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Tied-ridging and soil inputs enhance small-scale maize productivity and profitability under erratic rainfall conditions in central Kenya

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ABSTRACT

Deficits in soil moisture and low soil fertility are the major constraints to smallholder farming systems in the SSA (sub-Saharan Africa) region. This study evaluated the effects of tied ridging and selected soil fertility inputs on; soil water content at different depths, maize yields, and economic returns. The treatments were: *Tithonia diversifolia* + inorganic fertilizer, manure + inorganic fertilizer, inorganic fertilizer, and control with or without tied ridging as the soil water conservation factor. Data were subjected to analysis of variance, and the means were separated using LSD at $p \leq 0.05$. Treatments with *Tithonia diversifolia* or manure combined with inorganic fertilizer with or without tied ridging consistently affected soil water content positively. The effect of tied ridging on soil water content was greater during the short rain season compared to the long rains. In addition, there was evidence that tied ridging and organic soil inputs resulted in greater soil moisture conservation during the critical silking and tasselling maize phenological stages during the short rain season. Treatments had significant effects on grain and stover yields during the long rain 2016 season ($p < 0.0001$ and $p = 0.0477$, respectively) and the short rain 2016 season ($p < 0.0001$ and $p = 0.0035$, respectively). The highest (4.87 Mg ha^{-1}) maize grain yield was recorded in *Tithonia diversifolia* plus inorganic fertilizer under tied ridging in the long rain 2016 season, while manure + inorganic fertilizer without tied ridging gave the highest yields (1.27 Mg ha^{-1}) in the short rain 2016 season. The highest net benefits of US$ 1229.90 ha^{-1} and US$ 171.57 ha^{-1} were recorded under *Tithonia diversifolia* plus inorganic fertilizer with tied ridging during the long and short rain seasons, respectively. Overall, the best-performing treatments in yields and profitability were those that combined organic and inorganic fertilizers, regardless of the presence or absence of tied ridging. Climate-smart agricultural strategies combining tied ridges and organic inputs should be an integral component of farmer management if losses related to soil fertility and water stress are to be minimized under erratic rainfall regimes in the semiarid farming systems of the SSA region.

1. Introduction

In the SSA region, farming systems rely to a great extent on rain-fed agriculture, which exposes smallholder farmers to increasingly erratic rainfall patterns and unpredictable climate conditions (Mairura et al., 2021). More than 95 % of the arable land area in the SSA is rain-fed, providing food security and livelihood strategies for more than 80 % of the population in the region (Serdeczny et al., 2019). However, changing climatic patterns characterized by erratic rainfall, prolonged dry spells, and frequent droughts have contributed to reduced productivity, unpredictable yields, and crop failure (Macharia et al., 2020; Oduor et al., 2020, 2021). The food insecurity index in the SSA region was at 23 % by the year 2013, with 32.4 % of its children manifesting stunted growth in 2020 (UNICEF-WHO-World Bank, 2021). In the Central Kenya Highlands, erratic and insufficient rainfall often results in soil moisture stress, surface runoff losses, soil degradation, and poor crop performance (Oduor et al., 2021).

Maize is the major staple food crop in the SSA region, accounting for

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30 % of the total cropping area under cereal production: 29 % in Eastern Africa, 61 % in Central Africa, 19 % in West Africa, and 65 % in Southern Africa (FAO, 2010). The cereal accounts for approximately 40 % of the total crop area in Kenya (Naseem et al., 2018). The crop provides about 30 % of the calorific requirement in low-income countries for about 4.6 billion people (FAO, 2021) and approximately 70 % of the daily cereal intake (Kariuki et al., 2020). With the expected world population to reach 9.73 billion in 2050, maize production will have to triple by 2020, particularly in the SSA, which will experience a 2.5 % population growth (Ekpa et al., 2018).

The rainfall pattern in the SSA region is estimated to reduce by 10 % in 2050, leading to reductions in drainage by 17 % (de Wit and Stankiewicz, 2006). The changes in climate patterns and increased soil water stress experienced over the last few years have equally become a major limiting factor to maize production (Hadebe et al., 2017). This is because of the inadequate, erratic, and unreliable rainfall due to climate variability experienced in the region (Abrams, 2018), coupled with inadequate soil water conservation practices (Mwaura et al., 2021; Mairura et al., 2022). Most smallholder farmers depend on rain-fed agriculture, making them vulnerable to partial or total crop failures (Ngetich et al., 2014a). The main effect of climate change in Africa is likely to be altered in precipitation, evapotranspiration, and soil water balances (Muluneh et al., 2020). Small-scale farmers are exposed to unmitigated socio-economic risks because the effects of drought on agricultural productivity are incredibly severe, and farmers lack appropriate soil water management options (Thornton et al., 2017).

According to meteorological legacy data, the temperature in Tharaka Nithi County increased while the annual rainfall declined between 1960 and 2009 (Gioto et al., 2016). In addition, soil moisture stress and temperature increases will likely occur with greater frequency in Tharaka Nithi County and several arid and semiarid SSA regions in the future (MoALF Ministry of Agriculture, Livestock and Forestry, 2017). This calls for strategies to enhance the capacity of small-scale farmers to cope with changing climatic conditions, including efficient and cost-effective soil water conservation options (Zougmoré et al., 2014). Tied-ridging is a successful climate-smart agricultural technology under various cereal and legume cropping systems in arid and semiarid areas (Thornton et al., 2017; Ngetich et al., 2014b). The technology can improve moisture storage and enhance crops' efficient water and nutrient utilization (Kiboi et al., 2021). Tied ridging saves soil moisture within the root zone, improving the probability of crop survival during extended periods of dry spells and meteorological drought (Gan et al., 2013). Applying farmyard manure combined with tied ridges increased grain yield in Kenya compared to farms without tied ridges (Mwende et al., 2019). Ngetich et al. (2014b) found that tied ridges significantly improved soil properties and crop yields in the semiarid conditions of Kenya. The economic benefits of climate-smart agricultural technologies, such as tied ridges, are essential for farmer adoption. Many studies on tied-ridging have focused on the relationship between tied-ridging and crop yield, while few studies have addressed their effects on soil water status under different soils, rainfall regimes, and crops. Muluneh (2020) observed that future climate change in the Ethiopian drylands is likely to affect the maize yield negatively and proposed tied ridges and better soil fertility adaptation measures to offset the negative impacts of climate change.

Studies must examine the productivity and profitability of tied ridging and input application under different soil types and climates characterized by variable dry spells and meteorological drought regimes. An integrated method intended to achieve an adequate supply of soil water and nutrients efficiently and cost-effectively is necessary for semiarid small-scale agricultural systems. In addition, integrated tillage and nutrient management practices are required for sustainable crop production, especially in agroecological zones where soil fertility and moisture stress limit crop response to input applications. The objectives of this study were as follows: i) to determine the impacts of tied ridging and integrated soil fertility management technologies on soil water conservation and maize yields and ii) to estimate the economic returns of tied ridging and integrated soil fertility management technologies. We hypothesized that combining organic resources (manure or *Tithonia*) with inorganic fertilizer and tied ridging can increase maize yields and net benefits for small-scale farmers in semiarid agricultural systems.

2. Materials and methods

2.1. Site description

This field experiment was implemented in Tharaka Nithi South Sub-County in Tharaka Nithi County, Kenya. The site was based at Kigogo Primary School in Mukuuni location, Magumoni Division, with the following geocodes (00^0 23' S, 37^0 38' E). The site is located in the Upper Midland Agroecological Zone (UM2-UM3) (Jaetzold et al., 2007) on the eastern slopes of Mount Kenya at an altitude of approximately 1500 masl. The annual rainfall pattern is bimodal, with a total annual rainfall ranging from 1200 to 1400 mm and a mean annual temperature of 20^0 C. The long rain season usually commences from March to May, while the short rains are experienced from October to December. The soil type includes well-weathered and drained *Humic Nitisols,* characterized by high inherent fertility that is declining due to unsustainable soil fertility management practices. The soil has a pH of 5.5, with an average bulk density of 0.95 and a clay content of 83 % (Table 1).

Small-scale mixed farming enterprises, including cash crops, food crops, and livestock farming, characterize Tharaka Nithi County. The dominant crop enterprises include tea, coffee, macadamia nut, maize, banana, beans, and sorghum. The major livestock enterprises include cattle, goat, and sheep production. The area also represents critical agricultural systems in the East African Highlands which require efficient utilization of agricultural resources (Vanlauwe et al., 2016) due to low and unpredictable crop yields, changing climates (Morton, 2007), land sub-division, expected population increases in the next three decades (United Nations, 2015), lack of fallowing land, and the proximity of the region to the Mount Kenya forest ecosystem.

2.2. Experiment design and management

The experiment implemented a randomized complete block design (RCBD) with eight treatments replicated four times (Table 2). The selected treatments included *Tithonia diversifolia* + inorganic fertilizer, cattle manure + inorganic fertilizer, sole inorganic fertilizer, and control in combination with tied-ridging or no tied-ridging. *Tithonia* and cattle manure organic resources were selected to capture the varying organic resource qualities (lignin, C, and N contents), including high-quality organic resources (*Tithonia*) and low-quality organic resources (Cattle manure) (Palm et al., 2001).

Table 1
Characterization of soil properties at Kigogo site, Tharaka Nithi South Sub-County, Kenya.

Soil chemical properties	Mean baseline value
pH_{water}	5.5
Soil organic C (%)	1.9
Soil organic matter (%)	3.3
Total soil N (%)	0.2
Available soil P (ppm)	35.8
Exchangeable soil K^+ (C mol kg^{-1})	0.6
Exchangeable soil Ca^{2+} (C mol kg^{-1})	3.7
Exchangeable soil Mg^{2+} (C mol kg^{-1})	1.4
Exchangeable soil Na^+ (C mol kg^{-1})	0.4
Soil physical properties	
Soil bulk density (g/cm^3)	0.95
Sand (%)	7.5
Silt (%)	9.5
Clay (%)	83
Texture class (USDA)	Clay

Table 2
Description of experimental treatments in Kigogo (2016).

Trial treatments	Treatments code	Soil input application rates	
		Organic (Mg ha^{-1})	Inorganic fertilizer (kg ha^{-1})
With tied ridging, with *Tithonia*, with inorganic fertilizer	TRTIF	5	30
With tied ridging, with manure, with inorganic fertilizer	TRMIF	5	30
With tied ridging, with inorganic fertilizer	TRIF	0	60
With tied ridging, without inputs	TRC	0	0
Without tied ridging, with *Tithonia*, with inorganic fertilizer	NTRTIF	5	30
Without tied ridging, with manure, with inorganic fertilizer	NTRMIF	5	30
Without tied ridging, with inorganic fertilizer	NTRIF	0	60
Without tied ridging, without inputs	NTRC	0	0

The gross plot dimensions were 6 m by 4.5 m with a 1 m wide path left between plots. Maize (*Zea mays L.* variety H516) was the test crop. It was planted at 0.75 m x 0.50 m spacing between and within maize rows, respectively. Three seeds per hill were sown to guarantee the greatest plant population and thinned out two weeks after germination to retain two plants per hill; hence a plant population density of 53333 plants ha^{-1} was attained. NPK 23–23–0 was applied at a full rate of 60 kg N ha^{-1} and 60 kg P ha^{-1} for treatments without organic inputs, while this was applied at a half rate of 30 kg N ha^{-1} and 30 kg P ha^{-1} (Fertilizer Use Recommendation Project (FURP) (FURP), 1987) for treatments that integrated organic and inorganic soil inputs.

Organic inputs (including *Tithonia diversifolia* and animal manure) were incorporated in the soil using a hand hoe two weeks before planting. *Tithonia diversifolia* was locally harvested from nearby biomass transfer hedges, weighed, chopped then incorporated into the soil. Representative samples from the organic inputs were taken to the laboratory for N content determination (*Tithonia diversifolia* had 3.8 % N, while animal manure had 2.1 % N) using a CN analyzer. From these results, the amount of organic inputs to be applied to give an equivalent of 30 kg N ha^{-1} was calculated. Weeding was carried out twice in each season using a hand hoe. Tillage was also done by hand hoeing to a depth of about 0.15 m before the onset of the season. Tied ridges were constructed at the commencement of each cropping season for required experimental plots and reconstructed during weeding and when they collapsed during heavy rainfall events throughout the season.

2.3. Soil sampling and soil moisture and rainfall measurement

Soil sampling for soil characterization was composited for each plot using the Zigzag sampling framework at 0–20 cm depth using a soil auger at the start of the experiment. Soil water content measurements were determined using a Diviner 2000® capacitance sensor (Sentek Sensor Technologies, Stepney, South Australia) at regular 10 cm depths in a PVC access tube installed in the middle net plot area of the experimental plots. The rainfall data were measured on a daily basis using a HOBO® automatic weather station tipping bucket rain gauge smart sensor with a resolution of 0.2 mm. The daily rainfall was determined as a product of the daily number of bucket tips logged in by 0.2 mm resolution.

2.4. Soil sample analysis

In the laboratory, the soil samples were oven-dried at 40 °C for 72 h, after which they were ground using a ball mill and sifted with a 2 mm mesh sieve. Soil samples were analyzed for soil pH, texture, organic carbon, total N, available P, and exchangeable bases. The methods employed the standard methods of soil analysis described by Okalebo et al. (2002). The soil pH (water) was measured in a 1:2.5 soil-water ratio using a glass electrode for 30–60 s until a constant reading was attained (Okalebo et al., 2002). Soil texture was determined by the hydrometer method (Okalebo et al., 2002). Both total soil nitrogen and soil carbon were determined using the flash combustion method with the CN Elemental Analyzer (Krotz et al., 2013). The soil P was determined using Mehlich 3 (Mehlich, 1984) method, while exchangeable cations were determined using the ammonium acetate extraction method. Field capacity and wilting point thresholds were estimated from soil texture and organic carbon content using pedo-transfer functions available in the hydraulic properties calculator after Saxton and Rawls (2006).

2.5. Crop yields and profitability determination

Maize grain and stover samples were harvested from a net plot area of 21 m^2 in the middle of the gross plot area, and the total maize grain weight was determined after threshing. The grain weights were adjusted to 12.5 % moisture content after two weeks of air drying the samples using a moisture meter. Ten maize plants were randomly selected and harvested within the net plot area, after which their dry weights were extrapolated to estimate the total above-ground biomass for each plot. The net benefits, returns to labor, and Benefit/Cost ratios were used as the economic assessment tools following CIMMYT (1988) guidelines to assess the profitability of different treatments. Benefits and costs associated with each treatment were evaluated relative to not using different soil fertility inputs with tied ridging. The cost of farm inputs was estimated using local farm input dealers' prices, while manure prices were based on local valuation with farmers and converted to US$ Mg^{-1} at 1 USD = Ksh.101 exchange rate (Table 3). The prices of maize grain and stover were estimated using prevailing local market prices during harvesting (Table 3). Farm labor data was collected for all field activities during the season by recording the time taken and the number of individuals performing the tasks (CIMMYT, 1988). The costed field activities included land preparation, construction of tied-ridges, fertilizer and manure application, *Tithonia* incorporation, planting, weeding, harvesting, and threshing. The input and output prices (USD ha^{-1}) for economic benefit determination are presented as Supplementary Materials 1.

2.6. Statistical data analysis

Before analysis, experimental data was first subjected to cleaning, checking for outliers, and exploring general trends in the data. The data were subjected to Analysis of Variance (ANOVA) and separation of means using Least Significant Difference (LSD) at $p \leq 0.05$ using SAS 9.2 software (Statistical Analysis Software (SAS) (SAS), 2004) to compare

Table 3
Input and output price components of the economic analysis of soil treatment effects.

Parameter	Actual values (USD)
Cost of maize seed (USD kg^{-1})	1.80
Cost of NPK (23:23:0) fertilizer (USD kg^{-1} N)	1.44
Cost of manure (USD Mg^{-1})	11.32
Labour cost (USD day^{-1})	2.00
Price of maize grains (USD kg^{-1})	0.27
Price of maize stover (USD Mg^{-1})	19.80
Official exchange rate (December, 2016)	1 USD= Ksh. 101

soil treatment effects on crop yield and economic benefits. Different R software procedures were used to analyze rainfall and soil moisture patterns and to plot biophysical and economic performance data during the two cropping seasons. The R base plotting procedures were used to visualize rainfall and soil moisture trends, while the *ggpubr* package, the *ggbarplot* procedure, was used to visualize economic returns data.

3. Results

3.1. Rainfall pattern

The precipitation data indicated that the rainfall patterns during the long and short rain seasons of 2016 were different (Fig. 1). The total seasonal rainfall recorded at the experimental site during the long rain season was 496.5 mm, while it declined to 383.5 mm during the short rains. This resulted in a total bimodal rainfall of 880 mm in 2016. The single rainfall event with the highest rainfall amount during the long rains was 109 mm (25th day after planting), while in the short rain season, this was experienced 20 days after planting (40 mm) (Fig. 1).

The cumulative seasonal rainfall in the long rains was higher than in the short rain season, representing a 23 % decline and a cumulative seasonal difference of 113 mm. The rainfall patterns in both seasons included intra-seasonal drought periods.

3.2. Volumetric soil water content (SWC)

Soil water content varied between the seasons and across the seasons. Soil moisture during the long rains increased to 53 DAP (days after planting), declined to 67 DAP, increased again to 89 DAP, and finally declined. Long dry spells affected the soil water pattern during the long rain season. The mean soil water content recorded variations under different treatments at 0–30 cm soil depth. The soil water distribution fluctuated greatly with depth across the treatments during the long rains, while it recorded a declining trend in the short rain season at 10 and 20 cm depths. About 409.5 mm of rainfall fell cumulatively in the first 30 days after planting (DAP) (long rain season), resulting in simultaneous increments in soil moisture within the three soil depths (Fig. 2. a, b, c). Generally, soil moisture content increased to 53 DAP. It then simultaneously reduced in all the treatments to 67 DAP, and the trend was repeated till the end of the season (Fig. 2a, b, c), followed by an increase (89 DAP) during the long rain season. Fig. 3.

The soil moisture difference relative to the control (NTRC) varied by − 7.1 to 8.0 % (averaging 0.6 %) across treatments, depth, and time in the long rain season, while this ranged between −2.9 % and 19.2 % (mean=2.3 %) in the short rain season. The highest moisture difference paired with the control was recorded in NTRTIF (8.0 %), TRMIF (5.4 %), and TRTIF(4.4 %) at 10 cm depth 18 days after planting. During 103 DAP at the 10 cm depth, the highest moisture gain over the control was observed in TRTIF (2.2 %), TRIF (2.1 %), TRMIF (0.6 %), NTRIF (1.0 %) and NTRMIF (%). In the 20 cm depth during long rains, treatments that included organic soil inputs and tried-ridging predominantly recorded higher differences in soil moisture relative to the control than those that did not. Across six sampling time points, the NTRMIF treatment recorded six instances of soil moisture gains over the control, while this was five instances (TRMIF, TRIF, NTRTIF) at the 20 cm depth. In the 30 cm depth, only the TRC (−1.5 %) and NTRIF (−0.1 %) treatments recorded mean negative gains over the control across sampling times. These were observed to be greater in NTRMIF (1.8 %), NTRTIF (1.3 %), TRIF (0.7 %), and NTRMIF (0.6 %) treatments. In addition, the TRTIF treatment recorded five sampling times with greater moisture relative to the control, while this was observed in four sampling instances (TRMIF, NTRMIF) and in 3 moisture sampling times (TRMIF, NTRTIF, NTRIF).

Soil water content recorded a general declining trend during the short season at 10–20 cm depths, while this fluctuated in the 30 cm depth with sampling time. The moisture difference relative to the control was more prominent in the short rain season compared to the long rain season. In terms of variations in treatment, depth, and time, soil moisture difference over the control (NTRC) varied by −2.9 to 19.2 % (averaging 2.3 %) during the short rains, while this averaged 2.8 % during the maize tasselling and silking stage (DAP 40–77). The greatest moisture differences over the control across five sampling times were recorded in NTRMIF (6.4 %), TRC (4.0 %), NTRTIF (2.2 %), TRMIF (2.0 %), NTRTIF (1.9 %), and TRIF (1.3 %) at 10 cm depth. TRIF also resulted in the least soil water differences relative to the control across observation times at 20 and 30 cm depths. At the 20 cm depth, the NTRMIF (6.4 %, all five instances >control), TRC (4.0 %, four instances >control), NTRTIF (2.2 %, all five instances >control), and TRMIF (2.0 %, all five instances >control) recorded the higher mean soil moisture

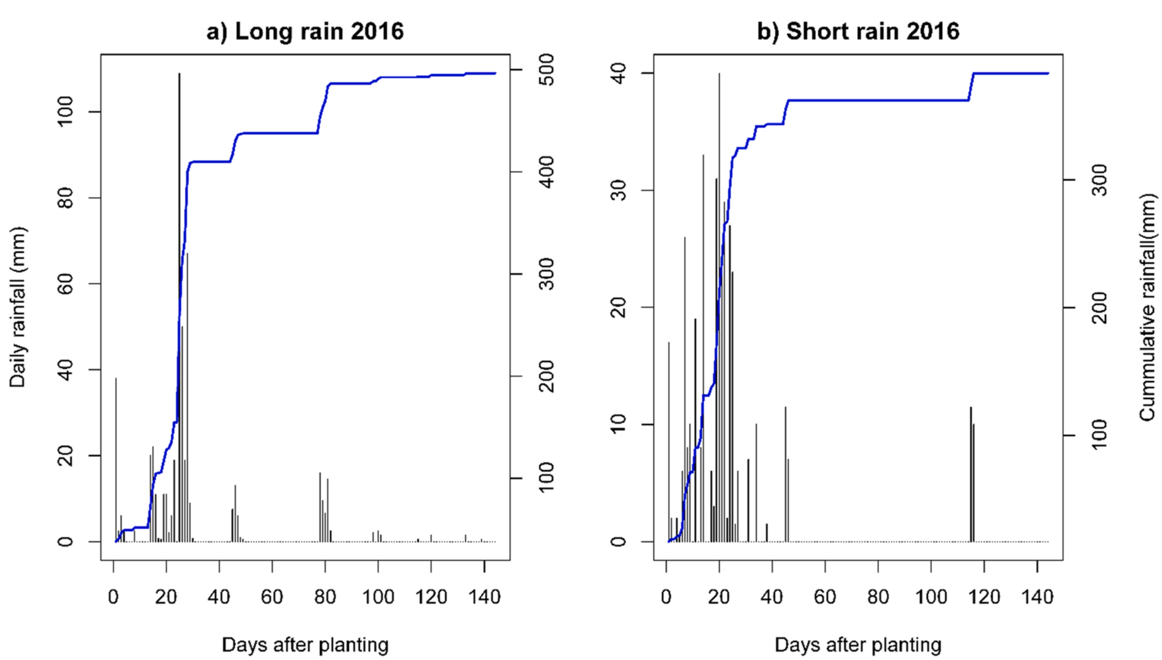

Fig. 1. Daily and cumulative rainfall pattern during the experimental period (a, Long rains 2016 daily and cumulative rainfall, b) Short rains 2016 daily and cumulative rainfall).

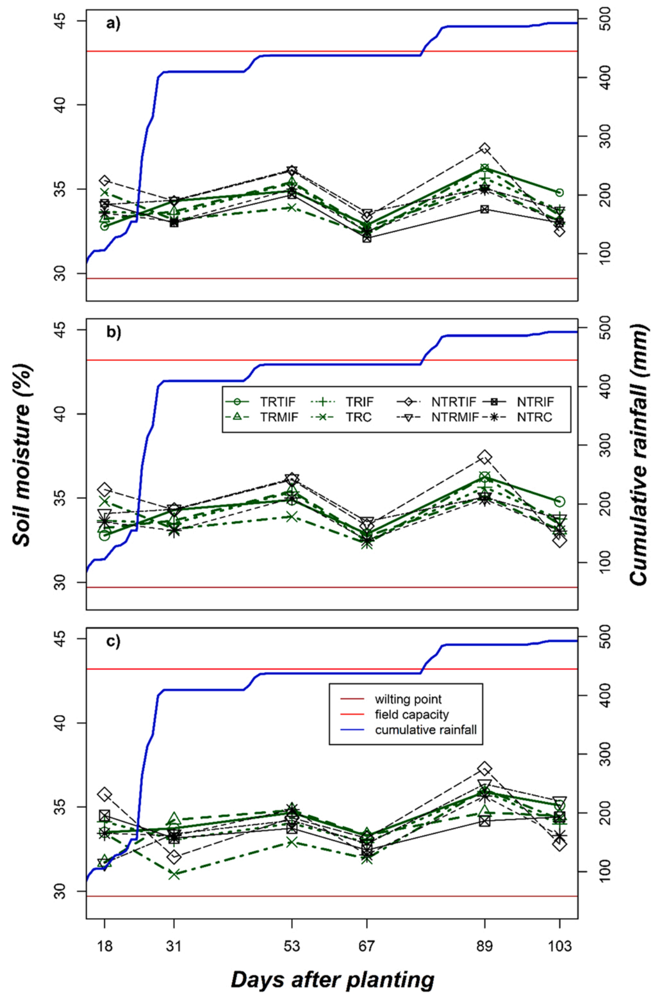

Fig. 2. Soil moisture pattern for different soil treatments (0–30 cm soil profile), a) 10 cm depth, b) 20 cm depth, c) 30 cm depth, throughout the Long rains 2016 in Kigogo.

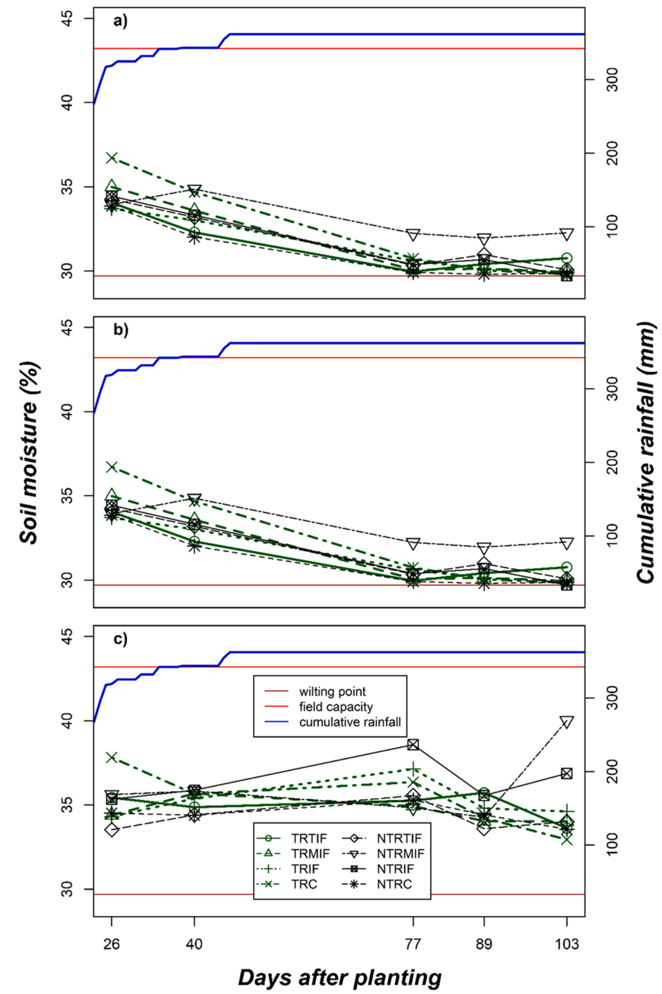

Fig. 3. Soil moisture pattern for different soil treatments (0–30 cm soil profile), a) 10 cm depth, b) 20 cm depth, c) 30 cm depth, throughout the Short rains 2016 in Kigogo.

over the control across sampling time. At the 30 cm depth, the soil moisture gain during the critical maize tasselling stage (DAP 67) was observed for TRTIF (3.5 %), TRMIF (3.6 %), NTRTIF (3.0 %), NTRMIF (2.0 %) and NTRIF (0.9 %). The NTRIF treatment recorded the highest mean moisture advantage across sampling time over the control (NTRC: 5.4 %), followed by NRMIF (5.0 %), TRC (2.8 %), TRIF (2.4 %), TRTIF (1.6 %) and TRMIF (0.5 %) at 30 cm depth.

3.3. Maize grain yield and yield components

The overall maize grain yield was 1.8 Mg ha^{-1} (long rains) and 0.53 Mg ha^{-1} (short rains), while maize stover yields were 4.7 and 3.3 Mg ha^{-1} in both seasons, respectively, due to the impacts of the seasonal decline in rainfall. Maize grain and stover yields ranged from 0.52 Mg ha^{-1} to 4.87 Mg ha^{-1} and 2.89 Mg ha^{-1} to 5.77 Mg ha^{-1}, respectively (Table 4). The highest grain and stover yields (4.87 Mg ha^{-1} and 5.76 Mg ha^{-1}) were observed during the long rains (TRTIF). There were significant differences in tied ridging and soil fertility management inputs on maize grain yields during the long rain season ($p < 0.0001$) (Table 4), while there were no differences observed in stover yield among treatments. Manure and *Tithonia diversifolia* plus inorganic fertilizer recorded the highest grain yields. Significant differences were not observed in grain yield among all treatments without tied ridging in the long rains. In the long rains, treatments with tied ridging, fertilizer, and organic soil inputs recorded significantly higher maize grain yields than treatments without tied ridging.

During the short rain season, treatments similarly recorded significant ($p < 0.0001$ and $p = 0.0035$, respectively) effects on grain and stover yields. The highest grain yields were observed in manure or *Tithonia diversifolia* +inorganic fertilizer with and with no tied ridging. In the same season, maize grain yields increased by > 100 % under manure +inorganic fertilizer with and with no tied ridging (Table 4), compared with the control. The TRTIF treatment contributed 169 % more grain yield over the control, while TRMIF contributed 127 % extra grain yield in the long rains. NTRMIF and TRMIF generated 140 % and 121 % extra grain in the short rain season. For stover, NTRTIF and TRTIF generated over 20 % gains (long rains), while the same treatments contributed over 65 % more stover over the control in the short rains. Generally, soil treatments that integrated organic inputs and inorganic fertilizers performed better than sole inorganic fertilizers or those without tied ridging. In addition, treatments with tied ridging tended to record lower standard deviation values in grain and stover yields than treatments without tied ridging (Table 4).

3.4. Economic returns

Soil management treatments recorded significant ($p \leq 0.05$) effects with net benefits, BCR (benefit-cost ratios), and returns to labor during all cropping seasons. *Tithonia diversifolia* with inorganic fertilizer and tied ridging recorded the greatest net benefits, BCR, and returns to labor

Table 4

Average maize grain and stover yields for different soil treatments in Kigogo site, Kenya (LR and SR 2016).

Treatment	Long rain 2016		Short rain 2016	
	Grain yield (Mg ha^{-1})	Stover yield (Mg ha^{-1})	Grain yield (Mg ha^{-1})	Stover yield (Mg ha^{-1})
NTRC (Without tied ridging, without inputs)	1.82 ± 0.64^{a}	4.65 ± 0.95^{a}	0.53 ± 0.09^{a}	3.33 ± 0.44^{ab}
NTRIF (Without tied ridging, with inorganic fertilizer)	2.07 ± 0.52^{a}	4.47 ± 1.78^{a}	0.84 ± 0.17^{abc}	4.53 ± 0.39^{bc}
NTRMIF (Without tied ridging, with manure, with inorganic fertilizer)	3.15 ± 0.42^{a}	5.44 ± 2.31^{a}	1.27 ± 0.24^{d}	4.47 ± 0.79^{bc}
NTRTIF (Without tied ridging, with *Tithonia*, with inorganic fertilizer)	3.63 ± 0.21^{a}	5.77 ± 2.16^{a}	0.84 ± 0.13^{abc}	5.59 ± 0.47^{c}
TRC (With tied ridging, without inputs)	2.53 ± 0.21^{ab}	4.44 ± 2.33^{a}	0.52 ± 0.05^{a}	2.89 ± 0.53^{a}
TRIF (With tied ridging, with inorganic fertilizer)	2.22 ± 0.30^{cd}	3.44 ± 1.25^{a}	0.75 ± 0.08^{ab}	3.43 ± 0.56^{ab}
TRMIF (With tied ridging, with manure, with inorganic fertilizer)	4.10 ± 0.33^{de}	4.58 ± 1.49^{a}	1.17 ± 0.20^{cd}	4.47 ± 0.56^{bc}
TRTIF (With tied ridging, with *Tithonia*, with inorganic fertilizer)	4.87 ± 0.54^{e}	5.76 ± 1.06^{a}	1.05 ± 0.16^{bcd}	5.48 ± 0.64^{c}
LSD $_{(0.05)}$	**0.548**	**2.203**	**0.227**	**0.832**
Sig (Treatment)	**<0.001**	**0.382**	**<0.001**	**<0.001**

Column means with the same supescript letter(s) are not significantly different ($p < 0.05$), Values are arranged as means ± standard deviations

during the long rains (Fig. 4). During the long rains, net benefits ranged from US$ 1128.6 in treatments with Tithonia plus inorganic fertilizer with tied ridging (TRTIF) to US$ 462 in treatments without tied ridging or inputs (NTRC). The TRTIF (tied-ridging with *Tithonia* and inorganic fertilizer) treatment recorded a 144 % higher net benefit than the control treatment. The second best-performing treatments in terms of net benefits were those that had no tied ridging but with fertilizer (NTRIF) (US$ 1008.0), while the TRMIF treatment recorded a net benefit of US $906. These treatments recorded about 96 %−118 % higher net benefits than the control treatment.

Regarding the BCR in the long rain season, the highest means were recorded in TRTIF (5.0), gaining 39 % over the control. The second-ranking treatment was the NTRTIF treatment, followed by TRC. In regards to the returns to labor, the highest was observed in the NTRTIF treatment (10.5), with the highest gains of 81 % in labor productivity over the control treatment (81 %). The lowest returns to labor were recorded in the TRIF treatment (3.63), with the highest negative returns over the control (52.8 %). During the short rains, there were significant treatment effects on all economic performance measures. The highest net benefit was recorded in TRTIF (172, with 80 % extra net benefits over the control). Meanwhile, the lowest BCR was also recorded in TRTIF (1.21, 15 % benefit over the control), while the least BCR was observed in TRIF (0.3), with the highest negative benefits over the control (50.8 %) across treatments. Regarding returns to labor in the short rain season, the highest was observed in NTRMIF (1.32), with 50 % gains over the control, while the least returns to labor were observed in TRC (0.44), with the highest negative difference relative to the control (−50 %). Economic returns over the control treatment were the least in TRIF, followed by TRC in all seasons. In general, the rankings in terms of economic gains over the control tended to be highest in TRTIF, followed by NTRTIF, NTRMIF, TRMIF, NTRIF, TRC, and TRIF.

During the SR season, net benefits were higher in soil management treatments with no tied ridging than those with tied ridging, except the *Tithonia diversifolia* treatment (TRTIF), which had higher benefits than the NTRTIF treatment.

4. Discussion

4.1. Soil water content

Intra-seasonal drought periods were experienced in the study during both seasons. The short rains had two events during 47–114 DAP and 117–144 DAP, respectively. There were dry-spell events between 31 and 44 DAP (days after planting), 50–77 DAP, and 83–97 DAP during the long rain cropping season. A meteorological drought (defined as the absence of rainfall for a duration >28 days during the growing season) and dry spells (absence of rainfall in periods ranging between 10 and 28 days during the cropping season) (Kiboi et al., 2017) were experienced. Dry spells were more common in the long rains, while meteorological droughts were more prominent in the short rains, consistent with Mucheru-Muna et al. (2014).

Seasonal rainfall amount and distribution were highly significant in all the parameters under investigation in this study. As Mucheru-Muna et al. (2014) observed, dry spells mostly occurred during the peak periods of crop water requirement. Rockström et al. (2010) reported that sub-humid agroecosystems experience a high frequency of droughts, dry spells, and rainfall variability; thus, adequate soil-crop water management strategies are needed. Adequate climate-smart agricultural management strategies are required in the SSA region's small-scale semiarid agroecosystems, which typically lack supplementary irrigation and are likely to experience extreme weather and climate extremes. Essential to crop growth and productivity, start days and the end of a rainy period and thus its length, plus rainfall amounts and risk of dry spells within the season, are pertinent aspects because they strongly affect crop yields (Ngetich et al., 2014b).

During all seasons, the meteorological drought and dry spell conditions influenced soil moisture distribution in the 0–30 cm soil depth. During these periods, tied ridging without organic inputs was insufficient in soil moisture conservation since there was little or no rainwater to be held in the basins. Tied-ridging is likely to benefit the maize crop in fine-textured soils and for seasonal rainfall between 500 and 900 mm during drought or dry years (Wiyo et al., 2000). The results, therefore, did not agree with similar studies that recorded higher soil water storage where tied ridges were employed (Gan et al., 2013). This was due to the rainfall amounts in these studies either being higher or better distributed as well compared to patterns observed in this study.

Treatments with organic inputs performed best in holding soil water relative to those without, while tied ridges without organics led to the least aggregate soil moisture gains. This was likely due to the improved soil physical conditions under these treatments increasing the available soil water-holding capacity (Enfors et al., 2011). This finding was supported by Hudson (1994), who found that soil organic matter and soil moisture content had a highly significant positive correlation.

Manure is well known to build up soil organic matter leading to improved soil physical conditions resulting from enhanced soil aggregation, porosity, hydrophobicity, infiltration rate, and water-holding capacity (Abiven et al., 2009). These results were in tandem with Adeleye et al. (2010) and Brar et al. (2015), who observed that manure conserved soil moisture, improved soil physicochemical properties, and reduced soil temperature, which minimized evaporation. Celik et al. (2004) also observed that the application of manure increased soil organic matter contents and soil water content by 56 %.

The integrated application of *Tithonia diversifolia* and inorganic fertilizer manifested higher soil moisture levels than the control treatment. This was likely due to increased soil organic matter and reductions in soil temperature and evaporation resulting from plant residue decomposition (Babajide et al., 2008). Being a high-quality organic soil

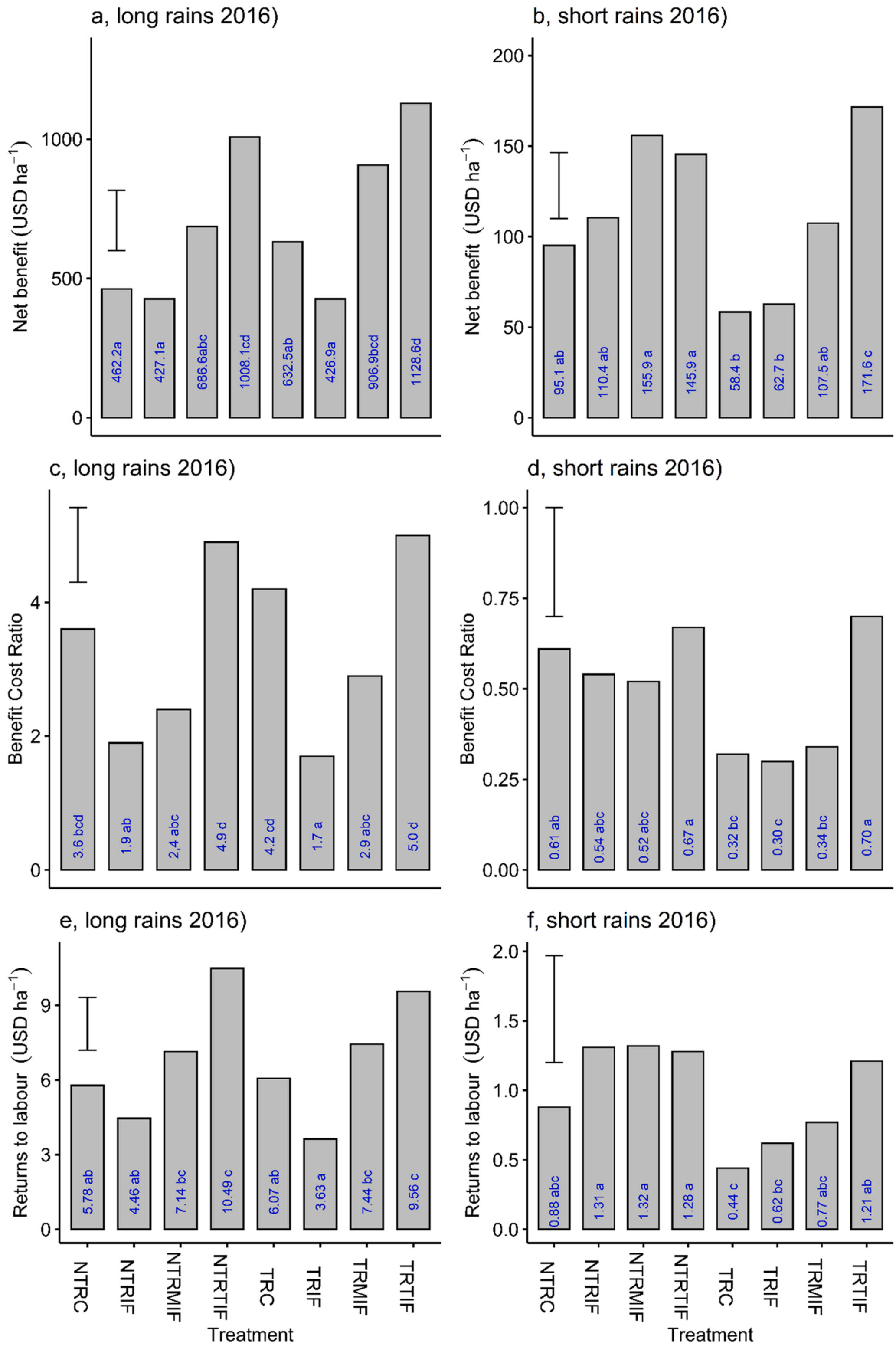

Fig. 4. Effects of soil treatments on net benefits, benefit-cost ratio and returns to labour for maize cultivation during the experimental period (Long and short rains, 2016) in Kigogo, Kenya (US $). Treatments with the same letter(s) are not significantly different ($p < 0.05$). Error bars are LSD (0.05) for treatment effects. Treatment descriptions are described in Table 2 and Table 4.

resource, the high rate of *Tithonia diversifolia* decay and integration results in improved soil hydrological properties during the short term compared to other organic materials (Kolawole et al., 2014). Soil organic matter reduces soil bulk density and compaction (Adekalu and Osunbitan, 1995), improving soil aggregation, resulting in greater soil porosity, thus retaining more soil moisture (Osunbitan and Adekalu, 1999) during the cropping season. Improvements in soil organic matter improved the soil structure, which enhanced the infiltration capacity of rainwater, thereby increasing soil water retention and availability for crop growth (Kolawole et al., 2014). *Tithonia diversifolia* is likely to have improved the soil's organic and hydrologic characteristics after its rapid decomposition.

Larger soil moisture gains were achieved in the short rain season (2.3 %), which included meteorological droughts, compared to the long rain season (0.6 %), characterized by dry spells and higher rainfall distribution aggregated across depth, treatment, and time over the control. This represented a much greater moisture gain in the short rain season compared to the long rains relative to the control. Motsi et al. (2004) found that tied ridges retained significantly higher soil moisture than conventional tillage systems, especially during the dry months. The effect of the ridges was reported to be generally higher in drier seasons and more so when the ends of the ridges were tied compared to open ridges in Southern Africa (Belay et al., 1998). The observed higher soil water content in the long rains than the short rains resulted from higher rainfall that was better distributed than in the short rain season. McHugh et al. (2007) observed fluctuations in soil water content due to rainfall variability between and within seasons. Due to the rainfall pattern, the soil profile was characterized by water accumulation and depletion throughout the two seasons.

Each season, the first half received much of the rainfall with the rest experiencing drier periods. Following rainfall events, treatments under tied ridging retained more rainwater than those without. Also, treatments with organic resources (manure or *Tithonia*) contributed to significant soil water conservation, especially in the short rains. Evidence also suggests that tied ridges and organic soil inputs were critical in conserving soil moisture in the dry season during the critical maize tasselling and silking growth stage. This could be due to the tied ridges' ability to trap rainwater instead of the flatbeds (Okeyo et al., 2014; Ngetich et al., 2014b). The penetration of rainwater and the resultant retention in the soil profile is influenced by several factors, including the amount, intensity, and distribution of rainfall in addition to the soil's physical properties (Moraru and Rusu, 2013).

4.2. Maize yields

Tithonia diversifolia with inorganic fertilizer and manure generally improved grain and stover yields in both cropping seasons relative to the control treatment. The good grain yields achieved by *Tithonia* could be attributed to nutrient supply by rapid decomposition, providing an effective source of N, P, and K as well as Ca, K, and Mg (Mugwe et al., 2009; Mucheru-Muna et al., 2014). Jama et al. (2000) found that *Tithonia* biomass increased maize yields compared to inorganic fertilizers at equivalent N, P, and K rates. Several other studies have reported increased maize yield where *Tithonia diversifolia* was used in combination with inorganic fertilizer as compared to sole inorganic fertilizers (Nziguheba and Mutuo, 2000; Mucheru-Muna et al., 2007; Gikonyo et al., 2010). However, *Tithonia diversifolia* is labor-intensive in cutting, carrying, and incorporating (Jama et al., 2000). Though *Tithonia* is labor-demanding, its opportunity cost is relatively low because farmers will cut it when it is dry with no other activities compared to manure which has a higher opportunity cost. It's high-quality organic content and nutrient values justify its application as a soil fertility management resource.

Integrating manure with inorganic fertilizers also increased maize grain and stover yields during 2016 than the control treatment. Combining manure with inorganic fertilizers increases nutrient availability and enables better synchronization of nutrient release and uptake (Chivenge et al., 2011; Gicheru, 2012; Mucheru-Muna et al., 2014). An increase of > 650 % in maize grain yields was reported by Mwende et al. (2019) after applying manure combined with inorganic fertilizers compared to the control treatment.

The study affirmed that using organic resources combined with inorganic fertilizers is a better option for increasing maize and stover yields. Several authors in the SSA agreed that mixing inorganic fertilizer and organic inputs produced the highest and most sustainable gains in yields per unit of applied nutrients (Mugwe et al., 2009; Vanlauwe et al., 2010; Mucheru-Muna et al., 2014; Mugwe et al., 2019). Gachengo et al. (1999) reported that in most cases, combined treatments would lead to higher yields because of the additive effect of the organic and inorganic nutrients compared to organic or inorganic treatments applied solely. Moreover, fertilizer use efficiency is increased by these combinations as they supply nutrients more balanced and other multiple agroecological benefits (Sanginga and Woomer, 2009; Vanlauwe et al., 2010). A meta-analysis indicated that combined applications of inorganic and organic fertilizers led to greater productivity and agronomic efficiency responses compared to sole applications (Gram et al., 2020).

Tied ridging performed better in enhancing grain yields during the long rain season than in the short rain. This can be attributed to the higher amount of rainfall received, which was better distributed than the short rain season (Fig. 1). The better performance of tied ridging corroborates the findings of Belay et al. (1998), who reported maize yield increases on vertisols of eastern Ethiopia where tied ridges were employed relative to flat planting. In Mbeere South Sub-County, similar results were observed where tied ridging had the highest increase in maize grain yields (1.23 Mg ha^{-1}) compared to mulching and the control (Ngetich, 2012). Araya and Stroosnijder (2010) also reported a 44 % increase in maize grain yield under tied ridging relative to the control.

The low performance of soil fertility treatments under tied ridging in the short rains may have resulted from poor rainfall distribution and meteorological droughts observed during the season. Hulugalle (1987) obtained similar results where treatments with tied ridging had no significant effect compared to those without tied ridging. In other studies, Bayu et al. (2012) did not observe significant responses of crop growth and yields to tied ridges. The immensity of the growth and yield response to the relative performance of tied ridges varies with several factors, including fertilization, total amount, and rainfall distribution, among others, during the cropping season (Bayu et al., 2012).

4.3. Economic benefits of treatments

The low performance of economic benefits in the short rain season was connected with lower yields realized due to changes in rainfall after farm investments had been incurred at the season onset. Higher economic net benefits were realized under integrated organic and inorganic fertilizer treatments relative to fertilizer and control treatments in both seasons. This is likely the result of higher maize yields that were observed under these treatments. These findings agree with Nziguheba et al. (2002) and Mucheru-Muna et al. (2014), who found greater benefits when combining *Tithonia diversifolia* with inorganic fertilizer. Integrating organic inputs and inorganic fertilizers generated positive net benefits, BCR, and returns to labor in all seasons. Denise and Meike (2020) found that integrated soil fertility management strategies resulted in higher labor demand, but the approach also increased labor productivity and financial returns.

Mutegi et al. (2012) highlighted that combined organic inputs and inorganic fertilizers exhibited higher net benefits and BCR than sole fertilizer applications. This can be associated with the ability of this integration to greatly increase crop yields, in tandem, generating higher economic proceeds (Jama et al., 2000). Nonetheless, this approach may also be hindered by the high proportional requirements for organic inputs and labor necessities for cutting, carrying, and incorporating these organics (Jama et al., 2000).

During the short rains, all the treatments besides the sole inorganic fertilizer with and without tied ridging treatments had a BCR > 2, considered the minimum BCR in determining the adoption of a given farming practice in smallholder farming systems (FAO, 2006). This means that the yields and the accrued benefits associated with the soil fertility inputs with and without tied ridging in this study could offset the labor and non-labor costs incurred. However, due to the low benefits realized, the soil fertility inputs with and without tied ridging could not reach the minimum BCR of 2 during the short rain season.

5. Conclusions

Dry spells characterized the long rain season in the experiment, while the short rain period featured meteorological droughts. Results showed enhanced soil water content and maize grain yields under soil fertility inputs. Treatments with *Tithonia diversifolia* or manure combined with inorganic fertilizer with or without tied ridging consistently positively affected soil water content. The effect of soil moisture conservation on soil water content was greater in the short rain season compared to the long rains in terms of soil moisture gains relative to the control. Tied ridging and organic applications led to soil moisture conservation during critical maize tasselling and silking stages in both seasons.

In aggregate terms, across soil moisture, yield, and economic benefits over the control treatment, integrated treatments recorded the highest moisture benefits relative to the control. Integrated treatments recorded the highest moisture benefits over the control across time at 10–30 cm depths. NTRIF contributed the highest moisture benefits over the control at 10–30 cm across time, while TRIF recorded the least benefits across soil moisture, yield, and profit measures. Sole fertilizer and tied ridging tended to register intermediate benefits over the control across agronomic and economic measures in the study.

Emerging from the study is the lack of a consistent advantage of tied ridging over no ridging within the period under consideration. These underpin the need to research long-term effects (> 4 seasons) of tied ridging and soil fertility inputs on soil physical properties, crop performance, and profitability under erratic and changing rainfall regimes of the Central Highlands of Kenya. Tied ridging and organic treatments potentially contribute to soil moisture conservation under dry spells and meteorological drought conditions, especially in the short rain season. Therefore, climate-smart in-situ soil water conservation interventions are needed in the SSA region's semiarid zones to reduce the risk of crop failure under erratic drought conditions and variable climatic scenarios.

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.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108390.

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