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Soil moisture management and fertilizer micro-dosing on yield and land utilization efficiency of inter-cropping maize-pigeon-pea in sub humid Tanzania

Paul S. Saidia[a,b,*], Folkard Asch[c], Anthony A. Kimaro[d], Jorn Germer[c], Frederick C. Kahimba[e], Frieder Graef[f], Johnson M.R. Semoka[g], Cornel L. Rweyemamu[b]

[a] Tanzania Agriculture Research Institute (TARI) Ukiriguru, Mwanza, Tanzania
[b] Sokoine University of Agriculture, Department of Crop Science and Horticulture, Morogoro, Tanzania
[c] University of Hohenheim, Institute for Plant Production and Agroecology in the Tropics and Subtropics, Stuttgart, Germany
[d] World Agroforestry Centre (ICRAF), Country Head Office, Dar es Salaam, Tanzania
[e] Sokoine University of Agriculture, Department of Engineering Sciences and Technology, Morogoro, Tanzania
[f] ZALF, Institute of Land Use Systems, Müncheberg, Germany
[g] SokoineUniversity of Agriculture, Department of Soil and Geological Sciences, Morogoro, Tanzania

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ABSTRACT

Principally caused by soil water stress and declining soil fertility, low crop productivity results in both food and income insecurity. The effects of nitrogen and phosphorus fertilizer micro-dosing with inter-row rainwater harvesting practices for maize and pigeon-pea inter-cropping on yield and land use efficiency are inadequately documented in sub humid tropics. A field experiment on sandy loam soils in sub humid conditions using a split-split plot design was conducted. Plots used *in situ* rainwater harvesting practices of tied ridges, open ridges, and flat cultivation. Sub-plots were sole maize, sole pigeon-pea, and 1:1 maize-pigeon pea inter-cropping. The sub-sub plots were control, fertilizer (N and P) application at the micro-dose level, and recommended rates. Tied ridges significantly ($p < 0.001$) conserved more soil moisture than flat cultivation at 30 cm depth after ten days of rainfall. Ridges increased maize yield by 0.3 t ha^{-1} over flat cultivation. Fertilizer application significantly ($p < 0.001$) increased maize yield by 1.12 t ha^{-1} with micro-dosing and by 1.60 t ha^{-1} with recommended rates over the control. Combining tied ridges and fertilizer significantly ($p < 0.040$) increased maize yield by 132–156% compared to flat cultivation without fertilizer. Reflecting a land equivalent ratio, land use efficiency was 67–122% higher in inter-cropping than sole crop. Tied ridges conserved more soil moisture than flat cultivation, enhancing fertilizer use efficiency that improved crop yields and land equivalent ratio under inter-cropping. This strategy could increase food availability and income generation under smallholder farming systems in sub-humid tropic areas.

1. Introduction

Globally, declining soil fertility and water stress are among the main factors causing low crop productivity. Consequently, smallholder production systems are experiencing increased food, nutrition, and income insecurity. Maize (*Zea mays* L.), the most important cereal crop in Sub-Saharan Africa (SSA) grown for both food and cash (Smale et al., 2011; Sule et al., 2014), yields an average 1.0-1.5 t ha^{-1} in smallholder systems. The potential for tropical maize yield is estimated to be 7.5 to 8.2 t ha^{-1} (van Ittersum et al., 2016). Maize is often intercropped with pigeon pea (Egbe and Idoko, 2012; Weldeslassie et al., 2016; Kimaro et al., 2009; Myaka et al., 2006). Pigeon-pea (*Cajanus cajan* L.) yields 0.5 – 0.7 t ha^{-1}, representing only 20–26% of its potential (Cheboi et al., 2016).

Thus, when pigeon-pea is intercropped with maize, it may benefit from management practices aimed at maize (Sharma et al., 2011; Dania et al., 2014). Intercropping cereals and legumes diversify crop production, subsequently improving food, nutrition, and income (Kimaro et al., 2009). Pigeon pea improves soil fertility through biological nitrogen fixation and incorporation of green manure that may facilitate yields of maize crops to increase.

Fertilizer application is important for maintaining soil health, as

* Corresponding author at: Tanzania Agriculture Research Institute (TARI) Ukiriguru, Mwanza, Tanzania.
E-mail address: paulsaidia@yahoo.com (P.S. Saidia).

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extraction rates for nutrients exceeds the natural delivery from the soils. Thus, nutrients balances and organic matter balances are negative (Bitew and Alemayehu, 2017). Fertilizer use by smallholder farmers is low, with only 35% of cultivating households use fertilizers, averaging 57 kg/ha in SSA (Sheahan and Barrett, 2017). The low fertilizer adoption by smallholder farmers is mainly due to untimely availability of inorganic fertilizers in rural areas and its low affordability (Emmanuel et al., 2016; Mohapatra and Kameswari, 2014). Hence, fertilizer microdosing, appropriately placing reduced doses, is important. Fertilizer microdosing technology is the application of low amount (25–33 %) of the rates recommended by advisory services placed close to a plant during sowing and/ -or the vegetative growth stage in SSA (Tovihoudji et al., 2017; Camara et al., 2013; Okebalama et al., 2016). This enables farmers to start with the lowest cost effective fertilizer rates that is affordable for resource poor farmers. Fertilizer micro-dosing is proven efficient and economical in semi-arid and arid conditions of Africa (Adams et al., 2016; Tovihoudji et al., 2017; Mwinuka et al., 2017; Aune and Coulibaly, 2015). This strategy is an entry point for fertilizer use in sub-humid tropical areas and reportedly doubles maize yields (Saidia et al., 2018).

Inadequate rainfall and poor distribution results in prolonged dry spells, which are becoming a common problem for smallholder farmers in SSA. Rowhan et al. (2011) report that a 20% increase in seasonal precipitation variability reduces yields by 4.2% for maize, 7.2% for sorghum, and 7.6% for rice in Tanzania. Most of SSA is characterized by high spatial and temporal variability of rainfall (Kotir, 2011; Msaki et al., 2015). Poor runoff management practices under the flat cultivation that is commonly used by smallholder farmers increase water loss, moisture stress, soil erosion, while affecting plant nutrient availability and uptake (Nyamadzawo et al., 2013). Research shows that inter-row rainwater harvesting techniques, such as ridges and pits, increase crop yields in rain-fed farming areas while minimizing risks of crop failure in drought prone areas (Adimassu et al., 2017; Nyamadzawo et al., 2013).

Fertilizer micro-dosing and soil moisture management practices improve plant nutrient availability, uptake, and utilization, thus enhancing crop yields under erratic rainfall conditions. Although some studies about fertilizer use and inter-row rainwater harvesting on maize and pigeon-pea inter-cropping in SSA exist, none are mentioned explicitly. Therefore, to sustainably increase the efficient use of water and nutrients in sole and inter-cropping systems, improving crop management with simple measures like ridging and fertilizer placement with reduced doses are increasingly important in sub humid tropical conditions across Africa.

The objectives of this study are to examine the influence of inter-row rainwater harvesting methods, as well as nitrogen and phosphorus micro-dosing, on yields and land use efficiency of maize and pigeon-pea sole and inter-cropping systems in sub-humid tropical areas of Tanzania.

2. Materials and methods

2.1. Description of the study area

Field experiments were conducted during the 2014/15 and 2015/16 cropping seasons at Ilakala village in Ulaya ward and Changarawe village in Masanze ward, Kilosa District in the Morogoro Region of Tanzania. The Ilakala study site is located at 7° 8′ 24″ latitude, 36° 55′ 12″ longitude and 599 m above sea level (masl), and the Changarawe site is at 6° 55′ 12″ latitude, 36° 57′ 0″ longitude and 502 masl. These sites are farmer's fields used for research managed experiments.

The total amount of rainfall, measured using a standard rain-gauge, is 490 and 892 mm at Ilakala, and 359 and 695 mm at Changarawe for the 2014/15 and 2015/16 seasons, respectively. Cropping seasons at both sites started in November which is indicated as the first 30 days (Fig. 1). Rainfall distribution in this sub-humid area is usually bimodal with a short rainy season ("*Vuli*") from November to January with 200–380 mm of precipitation and a long rainy season ("*Masika*") from February or early March to late May with 400–800 mm precipitation. During 2014/15 and 2015/16 rainfall was erratic see Tables 1 and 2 in Saidia et al. (2019).

Soils in Ilakala and Changarawe are categorized as Haplic Acrisols and Mollic Fluvisols, based on the Tanzania Land Evaluation Tool developed by Trans-SEC (2017). According to Soil Survey Staff (2014) and Landon (1991), the physical and chemical analysis of soils at the study sites (Table 1) indicate that soil texture is sandy loam, with soil pH (1:2.5 H_2O) medium acidic to neutral at Ilakala and strongly acidic to medium acidic at Changarawe. Total nitrogen, organic carbon, and phosphorus (mg/kg P- Bray 1) are low. Exchangeable potassium is medium to high. Micronutrients, such as copper, iron and manganese are medium to high, except zinc, which is low.

At the study site in Ilakala pigeon-pea was previously grown in three quarter and the remaining part was under fallow. The average slope at the site is 9.7% determined as shown in Equation 1.

$$Slope = \frac{Height\ (m)}{Horizontal\ (m)} X\ 100\% \tag{1}$$

The study site in Changarawe was left fallow from 2011 to 2013; during the 2013/14 season, sesame (*Sesamum indicum* L.) was grown. The Changarawe trial site slope is 11.5% (Equation 1).

2.2. Experimental design, treatments and management

In all experiments, maize 'TMV1', medium maturing (110 days) and open pollinated (Lyimo et al., 2014), and pigeon-pea 'Babati white', a long maturing variety that takes about nine months to mature (Saxena et al., 2010) were planted. Sowing was done on January 21–22, 2015 in Ilakala, with replanting on March 23–24, 2015; the Changarawe site was sown on March 07, 2015, and replanted on March 20, 2015 due to drought. In 2016, both sites were sown January 16 – 23. The decision on sowing dates was based on farmers experience, advice from the Tanzania Meteorological Agent (TMA), and advice from researchers at the Tanzania Agriculture Research Institute (TARI) Ilonga. Both varieties are commonly used in the area (Kanyeka et al., 2007; Myaka et al., 2006). Fertilizers used were di-ammonium phosphate DAP $(NH_4)_2HPO_4$ a granulated solid fertilizer (18% N and 46% P_2O_5), and urea (46% N).

In each village, an experiment was laid out in split-split plot design with five replications as described by Montgomery (2013). The main plot comprised three moisture management options: (1) tied ridges, (2) open ridges, and (3) flat cultivation. The sub-plot factor composed of three cropping options: (1) maize sole crop, (2) pigeon-pea sole crop, and (3) 1:1 additive inter-cropping of maize with pigeon-pea, as described by Natarajan (1990). The sub-sub plot factor comprised three crop specific fertilizer application rates: (1) control (0 kg P and 0 kg N/ha), (2) micro-dosing rate (10 kg P and 20 kg N/ha in maize; 10 kg P and 9 kg N/ha in pigeon-pea) and (3) recommended rates of 40 kg P/ha and 80 kg N/ ha for maize (Marandu et al., 2014) and 20 kg P/ha (Kuma Rao et al., 1995) and18 kg N/ha for pigeon-pea.

Orientation of plots and treatments on the gently to moderately sloping field was arranged based on Montgomery (2013). Replications were oriented along a slope with replication one starting at the upper part of the field. Plots were oriented across the slope. Ridges were constructed across the slope in order to reduce runoff and harvest rainwater in the field.

Ridges were 75 cm apart with 20 cm height; while the distance between ties was 150 cm and 15 cm high, as recommended by Edje and Ossom (2010). Plot sizes were 5 m x 4 m resulting in 20m^2. Maize seeds on ridges were sown on the fore side and pigeon-pea on the back side of the ridges because maize need more moisture than pigeon-pea, which is drought tolerant. Additionally, the purpose of these ridges was rain water harvesting and soil moisture conservation in the field. The

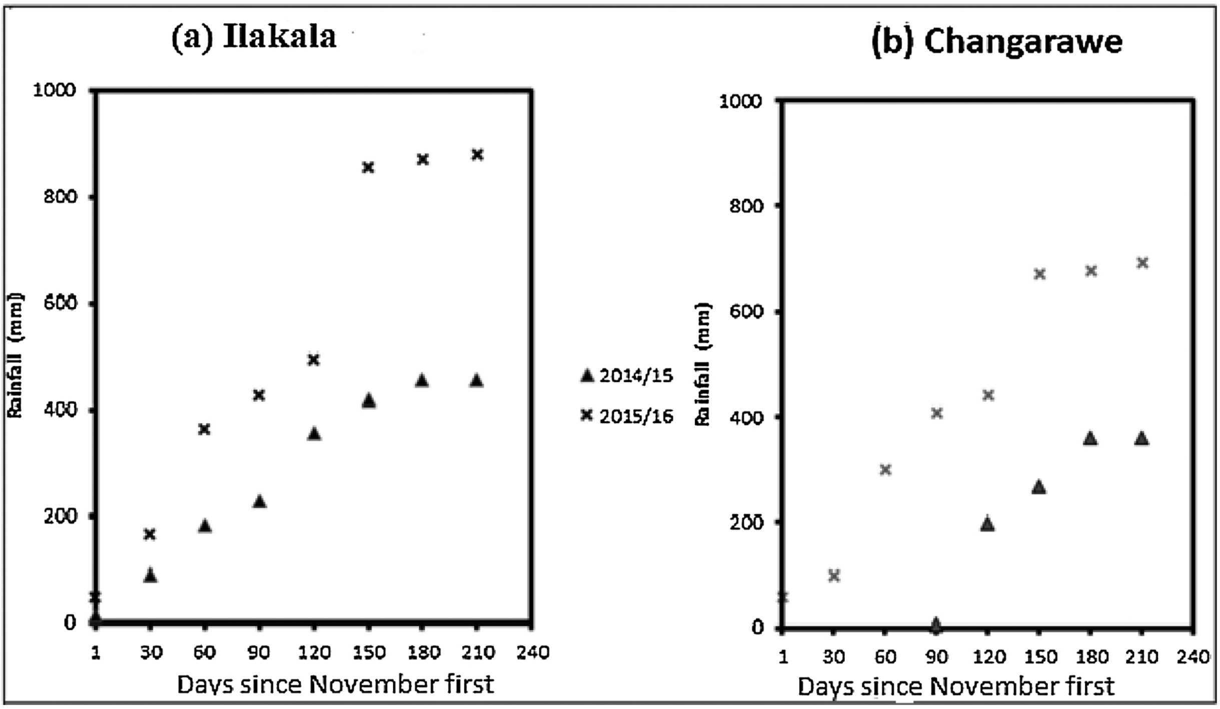

Fig. 1. Cumulative amount of rainfall during 2014/15 and 2015/16 cropping seasons.

Table 1
Soil characteristics at Ilakala and Changarawe study sites.

Soil characteristics	Ilakala (0–15 cm)	Ilakala (15–30 cm)	Chanagarawe (0–15 cm)	Changarawe (15–30 cm)
Sand (%)`	81	73	79	77
Clay (%)	14	20	12	14
Texture class	SL	SL	SL	SL
Soil pH	6.8^{neutral}	6.0$^{medium\ acidic}$	5.8$^{medium\ acidic}$	5.3$^{strongly\ acidic}$
Total nitrogen (%)	0.05^{VL}	0.05^{VL}	0.06 ^{VL}	0.04 ^{VL}
Organic carbon (%)	0.68^{L}	0.8^{L}	0.60^{L}	0.43^{VL}
P- Bray 1 (mg/ kg)	4.72^{L}	1.32 ^{L}	1.84^{L}	3.07 ^{L}
Exchangeable potassium (cmol +/ kg)	0.41 ^{H}	0.23^{M}	0.67^{H}	0.51^{H}
Exchangeable magnesium (cmol +/ kg)	0.11^{VL}	0.11^{VL}	1.89 ^{H}	1.72 ^{H}
Exchangeable calcium (cmol +/ kg)	0.48^{L}	0.48^{L}	3.89 ^{L}	3.89^{L}
Exchangeable sodium (cmol +/ kg)	0.52^{M}	0.52^{M}	0.24 ^{L}	0.16^{L}
Extractable Sulphur (mg/kg)	19.39^{H}	26.48^{H}	21.97^{H}	22.62^{H}
Copper (mg/ kg)	0.37^{M}	0.50^{M}	0.24 ^{M}	0.50^{M}
Zinc (mg/ kg)	0.43^{L}	0.60^{L}	0.89^{M}	0.31^{L}
Iron (mg/ kg)	19.78 ^{H}	25.62 ^{H}	38.76 ^{H}	41.68 ^{H}
Manganese (mg/ kg)	72.42^{H}	52.36^{H}	42.81^{H}	47.59^{H}

Letters represent abbreviation for remarks, baed on Landon (1991): SL = sandy loam, and VL = very low, L = low, M = medium, H = high, VH = very high.

germination test for both maize and pigeon-pea was 97–99%. Two seeds were sown in holes at a spacing of 75 cm x 30 cm for maize and 75 cm x 50 cm for pigeon-pea in both sole and inter-cropping. Thinning was done three weeks after sowing, resulting in one plant per hill. Di-ammonium phosphate (DAP) was applied at planting by placing fertilizer in holes 5 cm away from seed hole, 5–7 cm deep and covering fertilizer by soil on both maize and pigeon-pea crops. However, in intercropping, fertilizer application was done only for maize plants, with the assumption that the associate crop would benefit from the main crop. Urea was applied to maize during the fourth leaf vegetative stage (V4) by placing fertilizer in a hole 5 cm deep close to a plant (Camara et al., 2013; Kanyeka et al., 2007). Other nutrients were not applied, but weeding, and insecticide application were done as recommended (Kanyeka et al., 2007).

2.3. Data collection

2.3.1. Soil moisture

Soil moisture content was determined using a Delta T Device Moisture Meter type HH2, a Frequency Domain Reflectometry (FDR) with SM300 moisture sensor that measures volumetric soil moisture content by responding to changes in the apparent dielectric constant of moist soil (Anchit et al., 2016). Volumetric soil moisture content as the ratio between the volume of water present and the total volume of the sample is expressed in percentage (% vol) as described by Delta T Devices Ltd (2013). The sampling hole was dug at a center of each plot in all treatments and for ridges the hole was dug at a bottom. Measurements were taken from a hole dug by hand-hoe at a soil depth of 35 cm, where a pair of metal rings from a sensor was inserted directly at 5 cm, 15 cm, and 30 cm depths down the soil, respectively. Four sides in each depth were marked and the pair of metal rings was inserted three times in each side, with moisture content averaged per depth. To determine duration of soil moisture conservation in each inter-row rainwater harvesting practice, soil moisture content was measured 0.5, 2, and 10 days after rainfall for three consecutive events.

2.3.2. Yields of maize and pigeon-pea

Crops were harvested at harvest maturity from a harvest area of 3 m^2. Four rows in flat cultivation and four ridges in open and tied ridges were harvested. About 12 to 13 maize plants were cut 5 cm above the ground from each 3 m^2 sampling area, cobs were dehusked and shelled. Grains collected were oven dried untill 12.5% grain moisture content was achieved using the grain moisture meter (CIMMYT, 2013). Procedures for harvesting pigeon pea were based on ICRISAT (1992), with 8 or 9 plants harvested from each 3 m^2 sampling area plot. Grains collected from pods were oven dried at 80 °C to 10% grain moisture content. Grain weight was measured using the Advanced Electronic Balance ENDEL™ K- 3000BH and converted into hectare basis (t ha^{-1}) for maize and pigeon-pea in both sole and inter-cropping plots.

2.4. Data analysis

Data collected were subjected to Shapiro-Wilk test for normality (W Test Statistic) using GenStat 17 Version, most of variables were between 0.8 and 1.0 indicating normal distribution. Then analysis of variance (ANOVA) was completed based on the statistical model for the three factors main effects and their interaction effects as follows:

$$Y_{ijkm} = \mu + \beta_i + A_j + \delta_{ij} + B_k + AB_{ik} + \omega_{ijk} + C_m + AC_{jm} + BC_{km} + ABC_{jkm} + \varepsilon_{ijkm} \quad (2)$$

Where: Y_{ijkm} = response level, μ = general mean, β_i = block effect, A_j = main plot effect, δ_{ij} = the main plot random error (Error a), B_k = sub-plot effect, AB_{ik} = interaction effect between the main plot and the sub-plot, ω_{ijk} = subject error (Error b), C_m = sub-subplot effect, AC_{jm} = interaction effect between main plot and sub-subplot, BC_{km} = interaction effect between sub-plot and sub-subplot, ABC_{jkm} = the three way (Factors A* B* C), and ε_{ijkm} = sub-sub-plot random error effect (Error c) was used to test the treatment effects on the indices calculated.

Comparison of means used Tukey's test at p ≤ 0.05, as described by Montgomery (2013). The *T*-test compares soil moisture content between tied ridges and flat cultivation, with the hypothesis that the means of flat cultivations were equal to tied ridges.

Land equivalent ratio (LER) is the relative land area under sole crops that is required to produce the yields achieved by inter-cropping. It is an index of biological advantage used to compare the effectiveness of the inter-cropping system used in the study, as proposed by Federer (1993), where yields from intercrop and sole crop of each crop were used as follows:

$$LER = \frac{Xi}{Xs} + \frac{Yi}{Ys} \quad (3)$$

Where X and Y are the component crops, namely maize and pigeon-pea, in the sole (*s*) and intercrop (*i*).

3. Results

3.1. Soil moisture dynamics

Soil moisture content at different soil depths varied with duration after rainfall across rainwater harvesting (RWH) practices (Fig. 2). Flat cultivation, open ridges, and tied ridges at 5 cm soil depth had no significant differences (P ≤ 0.05) in moisture conservation at 12 h after rainfall. Soil moisture content decreased with soil depth after 12 h and two days after rainfall from flat cultivation, while in open and tied ridge plots moisture increased from 5 cm depth down the soil. Two days after rainfall, open and tied ridges had highest soil moisture content at 15 cm depth. Ten days after rainfall, soil moisture content increased with soil depths from 5 cm to 30 cm in all RWH practices (Fig. 2). When *T*-test was done at 30 cm soil depth, tied ridges had significantly higher (P = 0.001) soil moisture content; this increased by 24.77% more than flat cultivation 10 days after rainfall.

3.2. Effects of inter-row rainwater harvesting practices and fertilizer use on yield

Inter-row rainwater harvesting increases maize yields significantly (P = 0.001 and 0.004) at Ilakala in 2016 and Changarawe in 2015 only (Table 2). Yields increased from flat cultivation to tied ridges, except at Ilakala in 2015, where maize yields decreased toward tied ridges. Maize sole cropping had significantly higher grain yields than inter-cropping system (P = 0.001) at Ilakala in 2016 and Changarawe in 2015 and 2016. Application of fertilizer increased maize yields significantly (P = 0.001) at Ilakala in 2015, 2016 and Changarawe in 2015, 2016. Yields increased with increasing application rate from none to micro-dosing and recommended fertilizer (Table 2).

Table 2
Main and interaction effects of inter-row rainwater harvesting cropping systems and fertilizer use on maize grain yield (t ha^{-1}).

Treatment	Ilakala 2015	Ilakala 2016	Changarawe 2015	Changarawe 2016
RWH				
Tied ridges	0.96 a	2.58 c	1.01 ab	1.28 a
Open ridges	0.97 a	1.89 b	1.08 b	1.23 a
Flat	0.99 a	1.72 a	0.91 a	1.23 a
P Value	0.50	0.001	0.004	0.07
CV (%)	5.20	2.40	4.70	2.80
Cropping system				
Sole maize crop	0.97 a	2.06 b	1.00 b	1.25 b
Inter-cropping	0.94 a	1.53 a	0.83 a	1.01 a
P Value	0.23	0.001	0.001	0.001
CV (%)	6.20	4.30	6.20	17.5
Fertilizer use				
None	0.99 a	1.72 a	0.91 a	1.23 a
MF	1.82 b	3.24 b	2.07 b	2.17 b
RF	2.24 c	3.54 c	2.71 c	2.76 c
P Value	0.001	0.001	0.001	0.001
CV (%)	7.70	2.20	4.30	2.60
RWH X Fertilizer use				
TR + NF	0.957 a	2.577 c	1.006 a	1.283 a
TR + MF	2.431 cd	3.760 g	2.293 c	2.870 e
TR + RF	2.608 d	3.776 g	3.040 e	3.078 f
OR + NF	0.965 a	1.887 b	1.080 a	1.227 a
OR + MF	2.165 c	3.457 e	2.185 bc	2.523 c
OR + RF	2.573 d	3.643 fg	2.880 de	2.849 de
Fl + NF	0.991 a	1.720 a	0.913 a	1.230 a
Fl + MF	1.821 b	3.236 d	2.068 b	2.166 b
Fl + RF	2.238 c	3.540 ef	2.711 d	2.755 d
P Value	0.001	0.001	0.040	0.001
CV (%)	5.00	2.30	4.40	2.00
P Value (RWH x Cropping system x Fertilizer use)	0.09	0.001	0.001	0.001

Means followed by same letter (s) in the same column are not significantly different according to Tukey's Test at P ≤ 0.05. CV is the coefficient of variation. RWH is the rainwater harvest.

Maize yields increased significantly (P = 0.001 and 0.004) under the combined effects of inter-row rainwater harvesting and fertilizer. Interaction effects between inter-row rainwater harvesting and fertilizer use at micro-dosing and recommended rates had higher maize yields than fertilizer use and rainwater harvesting alone. The combination of tied ridges and fertilizer application at recommended rates had the highest maize yield at both study sites in 2015 and 2016. The yield difference between fertilizer use alone and its combination with tied ridges was higher by 0.37 t/ha (Ilakala 2015), 0.24 t/ha (Ilakala 2016), 0.33 t/ha (Changarawe 2015) and 0.32 t/ha (Changarawe 2016)

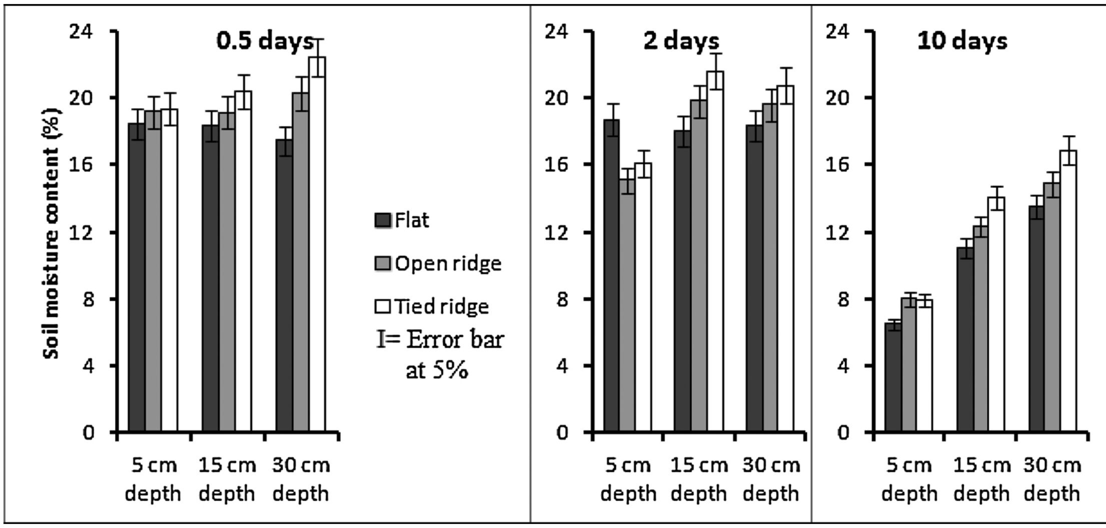

Fig. 2. Soil moisture at different soil depths with time (days) after a rainfall event under flat cultivation, open ridges, and tied ridges.

Table 3
Main and interaction effects of inter-row rainwater harvesting cropping systems and fertilizer use on pigeon pea grain yield (t ha-1).

Treatment	Ilakala 2015	Ilakala 2016	Changarawe 2015	Changarawe 2016
RWH				
Tied ridges (TR)	0.47 a	1.04 a	0.89 a	1.01 a
Open ridges (OR)	0.78 b	0.99 a	1.02 a	0.78 a
Flat (Fl)	0.83 b	1.20 a	0.82 a	1.30 a
P Value	0.009	0.81	0.45	0.16
CV (%)	16.90	43.80	22.60	31.70
Cropping system				
Sole pigeon pea crop	0.69 b	1.07 a	0.91 a	1.03 a
Inter-cropping	0.45 a	1.19 a	1.06 a	0.91 a
P Value	0.001	0.47	0.06	0.38
CV (%)	21.10	33.10	18.00	33.30
Fertilizer use				
None (NF)	0.83 b	1.20 a	0.82 a	1.29 a
Micro-dose (MF)	0.57 a	0.79 a	1.01 a	1.35 a
Recommended (RF)	0.61 ab	1.17 a	1.64 b	1.08 a
P Value	0.04	0.28	0.005	0.67
CV (%)	17.60	34.40	19.50	36.00
RWH X Fertilizer use				
TR + NF	0.468 a	1.040 a	0.890 a	1.013 a
TR + MF	0.766 bc	1.518 a	0.790 a	0.988 a
TR + RF	0.646 abc	1.037 a	0.823 a	0.854 a
OR + NF	0.784 bc	0.985 a	1.017 a	0.776 a
OR + MF	0.885 c	0.430 a	0.854 a	1.046 a
OR + RF	0.709 abc	0.859 a	1.521 b	0.884 a
Fl + NF	0.827 bc	1.196 a	0.823 a	1.290 a
Fl + MF	0.570 ab	0.793 a	1.011 a	1.353 a
Fl + RF	0.609 ab	1.169 a	1.641 b	1.077 a
P Value	0.001	0.141	0.001	0.829
CV (%)	17.70	49.10	18.00	35.10
P Value (RWH x Cropping system x Fertilizer use)	0.001	0.430	0.001	0.700

Means followed by same letter (s) in the same column are not significantly different according to Tukey's Test at P ≤ 0.05. CV is the coefficient of variation. RWH is the rainwater harvest.

(Table 2).

Rainwater harvest had significant effect on pigeon pea yield (P = 0.009) at Ilakala during 2015 only (Table 3). On average, flat cultivation had higher grain yields than ridging cultivation. Pigeon pea sole cropping had significantly higher yields (P = 0.001) than inter-cropping at Ilakala in 2015. On average, sole cropping had higher yields than inter-cropping. However, the yield difference is very small (< 2.5%). Fertilizer application increased pigeon pea yields significantly (P = 0.005) at Changarawe in 2015; however, yields decreased significantly (P = 0.04) with fertilizer application in 2015 at Ilakala (Table 3).

Interaction of inter-row rainwater harvesting, cropping systems and fertilizer use (3 × 3 × 3) on grain yields were significant (P ≤ 0.05), see Table 3 in Saidia et al. (2019) and Fig. 3. Fertilizer application increased grain yields in sole maize from control (1 t ha^{-1}) to recommended rates (2.5–3 t ha^{-1}) in 2015 with a significant increase to 3.8 t ha^{-1} in 2016. The trend of sole pigeon-pea yield was inconsistency with fertilizer use and soil moisture management practice. However, fertilizer application in flat cultivation increased pigeon pea yields in 2015 at Changarawe. Inter-cropping maize and pigeon-pea had overall higher yields than sole cropping plots, with yields increasing with fertilizer application. The intercropping system between maize and pigeon pea was affected by cropping season and locations (Fig. 3). Flat cultivation and fertilizer (micro-dosing and recommended rates) had the highest grain yields of 4–5 t ha^{-1} (Fig. 3).

3.3. Land use efficiency of cropping systems under rainwater harvesting (RWH) practices and fertilizer use

Land equivalent ratio (LER) is used to describe land use efficiency in maize and pigeon-pea cropping systems as shown in Table 4. The LER values range from 1.36 to 2.68 at Ilakala and from 1.40 to 2.79 at Changarawe for RWH. Tied ridge plots have higher land use efficiency (0.36 – 0.91) under intercropping than sole crop, while flat cultivation plots have 0.99–1.79 higher land use than sole crop. Fertilizer micro-dosing and recommended rates had the highest LER (2.29–2.73), except at Ilakala in 2015. Tied ridges with recommended fertilizer application had highest LER (2.62) at Changarawe in 2016. Open ridges with micro-dose fertilizer application resulted in the highest LER of 3.53 in 2016 at Ilakala. Flat cultivation combined with fertilizer application had the highest LER of 2.58 from recommended rates at Ilakala and 3.61 from micro-dosing rates at Changarawe in 2015.

4. Discussion

4.1. Site characteristics and effects of rainwater harvesting and fertilizer on yield

Variations in rainfall amount and distribution between Ilakala and Changarawe during the seasons are due to their distance from each

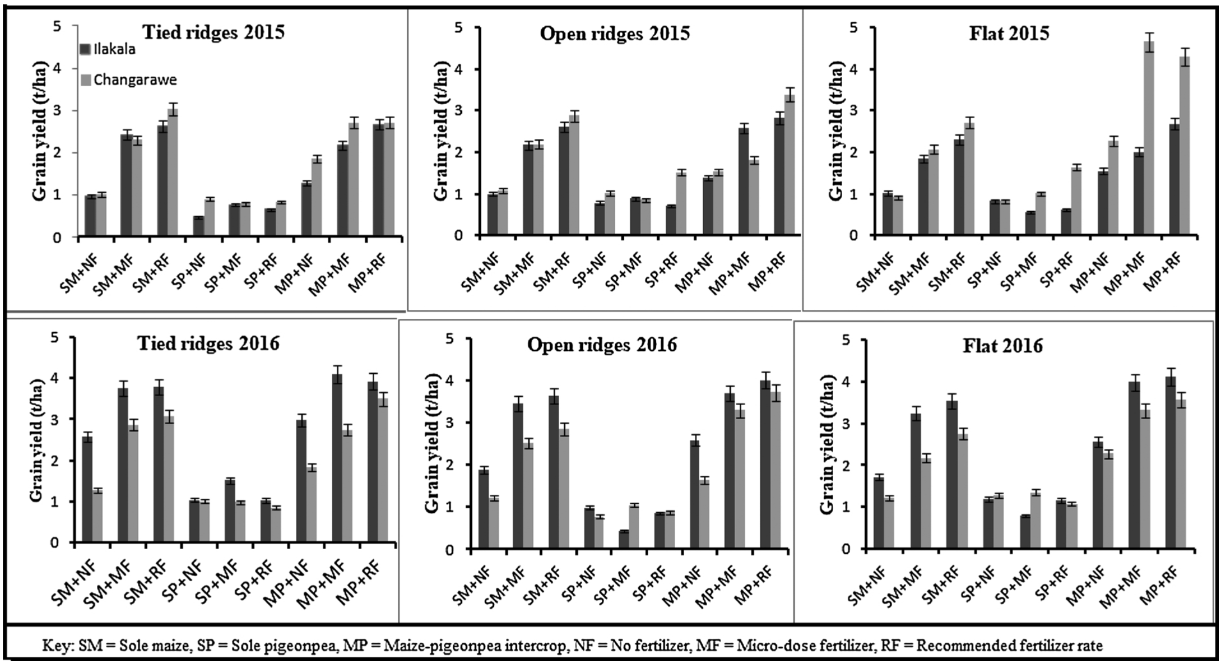

Fig. 3. Interaction effects of rainwater harvest, cropping system and fertilizer use on maize and pigeon-pea yield at Ilakala and Changarawe sites.

Table 4
Land equivalent ratios in maize and pigeon-pea intercrops grown under different rainwater harvesting (RWH) practices and fertilizer levels.

Treatment	Ilakala		Changarawe	
	2015	2016	2015	2016
RWH (a)				
Tied ridges (1)	1.36 a	1.82 a	1.91 b	1.90 a
Open ridge (2)	1.49 a	2.68 a	1.40 a	2.03 a
Flat (3)	2.15 a	2.16 a	2.79 c	1.99 a
P value	0.25	0.13	0.001	0.70
SEM (±)	0.32	0.25	0.07	0.11
CV (%)	38.80	23.10	6.90	10.90
Fertilizer use (b)				
Control (1)	1.82 b	2.08 ab	2.07 b	1.76 a
Micro-dose (2)	1.39 a	2.73 b	2.34 b	1.86 a
Recommended (3)	1.79 b	1.86 a	1.68 a	2.29 a
P value	0.01	0.02	0.001	0.16
SEM (±)	0.10	0.21	0.10	0.20
CV (%)	21.60	33.40	17.40	35.10
RWH x Fertilizer (a x b)				
1 × 1	1.76 a	1.91 a	1.97 ab	1.57 a
1 × 2	1.04 a	1.89 a	2.11 ab	1.52 a
1 × 3	1.29 a	1.67 a	1.65 a	2.62 a
2 × 1	1.54 a	2.35 a	1.53 a	1.78 a
2 × 2	1.43 a	3.53 a	1.29 a	2.03 a
2 × 3	1.51 a	2.17 a	1.37 a	2.27 a
3 × 1	2.17 a	2.00 a	2.74 bc	1.93 a
3 × 2	1.70 a	2.76 a	3.61 c	2.03 a
3 × 3	2.58 a	1.74 a	2.03 ab	2.00 a
Mean	1.67	2.22	2.03	1.98
P value	0.08	0.50	0.003	0.51
SEM (±)	0.35	0.39	0.16	0.30
CV (%)	21.60	33.40	17.40	35.10

Means followed by same letter (s) in the same column are not significantly different according to Tukey's Test at P ≤ 0.05. CV is the coefficient of variation, and SEM is a standard error of mean.

other and other differences in geographical locations. The Ilakala site is hilly, surrounded by mountains, and characterized by high vegetation cover, including forests. In contrast, Changarawe is undulating and has a moderate vegetation cover. During the study, there was a strong difference in rainfall pattern between the two cropping seasons, especially with regard to the onset of rain and erratic rainfall (Fig. 1) but their patterns were typical (Mary and Majule, 2009; Germer et al., 2011). This inter- and intra-seasonal variation of rainfall is increasingly influenced by climate change (Kijazi et al., 2012). Different geographical characteristics and rainfall variation between cropping seasons influenced maize and pigeon-pea yields see Table 4 in Saidia et al. (2019).

Tied ridges had higher maize grain yields than flat cultivation due to reduced runoff and increased soil moisture conservation (Fig. 2) in moderate slopping landscape 9–15% (Equation 1). However, in extreme moisture stress conditions, maize growth may be poorer contrary to what is expected under inter-row rainwater harvesting. For instance, Changarawe had a low amount of rainfall (358 mm), characterized by flooding in March and prolonged dry spells in April and May 2015. This condition confines runoff in ridges and increases surface evapo-transpiration, which probably affected yields negatively, as reported by Karuma et al. (2016). In general, maize yields was increase from flat cultivation to tied ridges because the crop grows well under moderate soil moisture conditions, hence it is susceptible to moisture stress (Awosanmi et al., 2017). In contrast to maize, pigeon pea yields were better in flat cultivation than tied ridges because it is more sensitive to excess water. Pigeon pea is well adapted to drought due to its deep tap root system that reaches up to two meters as well as its osmotic adjustment in leaves (Emefiene et al., 2013). Thus, pigeon pea has an inherent advantage due to its increased tolerance to drought under current climate changes (Augustino et al., 2012).

Significant increase in yields from micro-dosing and recommended rates indicate the importance of applying fertilizer under low soil nitrogen and phosphorus (Saidia et al., 2018; Masunga and Kazumba, 2017; Amuri et al., 2013). However, further increases in yields were due to interaction effects of inter-row rainwater harvesting using ridges and fertilizer application under the current changes of rainfall distribution. Therefore, the combination of inter-row rainwater harvesting and fertilizer use would reduce gap between actual and potential yields by 40% in a bad year and 53% in a good year for tropical maize with 7.5 t/ha potential yield (van Ittersum et al., 2016).

Inter-cropping maize and pigeon-pea had higher substantial yields than sole crops due to complementary and facilitative effects between these crops (Kimaro et al., 2009). Pigeon pea benefits from managements aimed at maize, while maize simultaneously benefits from soil fertility improvement due to biological nitrogen fixation and incorporation of green manure from pigeon pea crop. Further, different growth habits below and above the ground which reduced inter-specific competition for resources, could substantially increase yields compared to sole crop yields. This diversification of maize and pigeon pea crops is advantageous for the food, nutritional, and income security of small-scale farmers (Karuma et al., 2016).

4.2. Land utilization in cropping systems

Land equivalent ratios (LER) higher than 1.0 indicate that the maize-pigeon-pea inter-cropping system is more efficient with respect to land utilization than sole cropping (Federer, 1993). On average, LER in this study are within the range of 1.66–2.79 recorded by Dania et al. (2014) in Nigeria. However, some extreme land equivalent ratios were due to water harvesting practices and fertilizer use that was site and seasonal dependent. Prolonged dry spells of more than two weeks negatively affected yields and resulted in low LER of tied ridges compared with flat cultivation. However, during 2016 ridges both improved crop growth and had higher LER than flat cultivation due to soil moisture conservation under short-term dry spells of a week and not more than two weeks.

Differences in crop growth above and below architecture of maize and pigeon-pea reduced inter-specific competition and enhanced resource use efficiency. This is complementary, facilitative interaction effects that increase LER under maize and pigeon-pea intercropping (Kimaro et al., 2009). Pigeon pea has a tap root system that can penetrate up to 2 m deep, extracting more water and nutrients from both top and deep soil layers than maize, which is shallow rooted.Further, pigeon pea (Babati white variety) grows slowly during its first two months, ultimately flowering 6–7 months after sowing, while maize growth is faster, reaching tasselling two months after sowing. The addition of 10 and 20 kg P/ha in form of DAP at planting increases LER, indicating the importance of applying N as starter dose and P for root development and enhanced nitrogen fixation in low soil N and P. Rao et al. (1987) also report a similar trend for LER under flat cultivation in sorghum and pigeon-pea intercrops when nitrogen and phosphorus are applied. Therefore, maize and pigeon pea inter-cropping under inter-row rainwater harvesting and fertilizer use would reduce land use conflict between farmers and pastoralists in Africa, as reported by Cabot (2017); Roseline and Amusain (2017), and Walwa (2017).

5. Conclussion and recommendations

Tied ridges conserved more soil moisture than flat cultivation over ten days dry spell. Fertilizer application increases maize yields significantly under low soil nitrogen and phosphorus conditions when combined with inter-row rainwater harvesting. Tied ridging is the best strategy in sub-humid tropical areas where water stress from drought is increasingly common. The main rain season is experiencing shortage of rainfall, especially for cereal crops like maize, which are sensitive to dry spells, even short-term ones lasting a week. Adoption of micro-dosing at a rate of 10 kg P/ha to promote land productivity under maize-pigeon-pea intercrops is encouraged as an entry point for small-scale farmers. The strategy of inter-cropping under inter-row rainwater harvesting and fertilizer micro-dosing is encouraged to increase the food and income security of smallholder farms in sub-humid tropical conditions. Inter-cropping maize and pigeon pea is suitable in both ridged and flat cultivation as long as fertilizers are properly applied.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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