THE EFFECTS OF INTEGRATED SOIL FERTILITY MANAGEMENT AND CROPPING SYSTEMS ON SOIL WATER CONTENT ON SORGHUM AND COWPEA PRODUCTION IN CENTRAL HIGHLANDS OF KENYA †

[LOS EFECTOS DE LA GESTIÓN INTEGRADA DE LA FERTILIDAD DEL SUELO Y LOS SISTEMAS DE CULTIVO SOBRE EL CONTENIDO DE AGUA DEL SUELO EN LA PRODUCCIÓN DE SORGO Y CAUPÍ EN LAS TIERRAS ALTAS CENTRALES DE KENIA]

Peterson N.M. Njeru[1,2*], Jayne Mugwe[2], Monicah Mucheru-Muna[2] and Stephen Kimani[1]

[1]Kenya Agricultural and Livestock Research Organization, P.O. Box 57811-00200, Nairobi, Kenya. Email: njerupeterson1@gmail.com
[2]School of Agriculture and Environmental Sciences, Kenyatta University, P.O. Box 43844-00100, Nairobi, Kenya.
**Corresponding author*

SUMMARY

Background: Soil fertility degradation remains the major biophysical cause of declining *per capita* crop production on smallholder farmers in Central Kenya highlands. The study was carried out for 3 consecutive seasons in Embu County classified as semi-arid lands in Kenya. **Objectives:** To determine the effect of Soil Water Harvesting (SWH), cropping systems and Integrated Soil Fertility Management technologies on sorghum and cowpea production in Mbeere South Sub-County, Kenya. **Methodology:** The treatments were arranged in a factorial structure with 3 levels of SWH, 2 cropping systems and 6 soil fertility management options laid out in a partially balanced incomplete block design. The SWC was measured after 2 weeks after planting interval stages in the whole season. Data were analyzed by ANOVA and significant means separated using Least Significant Difference (LSD) at 95% Confidence Interval. **Results:** There was a two way interactions effect between SWH*Fertility management options on sorghum grain yields was significant (p=0.0027, p=0.0008 and p=0.0057) during long rains (LR) of 2011 and 2012, and short rains (SR) of 2011, respectively. Additionally, SWH methods significantly affected sorghum grain yields in a similar trend (p=0.002, p=0.0005 and p=0.0003) in their respective seasons. In SR 2011 and LR 2012, soil fertility options also produced significant effects (p=0.0047 and p=0.0024) on cowpea grain yields, respectively. The results further indicated that there were significant higher SWC measurements at initial stages of 2 WAP, 4 WAP and 6 WAP intervals as compared to the late stages of the season. However, sole cropping systems had significantly more SWC measurement than those in intercropping systems in both seasons. **Implications:** Manure added treatments positively affected SWC conservation and this could be as a result of increased soil organic carbon which improved soil fertility. The available SWC played a great role in drought effect mitigation by availing moisture to sorghum and cowpea productivity especially when prolonged dry spells coincide with crop's sensitive phenological growing stages. **Conclusions:** Water harvesting methods cropping systems and soil fertility management options had positive influence on soil moisture conservation and crop yields production in Central Kenya Highland.

Key words: Smallholder farmers; soil water content; soil fertility management; phenological stages; climate change.

RESUMEN

Antecedentes: La degradación de la fertilidad del suelo sigue siendo la principal causa biofísica de la disminución de la producción agrícola per cápita de los pequeños agricultores de las tierras altas de Kenia Central. El estudio se llevó a cabo durante 3 temporadas consecutivas en el condado de Embu clasificado como tierras semiáridas de Kenia. **Objetivos:** Determinar el efecto de la recolección de agua en el suelo (SWH), los sistemas de cultivo y las tecnologías de gestión integrada de la fertilidad del suelo en la producción de sorgo y caupí en el subcondado de Mbeere Sur, Kenia. **Metodología:** Los tratamientos se dispusieron en una estructura factorial con 3 niveles de SWH, 2 sistemas de cultivo y 6 opciones de manejo de la fertilidad del suelo dispuestas en un diseño de bloques incompletos parcialmente balanceado. El SWC se midió después de 2 semanas después de las etapas de intervalo de siembra en toda la temporada. Los datos se analizaron mediante ANOVA y las medias significativas se separaron mediante la diferencia mínima significativa (DSS) con un intervalo de confianza del 95%. **Resultados:** Hubo un efecto de interacción bidireccional

† *Submitted December 7, 2023 – Accepted September 7, 2024.* http://doi.org/10.56369/tsaes.5326

ISSN: 1870-0462.

entre las opciones de manejo de la fertilidad sobre los rendimientos de sorgo en grano (p=0.0027, p=0.0008 y p=0.0057) durante las lluvias largas (LR) de 2011 y 2012, y las lluvias cortas (SR) de 2011, respectivamente. Además, los métodos de SWH afectaron significativamente los rendimientos de grano de sorgo en una tendencia similar (p=0.002, p=0.0005 y p=0.0003) en sus respectivas temporadas. En SR 2011 y LR 2012, las opciones de fertilidad del suelo también produjeron efectos significativos (p=0.0047 y p=0.0024) en los rendimientos de grano de caupí, respectivamente. Los resultados indicaron además que hubo mediciones de SWC significativamente más altas en las etapas iniciales de los intervalos de 2 WAP, 4 WAP y 6 WAP en comparación con las últimas etapas de la temporada. Sin embargo, los sistemas de cultivo de monocultivo tuvieron significativamente más SWC que los de los sistemas de cultivo intercalado en ambas estaciones. **Implicaciones:** Los tratamientos añadidos con estiércol afectaron positivamente la conservación del SWC y esto podría ser el resultado del aumento del carbono orgánico del suelo, lo que mejoró la fertilidad del suelo. El SWC disponible desempeñó un gran papel en la mitigación del efecto de la sequía al aprovechar la humedad para la productividad del sorgo y el caupí, especialmente cuando los períodos de sequía prolongados coinciden con las etapas fenológicas sensibles de crecimiento del cultivo. **Conclusiones:** Los métodos de recolección de agua, los sistemas de cultivo y las opciones de manejo de la fertilidad del suelo tuvieron una influencia positiva en la conservación de la humedad del suelo y la producción de rendimientos de cultivos en las tierras altas de Kenia Central.

Palabras clave: Pequeños agricultores; contenido de agua del suelo; manejo de la fertilidad del suelo; estadios fenológicos; cambio climático.

INTRODUCTION

Drylands of Central highlands of Kenya, which produces about 20% of the country's maize, cover both areas with high and low agricultural potential for crop production (GoK, 2018). Maize (*Zea mays* L.) is one of the most important crops known to humankind, accounting for nearly 30% of the total global grain production (Heng *et al*., 2009). The crop is cultivated on more than 142 million hectares of land worldwide, producing over 637 million Mg of grain (Renault, 2003). Recently, demand for maize is increasing as it is used to produce ethanol as bio-fuel, besides being a staple food in many developing countries and a feed for livestock in the form of forage, silage, or grain in developed countries (Heng *et al*., 2009). In Kenya, maize is both staple food and cash crop, and is now a popular cereal virtually replacing the traditional sorghum (*Sorghum bicolor* (L.) Pers.) and millet (*Pennisetum americanum* L.) (FAO, 2022). The increased demand is putting tremendous pressure on production even in less suitable climatic zones, hence, intensifies competition for the available water. At the same time, competition for water increases the cost of production leading to higher price for maize, which in turn raises food prices in general. Improving the water use efficiency for sorghum production through adaptive farm management strategies in response to rainfall variability is thus of paramount importance to obtain "more crop per drop of rain" with uncertainty in precipitation from global climate change.

Agricultural production in Kenya is predominantly smallholder systems. Farmers' fields are characterized by low inherent soil fertility and low use of inputs (Bationo *et al*., 2006). Kenya has a relatively lower average productivity of major staples relative to the other countries in the East Africa region. For example, the observed yields for most cereals in most farmers' fields hardly exceeds 0.5 t/ha, yet a potential of 8 t/ha is attained in on-station trials and by some commercial farmers. A similar pattern is observed for legumes such as beans whose production is less than 0.3t/ha whereas the potential of most varieties is about 2t/ha (Githunguri *et al.,* 2020). There is a great yield gap between the experimental station yields, farmers' potential yields, and farmers' actual yields. Low productivity can be attributed to poor soil fertility, low and slow adoption of new technologies, pests, disease, and climate change (Githunguri *et al*., 2014).

Farming systems in Kenya rely on rain-fed agriculture, which exposes smallholder farmers to poor rainfall distribution patterns and unpredictable weather conditions (Mairura *et al*., 2021). However, changing climatic patterns characterized by erratic rainfall, prolonged dry spells, and frequent droughts have contributed to reduced crop productivity in the Country (Macharia *et al*., 2020; Oduor *et al*., 2021). Erratic and poorly distributed rainfall often results in soil moisture stress, surface runoff losses, soil degradation, and reduced crop production in drylands of Central Highlands of Kenya (Oduor *et al*., 2021). Therefore there is need enhance the capacity of small-scale farmers to cope with changing climatic conditions and soil water conservation practices (Zougmor´e *et al*., 2014). Tied ridging (TR) has proved to be a successful climate-smart agricultural techniques under various cropping systems in drylands of Kenya (Thornton *et al*., 2017; Ngetich *et al*., 2014). The techniques improve soil moisture retention, water use efficiency and nutrient utilization within the root zone of growing crops in the semi-arid conditions of Kenya (Kiboi *et al*., 2021; Mwende *et al*., 2019). An increase in productivity will require investing in restoring the soil health and adopting site-specific climate-smart integrated soil fertility management (ISFM) technologies, innovations and management practices (TIMPs).

Drought is also another risk to crop failure which has led to reluctance by farmers to invest on crop land (KARI, 2009). The dry spell analysis indicates that potentially yield-limiting dry spells occur at least in 75% of the seasons during a 20-year period (GoK, 2007). Therefore irrigation, which helps to maintain soil water content within the plant root zone at an optimal level, is recommended. This is not feasible to most smallholder farmers because they either lack resources to invest in irrigation technologies or water is not available for irrigation. This situation can be ameliorated through appropriate proven on-farm water harvesting and integrated nutrient management techniques as alternative option to mitigate drought and drought spells to increase high valued traditional crop production (Mugwe *et al*., 2019).

Water may be primarily the limiting factor to agricultural production in the semi-arid and arid lands (SALs), the inherent soil nutrient deficiency also limits crop growth. Studies have shown that low crop yield levels may persist even where soil moisture is adequate, if plant nutrients in the soil are inadequate (Miriti *et al.*, 2013; Esilaba, *et al*., 2005). Plants require adequate nutrients to grow. Healthy growing plants use more soil water thus increasing water use efficiency (i.e. crop production per unit water use). At the same time, the movement of nutrients to the plants roots zone requires a moist soil environment (Njeru *et al*., 2015); Mutuku *et al*., (2020). Researchers have observed that TR are effective in improving crop yields especially in semi-arid and sub-humid areas (Miriti *et al.*, 2012; Okeyo *et al*., 2014; Ngetich *et al*., 2014).

To enhance increased soil nutrients uptake by crops requires adequate soil moisture to enable nutrient movement to underneath soil layers. Therefore soil, water and nutrients play an important role in crop production. The status can also alternate during seasons and at the end which determines the final crop yields due to their synergistic effects (Mupangwa *et al*., 2007). Different farmyard manure can also improve nutrient use efficiency from inorganic fertilizers and can alternate to limit crop growth at different stages in a situation where water readily available (Mugwe et al., 2007; Okalebo, et al., 2006). Thus, optimizing land productivity should aim at having production systems that address both water harvesting and integrated soil fertility management technologies. Therefore, the main objective was to determine the effect of water harvesting technologies, integrated soil fertility management and cropping patterns on soil water content conservation.

MATERIALS AND METHODS

Description of the study area

The study was conducted in long rains 2011, 2012 and short rains 2011 in Mbeere South Sub-county of Embu County. These study site represent area that may be classified as being under acute food, lower poverty levels and livelihood crisis **(**Maina *et al*., 2012**)**. The experimental site was located at Mariari girl's secondary school in Kiritiri. The study trials were researcher-managed and the local farmers were involved in learning and exposure to the technologies at physiological maturity stage at the end of the season.

The rainfall distribution is received in two seasons; the long rains (LR) lasting from March to June, and short rains (SR) from October to December (Jaetzold *et al*., 2007). Mbeere South Sub-County study site is classified as arid lands occupying a total area of 2,821 km^2 and lies in the southeastern slopes of Mt. Kenya (Figure 1). It lies between latitude S 0º 55' 00.2" and longitude E37º 28' 36.5" and between latitude S 0º 28' 33.9" and longitude E37º 52' 48.0. The Sub-County lies under the altitude 800 m a.s.l with an average rainfall of 700 to 900 mm, temp of 21.7ºC to 22.5ºC and the soil type is ferralsols. However, it is covered by two agro-ecological zones namely; Low Midland-marginal cotton zone (LM4) and Lower Midland-livestock-millet zone (LM5) (Jaetzold *et al*., 2007).

However, Mbeere South Sub-County is characteristic of low potential area, but which is currently experiencing population pressure resulting from an influx of immigrants from the over-populated neighbouring high potential areas and is representative of semi-humid agro-climatic conditions. (County Government of Embu, 2020). In Mbeere South Sub-County, the study was carried out in agro-ecological zone (LM4) and it received rainfall distribution in 3 seasons as shown in (Figure 2). The main crops grown are maize, beans and green grams. Maize and beans are majorly planted in the mixed farming livelihood zone while in the marginal mixed farming livelihood zone; cowpeas, maize and green grams were largely grown. In marginal mixed farming livelihood zone, maize contributes 50 percent to food and 10 percent to cash income while it contributes 38 percent to food and 25 percent to cash income in the Mixed Farming livelihood zone (County Government of Embu, 2020).

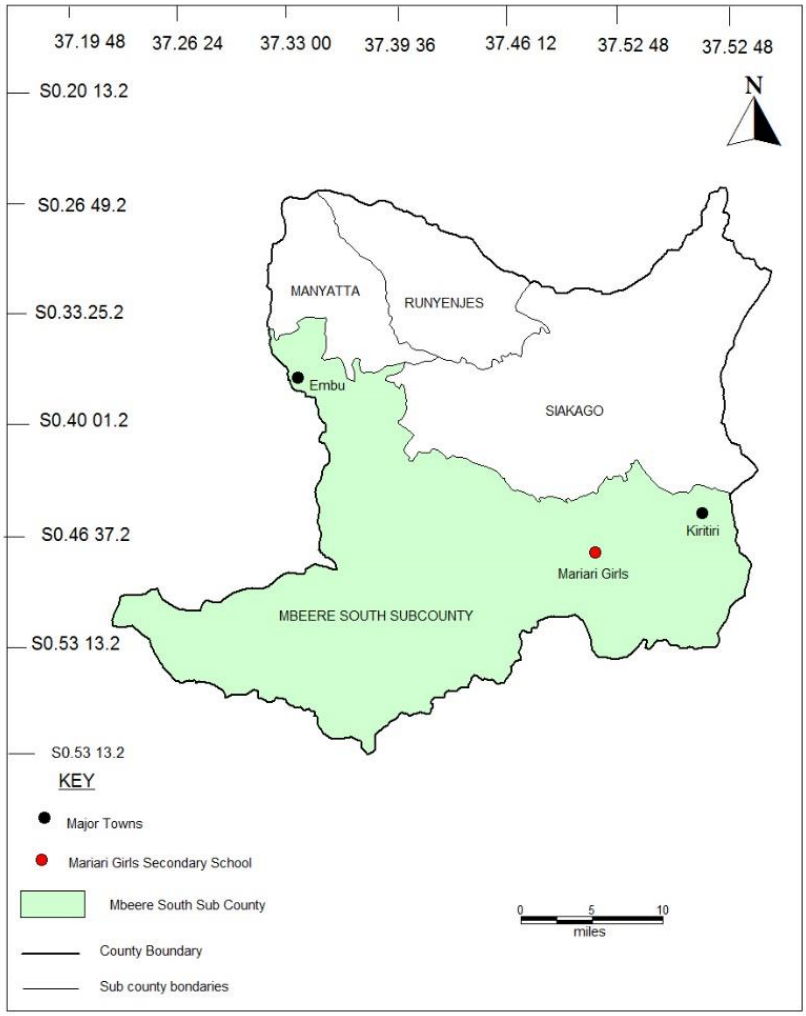

Figure 1. Map showing study site in Mbeere South Sub-County.

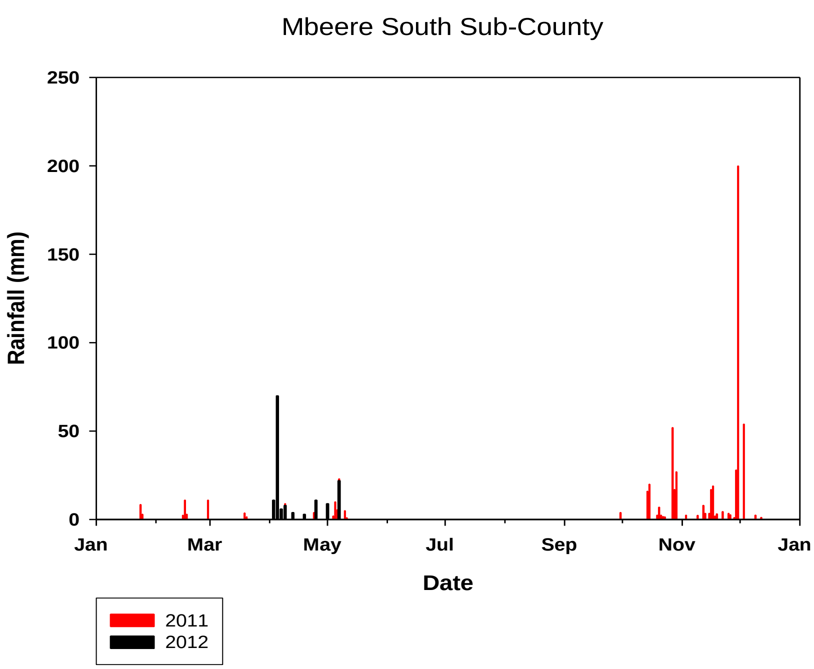

Figure 2. Rainfall distribution of LR 2011, 2012 and SR 2011 in Mbeere South Sub-County.

Farming systems

In Mbeere Sub-Counties, the main crops grown are maize, beans and green grams. Maize and beans are majorly planted in the mixed farming livelihood zone while in the marginal mixed farming livelihood zone; cowpeas, maize and green grams were largely grown. In marginal mixed farming livelihood zone, maize contributes 50 percent to food and 10 percent to cash income while it contributes 38 percent to food and 25 percent to cash income in the Mixed Farming livelihood zone (County Government of Embu, 2020).

Soil type of study areas

Soil types in the area varied in soil texture, sand, silt and clay. The soil texture (Table 1) is sandy loam in Mbeere South based on soil textural triangle (Ryan *et al*., 2001). The soil pH ranged from strong acidity to moderately acidic in Mariari site. This agrees with observations by Karuma, *et al.,* (2015) who reported low soil pH levels are associated with high Al saturation in some parts of Eastern Kenya. The main cause of acid soil was the loss of exchangeable bases through leaching from the top soil and their replacement with Al ions where the soil solution is occupied mostly by aluminium and hydrogen ions.

Table 1. Baseline soil characterization of study sites

Soil parameters	Mbeere South Sub-County Soil
Sand (%)	60
Silt (%)	23
Clay (%)	17
Soil type classification	Sandy loam
pH (1:2.5 water)	5.5
Total N (%)	0.12
Total P (%)	-
Total organic Carbon (%)	1.5
C:N ration	12.5
P (ppm)	31.48
K (ppm)	334.9
Ca (ppm)	929.3
Mg (ppm)	309.3
Cu (ppm)	5.9
Zn (ppm)	0.69
Fe (ppm)	2.5
Mn (ppm)	1158.7

The soils of experimental site had moderate organic C (1.5%) and total N (0.12%) which gives a C:N ratio of 12.5 in Mbeere South which is known to enhance N mineralization. Phosphorus (P) was found to be high (31.48 ppm) with P considered to be adequate at the range of 13 to 22 ppm. This could be possibly due to continuous additions of inorganic P fertilizers since P is a major plant nutrient needed for numerous metabolic processes for improved crop production. The source of P is different from that of N because is not usually supplied through biochemical fixation but it comes from other external sources to meet plant requirements. Therefore, the results indicated that there was need for a blanket application of P to maintain its levels to avoid its depletion in the soils.

The analysis for manure used in study site indicated that pH water was 9.41. However, it had a total N, P and Organic carbon of (1.70%, 0.49%, 22.5%) and Ca, Mg and K of (0.88%, 0.48% and 1.91%) respectively, with a C:N ratio of 13.2 which favours net soil mineralization.

Experimental Design and management

The study design was an experiment with treatments arranged in a factorial arrangement layout in Partially Balanced Incomplete Block Design (PBIBD). There were three factors; 1. Water harvesting techniques at 3 levels (Tied Ridges, contour furrows and conventional tillage/farmers Practice), 2. Cropping systems at two levels (Sole sorghum-Gadam, Sorghum and cowpea (M66) intercrop and 3. Soil fertility amendment options at 6 levels (Control, 40 kg P /ha + 40 kg N /ha, 40 kg P /ha + 20 kg N /ha, 40 kg P /ha + 40kg N /ha + Manure 5 t/ha, 40 kg P /ha + 20 kg N /ha + Manure 2.5 t/ha and manure 5 t/ha). This structure gave 36 treatment combinations (3 * 2 * 6 = 36). The experiment was replicated 3 times, giving a total of 108 plots in each of the sites with a blanket application of P at 40 kg P /ha (Table 2).

Land preparation was done using hand hoe up to a depth of 15 cm and this represented farmers practice plots**.** Tied ridges and contour furrows were made manually as these were not yet mechanized. The furrows were made at spacing of 75 cm in the whole plots which represented contour furrows. Then for tied ridges plots, the furrow were cross ties (small ridges joining big ridges) were made at 1 m intervals to prevent water movement along the furrow and create small check dams for rainwater harvesting within a plot. Fertilizer and Farm Yard Manure (FYM) application was done by banding along shallow furrows. Dry planting and weeding was done on need basis to ensure clean plots throughout the season. Inorganic fertilizers (NPK 23:23:0 and Triple Super Phosphate, TSP) were also applied along the shallow furrows and thoroughly mixed with soil during planting**.** The crops were planted in rows in 6m x 4m plots with a designed net plot of 2.25 m x 2 m at the center of the plot. Sorghum crop was planted at a spacing of 75 × 20 cm in pure stands. Sorghum and

Table 2. Treatments arrangement structure for Mbeere South and Kirinyaga West Sub-Counties.

Soil Water harvesting (SWH) techniques (3 levels)	Cropping systems (2 levels)	Organic and inorganic fertilizer rates (6 levels)
Tied Ridges (TR)	(i) Sole sorghum (Gadam)	i. Control
Contour furrow (CF)	(ii) Sorghum and cowpea (M66)	ii. 40 kg P /ha + 40 kg N /ha (optimal rate)
Farmers Practice (FP)		iii. 40 kg P /ha + 20 kg N /ha (half optimal rate)
		iv. 40 kg P /ha + 40 kg N /ha + Manure 5 t/ha (optimal rates)
		v. 40 kg P /ha + 20 kg N /ha + Manure 2.5 t/ha (half optimal rates)
		vi. Manure 5 t/ha

cowpea were planted in the same row but in alternating hills at the same spacing in intercrop plots. Thinning to a single plant per hill for sorghum and cowpea was done 2 to 3 weeks after emergence.

Crop yield parameters

In sorghum, heads weight, stovers and grain yields were recorded while only dry grain and dry biomass yield were measured in cowpeas. Harvesting of sorghum and cowpea was at physiological maturity in the net plot area (225 cm x 200 cm) in the centre of the plot by leaving either 3 or 2 outermost rows on either plot's side or 100 cm on each row from both ends to reduce the edge effect. Total plants and the corresponding field fresh weights were also determined during the experimentation period. Samples and sub-sample fresh weights of grain pods and stovers were recorded at harvesting. Then, samples were transported to laboratory for oven drying for the measurement of dry weights. Thereafter, threshing was done and the grain moisture content was regulated at 13.5%. Dry weights of grains (Grain yields) after hand shelling were determined after oven-drying at 65° C to a constant weight. The weights were extrapolated to reflect crop yield in each treatment. These yields were expressed in tonnes/ha (which is equivalent to Mg ha^{-1}). Finally, Biomass plus Husks (t/ha) and grains yields (t/ha) were also calculated by combining them to give amount of Total Dry Matter (TDM).

Soil Moisture Content Measurement

Soil moisture measurements were done using portable diviner 2000 technique. This technique involves measuring SWC around the tube at 5cm radius and taking measurements after every 10 cm interval to the bottom depth of the tube. Access tubes in the experiment were installed manually in the middle of the plot by drilling the soil with an auger and installing polyvinyl chloride (PVC) tubes (130 cm length) with a water tight lid at the bottom during the Long rains 2011. A portion of 30 cm of the access tube was left above the soil surface and was also covered to prevent runoff entry into the tubes. Another three extra tubes were also installed for calibration and they were set alongside the experimental plots in a representative position.

The access tubes were left to equilibrate and stabilize with the soils for a whole season until SR 2011 when soil moisture monitoring begun until LR 2012. A calibration pit was dug near the access tubes and soil samples were taken in intact core rings at the depth interval of 10 cm at which Diviner2000 readings were taken. Dry bulk density was determined gravimetrically from the ratio of mass of dry soil per unit volume of soil cores by oven-drying at 105 °C for 24 h and volumetric SWC was obtained by accounting for bulk density, determined concurrently on the same cores. Soil water content measurements were taken forthrightly starting from 2 weeks after planting time until just before harvest of sorghum every season. The SWC was measured at different stages of growing season at 2 Weeks after Planting (WAP), 4 WAP, 6 WAP, 8 WAP, 10 WAP, 12 WAP and 14 WAP and16 WAP up to a depth of 70cm cm depending on the length of the season.

Data analysis

Biophysical data for SWC measurements were subjected to Analysis of variance (ANOVA by use of SAS software version 9.1. Treatment means were separated using the Least Significant Different (LSD) method at 5% level of significant. Interaction and main effects was also performed to determine if combination of factors at different levels were significant different.

RESULTS

Treatments Effects of Sorghum and Cowpea Grain Yields in Mbeere South Sub-County

Comparative sorghum and cowpea yield during the three seasons indicated that there was better crop performance during the SR 2011 and LR 2012 seasons as compared to the LR 2011 season which was the worst season (Table 3). Sorghum yields recorded was 0.21–1.44 t ha^{-1} in LR 2011, 0.10–3.50 t ha^{-1} in SR 2011 and 0.50–3.80 t ha^{-1} in LR 2012. There was no data reported for cowpea grain yields in LR 2011 due to failed rains (Figure 2).

Three way interactions effect between SWH*cropping system*soil fertility options on sorghum grain yields was significant (p=0.0396) during LR 2012 only. SWH*soil fertility options had significantly interacted (p=0.0027, p=0.0008 and p=0.0057) and affected sorghum grain yields during long rains of 2011 and 2012, and short rains of 2011, in that order. During the three cropping seasons, the effects of SWH methods on sorghum grain yields differed significantly (p=0.002, p=0.0003 and p=0.0005), respectively, in LR 2011, SR 2011 and LR 2012. At the same time soil fertility options had significant effects (p=0.00) on sorghum grain yields during the three cropping seasons. In SR 2011 and LR 2012, soil fertility options also produced significant effects (p=0.0047 and p=0.0024) on cowpea grain yields, respectively (Table 3).

The treatments with the highest sorghum and cowpea yields significantly differed (p<0.05) from the least producers, i.e., the "control group" during the entire experimental period. The highest sorghum grain yields (1.44 t ha^{-1}, 3.50 and 3.80 t ha^{-1}) were recorded under Tied ridging in LR 2011, SR 2011 and LR 2012, respectively. While the best cowpea grain yields (1.3 and 0.96 t ha^{-1}) were recorded in treatments under Contour Furrows-Intercropping at 20N+40P+M2.5 and tied ridging-mono-cropping at 40N+40P+M5 during the SR 2011 and LR 2012 seasons, respectively. During LR 2011, SR 2011 and LR 2012, reported sorghum grain yields were 0.26 t ha^{-1}, 0.9 and 1.10 t ha^{-1}, respectively in the control treatment. On the other hand, cowpea yields in SR 2011 and LR 2012 were < 0.67 t ha^{-1} and 0.22 t ha^{-1}, respectively.

Table 3. Sorghum and Cowpea Grain Yields in Various Treatments at Mariari Site During the LR 2011, SR 2011 and LR 2012 Cropping Seasons.

Soil Water Harvesting	Cropping Systems	Fertility management	Crop yields (t ha^{-1}) Sorghum LR 2011	Sorghum SR 2011	Sorghum LR 2012	Cowpeas SR 2011	Cowpeas LR 2012
Tied ridging	Intercropping	40P20N	1.40ab	2.70ab	2.60bc	0.45b	0.9ab
Tied ridging	Intercropping	40P20NM2.5	1.33b	3.50a	3.00ab	1.01ab	0.77ab
Tied ridging	Intercropping	40P40N	1.27bc	2.10b	2.20bc	0.75ab	0.59ab
Tied ridging	Intercropping	40P40NM5	1.32bc	2.70ab	2.90ab	0.69ab	0.96a
Tied ridging	Intercropping	C	0.21d	1.10c	0.50c	0.21b	0.06b
Tied ridging	Intercropping	M5	1.22bc	2.00b	1.50c	0.75ab	0.45ab
Tied ridging	mono-cropped	40P20N	1.26bc	2.00b	2.00bc	.	.
Tied ridging	mono-cropped	40P20NM2.5	1.44a	3.00ab	3.80a	.	.
Tied ridging	mono-cropped	40P40N	1.29bc	2.80ab	2.00bc	.	.
Tied ridging	mono-cropped	40P40NM5	1.44a	2.00b	2.30bc	.	.
Tied ridging	mono-cropped	C	0.24d	1.10c	0.90c	.	.
Tied ridging	mono-cropped	M5	1.34ab	2.30b	1.90bc	.	.
Contour furrow	Intercropping	40P20N	1.26bc	2.50b	1.80bc	0.87ab	0.6ab
Contour furrow	Intercropping	40P20NM2.5	1.34ab	2.40b	1.70bc	1.3a	0.66ab
Contour furrow	Intercropping	40P40N	1.28bc	2.80ab	2.20bc	0.83ab	0.6ab
Contour furrow	Intercropping	40P40NM5	1.31bc	2.30b	1.70bc	0.7ab	0.73ab
Contour furrow	Intercropping	C	0.21d	1.00c	0.90c	0.42b	0.22b
Contour furrow	Intercropping	M5	1.32bc	2.50b	1.70bc	1.09ab	0.57ab
Contour furrow	mono-cropped	40P20N	1.32bc	2.00b	2.70bc	.	.
Contour furrow	mono-cropped	40P20NM2.5	1.29bc	2.70ab	2.40bc	.	.
Contour furrow	mono-cropped	40P40N	1.25bc	2.80ab	1.90bc	.	.
Contour furrow	mono-cropped	40P40NM5	1.29bc	2.40b	1.40c	.	.
Contour furrow	mono-cropped	C	0.26d	0.50c	0.80c	.	.
Contour furrow	mono-cropped	M5	1.24bc	2.50b	1.80bc	.	.
Farmers Practice	Intercropping	40P20N	1.33b	2.40b	1.30c	0.7ab	0.48ab
Farmers Practice	Intercropping	40P20NM2.5	1.28bc	2.30b	1.80bc	0.67b	0.74ab
Farmers Practice	Intercropping	40P40N	1.31bc	2.60ab	1.30c	0.75ab	0.58ab
Farmers Practice	Intercropping	40P40NM5	1.29bc	2.60ab	1.90bc	0.93ab	0.13b
Farmers Practice	Intercropping	C	0.23d	0.10c	0.60c	0.19b	0.08b
Farmers Practice	Intercropping	M5	1.23bc	2.30b	1.70bc	0.86ab	0.63ab

Soil Water Harvesting	Cropping Systems	Fertility management	Crop yields (t ha^{-1}) Sorghum LR 2011	Sorghum SR 2011	Sorghum LR 2012	Cowpeas SR 2011	Cowpeas LR 2012
Farmers Practice	mono-cropped	40P20N	1.35ab	2.30b	2.20bc	.	.
Farmers Practice	mono-cropped	40P20NM2.5	1.26bc	2.10b	1.80bc	.	.
Farmers Practice	mono-cropped	40P40N	1.25bc	2.70ab	1.70bc	.	.
Farmers Practice	mono-cropped	40P40NM5	1.30bc	2.30b	1.20c	.	.
Farmers Practice	mono-cropped	C	0.24d	0.60c	0.70c	.	.
Farmers Practice	mono-cropped	M5	1.28bc	2.90ab	1.50c	.	.
CV (%)			13.3	12.4	10.9	11.0	10.5
$LSD_{(0.05)}$			0.107	0.933	1.08	0.622	0.537
SWH			0.002	0.0003	0.0005	0.5736	0.7309
Cropping Systems			0.423	0.5719	0.447	.	.
Fertility management			0.0003	0.0001	0.0001	0.0047	0.0024
SWH*cropping Systems			0.638	0.9604	0.9285	.	
SWH*Fertility management			0.0027	0.0057	0.0008	0.3155	0.8484
Cropping Systems *Fertility management			0.7527	0.0654	0.2508	.	.
SWH*Cropping Systems *Fertility management			0.6954	0.6019	0.0396	.	.

Note: Means followed by different letters in the same column are significantly different (p≤0.05) between the treatments. Monocropping=>Sorghum alone, Intercropping=>Sorghum plus cowpea.

Treatments Effects of Soil Moisture Content during SR 2011 in Mbeere South Sub-County

The Soil Water Content (SWC) was measured fortnightly 2 weeks after planting during SR 2011 (Table 4). The results indicated that SWC measurement levels- were higher during the initial stages of measurements at 2 WAP, 4 WAP and 6 WAP as compared to other intervals. This could be as result of low rainfall distribution towards the end of the season (Figure 2). However, that sole cropping systems had significantly more SWC measurement than those in intercropping systems. The lowest SWC measurement was recorded in treatments regarded as experiment “controls” in all the water harvesting methods but under different cropping systems categories at all the 2 WAP sampling periods.

However, it was only at 2WAP that there was a significant interaction of the factors in this study. All the other sampling periods did not show any significant interaction. Water harvesting methods and cropping systems significantly affected SWC during all the sampling periods, i.e., at 2WAP, 4WAP, 6WAP, 8WAP and 10WAP. But there was no significant effect (p=0.0823) of water harvesting methods on SWC measurement interval at 8WAP. However, soil fertility management options significantly affected (p=0.0018 and p=0.0476) SWC measurement at 2WAP and 10 WAP respectively.

The treatments under (TR-sole crop and 40P20NM2.5) recorded the highest SWC measurements of (45.8%, 40.4%, 31.6%, 28.1% and 23.2%) at all the intervals of 2 WAP during the whole sampling period of SR 2011 (Table 4). This was followed by soil fertility amendment of (40P40NM5) and (M5) at all stage intervals of for the whole season. These treatments were significantly superior in terms of SWC conservation as compared to the rest of the treatments. Surprisingly, manure treatments were among the soil fertility management options that retained higher SWC measurement as compared to other inorganic fertilizers combinations of (40P20N and 40P40N) in their respective cropping systems.

Treatments Effects of Soil Moisture Content during LR 2012 in Mbeere South Sub-County

Similar sampling period to that of SR 2011, the SWC was measured fortnightly 2 weeks after planting during LR 2012 (Table 5). Similar results also indicated that SWC measurement levels- were higher during the initial stages of measurements at 2 WAP, 4 WAP and 6 WAP as compared to other intervals. This could be as result of low rainfall distribution towards the end of the season the crop had already reached the physiological maturity stage (Figure 2). Similar results also indicated that sole cropping treatments had significantly higher SWC than those in intercropping system as observed in the 2 WAP, 4WAP, 6 WAP and 8 WAP measurement sampling intervals. This could be as a result of inadequate rainfall distribution and there was a interspecific competition of soil moisture content recorded in mixed stands.

Table 4. Soil water content (%) measurement across various weeks after planting during SR 2011 in Mariari study site.

Soil Water Harvesting	Cropping Systems	Fertility Management	Soil Water Content (%) 2 Weeks After Planting (2 WAP)				
			2WAP	4WAP	6WAP	8WAP	10WAP
Tied Ridges	Intercrop	40P20N	32.0bc	30.7b	18.4b	18.0b	15.4b
Tied Ridges	Intercrop	40P20NM2.5	37.5ab	36.3ab	27.2ab	23.8ab	15.6b
Tied Ridges	Intercrop	40P40N	29.2bc	30.7b	20.3b	18.9b	15.7b
Tied Ridges	Intercrop	40P40NM5	39.5ab	35.5ab	21.4b	18.9b	16.2b
Tied Ridges	Intercrop	C	25.0c	30.4b	21.1b	16.1b	14.4b
Tied Ridges	Intercrop	M5	33.4bc	30.9b	28.3ab	19.1b	16.7ab
Tied Ridges	Sole	40P20N	36.9ab	31.1b	29.9ab	18.9b	21.6ab
Tied Ridges	Sole	40P20NM2.5	45.8a	40.4a	31.6a	28.1a	23.2a
Tied Ridges	Sole	40P40N	36.8ab	32.7ab	26.5ab	21.3ab	14.2b
Tied Ridges	Sole	40P40NM5	43.9ab	37.3ab	30.0ab	25.8ab	21.2ab
Tied Ridges	Sole	C	28.0bc	25.6b	21.5b	17.7b	13.3b
Tied Ridges	Sole	M5	36.7ab	38.4ab	27.1ab	27.3ab	15.6b
Contour furrow	Intercrop	40P20N	32.5bc	33.5ab	21.8b	23.8ab	16.0b
Contour furrow	Intercrop	40P20NM2.5	31.0bc	34.8ab	25.2ab	22.8ab	20.6ab
Contour furrow	Intercrop	40P40N	32.5bc	31.8ab	21.7b	19.3b	15.2b
Contour furrow	Intercrop	40P40NM5	35.4b	34.5ab	23.4b	18.4b	20.3ab
Contour furrow	Intercrop	C	27.6bc	30b	22.9b	15.7b	14.7b
Contour furrow	Intercrop	M5	34.1bc	31.9ab	22.1b	24.3ab	16.0b
Contour furrow	Sole	40P20N	30.4bc	32.4ab	24.7ab	22.0ab	16.4ab
Contour furrow	Sole	40P20NM2.5	36.1ab	32.8ab	26.1ab	22.1ab	18.0ab
Contour furrow	Sole	40P40N	30.8bc	32.9ab	25.0ab	19.0b	17.1ab
Contour furrow	Sole	40P40NM5	34.5bc	36.6ab	26.0ab	22.1ab	16.1b
Contour furrow	Sole	C	22.4c	24.8b	17.4b	14.4b	10.4b
Contour furrow	Sole	M5	37.2ab	35.5ab	25.5ab	20.1b	16.7ab
Farmers Practice	Intercrop	40P20N	37ab	30.9b	22.6b	18.0b	20.6ab
Farmers Practice	Intercrop	40P20NM2.5	39.1ab	32.2ab	29.7ab	20.0b	19.8ab
Farmers Practice	Intercrop	40P40N	29.1bc	29b	21.2b	18.9b	15.8b
Farmers Practice	Intercrop	40P40NM5	41ab	35.2ab	26.3ab	20.7ab	17.3ab
Farmers Practice	Intercrop	C	27.9bc	28.7b	20.0b	16.8b	12.0b
Farmers Practice	Intercrop	M5	29.6bc	29.2b	23.5b	19.4b	16.7ab
Farmers Practice	Sole	40P20N	31.1bc	29.1b	23.5b	19.2b	15.3b
Farmers Practice	Sole	40P20NM2.5	32.6bc	31.8ab	23.2b	20.2ab	15.6b
Farmers Practice	Sole	40P40N	29.1bc	29.6b	21.8b	19.7b	19ab
Farmers Practice	Sole	40P40NM5	36.4ab	31.4ab	25.5ab	22.4ab	15.3b
Farmers Practice	Sole	C	24.0c	27.0b	21.1b	17.7b	12.9b
Farmers Practice	Sole	M5	33.3bc	34.3ab	26.1ab	21.8ab	16.5ab
CV (%)			15.9	15.3	16.7	21.5	22.5
$LSD_{(0.05)}$			9.78	9.08	7.43	8.08	6.9
SWH			0.0028	0.0432	0.0427	0.0823	0.0234
Cropping systems			0.0331	0.0097	0.0001	0.005	0.0272
Fertility management			0.0018	0.2525	0.29	0.1416	0.0476
SWH *cropping systems			0.0243	0.3649	0.1336	0.5226	0.7512
Water harvesting*Fertility management			0.0391	0.574	0.5196	0.6636	0.44
Cropping system*Fertility management			0.0345	0.8326	0.6517	0.499	0.3699
SWH *Cropping systems*Fertility management			0.5396	0.8432	0.9801	0.9966	0.9123

Note: Means followed by different letters in the same column are significantly different ($p \leq 0.05$) between the treatments, C=Control, 40P40N=40 Kg P /ha + 40Kg N /ha, 40P20N=40 Kg P /ha + 20 Kg N /ha, 40P40NM5=40 Kg P /ha + 40Kg N /ha + Manure 5 t/ha, 40P20NM2.5=40 Kg P /ha + 20 Kg N /ha + Manure 2.5 t/ha, M5=manure 5t/ha. Sole=Sorghum alone, Intercrop=Sorghum plus Cowpea

Table 5. Soil water content (%) measurement across various weeks after planting during LR 2012 in Mariari study site.

Soil Water Harvesting	Cropping systems	Fertility Management	Soil Water Content (%) 2 Weeks After Planting (2 WAP)					
			2WAP	4WAP	6WAP	8WAP	10WAP	12WAP
Tied Ridges	Intercrop	40P20N	24.7b	27.9ab	29.5b	19.8bc	18.1ab	15.9ab
Tied Ridges	Intercrop	40P20NM2.5	32.7ab	35.8ab	38.2ab	23.1bc	23.3ab	18.0ab
Tied Ridges	Intercrop	40P40N	25.5b	29.6ab	29.9b	20.0bc	16.8ab	15.9ab
Tied Ridges	Intercrop	40P40NM5	26.2ab	32.1ab	31.7b	21.7bc	20.6ab	16.1ab
Tied Ridges	Intercrop	C	23.7b	26.3b	27.6b	17.9bc	14.6b	13.0b
Tied Ridges	Intercrop	M5	26.3ab	30.7ab	41.3ab	20.9b	23.2ab	15.7ab
Tied Ridges	Sole	40P20N	27.1ab	37.1a	37.0ab	21.0bc	20.6ab	21.4ab
Tied Ridges	Sole	40P20NM2.5	34.0ab	39.0a	42.9ab	26.6ab	25.0a	22.7a
Tied Ridges	Sole	40P40N	29.3ab	35.1ab	38.6ab	26.5ab	17.4ab	18.6ab
Tied Ridges	Sole	40P40NM5	35.2a	33.7ab	32.7b	32.2a	19.4ab	22.0ab
Tied Ridges	Sole	C	21.3b	25.3b	28.8b	19.6bc	12.9b	13.6ab
Tied Ridges	Sole	M5	33.9ab	37.2a	43.3a	27.4ab	20.1ab	15.8ab
Contour Furrow	Intercrop	40P20N	27.3ab	29.5ab	33.8ab	22.6bc	18.9ab	15.4ab
Contour Furrow	Intercrop	40P20NM2.5	35.0ab	31.5ab	35.1ab	22.8bc	18.6ab	17.7ab
Contour Furrow	Intercrop	40P40N	24.7b	29.1ab	31.1b	21.4bc	16.3ab	14.7ab
Contour Furrow	Intercrop	40P40NM5	29.7ab	34.5ab	36.5ab	28.6ab	22.1ab	15.0ab
Contour Furrow	Intercrop	C	22.0b	24.5b	29.1b	19.0bc	13.3b	13.3b
Contour Furrow	Intercrop	M5	28.1ab	32.8ab	35.5ab	24.1ab	21.9ab	17.4ab
Contour Furrow	Sole	40P20N	32.6ab	34.2ab	35.3ab	22.2bc	17.0ab	16.0ab
Contour Furrow	Sole	40P20NM2.5	30.6ab	36.1ab	35.0ab	29.2ab	19.8ab	18.4ab
Contour Furrow	Sole	40P40N	30.9ab	34.1ab	32.6b	21.8bc	16.6ab	15.9ab
Contour Furrow	Sole	40P40NM5	31.4ab	37.1a	43.1ab	22.8bc	20.9ab	18.6ab
Contour Furrow	Sole	C	22.6b	25.2b	26.3b	19.5bc	13.7b	12.2b
Contour Furrow	Sole	M5	30.3ab	37.9a	39.8ab	23.3bc	19.9ab	17.0ab
Farmers Practice	Intercrop	40P20N	26.2ab	29.2ab	32.9b	20.0bc	19.7ab	20.2ab
Farmers Practice	Intercrop	40P20NM2.5	26.8ab	30.4ab	39.6ab	20.9bc	19.9ab	18.7ab
Farmers Practice	Intercrop	40P40N	26.0b	29.7ab	31.1b	20.9bc	19.7ab	16.6ab
Farmers Practice	Intercrop	40P40NM5	26.4ab	30.6ab	32.1b	24.0b	20.3ab	18.2ab
Farmers Practice	Intercrop	C	22.4b	23.6b	28.3b	15.2c	15.6b	12.4b
Farmers Practice	Intercrop	M5	26.2ab	31.2ab	33.8ab	23.3bc	20.8ab	18.6ab
Farmers Practice	Sole	40P20N	23.8b	29.2ab	31.6b	23.3bc	16.7ab	13.7ab
Farmers Practice	Sole	40P20NM2.5	29.5ab	29.0ab	33.5ab	25.7ab	18.7ab	18.0ab
Farmers Practice	Sole	40P40N	26.1ab	27.6ab	29.4b	20.4bc	18.4ab	15.4ab
Farmers Practice	Sole	40P40NM5	29.3ab	33.1ab	38.1ab	23.0bc	19.3ab	16.9ab
Farmers Practice	Sole	C	22.8b	24.0b	23.8b	18.0bc	14.1b	12.8b
Farmers Practice	Sole	M5	23.9b	32.0ab	33.5ab	27.5ab	19.2ab	18.6ab
CV (%)			17.9	17.9	16.6	17.6	26.7	29.7
$LSD_{(0.05)}$			9.14	10.3	10.38	8.19	9.21	9.14
SWH			0.0009	0.0029	0.001	0.8161	0.497	0.5838
Cropping systems			0.0188	0.0669	0.0053	0.1437	0.9911	0.7757
Fertility management			0.5062	0.286	0.1627	0.2862	0.207	0.363
SWH *cropping systems			0.3928	0.356	0.1517	0.697	0.4733	0.6559
SWH *Fertility management			0.3795	0.6537	0.4996	0.2286	0.612	0.7269
Cropping system*Fertility management			0.8061	0.713	0.8646	0.0043	0.6559	0.9314
SWH *Cropping systems*Fertility management			0.6135	0.6002	0.2307	0.5349	0.8067	0.6435

Note: Means followed by different letters in the same column are significantly different ($p \leq 0.05$) between the treatments, C=Control, 40P40N=40 Kg P /ha + 40Kg N /ha, 40P20N=40 Kg P /ha + 20 Kg N /ha, 40P40NM5=40 Kg P /ha + 40Kg N /ha + Manure 5 t/ha, 40P20NM2.5=40 Kg P /ha + 20 Kg N /ha + Manure 2.5 t/ha, M5=manure 5t/ha. Sole=Sorghum alone, Intercrop=Sorghum plus Cowpea

Surprisingly, there was no 2 or 3 ways interaction effect of (water harvesting methods*cropping systems*soil fertility management options) variables on SWC measurements at all sampling intervals of 2

WAP. But except at 6WAP where (cropping systems *soil fertility management options) had significant interaction effect (p=0.0043) on SWC measurement.

Similar observations to the SR 2011, indicated that there was a significant effect (p=0.0009, p=0.0029 and p=0.0010) and (p=0.0188, p=0.0669 and p=0.0053) of water harvesting methods and cropping systems on SWC measurement sampling intervals at 2 WAP, 4 WAP and 6 WAP during LR 2012 respectively. Unlike to these results, there was no significant effect (p>0.05) of soil fertility management options on SWC measurement at all the sampling intervals of 2WAP during LR 2012.

Similar to results of SR 2011, the highest SWC measurements were recorded in treatment (TR-sole cropping system) measuring (35.2%, 39%, 43.3%, 32.2%, 25% and 22.7%) in all the sampling intervals of 2 WAP during LR 2012 (Table 5). However, the treatments under (TR-sole cropping system) recorded the highest SCW measurements as compared to intercrop system at all stage intervals of 2 WAP for the whole season. Similarly to SR 2011, manure added treatments were among the soil fertility management options that retained higher SWC at all measurements intervals of 2 WAP in their respective cropping system categories. Also, the treatments with added external soil amendment of 40P20N and 40P40N recorded the lowest SWC measurements in their respective cropping systems categories except in experiment "Controls".

However, the highest SWC measurements (>40%) was recorded under 5 treatments (TR, intercrop and M5), (TR, sole crop and 40P20NM2.5), (TR, sole crop and M5), (CF, sole crop and 40P40NM5) and (CF, sole crop and M5) observed at 6th sampling interval of 2 WAP and they were insignificant. Similar to the SR 2011 results, the lowest SWC was recorded in treatments regarded as experiment "controls" in all the water harvesting methods but in different cropping systems categories in all the sampling intervals during LR 2012.

DISCUSSION

Crop Yields parameters

The study observed that sorghum intercropped with cowpea produced lower yields than sole cropped sorghum (Table 3). This outcome for sorghum yields is in line with the findings on maize cowpea intercropping on nutrient competition resulting to reduced crop yields in Kenya (Mwende *et al*., (2019) and in southwest Nigeria (Saka *et al.*, 2018). Elsewhere, intercropping maize and cowpea reduced maize yields by 46–57% and cowpea by 9% due to competition for soil moisture (Jensen *et al*., 2003). According to Karuma *et al.* (2014), maize grain yields reduction in intercropped system with beans as compared to the monocropping was also contributed by interspecific soil nutrient competition in the intercrop system and there was no interspecific nutrient competition in a Monocropping ping system. Explaining the current findings, Baoua *et al.* (2021) and Nelson *et al*. (2018) established that intercropping cowpeas and a cereal in arid areas decreases the crop productivity due to competition for limited growth resources. But farmers commonly optimize farm resource utilization efficiency through intercropping to reduce risk of food productivity (Ngetich *et al.*, 2014a). Contrary observations by Mucheru-muna *et al.* (2010) and Martínez-Mena *et al*. (2020) demonstrated that intercropped systems were associated with high utilization efficiency of growth resources compared to sole crop systems, leading to relatively higher production.

Generally, grain yields increased with time from the 1st to the 3rd season in this study. The reported yields for cowpea yields were < 2 t ha^{-1} in this study. The crop were introduced as a legumes as they have ability to biologically fix atmospheric nitrogen planted as an intercropping of sorghum. The low cowpea yields reported could be due to competition for soil nutrients, water and light in the intercropping systems in drier part of this study. Similar findings have been reported by Woomer (2010) and Odendo *et al*. (2011) that bean yields in SSA are extremely low (<1 t/ha) due to declining soil fertility and commonly grown by small scale farmers who are resource-poor.

There was a consistency of higher grain, biomass and total dry matter yields results under Tied ridging-Monocropping system with addition of minimal application of synthetic fertilizers and manure inputs at half rate of 20N and M2.5 as compared to experiment controls. The soils are designed to release specific nutrients at different stages of cropping system in the season (Bindraban *et al*., 2015). This was an indication that soil nutrient supplement was a key requirement for improving soil fertility status in all the seasons in both study sites. These results corroborate Mugendi *et al*. (1999) that soils require nutrient re-application seasonally from inorganic, organic inputs and incorporation of crop residue in the soil in farms in Central Kenya Highlands. In Mbeere South, similar observations where Tied ridging showed greater maize grain yields relative to zero input control (Ngetich, 2012; Mwende *et al*., 2019) and in Tharaka Nithi Sub-County Ndung'u *et al.* (2023), and Eastern Ethiopia (Araya and Stroosnijder, 2010).

There were significant effect of SWH and interaction effect of SWH methods*soil fertility management options on sorghum grain yields. This is an indication that SWH methods and ISFM practices played an important role in conservation of soil moisture content which led to increased sorghum yields in drier part of this study. This is probably because water is a limiting factor under arid conditions (Figure 2). The findings corroborate Miriti *et al*. (2012) and Mucheru-Muna *et al*. (2010) who observed that combination of SWH methods and organic sources crop yields in Eastern Kenya. These findings suggest that mixed crop-livestock systems could be crucial in supporting crop production SSA (Herrero *et al*., 2010). However, since good quality and sufficient quantities of manure is not always available to many smallholder farmers in SSA, soil fertility can be maintained through cereal-legume and forage rotations and intercropping (Namatsheve *et al*., 2020).

The results further indicated that treatments under tied ridging and contour furrows recorded the highest sorghum grain yields. This could be attributed to lower than average and poorly distributed rainfall (Figure 2), as they conserved more soil moisture as compared to conventional tillage/farmers practice. Soil moisture deficit is the most limiting factors to crop performance in dry areas of Kenya (Muindi, 2019). This could be improved in on-farm water management through SWH and may be pivotal in supporting smallholder farming systems in SSA (Biamah, 2005). Similar observations by Singh *et al.* (2015) and Mwende *et al*. (2019) have shown that tied ridging and contour furrows SWH methods in combination of external soil fertility amendment has potential to significantly increase crop production. Also, this agrees with other studies that reported SWH technologies that retain rainwater in situ in the farms for crops to be efficient in increasing crop productivity (Itabari *et al.,* 2004). The SWH techniques perform well under prolonged rainwater infiltration and retention, thus increasing soil moisture and soil moisture holding capacity like the tied and open ridges (Singh *et al.,* 2015).

Generally, sole cropped sorghum and cowpea had higher grain yields relative to their intercropped counterparts in drier part of this study. This could be as a result of crops competition for limiting SWC and soil nutrient resources. Cowpeas have high demand for soil nutrient and they usually exhibit interspecific competition in an intercropping system (Kagwiria *et al.,* 2019). The consistency of increased crop grains, biomass and total dry matter yields in monocropping system in drier part of this study agrees with Kagwiria *et al.* (2019) observations that intercropping fields showed high competition for water and reduced sorghum and cowpea yields in Makueni County. Similar findings by Katsaruware *et al.* (2009) have shown reduction in crop yields in mixed stands and associated this to competition for available nutrients in intercropping compared Monocropping s. Increased sorghum and cowpea productivity could have been as a result of application of inorganic fertilizers that lead to increased crop residue contributing to high biomass productivity (Fofana *et al*., 2005; Mwende *et al*., 2019). The crop residue improves soil biophysical characteristics which improves water use efficiency for crop productivity (Fofana *et al*., 2005).

Soil Moisture Content Measurement

The overall soil water content per season varied depending on the seasonal rainfall amounts and patterns of distribution during the season (Table 4 & 5). Seasons with low rainfall, for instance, SR 2011 had equally relatively low SWC measurements at every 2 weeks after planting (2 WAP) interval as compared to (LR 2012) which had high rainfall amount during the seasons.

The treatments with CF and TR with soil fertility management options 40P20NM2.5, 40P40NM5 and M5 contained more SWC as compared to inorganic fertilizer alone treatments in both study sites. This corroborates findings of Ajeigbe (2010), who found significantly higher SWC under no tillage compared to conventional tillage. The increased moisture conservation could have been responsible for the increased grain yields in the current study. Similar findings on winter wheat-spring maize rotations and maize production by Zhang *et al*., (2018) and Mupangwa *et al*., (2012) have been reported in China and Zimbabwe respectively. These authors reported that CA- based practices improve soil water retention and increase maize grain yields. However, other authors, for example, Mutuku *et al*. (2020) have also reported that CA necessarily translated to increased maize grain yields. For example, in the sub-humid region of Zimbabwe, Mupangwa *et al*. (2017) reported a high soil water retention while using maize residue as mulch.

Tied ridging conserved more SWC throughout the whole season in both study sites. Similar results have been reported in another study in Mbeere South sub-county by Kiboi *et al.* (2019) who observed improved maize yield performance under TR which was attributed by ability of the ridges to conserve soil moisture influencing increased grain yields. Furthermore, several researchers have observed that TR are effective in improving crop yields especially in semi-arid and sub-humid areas (Miriti *et al.,* 2013; Okeyo *et al*., 2014; Ngetich *et al*., 2014). This, however, depended on the soil type, climate, the crop grown as well as the cropping system methods employed.

The results further demonstrated that treatments that had inorganic fertilizer application alone were poor in enhancing SWC during the two seasons in both study sites. This could be due to an increased rate of soil moisture utilization by the crop. Application of inorganic fertilizer leads to faster crop growth and development, which translates to a high rate of soil moisture depletion and utilization by crops leading to low amount of SWC (Hatfield *et al.*, 2001; Deng *et al.*, 2006). Similar results were reported by Mugendi *et al.* (2012) and Bindraban *et al.* (2015) who indicated that inorganic fertilizers contain nutrients which are quite high in content, soluble and readily available for crop uptake by increasing the crops demand for SWC. These findings by authors are also in conformity with those of Ngetich (2012) who observed increased water use efficiency and rates of evapotranspiration after application of inorganic fertilizer.

The results further indicated that control treatments under normal farmers practice recorded the lowest SWC during the 2 seasons in both study sites. In China and Malawi, Liu *et al*. (2010) reported water stress occurred mainly under minimal tillage systems which recorded the lowest SWC. The low SWC could be also be linked to low SOC in the no input treatments regarded as experiment “control”. Similar results were reported in semi-arid areas by Mburu *et al.* (2011) that by use of crop growth models, he predicted no maize crop water stress at the grain filling stage during the short rains in the semi-arid regions of Kenya.

However, treatment with manure application of 40P40NM5, M5 and 40P20NM2.5 recorded higher SWC this could be as a result of increased soil organic carborn (SOC) derived from incorporation of manure into the soil. Studies by Enfors *et al.* (2011) have reported that soil organic matter increases soil porosity and this increases soil water holding capacity. These results are also in conformity with Kolawole *et al.* (2014) that improved soil structure increases soil organic matter content enhancing infiltration of rain water thereby improving soil water retention and availability to crops. The results have indicated that sole cropping system recorded higher SWC in both study sites. This was contrary for sorghum and cowpea intercrop production in dry areas to what was reported by Sibomana (2016) that the greater canopy cover provided by maize-bean intercrop reduced wastage of available SWC, but findings indicated that sorghum and cowpea intercropping systems created competition for soil moisture in drier areas as compared to sole crop which conserved more SWC in Mbeere South Sub-County.

CONCLUSION

The results have demonstrated that selected SWH and integrated soil fertility amendment practices are key requirements for sorghum and cowpea production in Central Highlands of Kenya. The finding of this study showed consistency of higher grain, biomass and total dry matter yields results under tied ridging-Monocropping patters with addition of minimal application of synthetic fertilizers and organic inputs at half rate of 20N and M2.5 as compared to experiment controls. The study further showed that intercropping sorghum with cowpea reduced sorghum yields as a result of interspecific competition in intercropping pattern in drier part of this study. The findings also suggest that only low-input practices that are recommended for adoption through diversification of known crop in these areas.

The results indicated that TR and sole cropping system conserved substantive higher SWC throughout the season translating to high grain yields. The available soil water content played a great role in drought effect mitigation by availing moisture to sorghum and cowpea productivity especially when prolonged dry spells coincide with crop’s sensitive phonological stages. The impact of drought stress on crop productivity is particularly severe when the drought coincides with the moisture-sensitive stage of the crop and if farmers have no management alternatives to overcome the problem.

Among the water harvesting technologies, Inconsistencies in relative grain and biomass yields among water harvesting methods are likely associated with the amount of SWC under prevailing climatic conditions during the growing seasons. Therefore, soil moisture conservation techniques and soil fertility management have become an important practices need to be considered during land preparation and growth of sorghum and cowpea. The results demonstrated clearly that water harvesting methods cropping system and soil fertility management options have positive influence on soil moisture conservation in Central Highland of Kenya. Therefore, farmers should have management alternatives to overcome the problem of rainfall distribution as a cause of recurring climate change in the World.

Acknowledgement

I thank my supervisors Prof. Jayne Mugwe, Prof. Monicah Mucheru-Muna and Prof. Daniel Mugendi for their unfailing guidance during my proposal development, fieldwork and the whole process of my Ph.D programme including thesis writing. I am grateful to my colleagues from KALRO Dr. Stephen Kimani, Seth Amboga, Peter Wakaba, Gladys Cheruto and Sarah Otsyula for the assistance they offered during my field trials management, data collection and laboratory analysis.

Funding. This work was supported through a grant from International Development Research Centre (IDRC) funded project entitled; - Making Agri-food Systems work for rural poor in Eastern and Central Africa. I appreciate and thank the project for scholarship and funding my research work.

Conflict of interest. The authors declare that there are no known conflicts of interest associated with this article.

Compliance with ethical standards do not apply. Not applicable. There were no animal or human subjects used in this study by any of the authors.

Data availability. Data is available with Peterson Njeru (njerupeterson1@gmail.com) upon reasonable request.

Author contribution statement (CRediT). P N.M. Njeru – conceptualization, funding acquisition, methodology, project administration, investigation, data curation, formal analysis, visualization, Writing – original draft. **J. Mugwe -** supervision, validation, writing – review and editing. **M. Mucheru-Muna –** supervision, validation, writing – review and editing. **S. Kimani –** project administration, supervision, writing – review and editing.

REFERENCES

Ajeigbe, H.A., Singh, B.B., Adeosun, J.O. and Ezeaku, I.E., 2010. Participatory on-farm evaluation of improved legume-cereals cropping systems for crop-livestock farmers: Maize-double cowpea in Northern Guinea Savanna Zone of Nigeria. *African Journal of Agricultural Research*, *5*(16), pp.2080-2088. http://www.academicjournals.org/AJAR.

Araya, A. and Stroosnijder, L., 2010. Effects of tied ridges and mulch on barley (*Hordeum vulgare*) rainwater use efficiency and production in Northern Ethiopia. *Agricultural Water Management*, *97*(6), pp.841-847. https://doi.org/10.1016/j.agwat.2010.01.012

Baoua, I., Rabé, M.M., Murdock, L.L. and Baributsa, D., 2021. Cowpea production constraints on smallholders' farms in Maradi and Zinder regions, Niger. *Crop Protection*, *142*(2021), p.105533. https://doi.org/10.1016/j.cropro.2021.105533

Bationo, A., Waswa, B., Kihara, J. and Kimetu, J., 2007. Advances in integrated soil fertility management in Sub Saharan Africa: challenges and opportunities. *Nutrient Cycling in Agroecosystems*, pp.1-2. https://doi.org/10.1007/s10705-007-9096-4

Biamah, E.K., 2005. *Coping with drought: options for soil and water management in semi-arid Kenya*. Wageningen University and Research. http://edepot.wur.nl/40497

Bindraban, P.S., Dimkpa, C., Nagarajan, L., Roy, A. and Rabbinge, R., 2015. Revisiting fertilisers and fertilisation strategies for improved nutrient uptake by plants. *Biology and Fertility of Soils*, *51*(8), pp.897-911. https://doi.org/10.1007/s00374-015-1039-7

County Government of Embu, 2020. Short rains food and nutrition security assessment report. Embu County Nutrition Action plan 2020/2021-2024/2025. County Government of Embu, Embu, Kenya. https://www.nutritionintl.org/wp-content/uploads/2021/08/Nutrition-International-KEN-06-Embu-CNAP-1.pdf

Deng, X.P., Shan, L., Zhang, H. and Turner, N.C., 2006. Improving agricultural water use efficiency in arid and semiarid areas of China. *Agricultural Water Management*, *80*(1-3), pp.23-40. https://doi.org/10.1016/j.agwat.2005.07.021

Enfors, E., Barron, J., Makurira, H., Rockström, J. and Tumbo, S., 2011. Yield and soil system changes from conservation tillage in dryland farming: A case study from North Eastern Tanzania. *Agricultural Water Management*, *98*(11), pp.1687-1695. https://doi.org/10.1016/j.agwat.2010.02.013

Esilaba, A.O., Byalebeka, J.B., Delve, R.J., Okalebo, J.R., Ssenyange, D., Mbalule, M. and Ssali, H., 2005. On farm testing of integrated nutrient management strategies in eastern Uganda. *Agricultural Systems*, *86*(2), pp.144-165. https://doi.org/10.1016/j.agsy.2004.09.005

FAO., 2022. Agriculture in Kenya. Food and Agriculture Organization. http://www.fao.org/kenya/fao-in-kenya/kenya-at-a-glance/en/

Fofana, B., Tamélokpo, A., Wopereis, M.C.S., Breman, H., Dzotsi, K. and Carsky, R.J., 2005. Nitrogen use efficiency by maize as affected by a mucuna short fallow and P application in the coastal savanna of West Africa. *Nutrient Cycling in Agroecosystems*, *71*, pp.227-237. https://doi.org/10.1007/s10705-004-5084-0

Githunguri, C., Njaimwe, A.N., Thuranira, E. G., Mutai, G.K., Miriti, J. M. and Ndwiga, E.N., 2020. Cropping system, tillage and effects of fertilizer treatment on the grain yields of sorghum and green grams in Makueni

County, Kenya. In: Kolawole, O. D., ed. *Smallholder Farmers and Farming Practices: Challenges and Prospects*. New York: Nova Science Publishers, pp.15-54.

Githunguri, C.M. and Esilaba, A.O., 2014. Appropriate integrated nutrient management and field water harvesting options for maize production mitigating drought in the semi-arid southern rangelands of eastern Kenya. *International Journal of Agricultural Resources, Governance and Ecology*, *10*(3), pp.217-226. http://doi.org/10.1504/IJARGE.2014.064000

GoK., 2018. National Climate Change Action Plan (Kenya) 2018-2022. Ministry of Environment and Forestry, Nairobi, Kenya. http://climate-laws.org/document/national-climate-change-action-plan-2018-2022-nccap_a381.

GoK., 2007. Government of Kenya. Ministry of planning and national development, Nairobi, Kenya. http://www.researchictafrica.net/countries/kenya/Kenya.

Hatfield, J.L., Sauer, T.J. and Prueger, J.H., 2001. Managing soils to achieve greater water use efficiency: A review. *Agronomy Journal*, *93*(2), pp.271-280. https://doi.org/10.2134/agronj2001.932271x

Heng, L.K., Hsiao, T., Evett, S., Howell, T. and Steduto, P., 2009. Validating the FAO AquaCrop model for irrigated and water deficient field maize. *Agronomy Journal*, *101*(3), pp.488-498. http://doi.org/10.2134/agronj2008.0029xs

Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J. and Lynam, J., 2010. Smart investments in sustainable food production: Revisiting mixed crop-livestock systems. *Science*, *327*(5967), pp.822-825. https://doi.org/10.1126/science.1183725

Jaetzold, R.H., Schmidt, Z., Hornet, B. and Shisanya, C. A., 2007. Farm Management Handbook of Kenya: Natural Conditions and Farm Information-Eastern Province, Vol.11/ C. 2nd Edition. Ministry of Agriculture. *Kenya and German Agency for Technical Cooperation (GTZ), Nairobi, Kenya*. http://edepotWurnl/487562

Jensen, L.T., Ajua-Alemanji, M. and Culotta, V.C., 2003. The *Saccharomyces cerevisiae* high affinity phosphate transporter encoded by PHO84 also functions in manganese homeostasis. *Journal of Biological Chemistry*, *278*(43), pp.42036-42040. http://doi.org/10.1074/jbc.M307413200

Kagwiria, D., Koech, O.K., Kinama, J.M., Chemining'wa, G.N. and Ojulong, H.F., 2019. Sorghum production practices in an integrated crop-livestock production system in Makueni County, Eastern Kenya. *Tropical and Subtropical Agroecosystems*, *22*(1), pp.13-23. http://dx.doi.org/10.56369/tsaes.2508

KARI., 2009. Kenya Agricultural Research Institute. Strategic plan Implementation framework (2009-2014). KARI, Nairobi, Kenya.

Karuma, A.N., Gachene, C.K., Msanya, B.M., Mtakwa, P.W., Amuri, N. and Gicheru, P.T., 2015. Soil morphology, physico-chemical properties and classification of typical soils of Mwala District, Kenya. *International Journal of Plant and Soil Science*, *4*(2), pp. 156-170. http://doi.org/10.9734/IJPSS/2015/13467

Karuma, A., Mtakwa, P., Amuri, N., Gachene, C.K. and Gicheru, P., 2014. Enhancing soil water content for increased food production in semi-arid areas of Kenya results from an on-farm trial in Mwala district, Kenya. *Journal of Agricultural Science*, *6*(4), p125. http://dx.doi.org/10.5539/jas.v6n4p125

Katsaruware, R.D. and Manyanhaire, I.O., 2009. Maize-cowpea intercropping and weed suppression in leaf stripped and detasselled maize in Zimbabwe. *Electronic Journal of Environmental, Agricultural and Food Chemistry*, *8*(12), pp.1218-1226. http://www.researchgate.net/publication/286938954

Kiboi, M.N., Ngetich, K.F., Fliessbach, A., Muriuki, A. and Mugendi, D.N., 2019. Soil fertility inputs and tillage influence on maize crop performance and soil water content in the Central Highlands of Kenya. *Agricultural Water Management*, *217*, pp.316-331. https://doi.org/10.1016/j.agwat.2019.03.014

Kiboi, M.N., Ngetich, F.K., Mucheru-Muna, M.W., Diels, J. and Mugendi, D.N., 2021. Soil nutrients and crop yield response to conservation-effective management practices in the sub-humid highlands agro-ecologies of

Kenya. *Heliyon*, *7*(6), e07156. https://doi.org/10.1016/j.heliyon.2021.e07156

Kolawole, O.K., Awodun, M.A. and Ojeniyi, S.O., 2014. Soil fertility improvement by *Tithonia diversifolia* (Hemsl.) A Gray and its effect on cassava performance and yield. *International Journal of Engineering and Science*, *3*(8), pp.36-43. http://www.theijes.com/papers/v3-i8/Version-4/F0384036043.pdf

Liu, E.K., Zhao, B.Q., Mei, X.R., So, H.B., Li, J. and Li, X.Y., 2010. Effects of no-tillage management on soil biochemical characteristics in northern China. *The Journal of Agricultural Science, 148*(2), pp.217-223. http://doi.org/10.1017/S0021859609990463

Macharia, J.M., Ngetich, F.K. and Shisanya, C.A., 2020. Comparison of satellite remote sensing derived precipitation estimates and observed data in Kenya. *Agricultural and Forest Meteorology*, *284*, p.107875. https://doi.org/10.1016/j.agrformet.2019.107875

Maina, I., Miruka, M., Rono, B., Njeru, P.N.M., Amboga, S., Gitari, J., Mahasi, M. and Murithi, F., 2012. Adaptive strategies and local innovations of smallholder farmers in selected agri-food systems of central Kenya. *African Crop Science Journal*, *20*(1), pp.77-84. http://www.bioline.org.br/pdf?cs12008

Mairura, F.S., Musafiri, C.M., Kiboi, M.N., Macharia, J.M., Ng'etich, O.K., Shisanya, C.A., Okeyo, J.M., Mugendi, D.N., Okwuosa, E.A. and Ngetich, F.K., 2021. Determinants of farmers' perceptions of climate variability, mitigation, and adaptation strategies in the central highlands of Kenya. *Weather and Climate Extremes*, *34*, p.100374. http://doi.org/10.1016/j.wace.2021.100374

Martínez-Mena, M., Carrillo-López, E., Boix-Fayos, C., Almagro, M., Franco, N.G., Díaz-Pereira, E., Montoya, I. and De Vente, J., 2020. Long-term effectiveness of sustainable land management practices to control runoff, soil erosion, and nutrient loss and the role of rainfall intensity in Mediterranean rainfed agroecosystems. *Catena*, *187*, p.104352. http://doi.org/10.1016/j.catena.2019.104352

Mburu, M.W., Lenga, F.K. and Mburu, D., 2011. Assessment of maize yield response to nitrogen fertiliser in two semi-arid areas of Kenya with similar rainfall pattern. *Journal of Agriculture, Science and Technology*, *13*(1), pp.22-34. http://hdl.handle.net/123456789/493

Miriti, J.M., Kironchi, G., Esilaba, A.O., Gachene, C.K.K., Heng, L.K. and Mwangi, D.M., 2013. The effects of tillage systems on soil physical properties and water conservation in a sandy loam soil in Eastern Kenya. *Journal of Soil Science and Environmental Management*, *4* (7), pp.146-154. http://doi.org/10.5897/JSSEM2013.0395

Miriti, J.M., Kironchi, G., Esilaba, A.O., Heng, L.K., Gachene, C.K.K. and Mwangi, D.M., 2012. Yield and water use efficiencies of maize and cowpea as affected by tillage and cropping systems in semi-arid Eastern Kenya. *Agricultural Water Management*, *115*, pp.148-155. https://doi.org/10.1016/j.agwat.2012.09.002

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

Mugendi, D.N., Mucheru-Muna, M.W. and Mugwe, J.N., 2012. *Soil Fertility Enhancing Community Extension*. Nairobi: Manilla. http://irlibrary.ku.ac.ke/handle/123456789/9346

Mugendi, D.N., Nair, P.K.R., Mugwe, J.N., O'neill, M.K., Swift, M.J. and Woomer, P., 1999. Alley cropping of maize with calliandra and leucaena in the subhumid highlands of Kenya: Part 2. Biomass decomposition, N mineralization, and N uptake by maize. *Agroforestry Systems*, *46*, pp.51-64. https://doi.org/10.1023/A:1006269217882

Mugwe, J., Mugendi, D., Kungu, J. and Mucheru-Muna, M., 2007. Effect of plant biomass, manure and inorganic fertilizer on maize yield in the Central highlands of Kenya. *African Crop Science Journal*, *15*(3). https://doi.org/10.4314/acsj.v15i3.54424

Mugwe, J., Ngetich, F. and Otieno, E.O., 2019. Integrated soil fertility management in Sub-Saharan Africa: Evolving paradigms toward integration. In *Zero Hunger Encyclopedia of the UN Sustainable Development Goals*, Springer: Berlin, Germany. pp.1-12, https://doi.org/10.1007/978-3-319-69626-3_71-1

Muindi, E.D.M., 2019. Understanding soil phosphorus. *International Journal of Plant and Soil Science*, *31*(2), pp.1-18. https://dx.doi.org/10.9734/IJPSS/2019/v31i230208

Mupangwa, W., Thierfelder, C. and Ngwira, A., 2017. Fertilization strategies in conservation agriculture systems with maize–legume cover crop rotations in Southern Africa. *Experimental Agriculture*, *53*(2), pp.288-307. http://doi.org/10.1017/S0014479716000387

Mupangwa, W., Twomlow, S. and Walker, S., 2012. Reduced tillage, mulching and rotational effects on maize (*Zea mays* L.), cowpea (*Vigna unguiculata* (Walp) L.) and sorghum (*Sorghum bicolor* L.(Moench)) yields under semi-arid conditions. *Field Crops Research*, *132*, pp.139-148. http://doi.org/10.1016/j.fcr.2012.02.020

Mupangwa, W., Twomlow, S., Walker, S. and Hove, L., 2007. Effect of minimum tillage and mulching on maize (Zea mays L.) yield and water content of clayey and sandy soils. *Physics and chemistry of the earth, parts A/B/C*, *32*(15-18), pp.1127-1134. https://doi.org/10.1016/j.pce.2007.07.030

Mutuku, E.A., Roobroeck, D., Vanlauwe, B., Boeckx, P. and Cornelis, W.M., 2020. Maize production under combined Conservation Agriculture and Integrated Soil Fertility Management in the sub-humid and semi-arid regions of Kenya. *Field Crops Research*, *254*, p.107833. https://doi.org/10.1016/j.fcr.2020.107833

Mwende, N., Danga, B.O., Mugwe, J. and Kwena, K., 2019. Effect of integrating tied ridging, fertilizers and cropping systems on maize performance in arid and semi-arid lands of Eastern Kenya. *African Journal of Education, Science and Technology*, *5*(2), pp.87-104. http://www.ajest.info/index.php/ajest/article/view/355

Namatsheve, T., Cardinael, R., Corbeels, M. and Chikowo, R., 2020. Productivity and biological N2-fixation in cereal-cowpea intercropping systems in Sub-Saharan Africa. A review. *Agronomy for sustainable development*, *40*(4), p.30. http://doi.org/10.1007/s13593-020-00629-0

Ndung'u, M., Mugwe, J.N., Mucheru-Muna, M.W., Ngetich, F.K., Mairura, F.S. and Mugendi, D.N., 2023. Tied-ridging and soil inputs enhance small-scale maize productivity and profitability under erratic rainfall conditions in central Kenya. *Agricultural Water Management*, *286*, p.108390. https://doi.org/10.1016/j.agwat.2023.108390

Nelson, W.C.D., Hoffmann, M.P., Vadez, V., Roetter, R.P. and Whitbread, A.M., 2018. Testing pearl millet and cowpea intercropping systems under high temperatures. *Field crops research*, *217*, pp.150-166. https://doi.org/10.1016/j.fcr.2017.12.014

Ngetich, F.K., 2012. *Enhancing farmers' agricultural productivity through improved field management practices in the central Highlands of Kenya*. Ph.D. Thesis, Kenyatta University, Kenya. http://doi.org/10.13140/2.1.1947.3283

Ngetich, K.F., Diels, J., Shisanya, C.A., Mugwe, J.N., Mucheru-Muna, M. and Mugendi, D.N., 2014. Effects of selected soil and water conservation techniques on runoff, sediment yield and maize productivity under sub-humid and semi-arid conditions in Kenya. *Catena*, *121*, pp.288-296. https://doi.org/10.1016/j.catena.2014.05.026

Njeru, P.N.M., Mugwe, J., Maina, I., Mucheru-muna, M., Mugendi, D., Lekasi, J.K. and Kimani, S.K., 2015. Adapting rain-fed agriculture to climate change variability: An overview of sorghum (*Sorghum bicolor* L.) and cowpea production in agro-pastoral areas of eastern Kenya. United Nations Development Programme-Kenya, Nairobi. *ISBN 978 9966 1805 5 1*. https://www.eld-initiative.org/fileadmin/pdf/slm_book.pdf.

Odendo, M., Bationo, A. and Kimani, S., 2011. Socio-economic contribution of legumes to livelihoods in Sub-Saharan Africa. In: Bationo, A., Waswa, B., Okeyo, J., Maina, F., Kihara, J., Mokwunye, U., eds. *Fighting poverty in Sub-Saharan Africa: the multiple roles of legumes in Integrated Soil Fertility Management*. Springer, Dordrecht, pp.27-46. https://doi.org/10.1007/978-94-007-1536-3_2

Oduor, N., Kiboi, M.N., Muriuki, A., Adamtey, N., Musafiri, C.M. and Ngetich, F.K., 2021. Soil management strategies enhanced crop yield, soil moisture, and water productivity in Nitisols of the Upper Eastern Kenya.

Environmental Challenges, *5*, p.100375. https://doi.org/10.1016/j.envc.2021.100375

Oduor, O.N., Ngetich, F.K., Kiboi, M.N., Muriuki, A., Adamtey, N. and Mugendi, D.N., 2020. Suitability of different data sources in rainfall pattern characterization in the tropical central highlands of Kenya. *Heliyon*, *6*, e05375. https://doi.org/10.1016/j.heliyon.2020.e05375

Okalebo, J.R., Othieno, C.O., Woomer, P.L., Karanja, N.K., Semoka, J.R.M., Bekunda, M.A., Mugendi, D.N., Muasya, R.M., Bationo, A. and Mukhwana, E.J., 2006. Available technologies to replenish soil fertility in East Africa. *Nutrient Cycling in Agroecosystems, 76*, pp.153-170. https://doi.org/10.1007/s10705-005-7126-7

Okeyo, A.I., Mucheru-Muna, M., Mugwe, J., Ngetich, K.F., Mugendi, D.N., Diels, J. and Shisanya, C.A., 2014. Effects of selected soil and water conservation technologies on nutrient losses and maize yields in the central highlands of Kenya. *Agricultural Water Management*, *137*, pp.52-58. http://doi.org/10.1016/j.agwat.2014.01.014

Renault, D., 2003. Value of virtual water in food: principles and virtues. In: Hoekstra, A.Y. ed. *UNESCO-IHE Virtual Water Trade, 12-13 December 2014, Delft*. Netherlands: FAO. Value of Water Research Report Series No. 12. Available from: https://openknowledge.fao.org/handle/20.500.14283/ap527e

Ryan, J., Estefan, G. and Rashid, A., 2001. *Soil and plant analysis laboratory manual*. 2nd ed. Jointly published by International Center for Agricultural Research in the Dry Areas (ICARDA) and the National Agricultural Research Center (NARC). https://www.researchgate.net/publication/236984396.

Saka, J.O., Agbeleye, O.A., Ayoola, O.T., Lawal, B.O., Adetumbi, J.A. and Oloyede-Kamiyo, Q.O., 2019. Assessment of varietal diversity and production systems of cowpea (*Vigna unguiculata* (L.) Walp.) in Southwest Nigeria. *Journal of Agriculture and Rural Development in the Tropics and Subtropics, 119*(2), pp.43-52. https://dx.doi.org/10.17170/kobra-2018121864

Sibomana, J.D., 2016. *Effects of integrated soil fertility management and tied-ridging on maize-soybean yields and selected soil properties in Tharaka-Nithi County, Kenya.* MSc Thesis, Kenyatta University, Kenya. http://ir-library.ku.ac.ke/handle/123456789/17605

Singh Brar, B., Singh, J., Singh, G. and Kaur, G., 2015. Effects of long term application of inorganic and organic fertilizers on soil organic carbon and physical properties in maize–wheat rotation. *Agronomy*, *5*(2), pp.220-238. https://doi.org/10.3390/agronomy5020220

Thornton, P., Aggarwal, P. and Parsons, D., 2017. Editorial: Prioritising climate-smart agricultural interventions at different scales. *Agricultural Systems*, *151*, pp.149-152. https://doi.org/10.1016/j.agsy.2016.12.007

Woomer, P.L., 2010. *Biological nitrogen fixation and grain legume enterprise: guidelines for N2 Africa lead farmers.* Tropical soil biology and fertility institute of the international centre for tropical agriculture, pp.17. https://www.n2africa.org/sites/default/files/Master%20farmer%20guidelines_BNF%20-%20GL%20enterprise%20s_0.pdf

Zhang, Y., Wang, S., Wang, H., Ning, F., Zhang, Y., Dong, Z., Wen, P., Wang, R., Wang, X. and Li, J., 2018. The effects of rotating conservation tillage with conventional tillage on soil properties and grain yields in winter wheat-spring maize rotations. *Agricultural and Forest Meteorology*, *263*, pp.107-117. https://doi.org/10.1016/j.agrformet.2018.08.012

Zougmoré, R., Jalloh, A. and Tioro, A., 2014. Climate-smart soil water and nutrient management options in semiarid West Africa: a review of evidence and analysis of stone bunds and zaï techniques. *Agriculture and Food Security*, *3*, pp.1-8. https://doi.org/10.1186/2048-7010-3-16