges, a series of closely spaced rectangular depressions (basins), were installed during seedbed preparation. The created basins retain surface runoff within the field. Spacing of the ridges was 90cm tied at 2.5m intervals. Ridges were 30cm high and ties (cross ridges) 20cm high. Cross-ties were made lower than the ridges to act as spillways in the event of heavy rainfall in such a manner that if full, the overflow was within the furrows but not down the slope (Bekele and Chemeda, 2022).

Planting was done at the onset of the rains from 6th to 13th November 2013, for SR 2013 and 5th to 12th November 2014 for SR 2014. The test crop, maize, KDV-1 (Katumani Drought Variety) was used in the experiment owing to its early maturity and good adaptability in the study area (semi-arid conditions). Two seeds were planted per hole at a spacing of 90cm between the rows with 30cm within each row on top of the ridges. A blanket application of 26kg P ha^{-1} in the form of Triple superphosphate (TSP 0-46-0), was applied per planting hole for all treatments. Farmyard manure was applied at planting time at a rate of 63kg N ha^{-1} by spot application. CAN was applied as a top dress four weeks after planting at a rate of 20kg N ha^{-1}. Thinning was done four weeks after germination to one plant per hole to reduce competition for nutrients and moisture and to promote uniform crop growth. First, weeding was done using a hand hoe, after four weeks and subsequently by hand pulling. Pest and disease incidences were minimal during the growing period of the crop. However, routine spraying was done using Duduthrin (active ingredient: Lambda cyhalothrin 17.5g /L) to manage leaf-eating insects. The pesticides were sprayed four times during the growing period at an interval of 14 days.

Maize harvesting. An effective harvesting area of 3.4m x 1.6m was demarcated for harvesting from each plot after the maize had attained physiological maturity. The outer rows were discarded from either side of the effective harvesting area to eliminate border effects. Fresh weight of aboveground biomass of the maize plants was recorded. Ears (maize cobs with grains) were separated from the entire biomass (stovers) and fresh weight recorded. Both stovers and ears were dried and their dry weights recorded. The ears were later hand-shelled and dry grain weight recorded for grain yield computations.

Rainfall measurements. During the study period, SR 2013 and SR 2014, daily rainfall data (mm) were obtained from the weather station in the research center using a /standard rain gauge (1 m above ground). The rainfall data were used to calculate of water use efficiency.

Soil moisture content measurements. During the start of the experiment, soil cores were taken to a depth of 20 cm from three randomly selected plots for determination of bulk density. The soil cores were dried in an oven at 105ºc for 48h (Jabro *et al*., 2021). Bulk density was then calculated following the procedures as outlined by Okalebo *et al.*(2002) using the Equation (Eq.1) below:

$$\rho b = m/v \qquad \text{Eq.1}$$

Where: - ρb = bulk density of the soil (g cm^{-3}), m = dry weight of the soil (g), v = sample volume (cm^3**).**

Thereafter, gravimetric water content was determined from core samples using equation (Eq.2) below: -

$$\Theta g = \frac{(W_{wet} - W_{dry})}{W_{dry}} \qquad \text{Eq. 2}$$

Where: - **Ɵg** =gravimetric water content,

Wwet = weight of the wet soil sample (g), **Wdry** = weight of the dried soil sample (g)

Volumetric soil water content, defined as the volume of water per unit volume of soil was computed by multiplying the obtained gravimetric water content by relative bulk density (ratio of bulk density of soil to the density of water (1 cm^3), using the equation (Eq.3) below as stated in Miriti *et al.*(2012):

$$\Theta = \omega * (\rho b \div \rho w) \qquad \text{Eq. 3}$$

Where:

Ɵ - volumetric water content (m^3 water/m^3 soil), ω -gravimetric water content (kg water/kg soil), ρb - soil bulk density (g cm^{-3}), ρw - water density (g cm^{-3}).

Soil moisture content was monitored using a neutron probe moisture meter, CPN 503-DR. Using an auger, access tubes were installed in each of the sub-plots before planting. The depth of interest was 0–20cm owing to the concentration of active roots at this level. Two points, **i.e**. field capacity and lower limit of water availability (wet/dry site) were obtained and used to calibrate the neutron probe as described by Evett.(2000). The neutron probe readings (neutron counts) were recorded fortnightly for SR

2013 and every three weeks for SR 2014. A graph of neutron counts against volumetric readings (obtained above) was plotted to develop a line of best fit with equation **y = mx + c**; Where **y** – gravimetric water content, **m** - gradient, **x** - is the neutron counts and **C** is the **y** interception, in this case, zero interception. Thereafter, all the neutron probe readings at the experimental site were multiplied by the **m** gradient obtained to convert to volumetric water content.

Water use efficiency computation. The amount of carbon assimilated as biomass or grain produced per unit of water used by the crop in form of evapotranspiration (ET) is what defines water use efficiency. The ET is the sum of water loss by evaporation from the soil and transpiration through the canopy and ET was quantified using hydrological method. It is founded on the principle of conservation of mass and estimated as described in Equation 4 (Eq.4) (Raes and Munoz, 2009):

$$ET = (P+I+C) - (R+D) - \Delta S \quad \text{Eq.4} \quad \Delta S = S_{initial} - S_{final}$$

where **P** is precipitation, **I** is irrigation, **C** is upward flow into the root zone, **D** is drainage, R is run-on or runoff and **ΔS** is the change in soil water content within the root zone at sowing ($S_{initial}$) and at harvesting (S_{final}). There was no irrigation (I), as the experiment was rain-fed. The upward flow into the root (C), was negligible. Runoff was not observed as the experimental field was relatively flat. There were no heavy rains or water logging events during the growing season, so drainage was assumed to be insignificant (Wang and Shangguan., 2015).

Consequently, ET was reduced to:

ET= P - ΔS Water use efficiency was calculated using the equation (Eq.5) described in Zhang *et al.*, (2021):

$$\textbf{WUE} = \left(\frac{\text{Grainyield } (kg/ha^{-1})}{ET\ (mm)}\right) \quad \textbf{Eq.5}$$

Nitrogen Use Efficiency (NUE)

This was calculated in units of yield increase per unit of nitrogen applied. It more closely reflects the direct production impact of applied fertilizer. The calculation of NUE requires knowledge of yield without nutrient input, so is only known when research plots with zero nutrient input have been implemented on the farm. NUE was calculated using equation 6 (Eq.6)

$$\textbf{NUE} = \frac{(Y - Y_0)}{F} \quad \textbf{Eq.6}$$

where; Y = yield of a harvested portion of the crop with nutrient applied (kgha1)Y0 = yield with no nutrient (N)+ applied/control yield (kg ha-1) F = amount of nutrient (N) applied (kg ha-1)

Statistical analysis Analysis of variance was executed on soil moisture, maize grain yield and water and Agronomic Nitrogen Use Efficiencies were generated using GENSTAT statistical software 14th edition. Treatments with significant differences were separated using Tukey's 95% confidence intervals.

RESULTS

Rainfall distribution during SR 2013 and 2014. There were large differences between the two study seasons (Figure 1). Cumulative seasonal rainfall in SR 2013 (347.1mm) was higher than in SR 2014 season (209.3mm) representing a 24.8% decline and a cumulative seasonal difference of 137.8 mm. Rainfall events for SR 2013 and SR 2014 occurred in 35 and 30 days with a cumulative dry spell of 81 and 86 days, respectively. Dry spell days for both seasons were approximately three times the number of rainy days hence uneven distribution. The highest rainfall amount during the SR 2013 was 119 mm (4th week after planting), while in SR 2014 season, this was experienced during the 14th week after planting (70.9mm). Both seasons had intra-seasonal drought periods occurring at different times between the 7th and 12th weeks of planting (Fig 1). In both seasons, the most critical month for rapid crop growth (January) had very little or no rainfall at all.

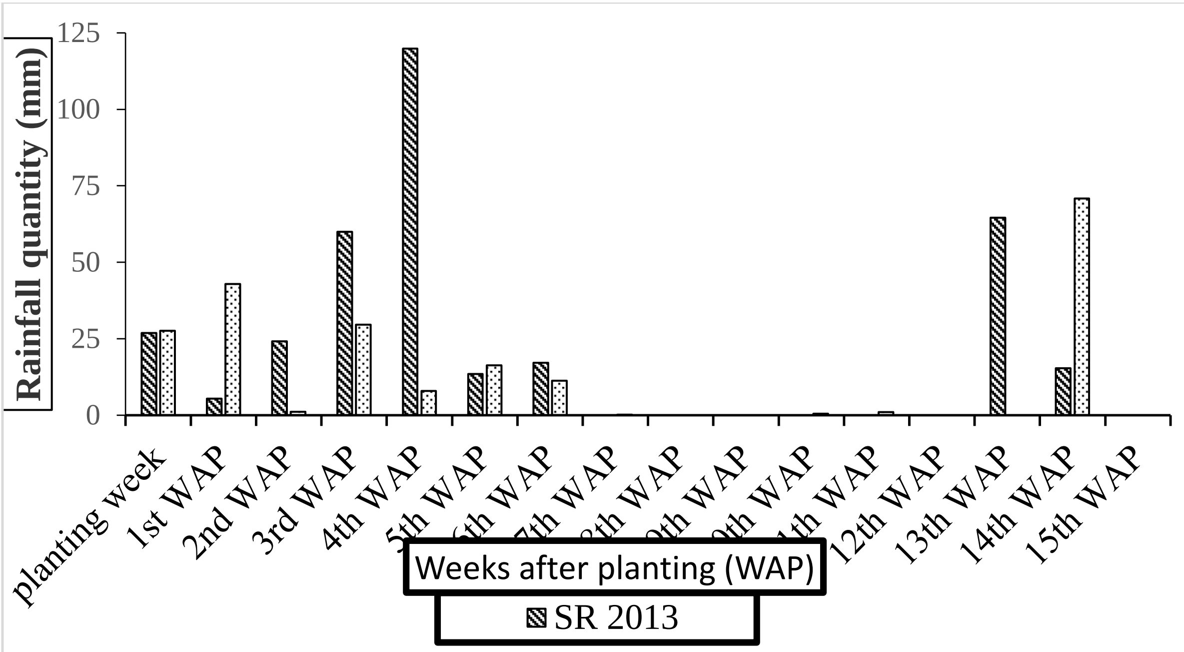

Figure 1. Amounts and distribution of rainfall during the study period

Soil moisture contents at Katumani during the cropping seasons as influenced by tied ridging and fertilizer application during SR 2013 and SR 2014 seasons. Generally, in both seasons, treatment combinations under untied ridges had more soil moisture than those in tied ridging (Figure 2). During 2013, tied ridging resulted in lower soil moisture (14.6%) compared to 17.2% observed from plots without ridging (untied ridging). Likewise, in 2014 SR, moisture recorded from untied ridges was 17.5% lower compared to 14.3% from plots with tied ridges.

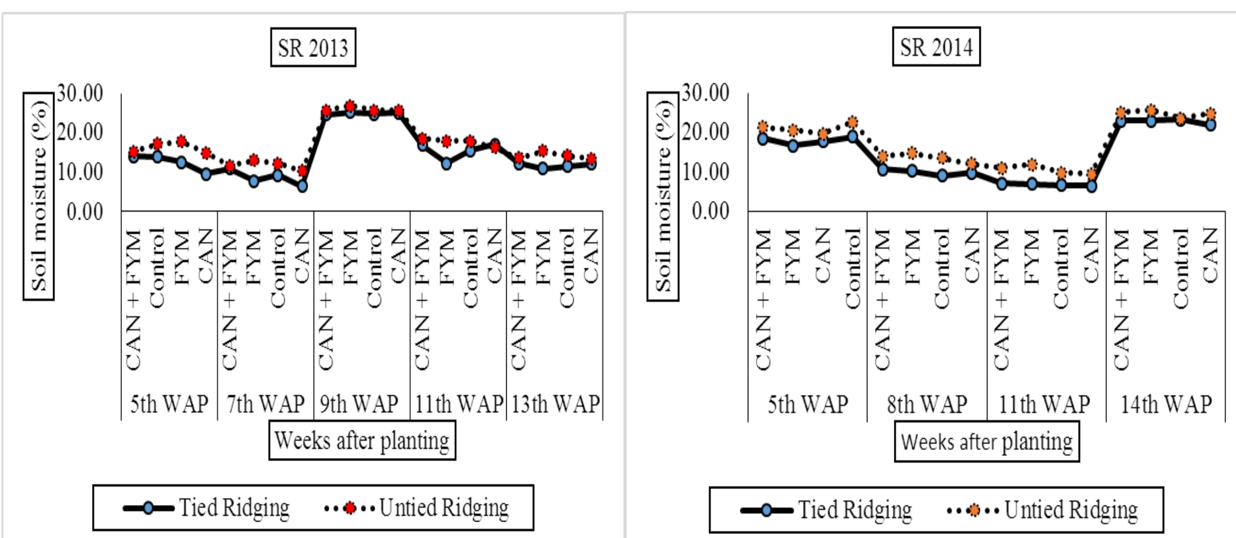

Figure 2. Soil moisture content (mm) per treatment in weeks after planting (WAP) during SR 2013 and SR 2014 seasons

Effects of tied ridging and fertilizer application on water use efficiency (kg ha^{-1} mm^{-1}) at Katumani during SR 2013 and SR 2014 seasons. All the treatments and their interactions had a significant effect on WUE regardless of seasons. Plots with tied ridges had higher WUE (1.87kg mm^{-1} ha^{-1}) compared to those with untied ridges (1.00kg mm^{-1} ha^{-1}) (Table 2). Plots with FYM (2.08kg mm^{-1} ha^{-1}) and FYM plus CAN (1.76kg mm^{-1} ha^{-1}) had higher WUE in comparison to sole application of CAN (1.02 kg mm^{-1} ha^{-1}). Tied ridge plus FYM plots recorded the largest WUE (3.23kg $mm^{-1}ha^{-1}$) regardless of seasons. It was followed by TR+CAN+FYM (1.86kg mm^{-1} ha^{-1}) which was followed closely by sole CAN (1.48kg mm^{-1} ha^{-1}) and the least was TR+ Control (0.89 kg mm^{-1} ha^{-1}).

Table 2. ANOVA table and means for effect of tied ridging and fertilizer application on WUE (kg mm^{-1} ha^{-1}) during SR 2013 and SR 2014.

Source of variation	Degree of freedom	Means of squares	F probability
Season	1	0.0523	0.608 ns
Ridging	1	12.0736	<.001 ***
Fertilizer source	3	5.4565	<.001 ***
Season*Ridging	1	1.4811	0.009 **
Season*Fertilizer source	3	1.5336	<.001***
Ridging*Fertilizer source	3	4.1853	<.001***
Season*Ridging*Fertilizer source	3	0.9333	0.006 **

	WUE (kg mm^{-1} ha^{-1})		
Treatments	**SR 2013**	**SR 2014**	**MEAN**
TR + Control	0.88	0.91	0.89^{ab}
TR + CAN	1.48	1.48	1.48^{bc}
TR + FYM	2.89	3.57	3.23^{d}
TR + CAN + FYM	1.50	2.23	1.86^{c}
MEAN	1.69	2.05	**1.87**
UTR + Control	1.38	0.30	0.84^{ab}
UTR + CAN	0.57	0.54	0.56^{a}
UTR + FYM	1.44	0.43	0.94^{ab}
UTR + CAN + FYM	1.10	2.23	1.66^{c}
MEAN	1.12	0.88	**1.00**
Grand mean	**1.41**	**1.46**	**1.43**

SED – Standard error of difference of means at P≤ 0.05; ***= significant at P = 0.001, ns- not significant, TR- Tied ridging, UTR - Untied ridging. Means followed by the same superscript within a column are not significantly different at 5% alpha level

Maize grain yield (kg ha^{-1}) in response to tied ridging and fertilizer application during SR 2013 and SR 2014 seasons at Katumani, Machakos County. The overall mean grain yield obtained over the two seasons was 161kg ha^{-1} (Table 3), irrespective of the experimental treatments. SR 2013 yielded higher than SR 2014 having 195kg ha^{-1} and 128kg ha^{-1}, respectively. Plots with tied-ridges gave 23% more grain yield (191kg ha^{-1}) than untied ridges (132kg ha^{-1}). FYM plots under tied ridging gave the highest mean yield of 294kg ha^{-1}.

Nitrogen use efficiency as influenced by tied ridging and fertilizer application. The grand mean NUE obtained during the two seasons was 1.50 kg grain-1 kg N-1 (Table 4). Ridging gave a mean NUE of 3.75kg grain-1 kg N-1 whereas untied ridges had -0.75kg grain-1 kg N-1. NUE was 3.05, 0.89 and 0.58kg of maize grain for each kilogram of nitrogen applied at 63 (FYM), 83 (CAN+ FYM) and 20kg ha-1 N (CAN), respectively. Interaction between ridging and fertilizer source was also observed with FYM (5.12kg grain-1 kg N-1) and CAN (4.72kg grain-1 kg N-1), both under tied ridging having the highest NUE. A negative NUE (-3.569 kg grain-1 kg N-1) was observed when CAN was applied without ridging. Further, 2013 tied ridged plots under FYM (6.62kg grain-1 kg N-1) and CAN (6.00kg grain-1 kg N-1) recorded the highest yields while NUE in 2013 CAN plots under flat ridges (-6.36kg grain-1 kg N-1) recorded low yield

Table 3. ANOVA table and table of means for effect of tied ridging and fertilizer application on maize grain yield (kg ha^{-1}) during SR 2013 and SR 2014

Source of variation	d.f.	m.s.	F pr.
Season	1	72727	0.002 **
Ridging	1	56053	0.005 **
Fertilizer source	3	32075	0.005 **
Season*Ridging	1	2	0.986 ns
Season*Fertilizer source	3	6242	0.417 ns
Ridging*Fertilizer source	3	27917	0.009 ***
Season*Ridging*Fertilizer source	3	6034	0.432 ns

	Grain Yield (kg ha^{-1})		
Treatments	**SR 2013**	**SR 2014**	**MEAN**
TR + Control	158 ^{abc}	47 ^{a}	102.2^{a}
TR + CAN	201 ^{abc}	158 ^{abc}	179.4^{ab}
TR + FYM	322^{c}	266^{bc}	294.1^{b}
TR + CAN + FYM	216 ^{abc}	159 ^{abc}	187.5^{ab}
MEAN	224	157	191
UTR + Control	184 ^{abc}	121 ^{abc}	152.6^{a}
UTR + CAN	93 ^{ab}	64 ^{ab}	78.3^{a}
UTR + FYM	237 ^{abc}	66 ^{ab}	151.6^{a}
UTR + CAN + FYM	148 ^{abc}	140^{abc}	144^{a}
MEAN	166	98	132
Grand mean	195	128	161

SED – Standard error of difference of means at P≤ 0.05; **, ***= significant at P≤ 0.05 and 0.001 respectively, ns- not significant, TR- Tied ridging, UTR - Untied ridging. Means followed by the same superscript within a column are not significantly different at 5% alpha level.

Table 4. Nitrogen use efficiency of various treatments at Katumani experimental site during SR 2013 and SR 2014 seasons.

Source of variation	Degree of freedom	Mean of squares	F probability
Season	1	0.3408	0.401 ns
Ridging	1	181.8428	<.001 ***
Fertilizer source	2	21.8673	<.001***
Season*Ridging	1	34.9578	<.001***
Season*Fertilizer source	2	13.4876	<.001***
Ridging*Fertilizer source	2	39.3436	<.001***
Season*Ridging*Fertilizer source	2	10.0261	<.001***

	NUE (kg grain^{-1} kg N^{-1})		
Treatment	**SR 2013**	**SR 2014**	**MEAN**
TR + CAN	6.00^{f}	3.44^{de}	4.72^{c}
TR + FYM	6.62^{f}	3.61^{e}	5.12^{c}
TR + CAN + FYM	1.30^{c}	1.54^{cd}	1.42^{b}
MEAN	4.64	2.86	**3.75**
UTR + CAN	-6.36^{a}	-0.78^{b}	-3.57^{a}
UTR + FYM	1.74^{cde}	0.24^{bc}	0.99^{b}
UTR + CAN + FYM	-0.86^{b}	1.55^{cd}	0.35^{b}
MEAN	-1.83	0.34	**-0.75**
Grand mean	**1.41**	**1.60**	**1.50**

SED – Standard error of difference of means at P≤ 0.05; **, ***= significant at P≤ 0.05and 0.001 respectively, ns- not significant, TR- Tied ridging, UTR - Untied ridging, CAN (20kgN ha^{-1}), FYM (63kgN ha^{-1}), CAN + FYM (83kgN ha^{-1}). Means across rows or columns followed by different letters are not significantly different at P≤ 0.05.

DISCUSSION

Soil moisture contents at Katumani during the cropping seasons as influenced by tied ridging and fertilizer application during SR 2013 and SR 2014 seasons Soil moisture content was affected during specific periods of maize growth. Untied-ridged plots consistently recorded higher moisture content in the soil compared to tied-ridged plots. This could be due to higher evaporation losses as a result of exposure of soil surface in plots under tied ridges unlike in untied ridged plots due to increased soil surface area (Karuma *et al*., 2014). While working in Machakos County, Karuma *et al.* (2014) observed that LR 2013 tied ridges had lower moisture levels (8.42%) compared to conventional tillage. The differences observed in soil moisture content in different weeks after planting could be related to the amount of rainfall received at that particular period, soil evaporation, transpiration and water crop uptake. The largest soil moisture levels were observed in the 13th WAP and 14th WAP for SR 2013 and SR 2014 seasons respectively. This coincided with the occurrence of high amounts of rainfall during these periods. During the SR 2014, plots with FYM had higher moisture content than CAN. This is in agreement with Miriti *et al*. (2012) who reported that manure improved overall mean available water content by 20% when compared with plots without manure. When farmyard manure is applied in sandy soils, it releases organic matter, which cements the soil particles together. The humus content formed from the manure could have helped in maintaining the soil's physical structure thus enhancing better soil moisture retention.

Effects of tied ridging and fertilizer application on water use efficiency (kg ha^{-1} mm^{-1}) at Katumani during SR 2013 and SR 2014 seasons Soil water use efficiency is an essential crop index used to assess how soil water is used efficiently for total biomass and grain yield. Tied ridges with fertilizer treatment had higher WUE than untied ridges. Oduor *et al*. (2023) also observed that WUE was enhanced by 50–65% by the tied ridges compared to conventional tillage. One of the components of a farm management system that affects WUE is soil fertility. In this case, plots with FYM had higher WUE than mineral fertilizer. This could be because manure boosts soil physical properties like soil structure since it acts as a binding agent thus reducing soil moisture loss. It also improves soil hydrological properties thus increasing WUE (Oduor *et al*., 2023). Kathuli and Itabari (2014) also stated that water use efficiency of crops is increased with addition of manures and fertilizers. Furthermore, FYM plots in tied ridges recorded highest WUE. Kathuli and Itabari (2014) Similarly stated that tied ridging with fertilizer application improved water use efficiency from 0.29 to 3.75 kg ha^{-1} mm^{-1}.

Maize grain yield (t ha^{-1}) in response to tied ridging and fertilizer application during SR 2013 and SR 2014 seasons at Katumani, Machakos County There was a difference in crop yields between the seasons which could have been brought about by variations in rainfall distribution and quantity. This is because rainfall amount and distribution are key to crop development and performance (Nathan *et al.,* 2020). The total amount of rainfall during the SR 2013 season was 24% higher than SR 2014. This could explain the 20% difference in yield between the two seasons. However, the distribution was more or less the same since both seasons had rains from the 1st week to the 6th week after planting, after which there was hardly any or no rain at all till the 13th week. The dry spell happened again on the 15th and 16th WAP. The shortages or dry spells in the midst of crop growth explains the generally low yields despite fertilizer application and water conservation measures. Plots with tied ridges gave 18% more grain yields than untied ridges. Karuma *et al.* (2014) who also worked in Machakos County Kenya, reported that, use of tied ridges made it possible to produce maize in low rainfall years in comparison to flat-planted crops gave minimal yields. This corroborates that findings of Adeboye *et al.* (2017), who reported that tied-ridge-furrow rainwater harvesting practices increased grain yield by 14.0–41.8% relative to flat planting. This could be attributed to larger amounts of soil water infiltrating the soil under tied ridging as compared to untied ridge thus enhancing crop response to fertilizer and rainfall.

Fertilizer application had an effect on maize grain yield in both tied and untied ridged plots. Plots with FYM had the highest yield (222.9 kg ha^{-1}), which was 14% higher than for that CAN + FYM (165.8 kg ha^{-1}), 26 % higher than CAN alone (128.8 kg ha^{-1}) and 28 % higher than Control (127.4 kg ha^{-1}). This could probably be due to greater soil water conserved by manure plots which probably enhanced plant nutrient supply and improved physical conditions. Even with poor rainfall during LR and SR 2008 seasons, Miriti *et al*. (2012) still recorded significant manure effects on the yield. They recorded 37% increase in maize grain yield in manure plots (1.22 Mg ha^{-1}) compared to treatments without manure (0.89 Mg ha^{-1}). FYM plots under tied ridging gave the highest mean yield. This might be because when tied ridge was coupled with FYM application, there was an improved soil physical conditions together with improved soil moisture retention hence higher crop yields. This is congruent to Kathuli and Itabari, (2014), findings that tied ridging with fertilizer application can increase crop yields by 100–359%. Mak-Mensah *et al,* (2021) they record also found that millet grain yield increased by 20% to 40% in tied-ridge-furrow treatments with fertilizer application compared to tied-ridge-furrow without mulching or fertilizer treatment.

Nitrogen use efficiency as influenced by tied ridging and fertilizer application Nitrogen Use Efficiency was determined to assess the efficiency of maize in utilizing nitrogen fertilizer for grain production. Tied ridges had 125 % higher NUE than untied ridges. This is probably because appropriate soil water content can promote the absorption and utilization of nutrients by crops and increase crop yield (Cao *et al*., 2023). Plots with FYM had highest NUE (3.05 kg grain^{-1} kg N^{-1}), which was 54% higher than for CAN + FYM (0.89 kg grain^{-1} kg N^{-1}) and 74 % higher than for CAN alone (0.58 kg grain^{-1} kg N^{-1}). This is in agreement with Kayuki *et al*. (2012) who reported that at a very high N application rate, the NUE declined despite the slight increase in grain yield. However, it contradicts Oduor *et al.* (2023) who found that integrated effect of animal manure and mineral fertilizer had a synergistic effect that improved nutrient use efficiency more than when either was used in isolation (Vanlauwe *et al*., 2015). Similarly, Salama *et al*. (2021) reported that combining mineral nitrogen and farmyard manure (FYM) results in a higher maize NUE compared to mineral nitrogen alone.

CONCLUSION AND RECOMMENDATION

Considering the inherent low soil fertility level of the ASALs of Katumani,, sole intervention through rainwater harvesting techniques may not have a substantial impact on crop productivity. There is a need to incorporate use of organic fertilizers to enhance the soil productivity. However, most farmers in such areas find it not worthwhile to invest in fertilizers (and other inputs) due to risk of crop failure and poor harvests emanating from periodic water shortages. Based on the results of this study, it can be concluded that tied-ridging resulted in a 30% increase on WUE and 125% increase in NUE with an overall 18% increase in grain yield of maize when combined with FYM application alone. Alleviating agricultural water deficit through the use of tied ridges may therefore encourage farmers to invest in soil enhancement practices (organic or inorganic fertilizers) for improved crop production in rain-fed regions. Therefore, a combined strategy of ridging and fertilizer application enhances crop yield. However, there is little information on how other conservation tillage systems will affect crop yield and nitrogen use efficiency under the same site conditions hence need to do more research on that.

ACKNOWLEDGEMENT

This study was supported by Association for Strengthening Agricultural Research in Eastern and Central Africa (ASARECA), through Kenya Agricultural and Livestock Research Organization (KALRO) –Katumani Research Station, International Atomic Energy Agency (IAEA). I am also grateful to University of Eldoret (Department of Soil Science) for the assistance accorded to the corresponding author

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest in this paper

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