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Soil management strategies enhanced crop yield, soil moisture, and water productivity in Nitisols of the Upper Eastern Kenya

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ABSTRACT

Low soil moisture and declining crop yield caused by erratic rainfall, and poor soil management practises contribute to the continuous decrease in water productivity. We sought to assess the effects of the selected soil management strategies on crop yield, soil moisture, and water productivity in the *Nitisols*. We carried out the study in Chuka, Tharaka-Nithi County, and Kandara, Murang'a County. The experiment was laid in a split-plot design. Minimum and conventional tillage were the main treatments, while soil fertility inputs were the sub-treatments. The soil fertility inputs included sole mineral fertilizer, mineral fertilizer plus animal manure, mineral fertilizer plus crop residue, *Tithonia diversifolia* plus phosphate rock (Minjingu), sole animal manure intercropped with *Dolichos Lablab L.*. Maize grain, stover yield, soil moisture, and water productivity significantly increased by 6–22, 10, and 31–33% under conventional tillage than minimum tillage. Mineral fertilizer with or without organic inputs and with or without crop residue mulch significantly (p>0.0002) enhanced maize grain yield by 96 – 729% and stover yield by 79 -276% compared to the control in the two sites during the experimental period. Soil fertility inputs significantly increased soil moisture at 0–20 cm depth at the Chuka site by 10 - 40%. Water productivity was significantly (p > 0.0001) improved under mineral fertilizer with or without organic inputs and with or without crop residue mulch by 46 - 279% in both sites. Generally, the combination of organic and inorganic resources plus crop residue mulch enhanced soil water productivity irrespective of the tillage method. Their use should be encouraged for improved water productivity. However, tillage effects on crop yield, soil moisture, and water productivity should be investigated under long-term conditions.

1. Introduction

Crop production is majorly rainfall-dependent globally and in sub-Saharan Africa (SSA) (Mafongoya et al., 2016). Over 95% of the arable land in SSA is rainfed and predominatly smallholder farming (Mupangwa et al., 2012). However, erratic rainfall patterns characterized by frequent droughts and prolonged dry spells reduce crop yields and every so often result in crop failure (Macharia et al., 2020; Oduor et al., 2020). In Kenya, particularly the Central Highlands of Kenya (CHK), erratic and insufficient rainfall results in moisture stress to crops, surface runoff losses, and soil quality degradation.Farming practices by the farmers' in the Central Highlands of Kenya are characterized by soil nutrient mining without replenishiment, non-use of organic amendments, and low application rates of mineral fertiliser, which leads to low agricultural productivity (Mucheru-muna et al., 2010). Low soil moisture subjects crop to moisture stress affecting their productivity and increase food insecurity (Kiboi et al., 2017). Degraded soil physical properties exacerbate soil moisture constraints as efficient soil moisture utilization is dependent on soil hydrological properties (Wang et al., 2017). Crop yield is reduced due to low soil fertility caused by runoff losses and nutrient mining (Mutuku et al., 2020; K.F. Ngetich et al., 2014; Wolka et al., 2021). Increasing agricultural water productivity requires enhanced crop yield through efficient soil moisture utilization and improved soil quality (Molden et al., 2010). Strategies to enhance soil moisture utilization and soil quality are thus critical in boosting water productivity.

Minimum tillage enhances soil moisture retention, improves soil infiltration, reduces surface runoff, and enhances crop yield and nutrient

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use efficiency (Abdullah, 2014). Ngetich et al. (K.F. Ngetich et al., 2014) and Huang et al. (Huang et al., 2021) reported improved infiltration unde reduced soil disturbance (minimum tillage) which encouraged the continuity of the soil pores. On the other hand, in conventional tillage, constant soil disturbance reduces infiltration rate due to surface sealing and soil crusting (Martínez-Mena et al., 2020; Miriti et al., 2013). Additionally, soil disturbance causes more tortuous soil pores that reduce infiltration rate, encouraging runoff losses (Saiz et al., 2016). Combining minimum tillage with mulch and organic resources enhances soil aggregate stability, bulk density, infiltration rate, and hydraulic conductivity (Biddoccu et al., 2017). The organics add soil organic carbon, improve the stability of the soil aggregates and water retention capacity (Wang et al., 2017). However, there have been inconsistent reports on the advantages of minimum over conventional tillage, especially in combination with other soil management practices. Furthermore, the effects of different tillage methods vary with the climate and soil type (Moraru and Rusu, 2013). Farmers in the CHK still practice conventional tillage and do not retain organic residue mulch after harvesting making efficient moisture utilization elusive (Kibunja, 2007). This necessitates a further evaluation of the impact of minimum and conventional tillage on agricultural productivity in sub-humid environments, before further promotion of the technologies (Pittelkow et al., 2015).

Soil fertility inputs like mineral fertiliser, animal manure, and *Tithonia Diversifolia* have been reported to enhance crop yield and soil properties (Kiboi et al., 2021; Kiboi et al., 2019). Mineral fertiliser is, however, expensive and unaffordable to a majority of resource-poor farmers in Kenya who lack financial resources to purchase sufficient fertiliser amounts, considering fertiliser's cost up to six times more in Africa than in Europe (Mugwe et al., 2009; Sitienei et al., 2017). The use and effectiveness on crop yields are, therefore, low. Organic inputs, e.g., animal manure, are needed in large quantities to be effective because of their low nutrient supply capacity (Lukuyu et al., 2011). The inputs' availability in sufficient amounts is a challenge considering they face other equally competitive uses such as construction material for the case of animal manure (Mulumba and Lal, 2008). Combination of mineral fertiliser and organic inputs, which is within the farmers' socioeconomic circumstance could be recommend. The combination has emerged to have the highest and most sustainable gain in water productivity per nutrient or water used in various studies across SSA (Vanlauwe et al., 2010). The combination results in a synergistic effect that improves nutrient release and eventual crop uptake (Ali and Talukder, 2008). However, the performance varies with the management. For instance, N immobilization has been observed when organic resources with a high C: N ratio, like maize stover, are used with mineral fertiliser, ensuing to a reduction in crop yield (Liang et al., 2011). However, in other studies, organic plus mineral fertiliser has recorded increased yields (Vanlauwe et al., 2015). Thus the influence of integrating fertiliser and organic inputs with different soil management practices on crop productivity and soil moisture needs further investigation in the CHK.

Legume intercropping conserves soil aggregate stability, reduces crusting and surface sealing, reduces runoff Losses, and improves soil quality (Guto et al., 2012). In Kenya's CHK, farmers practice maize-beans intercropping to spread crop failure risk and dietary diversification aside from the benefits of soil and water conservation. However, the legumes compete with the cereal crops for the limited soil resources, which lowers overall yield (Ngwira et al., 2012). The effect of cereal-legume intercrop with tillage, organic plus inorganic inputs on soil physical properties need evaluation. The legumes can replenish soil mineral nitrogen by biological fixation of the atmospheric nitrogen Giller, (Giller, 2001) without competing with maize for soil nitrogen (Adu-Gyamfi et al., 2007). Herbaceous legumes, such as Dolichos (Lablab purpureus (L.), can improve soil fertility and crop yield (Onyango, 2017). However, the legumes still compete with the cereal for other production resources, lowering the overall yield. The intercropping needs to be integrated with different soil management practices to achieve higher yields.

Table 1
Soil texture (0–15 cm) at Chuka and Kandara sites during the experimental period.

Proportion	Chuka	Kandara
Sand%	14	10
Clay%	70	80
Silt%	16	9
Textural class	**Clay**	**Clay**

In the CHK, most smallholder farmers practice conventional tillage (Ct), exposing moist soil to evapotranspiration loss by turning the soil (K.F. Ngetich et al., 2014). Soil disturbance under conventional tillage increases soil erosion as the topsoils are loosened (Miriti et al., 2013). The decomposition rate of organic matter is high under conventional tillage; thus, low soil organic carbon (SOC) affects the soil's physico-chemical properties (Kiboi et al., 2019). These have contributed to the continued decline in water productivity in the Nitisols of the CHK. Minimum tillage is advantageous in terms of crop yieldd, soil moisture retenition. However, other studies such as Kiboi et al. (Kiboi et al., 2019) reported a lack of advantage on minimum tillage over conventional in combination with soil inputs. Cereal-legume intercrop can also improve soil quality through foliation and providing vegetative barriers that enhance efficient water utilization leading to improved water productivity (K.F. Ngetich et al., 2014). While most soil management strategies can enhance water productivity, they have often been applied in isolation to either enhance water use efficiency or improve soil quality and yield.

Improvement in water productivity requires concurrent enhancement of water use efficiency, crop yield, and soil quality (Molden et al., 2010). Practices that simultaneously enhance efficient use of water, crop yield, and soil quality for improved water productivity are desirable. Therefore we investigated the influence of integrated soil management practices on maize yield, soil moisture, and water productivity in the Nitisols of the Central Highlands of Kenya.

2. Materials and methods

2.1. Site description

We established experimental trials in Kangutu primary school farm in Chuka, Tharaka Nithi County, and in Kenya Agricultural and Livestock Research Organization (KALRO) farm in Kandara, Murang'a County. The soil type in both sites is *Nitisols* which are well-drained and moderate to highly fertile (Jaetzold et al., 2007; Kiboi et al., 2019). The mean annual temperature in both sites was about 21 °C during the experimental period. The rainfall pattern in the two sites is bimodal. The long rains fall between March and June, and the short rains between October and December (Oduor et al., 2020). The soil texture at the two sites is clay (Table 1).

2.2. Experimental design

We used the split-plot design in laying out the experiment with 14 treatment combinations replicated four times (Table 2). Two tillage systems (Minimum and conventional) were the main treatments, while soil fertility inputs, the sub-treatments (Table 2). The experiment plots measured 6 × 4.5 m in Chuka and 4.5 × 4.5 m in Kandara. Maize (Zea mays L.), H516 variety was used as the test crop in both sites. Under minimum tillage, the land was surface scratched using a machete during land preparation, and weeds hand-pulled. Under conventional tillage, hand hoeing was done to a depth of 15 cm, and weeding was done thrice with a hand hoe during the cropping seasons.

Organic soil inputs, animal manure and *Tithonia Diversifolia* were incorporated into the soil a fortnight to the season's onset throughout the experimental period. Under conventional tillage, they were incorporated in the entire plot, while under minimum tillage, the incorporation

Table 2

Experimental treatments at Chuka and Kandara sites.

Tillage	Soil fertility inputs	Abbreviations
Minimum	Minimum tillage	Mt
Minimum	Sole Mineral fertilizer	MtF
Minimum	Crop residue mulch + Mineral fertilizer	MtRF
Minimum	Crop residue mulch +Mineral fertilizer + Animal manure	MtRFM
Minimum	Crop residue mulch +*Tithonia Diversifolia*+Phosphate rock (Minjingu)	MtRTP
Minimum	Crop residue mulch+ Animal manure+ Legume intercrop *(Lablab purpureus* (L.)	MtRML
Minimum	Crop residue mulch + *Tithonia Diversifolia* + Animal manure	MtRTM
Conventional	Control	C
Conventional	Sole Mineral fertilizer	CtF
Conventional	Crop residue mulch + Mineral fertilizer	CtRF
Conventional	Crop residue mulch + Mineral fertilizer + Animal manure	CtRFM
Conventional	Crop residue mulch +*Tithonia Diversifolia* + Phosphate rock (Minjingu)	CtRTP
Conventional	Crop residue mulch + Animal manure + Legume intercrop (Lablab purpureus (L.)	CtRML
Conventional	Crop residue mulch + *Tithonia Diversifolia* + Animal manure	CtRTM

was done in the planting holes only. The organic inputs were analysed for N content (animal manure contained 2.1% of N, *Tithonia diversifolia* had 3.8% N) and the application rate determined by calculating the equivalence for 30 N Kgha^{-1} for treatments with organic resources plus mineral fertiliser and 60 N Kg ha^{-1} for treatments with sole organics. The mineral fertiliser used was NPK 23:23:0 to supply the required N amount of 30 Kg ha^{-1} for treatments with mineral fertiliser plus organic resource or 60 N Kg ha^{-1} for sole mineral fertiliser treatments. Phosphorus was supplemented at the rate of 90 Kg ha^{-1} using Triple Super Phosphate (TSP) in all the treatments with mineral fertilizer.

The plant inter and intra-row spacing was 0.75 m by 0.5 m, respectively. The seeding rate was three seeds per hill. Two weeks after emergence, thinning was done to two plants per hill to ensure a maximum plant population density of 53,333 plants ha^{-1}. Except for plots with sole mineral fertiliser, sole minimum tillage, and control plots, crop residue mulch was surface applied after crop emergence at a rate of 5 megagrams per hectare (Mg ha^{-1}).

2.3. Data collection

2.3.1. Rainfall data collection

Manual rain gauges were installed at each site for daily rainfall data recording at 9. 00 am during the study period

2.3.2. Soil sampling

We sampled undisturbed soil samples using Kopecky rings at 0–15 cm depth for bulk density and hydraulic conductivity determination before and after the study. Two soil samples for each of the parameters were taken in each plot and trimmed to the ring's exact volume, and taken for laboratory analysis. We collected disturbed soil samples at two points in each plot within 0–15 cm depth using Edelman auger for aggregate stability. The composite sample of the two points per plot of about 0.5 Kg was packaged in polythene bags and taken for laboratory analysis.

2.3.3. Crop yield

Grain and stover yields were weighed at the end of every cropping season in kilograms (Kg) after harvesting from net plots measuring 21 and 15 m^2 at Chuka and Kandara, respectively. The grains' dry weight was expressed per hectare at 12.5% moisture content. Grain percentage moisture content was monitored while drying using a moisture meter (Dickey-John MiniGAC® moisture meter). Stover drying was done under a shade to a constant weight. The obtained dry stover weight was used in correcting stover moisture content before conversion to stover yield per hectare.

2.3.4. Soil moisture

We installed polyvinyl chloride (PVC) tubes at the center of each plot, 80 cm deep with a protrusion of about 10 cm above the soil's surface to ensure runoff does not flow into the tubes. The tubes' bottoms were covered with a watertight lid during installation to prevent water entry into the tubes from below. The tops of the tubes were covered with plastic caps to prevent rainwater from entering the tubes. Five extra tubes were installed in the guard zone plots beside the treatment plots to calibrate the moisture readings. We hastened the contact between the tube and the soil using the slurry method of re-filling. Then, left the access tubes to equilibrate with the soil until the beginning of the SR 2016 season (October 2016). We measured soil moisture weekly from planting to harvesting with a portable Diviner2000$^{\mathrm{TM}}$ Version 1.5 190 capacitance sensor (Sentek Sensor Technologies, Stepney, South Australia) (Evett and Tolk, 2009). We downloaded data from Diviner 2000 and processed it in MS excel before analysis.

2.4. Laboratory analysis and mathematical calculations

We determined bulk density gravimetrically (Reynolds, 1970). The samples were oven-dried at a temperature of 105 °C for 24 h, then bulk density was calculated as per Eq. (1).

$$\mathrm{p_b} = \frac{\mathrm{m_s}}{\mathrm{v_t}} \tag{1}$$

Where p_b is bulk density, m_s mass of soil solids, and v_t is total core volume.

The constant-water head method was used for saturated hydraulic conductivity (Ks) determination (Klute, 1982). We kept the water pressure constant at the top of the sample in the core rings with a one-dimensional flow created through the sample. The calculation was as per Eq. (2).

$$\mathrm{k_s} = \frac{\mathrm{VL}}{\mathrm{Aht}} \tag{2}$$

Where, k_s is saturated hydraulic conductivity coefficient, V collected water volume, L soil column length, A is soil column area, h head difference, and t time used to get the volume, V.

For aggregate stability, we air-dried the samples, broke the large clods by hand, and sieved through a 4 mm sieve. The rotary dry sieving method was used for aggregate stability determination (Lyles et al., 1970). The aggregates' resistance to abrasion was assessed by pouring back the weighed aggregates into the drying pan. We sieved and weighed severally to determine the changes in the distribution of aggregate size. The soil was transferred to a 75 µm aperture sieve which had been immersed previously in ethanol. It was slowly moved up and down in ethanol five-times to separate fragments less than 63 µm diameter from the bigger ones. The greater than 63 µm diameter particles were dried in the oven and sieved by hand on seven series sieves with 63, 150, 250, 500, 1000, 2000, and 3000 µm apertures. Then the weight of every size fraction was measured. A fraction less than 63 µm diameters were derived as the difference between the other six fractions' initial weight and total sum. The stability of the aggregates in each fraction was determined by calculating the mean weight diameter (MWD) of the seven classes: the sum of the weight fraction of the remaining soil on every sieve after sieving, multiplied by the mean aperture of the adjacent mesh as per Eq. (3).

$$\mathrm{MWD} = \sum_{i=1}^{8} \bar{\mathrm{x}}_{\mathrm{i}} \mathrm{w}_{\mathrm{i}} \tag{3}$$

Where MWD is mean weight diameter (mm), w_i is the total weight fraction of aggregates in the size class i with a diameter $\bar{\mathrm{x}}_{\mathrm{i}}$

To determine water productivity, we used the water balance equation to calculate evapotranspiration (ET) values from the ETo Calculator Ali and Talukder (Ali and Talukder, 2008) and Raes and Munoz (Raes and Munoz, 2009) as per Eqs. 4 and 5.

$$\mathrm{ET} = (P + I + \mathrm{C}) - (R + D) - \Delta\mathrm{SWS} \tag{4}$$

$$\Delta\mathrm{SWS} = \mathrm{S}_{\mathrm{initial}} - \mathrm{S}_{\mathrm{present}} \tag{5}$$

Where P is precipitation, I is irrigation, C is the upward flux into the root zone, R is a surface runoff, D is downward drainage out of the root zone, ΔSWS (mm) was the change in soil water storage between sowing ($\mathrm{S}_{\mathrm{initial}}$) and harvesting ($\mathrm{S}_{\mathrm{present}}$) stage.

The plots were fairly flat after embanking as erosion control; thus, the runoff wasn't observed. Being a mountainous region, the ground table was high; therefore, the groundwater table was very deep; thus, C was assumed to be insignificant. Waterlogging was not observed during the experimental period, so deep drainage was taken to be negligible. The experiment was under rainfed conditions; thus, there was no irrigation. ET value was then reduced to Eq. (6).

$$\mathrm{ET} = P - \Delta\mathrm{SWS} \tag{6}$$

Water productivity (WP) was calculated using Eq. (7) (Pereira et al., 2012)

$$\mathrm{WP} = \frac{\mathrm{B}}{\mathrm{ET}} \tag{7}$$

Where WP is the soil water productivity, and B is the above-ground biomass (Grains and stover).

2.5. Data analysis

Analysis of variance (ANOVA) was used for data analysis in SAS 9.4 software SAS Institute (SAS Institute 2013) at a 95% significance level. Where significance was detected, mean separations were done using Tukey Kramer honestly significant difference test at 95% confidence level.

3. Results and discussion

3.1. Rainfall amount and distribution

Chuka received a total rainfall amount of 1264 mm during the experimental period, with 879 mm and 385 mm received during the LR16 and SR16 seasons, respectively (Fig. 1a and Table 3). In Kandara, the total rainfall amount over the experimental period was 572 mm. The LR16 received 329 mm, while SR16 had 243 mm (Fig. 1b and Table 3). In Chuka, during the LR16 season, a dry spell of 14 days was experienced in Chuka during the LR16, while SR16 had 9 and 6 days' dry spells (Table 3). In Kandara, during the LR16 season, 10 and 24 days' dry spells were observed, while during the SR16, dry spells of 14 and 8 days were experienced (Table 3). A dry spell was defined as a series of more than five dry days in-between wet days during the cropping season (Shin et al., 2015).

The length of the growing period in Chuka was 46 and 65 days during the LR16 and SR16 seasons, respectively (Table 3). In Kandara, the crop growth period was 65 and 56 days for the LR16 and SR16 seasons. Length of crop growth period was the time between the reception of the first rains and the end of the rains in a season.

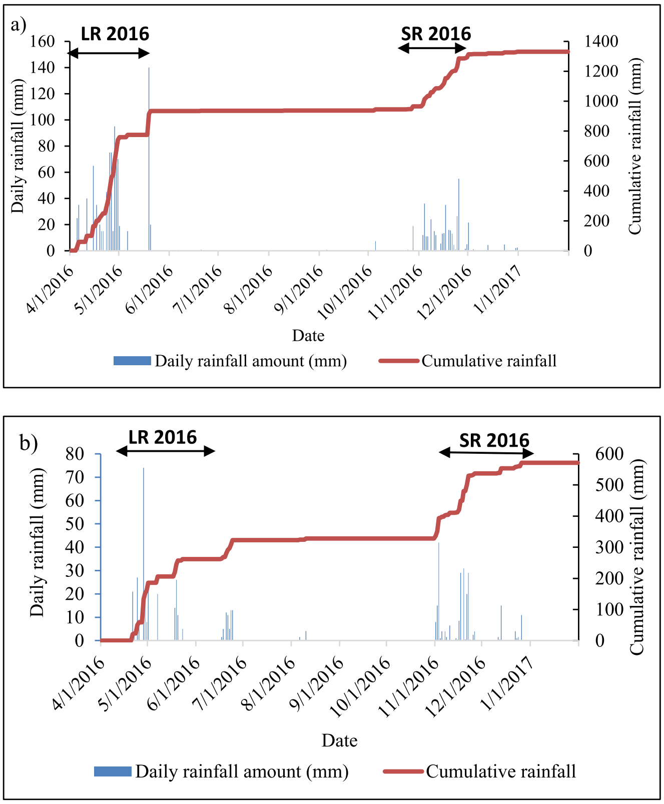

Fig. 1. Daily and cumulative rainfall during the experimental period in Chuka (a) and Kandara (b) sites.

Rainfall is a major crop productivity factor in rainfed agricultural production. Rainfall amounts and distribution play a critical role in crop growth and development (Oduor et al., 2020). Substantial rainfall amounts that are well distributed across the season resulted in high crop yield (Table 5). The long rains season generally received more rainfall in the two sites' than short rains during the study period. Consequently, more grain yield was observed during the LR compared to the SR in both sites. The findings collaborate with the observation of Ngetich et al. (K.F. Ngetich et al., 2014) that acknowledged rainfall as a key parameter for crop productivity. In Chuka, the SR season had a longer crop growing period than the LR, while in Kandara longer crop growing period was observed during the LR season. A dry spell occurred in all the seasons that could have affected the realization of the optimal maize yield in the region. Dry spells of more than five days can cause a significant influence on maize yield, especially at the critical stages of crop growth (Shin et al., 2015). Our observation corroborated the findings by Recha et al. (Recha et al., 2011) and Kisaka et al. (Kisaka et al., 2015), who reported that the dry spells were more frequent in the region. However, the dry spells we observed were of low magnitude except during the long rains in Kandara, where 16 and 24 days' dry spells were observed. Therefore, the reported dry spells did not have severe effects on the crop yield.

3.2. Soil physical properties

Both tillage and soil fertility inputs did not significantly influence soil physical properties in Chuka at the end of the study period (Table 4). In Kandara, soil bulk density significantly (p = 0.01) varied between the tillage (Table 4).

C= Conventional tillage Control, *F* = Mineral fertilizer, RF = Crop residue mulch + Mineral fertilizer, RFM = Crop residue mulch + Min-

Table 3
Rainfall characteristics of Chuka and Kandara sites during long and short rains seasons: rainfall onset and cessation dates; length of the season; cumulative rainfall; Dry spell frequency and magnitude.

		Chuka		Kandara	
		Long rain 2016	Short rain 2016	LR16	SR16
Onset		4th Apr, 2016	28th Oct, 2016	21st Apr, 2016	1st Nov, 2016
Cessation		20th May 2016	31st Dec, 2016	24th Jun, 2016	26th Dec, 2016
Length		46	65	65	56
Total rainfall		385 mm	341 mm	329	243
Dry spell magnitude	6–10 days	0	2	1	1
	11–15 days	1	0	0	1
	> 15 days	0	0	1	0
Dry spell frequency		1	2	2	2

Table 4
Soil physical properties at the end of the study in Chuka and Kandara sites.

Treatment	Chuka			Kandara		
Soil fertility inputs	Bulk Density	MWD[**]	Ks[*]	Bulk Density	MWD[**]	Ks[*]
C	0.95^{a}	0.98^{a}	20.36^{a}	1.00^{a}	1.07^{a}	17.91^{a}
F	0.99^{a}	0.96^{a}	20.27^{a}	1.09^{a}	1.17^{a}	10.33^{a}
RF	0.94^{a}	1.03^{a}	20.68^{a}	1.03^{a}	1.13^{a}	15.69^{a}
RFM	0.98^{a}	1.00^{a}	16.47^{a}	1.07^{a}	1.07^{a}	14.94^{a}
RML	0.96^{a}	1.24^{a}	21.07^{a}	1.04^{a}	1.06^{a}	16.75^{a}
RTM	0.97^{a}	1.03^{a}	17.10^{a}	1.03^{a}	1.08^{a}	14.81^{a}
RTP	0.94^{a}	1.03^{a}	17.22^{a}	1.08^{a}	1.10^{a}	18.84^{a}
Tillage						
Conventional	0.96^{a}	0.99^{a}	19.25^{a}	1.02^{b}	1.09^{a}	16.89^{a}
Minimum	0.97^{a}	1.01^{a}	18.44^{a}	1.04^{a}	1.10^{a}	17.01^{a}
Source of variation						
Tillage	Ns	Ns	Ns	0.01	Ns	Ns
Soil fertility inputs	Ns	Ns	Ns	Ns	Ns	Ns
Tillage*Soil fertility inputs	Ns	Ns	Ns	Ns	Ns	Ns

[*] Saturated hydraulic conductivity.

[**] Mean Weight Diameter.

eral fertilizer + Animal manure, RML = Crop residue mulch + Animal manure + Legume intercrop (Lablab purpureus (L.), RTM = Crop residue mulch + *Tithonia Diversifolia* + Animal manure, RTP = Crop residue mulch+ *Tithonia Diversifolia* + Phosphate rock (Minjingu), *F* = Mineral fertilizer, RF = Crop residue mulch + Mineral fertilizer, RFM = Crop residue mulch + Mineral fertilizer + Animal manure, RML = Crop residue mulch + Animal manure + Legume intercrop (Lablab purpureus (L.), RTM = Crop residue mulch + *Tithonia Diversifolia* + Animal manure, RTP = Crop residue mulch +*Tithonia Diversifolia* + Phosphate rock (Minjingu).

Means with the same letter(s) within the column are not significantly different at $p \leq 0.05$.

Minimum tillage increased soil bulk density by 3% than the conventional tillage in Kandara. Kiboi et al. (Kiboi et al., 2020) found significantly higher soil bulk density under minimum tillage than conventional tillage. Lack of significant influence by the treatments across different soil physical properties under investigation in both sites could be ascribed to the short period the study was conducted. This is consistent with the observation made by Kumari et al. (Kumari et al., 2011) and Meena et al. (Meena et al., 2015). Other studies with similar observations include Strudley et al. (Strudley et al., 2008) and Cantero-Martinez et al. (Cantero-Martinez and Cantero-Martínez, 2015), who reported a lack of significant influence of tillage and other crop management systems on soil bulk density and resistance to penetration under short-term period. Reduced tillage and green manure in the Mediterranean agroecosystem did not affect soil aggregate stability after two cropping seasons (Cantero-Martinez and Cantero-Martínez, 2015).

On the contrary, studies conducted for longer periods have shown significant changes in soil physical properties. For instance, in a 3-year study in Eastern Kenya, Miriti et al. (Miriti et al., 2013). Reported that tillage systems significantly affected soil aggregate stability, saturated hydraulic conductivity, and bulk density. In Inceptisols of Delhi, India, tillage and crop residue mulch significantly influenced soil bulk density, hydraulic conductivity, and aggregate stability after four years (8 cropping seasons) (Meena et al., 2015). Similarly, Stacy et al. (Zuber et al., 2015) reported tillage and crop rotation significantly influenced bulk density, aggregate stability, and saturated hydraulic conductivity after 15 years in the Muscatine and Osco soils in Illinois, United States of America (Soil Survey Staff 2014).

3.3. *Grain and stover yield*

Tillage significantly influenced grain yield,with an increase of 6% observed under minimum tillage during LR16 in the Kandara site. Soil fertility inputs significantly influenced grain yield in Chuka and Kandara sites (Table 5). In Chuka, RFM, RTM, RTP, and RF significantly ($p<0.0001$) improved grain yield by 124, 106, 97, and 96% during LR16, while during the SR16 RF, RFM and F improved grain yield by 729, 686, and 507 compared to the control, respectively. In Kandara RFM, F and RF improved grain yield by 91, 56, and 51% compared with the control, respectively, during the LR16. An increase of 129, 103, 100, and 88% was observed under F, RFM, RTM, and RF during the SR16.

Tillage significantly influenced stover yield in the two sites during the cropping seasons (Table 6). Minimum tillage increased maize stover yield in Chuka by 16 and 15% during the LR16 and SR16, respectively. In Kandara, minimum tillage increased maize stover yield during the LR16 only by 22%. Soil input significantly influenced stover yield in the two sites. In Chuka, during the LR16, RFM, RTM, RF, and F significantly increased maize stover yield by 87, 47, 39, and 37%, while during the SR16, RFM, RF, F, and RTP significantly improved the same by 276, 241, 216 and 96% compared to control. In Kandara, soil inputs influenced

Table 5

Grain yield (Mg ha^{-1}) in Chuka and Kandara during LR16 and SR16 season.

Treatment	Chuka		Kandara	
Soil fertility input	Long rain 2016	Short rain 2016	Long rain 2016	Short rain 2016
C	1.56^{c}	0.14^{c}	2.45^{c}	0.34^{cd}
F	2.22^{abc}	0.85^{ab}	3.83^{ab}	0.78^{a}
RF	3.05^{ab}	1.16^{a}	3.70^{b}	0.64^{ab}
RFM	3.49^{a}	1.10^{ab}	4.67^{a}	0.69^{a}
RML	2.11^{bc}	0.12^{c}	2.46^{c}	0.21^{d}
RTM	3.21^{ab}	0.58^{abc}	3.10^{bc}	0.68^{a}
RTP	3.07^{ab}	0.49^{bc}	2.93^{bc}	0.46^{bc}
Tillage				
Conventional	2.60^{a}	0.71^{a}	2.60^{b}	0.52^{a}
Minimum	2.76^{a}	0.56^{a}	2.76^{a}	0.52^{a}
Source of variation				
Tillage	Ns	Ns	Ns	Ns
Soil fertility input	0.0006	<0.0001	<0.0001	<0.0001
Tillage*Soil fertility inputs	Ns	Ns	0.03	Ns

C= Conventional tillage Control, *F* = Mineral fertilizer, RF = Crop residue mulch + Mineral fertilizer, RFM = Crop residue mulch + Mineral fertilizer + Animal manure, RML = Crop residue mulch + Animal manure + Legume intercrop (Lablab purpureus (L.), RTM = Crop residue mulch + *Tithonia Diversifolia* + Animal manure, RTP = Crop residue mulch+ *Tithonia Diversifolia* + Phosphate rock (Minjingu), *F* = Mineral fertilizer, RF = Crop residue mulch + Mineral fertilizer, RFM = Crop residue mulch + Mineral fertilizer + Animal manure, RML = Crop residue mulch + Animal manure + Legume intercrop (Lablab purpureus (L.), RTM = Crop residue mulch + *Tithonia Diversifolia* + Animal manure, RTP = Crop residue mulch +*Tithonia Diversifolia* + Phosphate rock (Minjingu). Means with the same letter (s) within the column are not significantly different at $p \leq 0.05$.

Table 6

Maize **s**tover yield (Mg ha^{-1}) during LR16 and SR16 seasons in Chuka and Kandara sites.

Treatment	Chuka		Kandara	
Soil fertility input	Long rain 2016	Short rain 2016	Long rain 2016	Short rain 2016
C	3.42^{de}	1.61^{cd}	2.56^{e}	5.33^{ab}
F	4.70^{bc}	5.09^{a}	5.50^{bc}	5.89^{ab}
RF	4.76^{bc}	5.49^{a}	5.68^{b}	6.80^{a}
RFM	6.38^{a}	6.06^{a}	7.68^{a}	6.42^{ab}
RML	4.14^{bcd}	1.42^{d}	3.16^{ed}	3.33^{bc}
RTM	5.02^{b}	2.83^{bc}	4.57^{bcd}	6.07^{ab}
RTP	3.65^{cd}	3.15^{b}	4.04^{cde}	5.48^{ab}
Tillage				
Conventional	4.82^{a}	3.93^{a}	5.28^{a}	5.80^{a}
Minimum	4.16^{b}	3.42^{b}	4.32^{b}	5.35^{a}
Source of variation				
Tillage	0.0012	0.0082	0.0001	Ns
Soil fertility inputs	<0.0001	<0.0001	<0.0001	Ns
Tillage*Soil fertility inputs	Ns	0.0057	<0.0001	Ns

C= Conventional tillage Control, *F* = Mineral fertilizer, RF = Crop residue mulch + Mineral fertilizer, RFM = Crop residue mulch + Mineral fertilizer + Animal manure, RML = Crop residue mulch + Animal manure + Legume intercrop (Lablab purpureus (L.), RTM = Crop residue mulch + *Tithonia Diversifolia* + Animal manure, RTP = Crop residue mulch+ *Tithonia Diversifolia* + Phosphate rock (Minjingu), *F* = Mineral fertilizer, RF = Crop residue mulch + Mineral fertilizer, RFM = Crop residue mulch + Mineral fertilizer + Animal manure, RML = Crop residue mulch + Animal manure + Legume intercrop (Lablab purpureus (L.), RTM = Crop residue mulch + *Tithonia Diversifolia* + Animal manure, RTP = Crop residue mulch +*Tithonia Diversifolia* + Phosphate rock (Minjingu). Means with the same letter (s) within the column are not significantly different at $p \leq 0.05$.

stover yield during the LR16 season only, with RFM, RF, F, and RTM increasing stover yield by 200, 122, 115, and 79%.

High crop yield is as a result of the availability of required nutrients and water, among other factors (Molden et al., 2010). In both sites, treatments with sole organic resources, sole mineral fertilizer, and a combination of mineral fertilizer plus organic input significantly increased grain and stover yield compared to the control, irrespective of the tillage method. Increased crop yield on treatments with sole organic inputs (RTM) could be due to enhanced soil moisture (Table 7) plus synchronized nutrients release into the soil during crop growth (Dikgwatlhe et al., 2014; Kiboi et al., 2019). This is because ideal plant productivity demands a good and balanced supply of nutrients and sufficient soil moisture conditions (Mutuku et al., 2020). This agrees with Wang et al. (Wang et al., 2017), who reported that organic resources application significantly improved maize yield. In the CHK, sole organics improved maize grain and stover yield (Kiboi et al., 2019).

Treatments with sole mineral fertilizer (F) improved grain and stover yield in the two sites. This was because mineral fertilizers' have readily available nutrients, thus enhancing crop growth and development (Vanlauwe et al., 2015). Mineral fertilizer is still the most reliable nutrient source in crop productivity (Lukuyu et al., 2011). In the CHK, Mucheru-Muna et al. (Mucheru-Muna et al., 2014) also observed increased maize crop yield with mineral fertilizer application. Kiboi et al. (Kiboi et al., 2019) made similar observations and attributed the improved crop yield to the mineral fertilizer's faster and efficient nutrient release into the soil.

A combination of animal manure plus mineral fertilizer has been observed to improve crop productivity than when used in isolation (Mucheru-Muna et al., 2014). Increased grain and stover yield under treatments with organic resources and inorganic fertilizer (RF, RFM, and RTP) could result from the synergistic effect of mixing the organic and inorganic nutrient sources and soil moisture conservation. The combined, results' synergetic effect to synchronized nutrient release (Partey et al., 2013; Vanlauwe et al., 2010). Additionally, mineral fertilizer plus organic resources conserve soil moisture and boost fertility (Chen et al., 2014; Verhulst et al., 2011). The observation

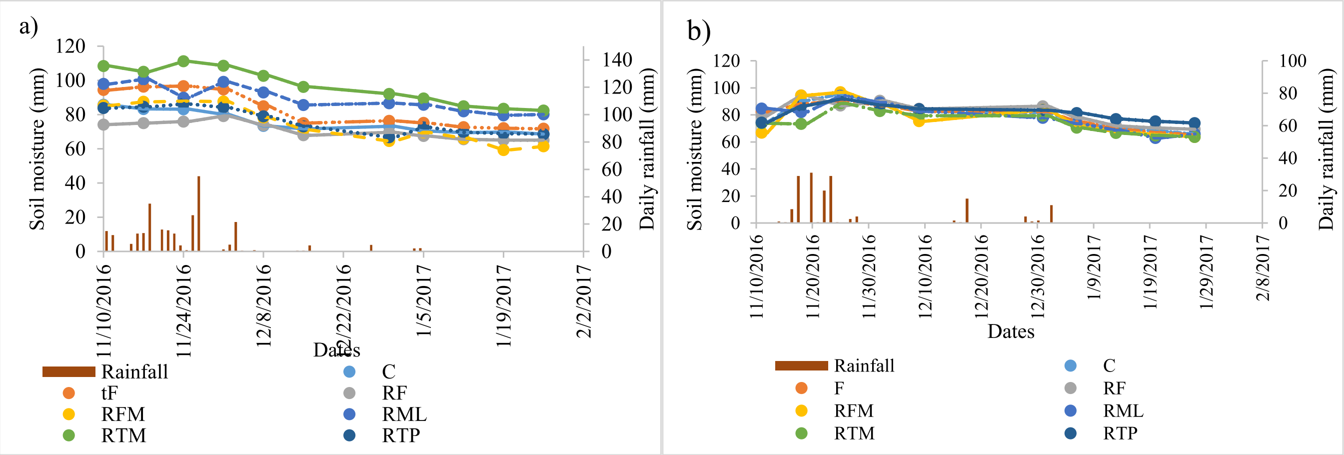

Fig. 2. Effects of soil inputs on soil moisture at 0–20 cm depth during short rains 2016 season in Chuka (a) and Kandara (b).

Table 7
Effects of treatment on soil moisture on various dates during SR16 season in Chuka and Kandara sites at 0–20 cm depths.

Date	Chuka	Date	Kandara
10/11/2016	*,[1]	11/11/2016	Ns
17/11/2016	*	18/11/2016	Ns
24/11/2016	Ns[2]	25/11/2016	Ns
1/12/2016	**[3]	2/12/2016	Ns
8/12/2016	*	9/12/2016	Ns
15/12/2016	**	16/12/2016	Ns
30/12/2016	**	31/12/2016	Ns
5/1/2017	**	6/1/2017	Ns
12/1/2017	***[4]	13/1/2017	Ns
19/1/2017	***	12/1/2017	Ns
26/1/2017	***	27/1/2017	Ns
Source of variation			
Tillage	*		Ns
Soil fertility inputs	***		Ns
Tillage*Soil fertility inputs	*		Ns

Significant difference of the Tukey post hoc HSD test.

*** , $p < 0.001$;.

** , $p < 0.01$;.

* , $p < 0.05$.

[1] p value=0.05.

[2] Ns=Not significant.

[3] p value=<0.01.

[4] p value=<0.001.

agrees with Mucheru-Muna et al.'s (Mucheru-Muna et al., 2014) findings in the Central Highlands of Kenya, where increased maize yield was observed using organic inputs plus mineral fertilizer. Chivenge et al. (Chivenge et al., 2011) also reported higher crop yield under combined use of organics and mineral fertilizer in comparison with sole application of either. We observed the highest increase in grain and stover yield in the treatments with mineral fertilizer plus animal manure. Treatments with crop residue mulch plus animal manure also increased grain and stover yield. This is because crop residue mulch improved water use efficiency while animal manure supplied additional nutrients and boosted nutrient use efficiency by crop (Mugwe et al., 2009). Vanlauwe et al. (Vanlauwe et al., 2015) made similar observations, ascribing the high performance to enhanced nutrient use efficiency.

3.4. Soil moisture

Tillage influenced soil moisture in the Chuka site, with conventional tillage significantly increasing soil moisture by 10%. Soil inputs greatly influenced soil moisture in the Chuka site at 0–20 cm depth only (Table 7 and Fig. 2). Crop residue plus tithonia plus manure significantly ($p < 0.01$) increased the soil moisture by 26, 36, and 27%, compared to control on dates 10/11/2016, 17/11/2016, 1/12/2016, and 8/12/2016. On date 8/12/2016, RML significantly ($p < 0.01$) increased soil moisture by 40% compared to control (Table 7 and Fig. 2). Significant ($p < 0.01$) increase in soil moisture by 34% under RTM was observed on 15/12/2016. On 30/12/2016, RTM, RML, Mt, and RFM significantly ($p < 0.01$) boosted soil moisture by 26, 18, 12, and 10% compared with the control. On 5/1/2017, RTM and RML significantly improved soil moisture by 27 and 22%, respectively, compared to the control. On 12/1/2017, RTM, RML, and Mt significantly ($p < 0.01$) increased soil moisture by 22, 18, and 12%, respectively, compared to control (Table 7 and Fig. 2). Towards the end of the season, on 19/1/2017, RTM significantly ($p < 0.001$) increased soil moisture by 19%, while RFM reduced soil moisture by 15% compared to the control. The RTM, RML, and Mt significantly ($p < 0.001$) increased soil moisture by 20, 17, and 12%, respectively, on 26/1/2017 (Table 7 and Fig. 2). Generally, RTM had the highest soil moisture in the Chuka site, while treatments with mineral fertilizers had the lowest available soil moisture (Table 7 and Fig. 2).

In the Kandara site, both tillage and soil input did not significantly influence soil moisture during the SR16 season (Table 7). The time series indicated general soil moisture reduction from the season's onset to the end of the crop growth period (Fig. 2).

Crop residue mulch and organic input (RTM and RML) enhanced soil moisture in the Chuka site during the study period. This could have been due to the quick integration of organic resources into the soil instigated by tillage that improved soil water retention capacity. In addition, crop residue mulch also reduced water loss through direct evaporation from the soil (Biddoccu et al., 2017). A similar observation was reported by Kiboi et al. (Kiboi et al., 2019) in the CHK, where soil organic resources under conventional tillage with mulch performed better than minimum tillage with mulch in soil moisture conservation. Our finding was consistent with Arora et al. (Arora et al., 2011), where residue mulch reduced soil temperatures and the surface runoff, reducing direct evaporation and improved infiltration rate, respectively. Contrary to our findings are the studies by Abdullah. (Abdullah, 2014) and Mrabet et al. (Mrabet et al., 2012) that reported minimum tillage with organic resources increased soil moisture more than conventional tillage during long-term experimental trials. Conventional tillage plus *Tithonia Diversifolia* and animal manure increased soil moisture besides enhancing soil fertility (Wang et al., 2017). Improved soil moisture availability under treatments with legume intercrop could be due to increased soil cover, reducing water loss through evaporation, and improved infiltration rate. Legume intercrops provide a vegetative barrier that reduces water loss through evaporation and surface runoff while enhancing infiltration into the soil (García-Franco et al., 2015). Our observation agrees with the studies in CHK by Mucheru-Muna et al. (Mucheru-muna et al., 2010). and Ngetich et al. (K.F. Ngetich et al., 2014) that legume intercropping enhances available soil moisture by shading the soils and acting as vegetative barriers that curb surface runoff.

A significant increase in soil moisture under treatments with crop residue mulch and organics

(RML, RTP, and RTM) towards the end of the season could be attributed to relatively low crop yield (Table 5 and 6). The low yield indicates foliation and poor maize development, which reduced moisture consumption by the crops. The relatively low maize yield could be due to the slow release of N from the organic inputs known to improve crop growth and development (Vanlauwe et al., 2015; Kiboi et al., 2019). Low foliation and development results in reduced soil moisture consumption rate by the crop, as observed by Steduto et al. (Steduto et al., 2009).

Significant reduction in soil moisture under treatments with mineral fertilizer such as RTP, RFM,

MtRF, RF, and RFM could be due to the crops' increased soil moisture utilization rate, resulting in the observed high yields. From the study, treatments with organic fertilizer had high grain and stover yields (Table 5 and 6). The addition of mineral fertilizer enhances faster crop growth and higher foliation, translating to a higher rate of soil moisture use due to increased transpiration (Mucheru-Muna et al., 2014). The finding corroborates Steduto et al. (Steduto et al., 2009) study who found that increased transpiration accelerates soil moisture depletion rate. A similar observation was made in the Central Highlands of Kenya, where mineral fertilizer improved crop growth that quickly used up the available soil moisture (Kiboi et al., 2019).

The control consistently had low soil moisture compared to other treatments. The soils' continuous turning under conventional tillage with no soil inputs exposes the topsoils to evaporation losses, reducing the available soil moisture (Kiboi et al., 2019). Our finding corroborates with the observation by Biazin and Sterk (Biazin and Sterk, 2013) that conventional tillage enhances soil moisture loss by evaporation as the topsoil moisture is continuously exposed to the surface during tillage. Treatments did not have a significant difference in soil moisture in the Kandara site. Low rainfall amounts received in the Kandara site (Fig. 2b) could have been the major contributor to the lack of significant effects of the treatments. Low rainfall amount translated to the observed low soil moisture content. Thus, the impact of treatments did not manifest.

3.5. Soil water productivity

Tillage significantly influenced soil water productivity in both sites (Table 8). Conventional tillage increased water productivity by 33 and 31% in Chuka and Kandara, respectively, compared to minimum tillage. The soil inputs' had a significant influence on soil water productivity in both sites (Table 8). In Chuka, RFM, RF, F, RTP, and RTM significantly ($p>0.0001$) increased soil water productivity by 279, 260, 162, 117, and 104%, compared with the control (Table 8). In Kandara, RTM, RFM, and RF significantly ($p>0.0001$) enhanced soil water productivity by 63, 50, and 46%, respectively, in comparison with the control (Table 8).

Water productivity (WP) is the ratio of agricultural output to the amount of water used (Molden et al., 2010). High soil water productivity could be due to either the same output from less water or more output from the same amount of water (Zwart and Bastiaanssen, 2004). Generally, treatments with mineral fertilizer (RFM, RF, and F) enhanced soil water productivity. Mineral fertilizer readily supplies N required for crop growth and development, resulting in improved above-ground biomass during the experimental period (Table 5 and 6) (Vanlauwe et al., 2010). The increased foliation reduces evaporation losses by enhancing the soil cover, leading to improved water productivity as losses through evaporation were reduced (Guto et al., 2012).

Improved WP under treatments with animal manure plus mineral fertilizer (RFM), on the other hand, could be due to the ability of animal manure to concurrently supply nutrients to the crops and enhance soil hydrological properties like soil water retention (Wang et al., 2017). The combined animal manure plus mineral fertilizer initiated positive synergies in crop nutrient supply and use efficiency, which resulted in higher water productivity than the control (Pincus et al., 2016). Anyanzwa et al. (Anyanzwa et al., 2010), reported a similar observation, whereby the combination of organic and mineral fertilizer improved water productivity, resulting in increased maize yield. The results also concur with Temesgen (Temesgen, 2007), who observed increased water productivity under mineral fertilizer plus organic resources use in Ethiopia.

Table 8
Soil water productivity (Kg m^{-3}) in Chuka and Kandara sites.

Treatment	Chuka	Kandara
C	4.59^{e}	13.49^{def}
F	12.03^{bc}	16.93^{bcd}
RF	16.51^{a}	21.96^{a}
RFM	17.41^{a}	19.76^{abc}
RML	3.37^{e}	11.03^{ef}
RTM	9.36^{cd}	20.23^{ab}
RTP	9.98^{cd}	15.40^{ed}
Tillage		
Conventional	12.8^{a}	17.6^{a}
Minimum	9.6^{b}	13.4^{b}
Source of variation		
Tillage	<. 0.0001	<. 0.0001
Soil fertility inputs	<. 0.0001	<. 0.0001
Tillage*Soil fertility inputs	<. 0.0001	<. 0.0001

C= Conventional tillage Control, *F* = Mineral fertilizer, RF = Crop residue mulch + Mineral fertilizer, RFM = Crop residue mulch + Mineral fertilizer + Animal manure, RML = Crop residue mulch + Animal manure + Legume intercrop (Lablab purpureus (L.), RTM = Crop residue mulch + *Tithonia Diversifolia* + Animal manure, RTP = Crop residue mulch+ *Tithonia Diversifolia* + Phosphate rock (Minjingu), *F* = Mineral fertilizer, RF = Crop residue mulch + Mineral fertilizer, RFM = Crop residue mulch + Mineral fertilizer + Animal manure, RML = Crop residue mulch + Animal manure + Legume intercrop (Lablab purpureus (L.), RTM = Crop residue mulch + *Tithonia Diversifolia* + Animal manure, RTP = Crop residue mulch +*Tithonia Diversifolia* + Phosphate rock (Minjingu). Means with the same letter (s) within the column are not significantly different at $p \leq 0.05$.

Compared to control, treatments with organic resources (RFM, RF, RTP, and RTM) enhanced soil moisture and water use efficiency; thus, higher water productivity was observed. Organic resources are known to boost soil physical properties and improve water use efficiency. However, from our study, organic resources did not significantly influence soil physical properties. This could be due to the short experimental period. Nevertheless, the observed increase in water productivity could be attributed to less water in producing the same yield (Rurinda et al., 2013). The highest water productivity was observed in the treatment with mineral fertilizer and organic inputs (RFM). The organic inputs could have improved soil organic carbon, enhancing soil water retention ability, while mineral fertilizer improved soil fertility, enhancing crop yield (Kiboi et al., 2019). The observation is consistent with Zwart and Bastiaanssen (Zwart and Bastiaanssen, 2004) and Molden et al. (Molden et al., 2010), that more gains in water productivity are achieved when both the yield and water use efficiency is enhanced. Conventional tillage improved water productivity than minimum tillage during the study period. This could be attributed to the hastened nutrients release from the organic resources due to constant tillage that speeds up the rate of decomposition (Kiboi et al., 2019; Meena et al., 2015). Oicha et al. (Oicha et al., 2010) reported similar observations, where treatment under minimum tillage had lower yield than under conventional tillage and consequently low water productivity. On the contrary, Araya et al. (Araya et al., 2012) reported higher water productivity under minimum than conventional tillage.

Water productivity was higher in Kandara than in Chuka during the trial period. This could be due to the high rainfall received within a short period in Chuka (Fig. 2a). The high rainfall received due to the poor distribution did not translate to commensurate yield, as significant rainwater was wasted. Water use efficiency was therefore low.

Conclusion

Conventional tillage combined with soil input was the best performing treatment combination in enhancing crop yield and water productivity during the study period. The combination of mineral fertilizer and organic resources was the best in increasing crop yield. On soil moisture, crop residue mulch plus organic resources were the best in improving soil moisture during the study period. Water productivity was highest under the combination of mineral fertilizer and organic resources. Therefore, conventional tillage with mulch combined with mineral fertilizer, organic resources, and crop residue mulch should be encouraged for improved water productivity in a short-term period. We recommend that the treatments' effects on crop yield, soil moisture, and water productivity be investigated in a long-term period.

Declaration of Competing Interests

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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