SIMULATING YIELDS OF SORGHUM (*Sorghum bicolor L.)* AND SWEET POTATO (*Ipomoea batatas L. lam*) UNDER DIFFERENT TILLAGE PRACTICES, CROPPING SYSTEMS AND ORGANIC INPUTS USING CROPSYST MODEL †

[SIMULACIÓN DE RENDIMIENTOS DE SORGO (*Sorghum bicolor* L.) Y BATATA (*Ipomoea batatas* L. lam) BAJO DIFERENTES PRÁCTICAS DE LABRANZA, SISTEMAS DE CULTIVO E INSUMOS ORGÁNICOS UTILIZANDO EL MODELO CROPSYST]

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SUMMARY

Background: Crop yields has been declining in the arid and semi-arid lands (ASALs) of Kenya due to low soil fertility and low soil water availability that is caused by low and unreliable rainfall and poor water harvesting techniques. Therefore, there is need for better management of available water. **Objective:** To simulate sorghum and sweet potato yields under different tillage practices. **Methodology:** The experiment was laid out in a randomized complete block design with split-split plot arrangement, replicated three times. The experimental factors were: tillage practices, cropping systems and organic inputs. The tested crops were sorghum (*Sorghum bicolor L.*) and sweet potato (*Ipomoea batatas L.lam*) rotated and/or intercropped with dolichos (*Lablab purpureus*) and chickpea (*Cicer arietinum*). The CropSyst model was calibrated using the observed final above ground biomass and yield of sorghum and sweet potato in the experimental site. Validation of the model was done using Wilmott index (WI) of agreement. **Results:** CropSyst model was accurately validated due to the low RMSE (0.629) and PD (less than ±3) values that were obtained and the WI index which was close to 1. In the sorghum based cropping systems, yield of 1,611 kg ha^{-1} obtained was significantly ($p \leq 0.05$) high in the tied ridges, compared to furrows and ridges at 1,559 kg and 1,383 kg ha^{-1} in the oxen plough in season I. In season II, simulated sorghum yield of 2,072 kg was high in the tied ridges ($p \leq 0.05$), followed by furrows and ridges at 2,005 kg and least at 1,779 kg ha^{-1}) in the oxen plough. In the first season; simulated sorghum yield (1,595 kg ha^{-1}) was significantly high in the RP +FYM and least (1,436 kg ha^{-1}) in the control. In the sweet potato based cropping systems, sweet potato yield (13,127 kg ha^{-1}) was significantly higher in the tied ridges and least (10,127 kg ha^{-1}) in the oxen plough in the first season. In both seasons, sweet potato yield was significantly higher in the tied ridges and least in the oxen plough. **Implication:** Water harvesting technologies and cropping systems improved yields in the research site**.** **Conclusion:** CropSyst model simulated sorghum and sweet potato yield reasonably well due to the good agreement between observed and simulated yield values.

Key words; ASALs; Cropping system; CropSyst model; Sorghum; Sweet potato; yield.

RESUMEN

Antecedentes: Los rendimientos de los cultivos han estado disminuyendo en las tierras áridas y semiáridas (ASAL) de Kenia debido a la baja fertilidad del suelo y la baja disponibilidad de agua en el suelo causada por las precipitaciones escasas e inestables y las técnicas deficientes de captación de agua. Por lo tanto, es necesario un mejor manejo del agua disponible. **Objetivo:** Simular los rendimientos de sorgo y batata bajo diferentes prácticas de labranza. **Metodología:** El experimento se diseñó en un diseño de bloques completamente al azar con arreglo de parcelas divididas, con tres repeticiones. Los factores experimentales fueron: prácticas de labranza, sistemas de cultivo e insumos orgánicos. Los cultivos probados fueron sorgo (*Sorghum bicolor* L.) y batata (*Ipomoea batatas* L. lam) rotados y/o intercalados con dolichos *(Lablab purpureus*) y garbanzo (*Cicer arietinum*). El modelo CropSyst se calibró utilizando la biomasa aérea final observada y el rendimiento de sorgo y batata en el sitio experimental. La validación del modelo se realizó utilizando el índice de acuerdo de Wilmott (WI). **Resultados**: El modelo CropSyst

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se validó con precisión debido a los bajos valores de RMSE (0.629) y PD (menos de ±3) que se obtuvieron y el índice WI que fue cercano a 1. En los sistemas de cultivo basados en sorgo, el rendimiento de 1.611 kg ha^{-1} obtenido fue alto en los camellones ($p \leq 0.05$), en comparación con los surcos y crestas de 1.559 kg y 1.383 kg ha^{-1} en el arado de bueyes en la temporada I. En la temporada II, el rendimiento simulado de sorgo de 2.072 kg fue alto en los camellones ($p \leq 0.05$), seguido por los surcos y crestas de 2.005 kg y el menor de 1.779 kg ha^{-1}) en el arado de bueyes. En la primera temporada; El rendimiento simulado de sorgo (1595 kg ha-1) fue significativamente alto en el sistema RP + FYM y menor (1436 kg ha^{-1}) en el control. En los sistemas de cultivo basados en batata, el rendimiento de batata (13 127 kg ha^{-1}) fue significativamente mayor en los camellones y menor (10 127 kg ha^{-1}) en el arado de bueyes en la primera temporada. En ambas temporadas, el rendimiento de batata fue significativamente mayor en los camellones y menor en el arado de bueyes. **Implicación**: Las tecnologías de captación de agua y los sistemas de cultivo mejoraron los rendimientos en el sitio de investigación. **Conclusión:** El modelo CropSyst simuló razonablemente bien el rendimiento de sorgo y batata debido a la buena concordancia entre los valores de rendimiento observados y simulados.
Palabras clave: Áreas de cultivo; árido; semiárido; Sistema de cultivo; Modelo CropSyst; Sorgo; Batata; Rendimiento.

INTRODUCTION

Agricultural production in the arid and semi-arid lands (ASALs) is negatively affected by the variability of rainfall onset and also, by distribution and frequent droughts that occur during the growing season. These factors cause decrements of yields and persistent crop failures (Miriti, 2011, Miriti *et al*., 2012). Cultivation of drought resistant crops in the ASALs could improve food production (KARI, 2006). In such context, sorghum (*Sorghum bicolor L*.) is well adapted in ASAL's and is appreciated as a food security crop (Mwadalu and Mwangi, 2013). The crop is the most important cereal crop in the semi–arid tropics (FAO, 1995), and quantitatively ranks second to maize (Zea mays) in Africa (Taylor, 2003). Sweet potato (*Ipomoea batatas (L.) Lam*.) is important in the economy of resource poor households in the ASALs (Qaim, 1999) and a major source of subsistence and cash income to farmers in agro-climatically disadvantaged regions of Kenya (Githunguri *et al*., 2007).

Accurate knowledge of soil water content in ASALs is essential for proper soil management and crop production. Studies have shown that agriculture in the ASALs of East Africa is mostly rain-fed (Hatibu and Mahoo, 2000; Critchley, *et al.,* 1999). Therefore, moisture stress is a major constraint to food production in these areas; hence, to guarantee food security, sound Agricultural Water Management (AWM) is necessary. AWM includes all deliberate human actions designed to optimize the availability and utilization of water for agricultural purposes (Mati, 2007) and include soil and water conservation, rainwater harvesting, soil fertility management, and conservation agriculture (Bashir *et al*., 2017; Karuku, 2018). Sound agricultural management should ensure that available rainwater becomes useful to crops and that it is not used for negative impacts such as soil erosion. Soil and water conservation with water harvesting are techniques used for supporting rain-fed agriculture in the ASAL (Hai, 1998; Mati, 2006). On-farm rainwater harvesting using structures such as ridges preserve soil moisture and result in improved crop yields (Chepkemoi *et al*., 2019; Karuku *et al*., 2019; Mati, 2007).

Crop simulation models can be used to assess the likely impact of climate, environment and management on grain yield and yield variability (Tingem *et al*., 2008). A number of simulation crop models such as Aquacrop, CropWat (Etissa *et al.,* 2016; Karuku *et al.,* 2013; Khalil *et al*., 2008) can predict yield responses to large variations in weather models. CropSyst (Stockle *et al.,* 1994) is one of those models that could be used along with a set of daily weather data spanning a reasonable number of years to assess the impact of climate on agriculture. CropSyst is a multi-year, multi-crop, daily time step cropping systems simulation model developed to serve as an analytical tool to study the effect of climate, soils and management on cropping systems productivity and the environment. CropSyst simulates the soil water budget, soil plant nitrogen budget, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water and salinity. These processes are affected by weather, soil properties, crop characteristics and cropping system management options including crop rotation, cultivar selection, irrigation, crop nutrition such as nitrogen fertilization, soil texture and irrigation.

The objective of this study was therefore to simulate the effects of different tillage practices, cropping systems and organic inputs on sorghum and sweet potato yields.

MATERIALS AND METHODS

Experimental site

The study was conducted in Matsu Sub-County in the Eastern province of Kenya. The site coordinates are; 1º37' S and 1º45' S latitude and 37º15' E and 37º23' E longitude at an altitude of 700-800 meters above level (Braun *et al*.,1982). Matsu Sub-County is in agro-climatic zone IV and is classified as semi-arid land (Jaetzold and Schmidt, 2006; Manzi *et al*., 2021). Rainfall patterns exhibit distinct bimodal distribution with long rains (LR) between mid-March and end of May and the short rains (SR), between mid-October and end of December. Average seasonal rainfall ranges between 250-400 mm per annum. Inter-seasonal rainfall variation is large with a coefficient of variation ranging between 45-58 per cent, while temperature ranges between 17-24^{0}C. The soils are a combination of Luvisols, Lithisols, and Ferralsols (USDA,1978; WRB, 2014). The soils are well drained, moderately to very deep, dark reddish brown to dark yellowish brown, friable to firm, sandy clay to clay, with high moisture storage capacity and low nutrient availability (Chepkemoi *et al*., 2014; Kibunja *et al*., 2010; Namoi *et al*., 2014). The majority of the farmers in the district are small-scale mixed farmers with low income investment for agricultural production. The major crops grown in semi-arid areas of eastern Africa include maize, beans, sorghum, millet, cassava, pigeon peas, sweet potatoes and cowpeas **(**Chepkemoi *et al*., 2014; Lyavoga *et al*., 2014; Madegwa *et al*., 2016; Macharia, 2004) Crop performance and yield are significantly influenced by the amount of rainfall and distribution throughout the rainy season.

Experimental design and treatments

For the purpose of both model calibration and validation of CropSyst model, field experiments were conducted for two seasons; short rain season (2012) and long rain season (2013). Data for season one was used to calibrate the model while season two data was used for model validation. The experimental layout was a Randomized Complete Block Design with split-split plot arrangement and replicated three times. The main plots were; tillage practices (Oxen plough, tied ridges and furrows, and ridges). Split plots were cropping systems (mono cropping, intercropping and crop rotation) and split-split plots were FYM, RP and FYM combined, RP and a control (no organic input was applied). The test crops were sorghum and sweet potato intercropped or grown in rotation with legumes legumes i.e. dolichos and chickpea.

Research Methodology

Land preparation and planting

The land was prepared using oxen to plough in late September 2012. Sorghum and sweet potato were planted in October during the short rains. Sorghum seeds were sown at a spacing of 30 cm by 60 cm. Sweet potato cuttings were planted at a spacing of 30 cm by 90 cm. Weeding was done every 4 weeks after planting. Harvesting sorghum was done by hand after 3 months when physiological maturity was reached, while sweet potato was harvested manually using implements such as hoe after 4 months.

Soil analysis

Soil sampling was done before planting, during flowering and at harvest stage in a transect. Soil was sampled using a soil auger (600 cm^3) at 0-15, 15-30 and 30-45 cm depths and composited in to one mosaic sample**.** The **s**oil was analyzed for chemical properties; pH, and mineral nitrogen (N) and physical characteristics, texture, bulk density, moisture at field capacity (FC) and permanent wilting point (PWP). The soil properties were used to create the soil file for use in calibrating CropSyst model. Soil moisture content was determined by gravimetric method for each plot before sowing, flowering and at harvest growing stages. Soil moisture was later converted to volumetric moisture content (v/v) proportion by multiplying by bulk density.

The soil texture was by hydrometer as described by Glendon and Doni (2002). Soil pH was measured with pH meter in a 1:2.5 ratio soil to water (pH-H_2O) and to KCl (pH-KCl) (Okalebo *et al*., 2002). Bulk density was determined according to Blake and Hartage (1986). The PWP was taken as -1500 kPa which is the lower limit of available water (Nemes *et al*., 2008) while the FC for individual soil layers was measured using the internal drainage procedure. Soil moisture content was determined by gravimetric method as described by Dane and Topp (2002). Total N and mineral N were determined by determined by Micro-Kjeldhal method as described by Bremner (1996).

CropSyst model description

The CropSyst model is premised on the assumption that actual biomass/ output is a result of interactions involving various independent variables which include weather, soil types, management practices and crop physiology (Table 1). The model simulates the soil water budget, crop canopy and root growth, dry matter production, yield, residue production and decomposition, and erosion. Management options include: cultivar selection, crop rotation, irrigation, nitrogen fertilization, tillage operations (>80 options) and residue management.

Model calibration

Management, soil, crop and weather files, sorghum and sweet potato crops were required for CropSyst model to run the model for Matuu division. For each cropping system and organic input, one management file was prepared to represent each tillage practice. The date of each phenological stage (emergence, flowering, and physiological maturity) was used to calculate growing degree days for that stage. The values of the crop input parameters were either taken from the CropSyst manual (Stockle *et al.,* 1994) or observed in the field. The dates for the phenological stages; emergence, flowering stage, grain filling and physiological maturity were used to calculate growing degree days (GDD = T_{mean} -T_{base}; where T_{mean} (T_{max} + T_{min})/2). The values of crop input parameters (maximum harvest index, maximum expected LAI, base temperature, cut-off temperature and maximum root depth were taken from the CropSyst manual (Table 2). Location file was also prepared using the actual observed weather data from the nearest weather station.

The calibrated values (Table 3) were PWP, FC and mineral nitrogen. Observed mineral nitrogen was adjusted from 28.54 to 58.91 $KgNha^{-1}$ in the top 0-10 cm depth. PWP was adjusted from $0.17m^3m^{-3}$ to 0.29 cm while FC was adjusted from $0.23m^3m^{-3}$ to-$0.38m^3m^{-3}$ (Table 3) in the 0-10 soil depth after comparing the observed soil water content with the model output. Also the model adjusts the FC and PWP units accordingly and the small overlap is normal (Karuku et al., 2014b) and ensured closeness between the observed soil water values and the simulated values. Crop growth was majorly affected by the soil moisture and nitrogen content and adjustment to the required amount was done. Soil texture and bulk density were not calibrated since they were within the required range.

Table 1. Data sets required to run CropSyst model.

File	Parameters Required by the Model	Parameters used in the model
*Location	Latitude, Longitude, Altitude	Latitude: 37º15’ E and 37º23’ E Longitude: 1º37’ S and 1º45’ S Altitude: 700-800m a.s.l
Soil	pH, PWP, FC, BD, Soil texture	Table 3 (observed in the field)
Crop,	Growing degree days (GDD) to emergence, GDD to peak leaf area index, GDD to flowering, GDD to maximum grain filling, GDD to maturity, Base temperatures, Cut-off temperatures, maximum root depth.	Table 2 (GDD were observed in the experimental site). Other crop input parameters were taken as default values.
Management	Nitrogen fertilization (application date, amount, source- organic and inorganic-, and application mode- broadcast, incorporated, injected), Tillage operations (primary and secondary tillage operations),	Organic inputs; FYM, RP, FYM + Tillage practices; Tillage operations were calibrated for oxen plough, tied ridges, furrows and ridges

Table 2. Crop parameters for CropSyst model calibration of sorghum and sweet potato based cropping systems.

Parameter	Sorghum	Sweet potatoes
Growing degree days emergence (°C-day)	100	300
Growing degree days peak leaf area index (LAI) (°C-day)	1867	22
Growing degree days flowering (°C-day)	1165	1440
Growing degree days maxi mum grain-filling (°C-day)	1209	1875
Growing degree days maturity (°C-day)	1846	2674
Maximum harvest index	1.47	0.49
Maximum expected LAI	7.0	9.0
Base temperature (°C)	8	3
Cut-off temperature (°C)	30	25
Optimum mean daily temperature (°C)	25	23
Maximum root depth (m)	1.2	0.6

Table 3. Observed and calibrated physic-chemical soil properties.

Soil properties	Observed soil properties			Calibrated soil properties		
Soil depth (cm)	0-10	10-20	20-30	0-10	10-20	20-30
Sand (%)	49.32	49.30	49.36	49.32	49.30	49.36
Silt (%)	38.88	38.97	38.77	38.88	38.97	38.77
Clay (%	11.8	11.71	11.78	11.8	11.71	11.78
Textural class	Sand Clay	Sand Clay	Sand Clay	Sand Clay	Sand Clay	Sand Clay
pH (H_20)	6.5	6.7	6.8	6.5	6.7	6.8
PWP (m^3m^{-3})	0.17	0.18	0.20	0.27	0.28	0.29
Field capacity (m^3m^{-3})	0.23	0.25	0.27	0.34	0.36	0.38
Bulk density (g $cm^{-3)}$	1.503	1.508	1.67	1.503	1.508	1.67
NH_4-N (Kg N ha^{-1})	28.54	27.02	34.76	58.91	57.39	55.46
NO_3--N (Kg N ha^{-1})	24.87	29.34	25.72	52.67	51.83	50.44

Model Evaluation and Validation

CropSyst was validated by comparing model outputs with the observed soil moisture in different tillage practices cropping systems and organic inputs. The agreement between model and reality was verified by means of percentage differences (PD) and root mean square error (RMSE). This is frequently used measure of the difference between values simulated by a model and those actually observed from the experiment that is being modeled (Equ 1).

$$\text{RMSE} = \left[n^{-1} \sum (\text{Yield}_{meas} - \text{Yield}_{pred})^2\right] \dots\dots\dots\dots (1)$$

Wilmott index (WI) of agreement was calculated, which take a value between 0.0 and 1.0; where 1.0 means perfect fit (Wilmott, 1981).

Simulations

The input files required by the CropSyst model for Matuu Division, sorghum and sweet potato crops were used to run the model. Planting dates were set as 10th October, 2012 for both crops. Simulations were run from 10th September, 2012 a month before planting and ended in 31st, March 2013 for sorghum and 31st May for sweet potato. The experiment was repeated for the second season in 2013. The starting and ending dates indicated the simulation period. Sweet potato takes more time to mature compared to sorghum and hence the difference in the simulation dates.

Statistical test

Effect of the different treatments on soil moisture were statistically evaluated by analysis of variance (ANOVA) (GenStat 15.0 for Windows). Least Significant Differences (LSD) at the 5% level were used to detect differences among means.

RESULTS AND DISCUSSION

CropSyst model Validation for sorghum and sweet potato based cropping system

Sorghum based cropping system

Table 4 show observed versus simulated sorghum grain yield in the three tillage practices, cropping systems and organic inputs. CropSyst model showed good agreement between observed and simulated values of sorghum grain yield with Willmott index (WI) of agreement close to 1 at 0.99.

In the oxen plough tillage practice, percentage differences (PD) between the observed and simulated values in all the cropping systems ranged from -0.15 to +0.41 when FYM organic input was applied, and a RMSE of 2.01 and WI 0.992. When RP + FYM organic inputs were applied, PD ranged from -0.07 to + 0.28 with RMSE of 1.935and WI of 0.998. PD ranged from -0.328 to + 0.03 when RP organic input was applied with RMSE of 1.41 and WI of 0.990 while in the control, PD ranged from -0.21 to + 0.53 with RMSE of 1.715 and WI of 0.994 (Table 4).

In the furrows and ridges, PD between the observed and simulated values in all the cropping systems ranged from -0.21 to +0.08 when FYM organic input was applied with a RMSE of 1.99 and WI of 0.997 and. When RP + FYM organic inputs was applied PD ranged -0.12 to +0.30 with RMSE of 1.653 and WI of 0.989. PD ranged from -0.92 to +0.11 when RP organic input was used with RMSE of 1.431 and WI of 0.993 while in the control, PD ranged from -0.05 to +0.24 with RMSE of 2.27 and WI of 0.991. Under tied ridges and in all cropping systems, PD ranged from -0.31 to +0.45 with RMSE of 1.385 and WI of 0.996 when FYM organic input, PD ranged from -0.12 to +0.32 with RMSE of 0.993 and WI of 0.991 when RP + FYM organic inputs were applied. When

RP organic input was used, PD ranged from -0.30 to +0.06 with RMSE of 1.498 and WI of 0.997 while in control PD ranged from -0.38 to +0.07 with RMSE of 1.253 and WI of 0.998.

Validation of CropSyst model showed good agreement between observed and simulated sorghum grain yield. This was revealed by low percentage of difference (±3.5%) between observed and simulated values, low root mean square error and high Wilmot index of agreement. These low values of RMSE (close to zero) and the higher WI values (close to unity) for sorghum grain yield indicated that the CropSyst model can reasonably predict sorghum grain yield. According to Ventrella and Rinaldi (1999), CropSyst model simulated grain yield with a percentage difference of 0.4 which is close to the results observed in this study (Table 5). Likewise, Singh *et al*. (2008) reported that RMSE between observed and predicted biomass by CropSyst was 1.27 t ha^{-1}. According to Claudio *et al*. (2003), Wilmot index of agreement fluctuated from 0.92 to 0.97 (close to unity) which is similar to results obtained in this study.

Sweet potato grain yield

Table (5) show observed versus simulated sweet potato yield values in the three tillage practices, cropping systems and organic inputs. CropSyst model showed good agreement between observed and simulated values of sweet potato grain yield. In the oxen plough tillage practice, PD in all cropping systems ranged from -0.018 to +0.012 with RMSE of 1.63 and WI of 0.998 when FYM organic input was applied. When RP + FYM organic inputs were applied, PD ranged from -0.018 to -0.006 with RMSE of 1.263 and WI of 0.999, When RP organic input was applied PD ranged from +0.002 to +0.032 with RMSE of 1.50 and WI of 0.996 while PD ranged from -0.012 to +0.033 with RMSE of 1.85 and WI of 0.99 in the control.

In the furrows and ridges tillage practice and in all cropping systems, PD ranged from -0.013 to +0.033 with RMSE of 0.999 and WI of 0.099 when FYM organic input was applied and a PD ranging from -0.031 to +0.007 with RMSE of 1.202 and WI of 0.992 when RP + FYM organic inputs were used. When RP organic input was used, PD ranged from-0.009 to +0.237 with RMSE of 1.493 and WI of 0.99 while in the control, PD ranged from -0.017 to +0.03 with RMSE of 1.298 and WI of 0.999.

In the tied ridges tillage practice and in all cropping systems, PD ranged from -0.024 to +0.05 with RMSE of 2.722 and WI of 0.997 when FYM organic input was used and PD ranging from -0.011 to +0.007, RMSE of 0.629 and WI of 0.992 when RP + FYM organic inputs were used. When RP organic input was used, PD ranged from -0.0.018 to + 0.028 with RMSE of 1.429 and WI of 0.992 while in control PD ranged from -0.012 to +0.029 with RMSE of 2.155 and WI of 0.996 (Table 5).

Percentage differences between observed and simulated sweet potato yield were less than 1% indicating a good agreement between observed and simulated values. Root mean square error were low (0.999 – 2.722) while Wilmot index of agreement was close to unity (0.990 -0.999). The low values of RMSE and high WI indicate that the model reasonably simulated yields of sweet potato. Abdrabbo et al. (2013) obtained percent difference between measured and predicted grain yield less than 1% and Wilmot index of agreement was 0.99 which is similar to the results shown in this study. Likewise, EL Baroudy et al. (2013) obtained low RMSE of 0.29 and 0.32 for grain yield.

Simulated grain yield in the sorghum and sweet potato based cropping systems

Sorghum based cropping system

In the first season, there were significant differences ($P \leq 0.05$) in the different tillage practices, cropping systems and organic inputs (Fig. 1). There were also significant interactions in the tillage practices and cropping systems. In season 1, simulated sorghum yield (1611 kg/ha) was significantly high in the tied ridges, followed by furrows and ridges (1559 kg/ha) and least (1383 kg/ha) in the oxen plough (Fig. 1). In the second season, simulated sorghum yield (2,072 kg/ha) was significantly high in the tied ridges, followed by furrows and ridges (2,005 kg/ha) and least (1,779 kg/ha) in the oxen plough.

Tied ridges plots had the highest sorghum yield compared to oxen plough and furrows and ridges plots. The increased yield in the tied ridges could have been contributed by the fact that tied ridges retain rainwater in situ in the farms for crops for longer period as the water infiltrates the soil. The prolonged rainwater infiltration and retention for long period increase soil moisture for the crops and hence increased sorghum yield. Itabari *et al*. (2003) indicated that farming techniques that increase rainwater harvesting such as tied and open ridges improve crop productivity. According to Mat (2005), tied ridges have been found to be efficient in storing rain water, resulting in substantial grain yield increase in some of the major dryland crops such as sorghum.

Table 4. Statistical comparisons of observed and simulated sorghum yields under different tillage practices, cropping systems and organic input.

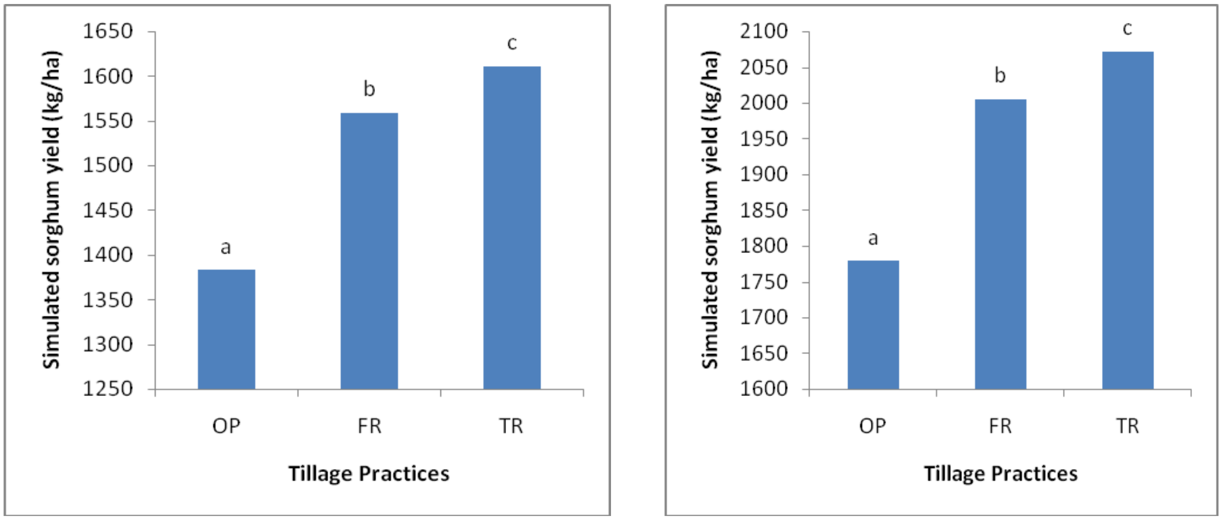
Treatments		**FYM**			**FYM+ RP**			**RP**			**CTRL**	
Oxen plough	Observed	Simulated	PC (%)	Observed	Simulated	PC (%)	Observed	Simulated	PC (%)	Observed	Simulated	PC (%)
SOR-	1003.44	1007.98	+0.38	1209.54	1212.88	+0.28	1184.01	1196.83	-1.08	1131.16	1125.13	+0.53
MONO	1311.23	1305.88	+0.41	1423.38	1420.29	+0.22	1203.02	1242.46	-3.28	1177.44	1175.41	+0.17
SOR/ DOL	1497.90	1504.82	-0.15	1505.07	1504.29	+ 0.05	1434.56	1435.76	-0.08	1221.74	1224.31	-0.21
SOR/CP	1447.87	1450.29	-0.10	1460.01	1462.97	-0.07	1413.95	1416.90	-0.03	1257.91	1260.09	-0.06
SOR-DOL	1453.06	1455.58	-0.04	1498.93	1493.82	+0.10	1437.06	1440.44	-0.08	1314.68	1309.87	+0.37
SOR-CP												
RMSE%		**2.01**			**1.935**			**1.41**			**1.715**	
WI		**0.992**			**0.998**			**0.990**			**0.994**	
Furrows and ridges												
SOR-	1117.26	1116.28	0.07	1425.22	1427.03	-0.11	1107.55	1106.06	0.11	1278.26	1276.62	0.12
MONO	1931.13	1930.22	0.05	1937.99	1940.32	-0.12	1915.42	1919.29	-0.20	1847.28	1842.76	0.24
SOR/ DOL	1364.33	1463.21	0.08	1478.98	1474.61	0.30	1420.11	1433.16	-0.92	1378.26	1376.62	0.12
SOR/CP	1633.73	1637.18	-0.21	1685.01	1681.89	0.19	1614.92	1616.70	-0.13	1479.88	1478.48	0.01
SOR-DOL	1681.36	1683.76	-0.14	1698.9	1697.04	0.03	1660.36	1661.39	-0.06	1596.97	1597.84	-0.05
SOR-CP												
RMSE		**1.99**			**1.653**			**1.431**			**2.27**	
WI		**0.997**			**0.989**			**0.993**			**0.991**	
Tied Ridges												
SOR-	1465.83	1469.46	-0.31	1457.05	1458.11	-0.07	1425.66	1428.21	-0.23	1352.34	1353.92	-0.13
MONO	1962.87	1960.64	0.45	1984.80	1987.21	-0.12	1958.97	1960.53	-0.07	1889.07	1890.44	-0.07
SOR/ DOL	1469.98	1370.20	-0.02	1528.93	1530.87	-0.05	1353.98	1357.98	-0.30	1305.89	1310.91	-0.38
SOR/CP	1752.18	1750.63	0.03	1785.48	1783.92	+0.32	1731.09	1733.74	+0.06	1705.34	1703.08	0.07
SOR-DOL	1744.92	1743.96	0.07	1758.92	1757.63	0.07	1705.11	1706.41	-0.08	1542.72	1547.25	-0.29
SOR-CP												
RMSE		**1.385**			**0.993**			**1.498**			**1.253**	
WI		**0.996**			**0.991**			**0.997**			**0.998**	

Legend: SOR-MONO; Sorghum mono-cropping, SOR/DOL; Sorghum dolichos intercrop, SOR/CP; Sorghum chickpea intercrop, SOR-DOL; Sorghum dolichos rotation, SOR-CP; Sorghum chickpea rotation, RP; Rock phosphate, FYM; Farm yard manure, PD; Percentage differences, RMSE; root mean square error, WI; Willmott index of agreement.

Table 5. Statistical comparisons of observed and simulated sweet potato yields under different tillage practices, cropping systems and organic input.

Treatments	FYM			RP+FYM			RP			CTRL		
Oxen plough	Observed	Simulated	PC (%)	Observed	Simulated	PC (%)	Observed	Simulated	PC (%)	Observed	Simulated	PC (%)
SP- MONO	9044.50	9043.43	+0.012	10267.02	10268.88	-0.018	9199.49	9196.56	+0.032	8845.32	8844.52	+0.009
SP/ DOL	9337.24	9338.88	-0.018	1107.24	11008.31	-0.009	9635.08	9634.05	+0.002	8445.39	8446.44	-0.012
SP/CP	10941.09	10940.03	+0.009	12217.59	12219.05	-0.012	10994.08	10991.53	+0.023	9896.78	9895.96	+0.008
SP-DOL	11758.88	11759.97	-0.009	12170.03	12170.79	-0.006	12178.06	12174.5	+0.029	10740.00	10739.12	+0.008
SP-CP	11588.68	11589.76	-0.009	13651.26	13652.07	-0.006	11951.22	11949/76	+0.012	10519.71	10516.2	+0.033
RMSE		**1.63**			**1.263**			**1.50**			**1.85**	
WI		**0.998**			**0.999**			**0.996**			**0.99**	
Furrows and ridges												
SP- MONO	9404.26	9404.85	-0.006	10845.05	10844.26	+0.007	9490.56	9489.232	+0.014	9213.55	9210.75	+0.03
SP/ DOL	9775.59	9772.38	+0.033	10762.99	10764.11	-0.01	10398.60	10398.6	-0.009	9319.18	9320.05	-0.009
SP/CP	8918.10	8915.20	+0.032	10506.07	10509.39	-0.031	9201.00	9198.23	+0.030	8064.71	8066.14	-0.017
SP-DOL	14435.83	14432.75	+0.021	14442.19	14445.02	-0.019	13950.86	13917.79	+0.237	13321.04	13321.46	-0.003
SP-CP	14260.64	14262.46	-0.013	16784.73	16783.86	+0.005	14692.24	14688.42	+0.026	12985.19	12984.57	+0.005
RMSE		**0.999**			**1.202**			**1.493**			**1.298**	
WI		**0.999**			**0.992**			**0.990**			**0.999**	
Tied Ridges												
SP- MONO	10627.26	10629.65	-0.022	12261.71	12263.1	-0.011	10729.23	10728.28	+0.008	10405.89	10402.82	+0.029
SP/ DOL	11077.00	11079.66	-0.024	13711.77	13710.82	+0.007	12003.68	12000.65	+0.025	8316.62	8315.11	+0.018
SP/CP	11197.09	11987.70	+0.05	14087.34	14088.26	-0.006	11991.09	11987.70	+0.028	7764.90	7763.78	+0.015
SP-DOL	15583.51	15580.60	+0.019	18333.35	18334.02	-0.004	16042.14	16045.04	-0.018	14187.95	14187.26	+0.018
SP-CP	15459.20	15459.71	-0.003	18785.51	18784.16	+0.007	15923.35	15924.15	-0.005	14068.11	14066.37	+0.012
RMSE		**2.722**			**0.629**			**1.429**			**2.155**	
WI		**0.997**			**0.998**			**0.992**			**0.996**	

Legend: SP-MONO; Sweet potato mono-cropping, SP/DOL; Sweet potato dolichos intercrop, SP/CP; Sweet potato chickpea intercrop, SP-DOL; Sweet potato dolichos rotation, SP-CP; Sweet potato chickpea rotation, RP; Rock phosphate, FYM; Farm yard manure, PD; Percentage differences, RMSE; root mean square error, WI; Willmott index of agreement

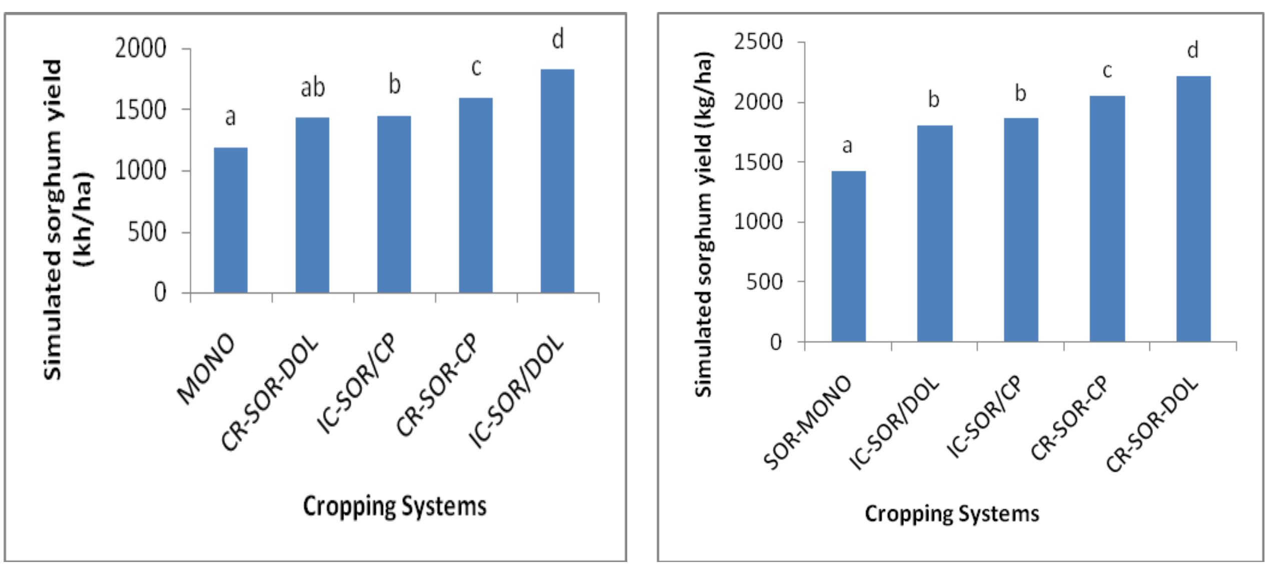


Season 1 Season 2

Figure 1. Simulated sorghum yield in the different practices for two seasons. Legend: OP; oxen plough, FR; furrows and ridges, TR; tied ridges

Cropping systems: In the first season, simulated sorghum yield (1,825 kg/ha) was significantly high in the sorghum/dolichos intercrop and least (1,191 kg/ha) in the sorghum mono-cropping (Fig.2). In the second season, sorghum yield (2,218 kg/ha) was significantly high in the sorghum-dolichos rotation and least (1,429 kg/ha) in the sorghum mono-cropping (Fig. 2).

Sorghum dolichos intercrop had the highest yield compared to sorghum mono-cropping and this could be attributed to increased soil fertility via raising soil organic content and available nitrogen fixed by legumes especially from the dolichos. Vandermeer (1989) stated that average dry matter and yields are higher with intercropping than when each of the plant species in the mixture is grown as a monoculture. When legumes are included in a crop mixture, an extra benefit is improved soil fertility due to the legume species' fixation of biological nitrogen (N), and increased protein content of the cereal component (Jensen, 2006).



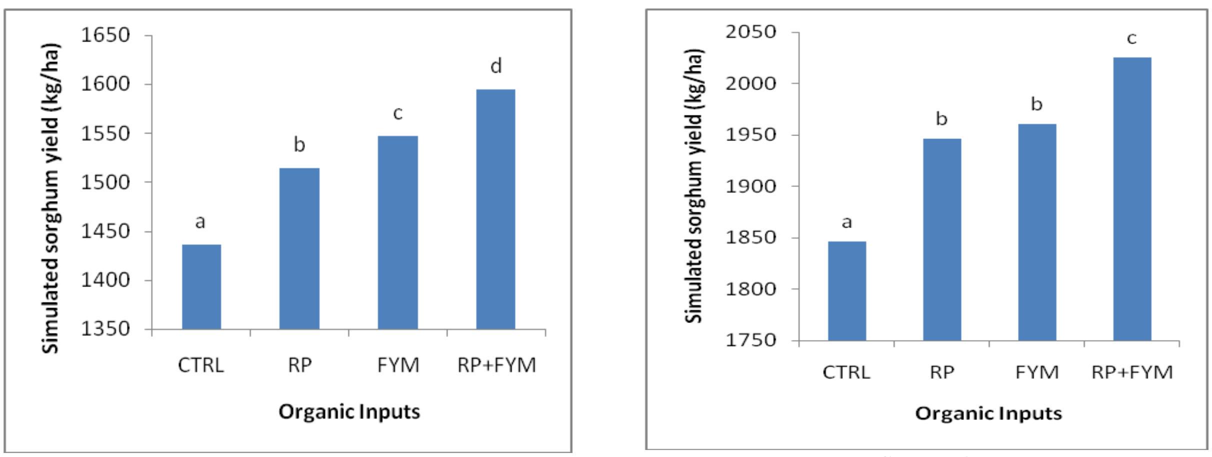
Season 1 Season 2

Figure 2. Simulated sorghum yield under different cropping systems. **Legend:** CR; crop rotation, IC; intercropping, CP; Chick pea; SOR; Sorghum

Organic inputs: In the first season; simulated sorghum yield (1595 kg/ha) was significantly high in the RP +FYM and least (1436 kg/ha) in the control (Fig.3). In the second season, sorghum yield (2,025 kg/ha) was significantly high when RP + FYM was applied and least (1,846 kg/ha) in the control when no organic input was applied.

RP + FYM increased sorghum yields than when the organic inputs were used solely. The increase in sorghum yield could be attributed to improved soil fertility. Okalebo *et al*. (1999) stated that soil fertility could be improved by the use of combinations of farm yard manure and organic inputs since this combination provide a cheap N input from the organics and the solubilization of phosphorus through formation of favorable acid environments.

Tillage practice and cropping systems interactions*:* In the first season, sorghum yield (1,955.6 kg/ha) was significantly high in the interaction between tied ridges and sorghum/dolichos intercrop and least (981.5 kg/ha) in the interaction between oxen plough and sorghum monocrop (Fig. 4). In the second season, sorghum yield (2,584 kg/ha) was significantly high in the tied ridges interaction with sorghum and dolichos rotation and least (11,519 kg/ha) in the oxen plough with sorghum mono-cropping.



Season 1 Season 2

Figure 3. Simulated sorghum yield (kg/ha) under different organic inputs. **Legend:** CRTL; control, RP; Rock phosphate, FYM; farm yard manure.

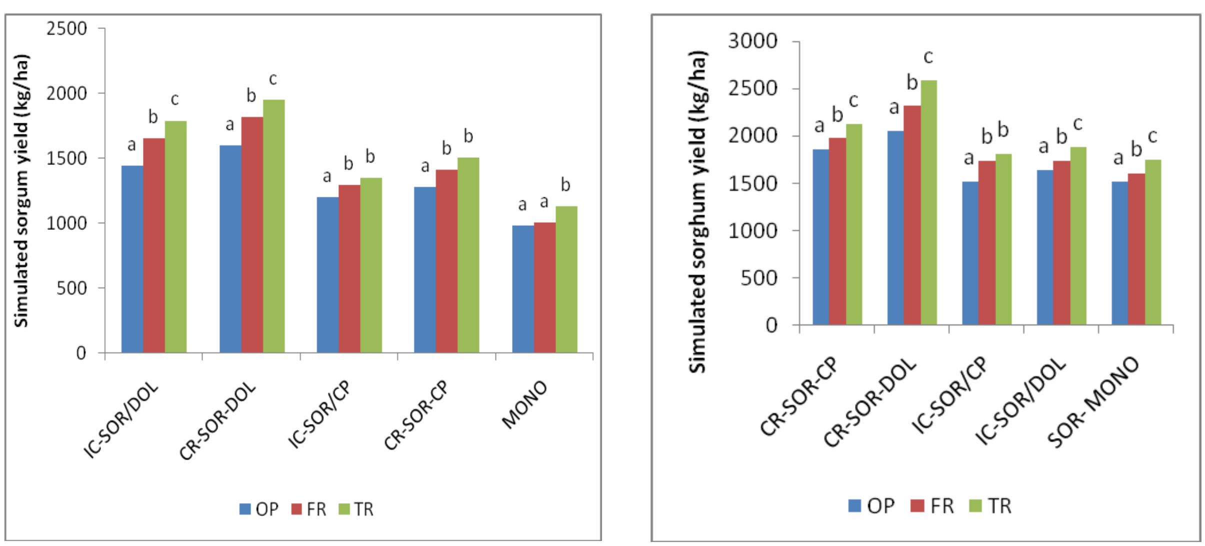


Figure 4. Simulated sorghum yield (kg/ha) under tillage practices interacting with cropping systems. **Legend:** SOR-SOR-Sorghum; DOL-Dolichos; CP-Cowpea; IC-Intercropping; CR-Crop rotation; Mono-Mono-cropping

High sorghum yield in the tied ridges and sorghum-dolichos rotation plots could be attributed to improved soil moisture since tied ridges are able to retain rainwater for long and soil fertility from the dolichos. Soil moisture conservation under such conditions requires appropriate tillage practices that not only improve rainwater infiltration but also conserves adequate soil moisture for plant growth (Miriti *et al*., 2012).

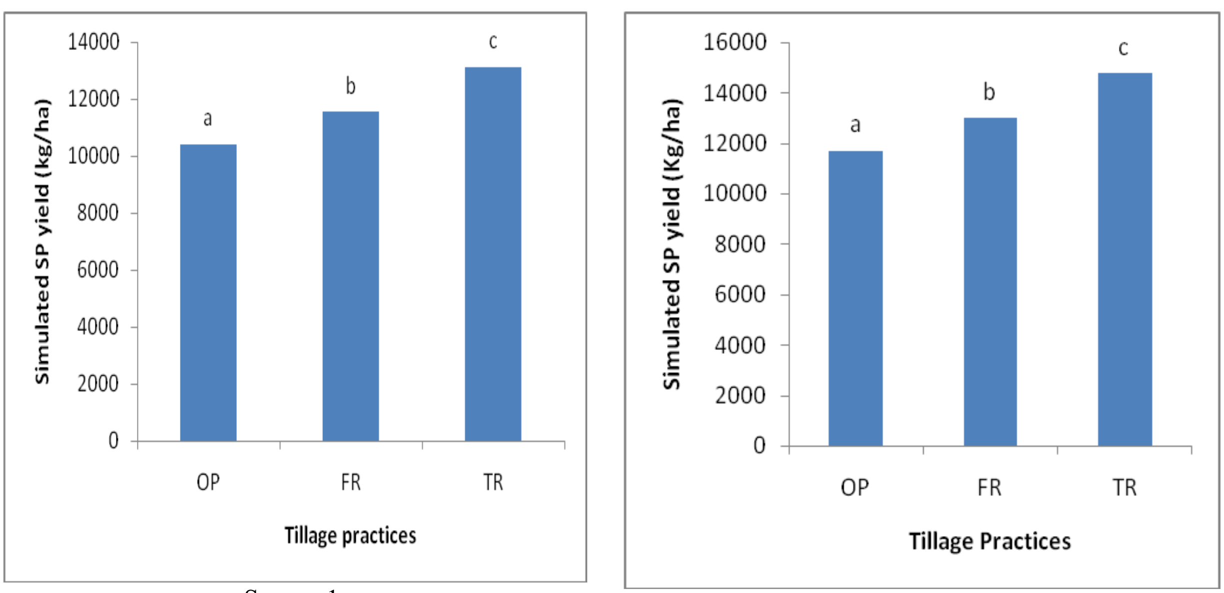
Sweet potato based cropping systems

There were significant (P ≤0.05) differences in sweet potato yield in the tillage practices, cropping systems and organic inputs. There were also significant interactions in tillage practices and copping systems. In the first season, sweet potato yield (13,127 kg/ha) was significantly high in the tied ridges and least (10,127 kg/ha) in the oxen plough (Fig. 5). In the second season, sweet potato yield (14,768 kg/ha) was significantly high in the tied ridges and least (11, 699 kg/ha) in the oxen plough.

Simulation data shows that tied plots with ridges had the highest sweet potato yield compared to oxen plough and furrows and ridges plots which could be attributed to better on-farm rainwater management that led to high sweet potato yield. Tied ridges are known to improve yields due to improved soil moisture (Rockström, 2003). Results from tied ridges techniques have been shown to give superior yields for different crops (Miriti *et al*., 2003; Kipserem, 1996).

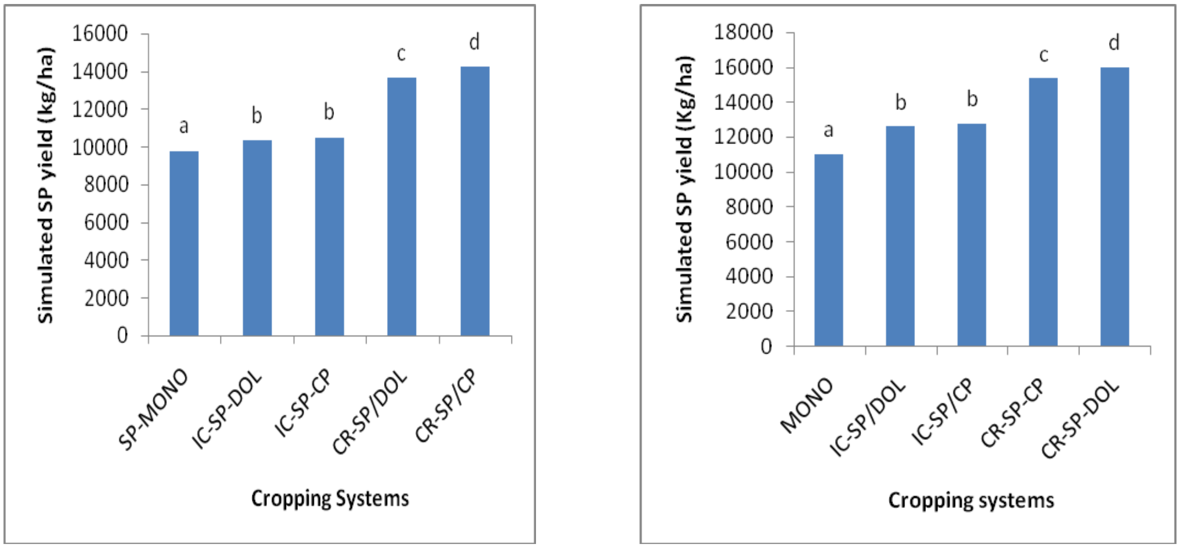
Cropping Systems: In season 1, sweet potato yield (14,222 kg/ha) was significantly higher in the sweet potato-chick pea rotation compared to all other treatments (p≤0.05) and least (9,772 kg/ha) in the sweet potato mono-cropping (Fig. 6). In season 2, sweet potato yield (16,000 kg/ha) was significantly high in the sweet potato rotation with dolichos compared to all other treatments (p≤0.05) and least (10,993 kg/ha) in the sweet potato mono cropping. Intercropping could have improved the soil fertility of the soil since chickpea and dolichos has the capacity to fix di-nitrogen with association with rhizobia bacteria in the soil. Intercropping sweet potato with chickpea/ dolichos enhances and maintains soil fertility through the fallen leaves and decaying roots after the chickpea is harvested which provide nitrogen and other nutrients in the soil.

Legumes are known to fix nitrogen in the soil hence improving soil fertility and thus sweet potato yield. Guretzky *et al*. (2004) reported that legumes have the potential to improve soil fertility through the release of nitrogen from decomposing leaf residues, roots and nodules leading to increased crop yields. Sweet potato rotation with dolichos increased sweet potato yield in the second season. Increased sweet potato could be attributed to improved soil fertility due litter fall from dolichos. The high yields could be attributed to improved soil fertility. Legumes have



Season 1 Season 2

Figure 5. Simulated Sweet potato yield under different tillage practices. **Legend:** OP; Open plough, FR; furrows and ridges, TR; tied ridges, SP; sweet potato



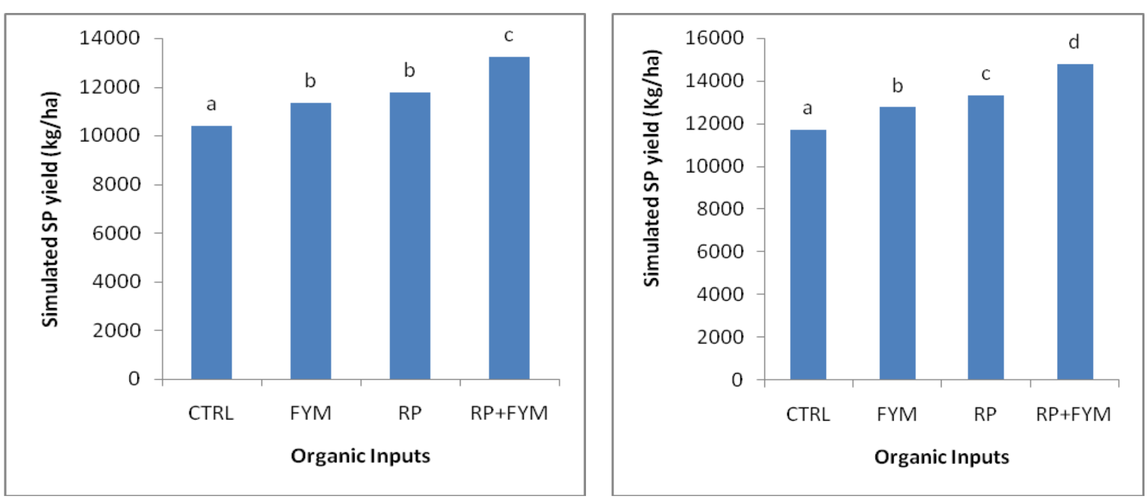
Season 1 **Season 2**

Figure 6. Simulated sweet potato yield (kg/ha) under different cropping systems. **Legend:** SP; Sweet Potato, IC; Intercropping, CR; crop rotation, DOL; Dolichos, CP; Chickpea

proven to be an effective means of sustaining soil fertility (Cheer *et al*., 2006).

Organic inputs: In season 1, sweet potato yield (13,247 kg/ha) was significantly ($P \leq 0.05$) high when RP + FYM was applied compared to all other treatments ($P \leq 0.05$) and least (10,405 kg/ha) in the control when no organic input was applied (Fig. 7). In season 2, sweet potato yield (14,034 Kg/ha) was significantly ($P \leq 0.05$) high in the RP + FYM compared to all other treatments and least (10,995 Kg/ha) in the control when no organic input was applied.

RP + FYM had significantly high ($P \leq 0.05$) sweet potato yield compared to sole application of the organic inputs and least in the control. The high sweet potato yield could be contributed to the enhanced soil fertility and improved soil moisture due to increased water retention from

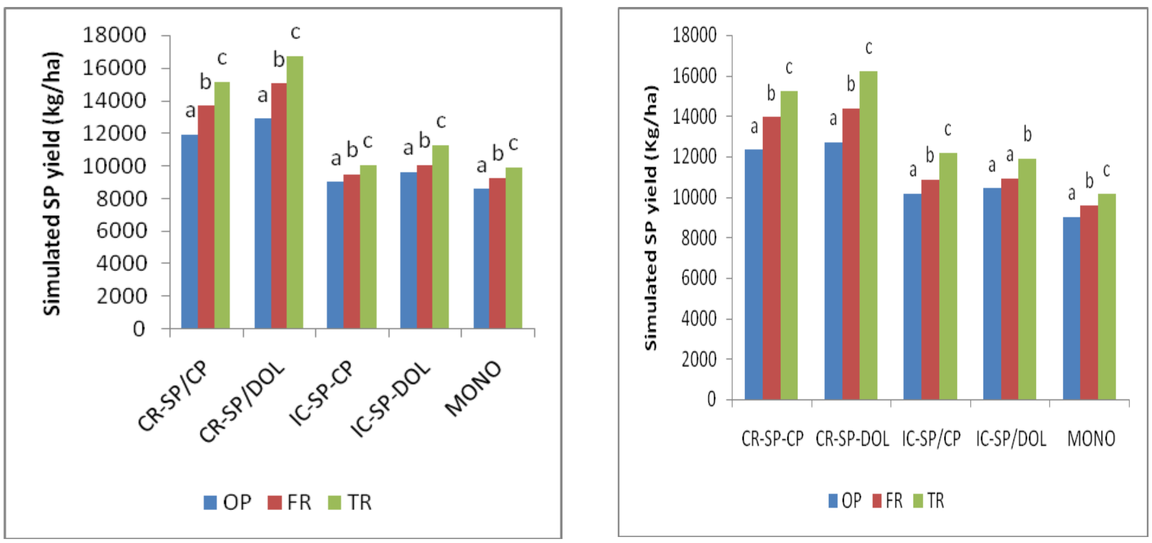


Season 1 Season 2

Figure 7. Simulated sweet potato yield (Kg/ha) in different organic inputs. **Legend:** SP; sweet potato, CTRL; control, FYM; Farm yard manure, RP; Rock Phosphate

organic residues and nutrients from the phosphate rock(RP). Combined application of farm yard manure and rock phosphate have resulted in significant increases in crop yield and increases in soil nutrients as compared with sole application of inorganic fertilizers (Liu *et al*., 1996).

Tillage practice and cropping systems interactions: In season 1, sweet potato yield (16,737 kg/ha) in the tied ridge-interaction with sweet potato intercropped with dolichos compared to all other treatments (P ≤ 0.05) and least (8572 kg/ha) in the oxen plough-interaction with sorghum mono-crop (Fig. 8). In season 2, sweet potato yield (18, 066 kg/ha) was significantly high in the tied ridges-interaction with sweet potato rotated with chick pea compared to all other treatments (P ≤ 0.05) and least (9643 kg/ha) in the oxen plough interaction with sweet potato monocrop. The combined use of tied ridges, intercropping and rotation of sweet potato with dolichos increased sweet potato yields probably due to increased soil moisture harvested during rains in tied ridges and also by improved soil fertility from dolichos residues. According to Gardener *et al*. (1999), tied ridges increase soil moisture content due to increased water storage and hence improves crop yields.



Season 1 Season 2

Figure 8. Simulated sweet potato yield (kg/ha) in tillage and cropping systems interactions. Legend: OP; oxen plough, FR; Furrows and ridges, TR; Tied ridges, CR; crop rotation, SP; sweet potato, CP; Chickpea, DOL; Dolichos, IC; intercropping

CONCLUSIONS

Tied ridges, intercropping and crop rotation systems and FYM + RP had high sorghum and sweet potato yield.

High yield was observed in the sorghum based cropping systems when the tied ridges water harvesting technology, sorghum intercropping and rotation with dolichos interacted.

Highest sweet potato yield was observed with tied ridges water harvesting technology when sweet potato was intercropped and rotated with dolichos and chickpea interacted.

CropSyst model simulated sorghum and sweet potato yield reasonably well due to the good agreement between observed and simulated yield values.

The farmers are therefore advised to use tied ridges in these dry environments to harvest water and also intercrop legumes with other crops for sustainable yields and mitigation against draught/poor harvests.

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Data availability. All the data is present in this paper.

Author contribution (CRediT). G.N. Karuku – Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Investigation, Project administration, Visualization, Resources, Software, Writing original draft, Validation, Review & editing.

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