Heliyon 7 (2021) e08005

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Zai pits for heightened sorghum production in drier parts of Upper Eastern Kenya

Serah W. Kimaru-Muchai [a,*], Felix K. Ngetich [b], Monica W. Mucheru- Muna [c], Mary Baaru [d]

[a] Department of Social and Development Studies, Mt. Kenya University, P.O Box 342-01000, Thika, Kenya
[b] Department of Land and Water Management, University of Embu, P.O Box 6-60100, Embu, Kenya
[c] Department of Environmental Science, Kenyatta University, P.O Box 43844, Nairobi, Kenya
[d] Department of Environmental Studies and Community Development, Kenyatta University, P.O Box 43844, Nairobi, Kenya

ARTICLE INFO

Keywords:
Water harvesting technologies
Tithonia diversifolia
Conventional planting

ABSTRACT

Water harvesting technologies and soil conservation measures promote water-nutrient synergy and increase agricultural production in the dryland zones of sub-Saharan Africa. To alleviate water stress, soil fertility decline and reduce runoff, soil and water conservation measures are promising options whose impact on agricultural productivity has not been fully explored. The objective of the study was to assess the effect of using zai pits in combination with selected soil fertility ammendments. An experiment was conducted in Tharaka Nithi County, Kenya to assess effects of using Zai pits in combination with selected amendments on sorghum production. The experiment was set up in a Randomized Complete Block Design (RCBD) involving 12 soil and water conservation treatments with three replications per block. Experimental data were subjected to analysis of variance and mean separation done using least significant difference (LSD) at $p < 0.05$. Zai pit in combination with *tithonia* amendment had the highest yields of 4.30 Mg ha^{-1} during short rains season of 2013 while Zai pit in combination with cattle manure had the highest yield of 4.18 Mg ha^{-1} during short rains season of 2014. Conventional planting with full rate NPK had the highest benefit-cost ratio (BCR) of 3.58 while Zai pit without input had the least BCR of 0.99. The experiment showed that Zai pit technology contributed to increments of yields in comparison to conventional planting although its BCR was lower than conventional planting with similar amendments. However, both Zai pit and conventional practices should be used in combination with organic and inorganic amendments to enhance yields in sorghum production.

1. Introduction

Nutrient replenishment and increasing water infiltration is essential to increasing soil productivity and improving livelihoods in drought prone areas in semi-arid environments (Baptista et al., 2015). Improvement of soil fertility and water conservation in sub-Saharan Africa is geared towards environmentally sound and economically feasible practices for sustainable food production (Van Beek et al., 2017). Combination of water harvesting technologies and soil fertility amendments in dryland areas has a promising influence on the optimisation of dryland crop production (Mekuriaw et al., 2018).

Researchers have explored various alternatives to curb the challenge of soil water insufficiency and increase crop yield in the semi-arid areas. Among the soil and water conservation technique are Zai pits, semi-circular bunds half moons and negarims (Nicol et al., 2015). Zai pit technology is designed to replenish soil moisture, restore soil fertility, and improve crop production (Danjuma and Mohammed, 2015). While promoting Zai pit technique as one of the promising option for enhancing crop production in dryland areas, it is pertinent to understand its effect on yields as well as its economic viability using different soil fertility amendments.

The farming systems of upper eastern Kenya are relatively complex because of the high rainfall variability typical of the semi-arid tropics (Rao et al., 2011). Insufficient soil moisture is one of the greatest impediment to agricultural productivity (Muindi et al., 2016). Most crop productivity related research conducted in this region have been geared towards addressing soil moisture conservation through different rain-water harvesting approaches, or soil fertility amendments for enhanced crop production (Gichangi et al., 2007). There is a paucity of knowledge on the combined effects of both water harvesting techniques and soil

* Corresponding author.
E-mail addresses: swkimaru@mku.ac.ke, sarahmuchai@yahoo.com (S.W. Kimaru-Muchai).

https://doi.org/10.1016/j.heliyon.2021.e08005
Received 27 April 2021; Received in revised form 26 June 2021; Accepted 13 September 2021
2405-8440/© 2021 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

fertility amendment ameliorating technologies on the crop performance and economic feasibility.

Hence, to alleviate food insecurity in the semi-arid areas of upper eastern Kenya, farmers have adopted crops that are tolerant to drought such as sorghum and millet (Umesh et al., 2015). Sorghum and millet are consumed locally where as surplus is sold to earn income. Unfortunately, the potential of this drought-tolerant traditional food crops has not been fully realised due to the frequent protracted dry seasons and droughts experienced in the drier agroecologies (Mwadalu and Mwangi, 2013). Hence, it is essential to realise efficient capture and use of the scarce water available in arid and Semi-arid areas (Evans and Sadler, 2008). Optimisation of available moisture through water harvesting in farming systems, can contribute towards food and income security and hence better livelihoods for the small-scale farmers (Nicol et al., 2015).

Research has revealed that the Zai technology has the potential to increase crop production and biomass production and lessen the severe effects of dry spells on highly degraded soils in the dryland areas (Kabore and Reij, 2004; Fatondji et al., 2006). A report by Kabore and Reij (2004) found that Zai increased sorghum yields by 310 kg ha^{-1} compared to the non-Zai treatment in the village of Donsin, which had adopted this Zai pits. In Niger's Illela district, average yields in Zai pits were 310% higher compared to untreated fields (Kabore and Reij, 2004). In Western Kenya, Zai pits technology (also known as Tumbukiza, locally) produced significantly higher dry matter yields than the conventional method (Muyekho et al., 2000). In West Africa, Bationo et al. (2006) found that Zai alone did not improve the yields as much as when the Zai was used in combination with manure and fertilizer. Again in Niger manure application with Zai showed a 2 to 69 times more grain yields than Zai pit with no nutrient amendment (Fatondji et al., 2006).

Given the high labour investment in many conservation farming technologies (Mango et al., 2017), it is imperative to examine the financial returns against the higher labour inputs required to achieve them. Zai pit is a resource-intensive technology (Muriu-Nganga et al., 2017). According to Kabore and Reij (2004), it takes 450 h ha^{-1} to dig the holes, and another 250 h ha^{-1} to incorporate fertilisers. Annual maintenance of the pits is estimated at 15–20 days per hectare (Mutunga, 2001). Nonetheless, the benefits of digging Zai pits are considered to be significant compared with the costs by the farmer (Mutunga, 2001). However, taking stock of documented knowledge on the Zai pits, Vohland and Barry (2009) reported that the Zai pit technology has not been fully studied. Despite the voluminous evidence on yield gains, the evidence on the financial returns to Zai pits remains comparatively sparse. Hence, we evaluated the agronomic and economic feasibility of sorghum production using Zai pits under different organic and inorganic soil fertility ameliorating amendments.

2. Materials and methods

2.1. Study area

The study was conducted in Tharaka South sub-county, Tharaka Nithi County, located in Eastern Kenya (Figure 1). The study area lies in the inner lowland zone (IL5) agroecological zone with bimodal rainfall: short rains season (SR) in October, November and December and long rains season (LR) in March, April and May. The annual average rainfall is 500–750 mm and mean annual temperatures 24 °C, respectively (Jaetzold et al., 2006; Smucker and Wisner, 2008). The study area has an uncertain first cropping season and the second season is short (Jaetzold et al., 2006). Despite bimodal distribution, the rainfall amount is mostly inadequate to meet crops and fodder requirements. The predominant soils in the study area are ferrasols which are highly weathered and leached (Jaetzold et al., 2006). The soil pH ranges from moderately acid (5.64) to moderately alkaline (8.31). The soil organic matter content ranges from 0.30% to 2.28% Total Organic Carbon (TOC)) and therefore inadequate soil organic matter content.

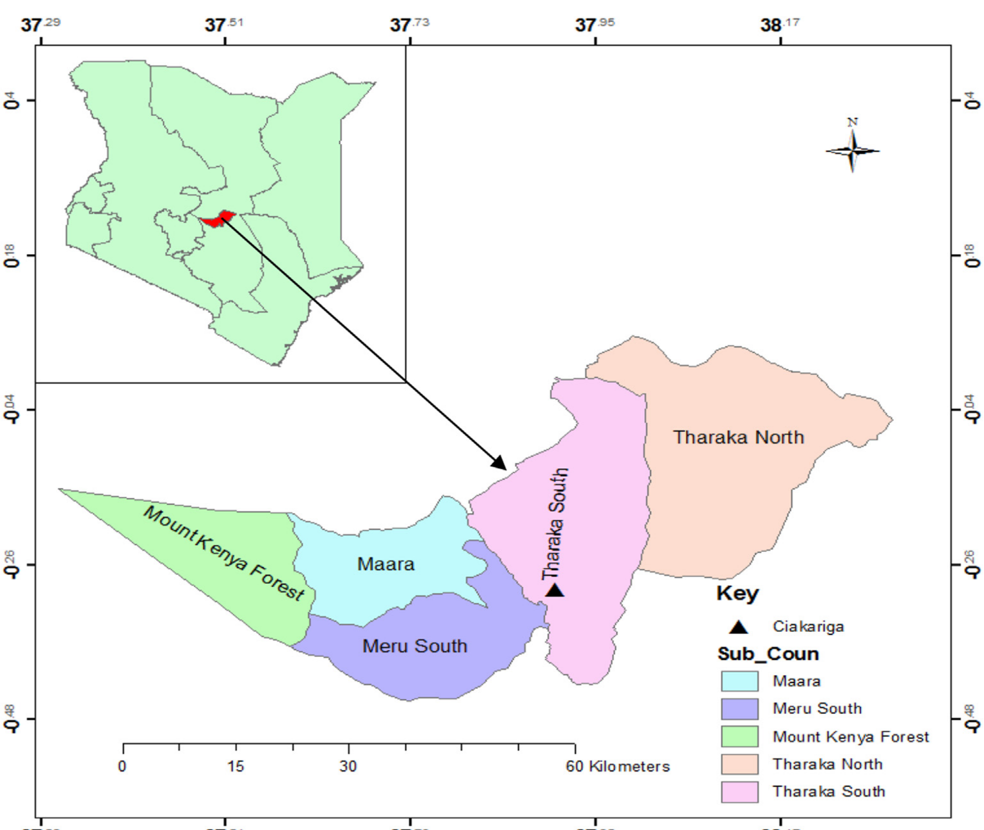

Figure 1. Map of the study area Tharaka Nithi County.

Crop farming and livestock rearing are the main activities for communities in Tharaka area (Jaetzold et al., 2006). Households keep indigenous breeds of cattle, goats, sheep and chicken. The major crops grown are maize(*Zea mays*), cowpea (*Vigna unguiculata),* green gram (*Phaseolus aureus)* mango (*Mangifera indica*), common millet (*Panicum* spp), pawpaw (*Carica papaya),* pigeon pea (*Cajanus cajan),* bulrush millet (*Pennisetum typhoideum*), sorghum (*Sorghum* spp.) and finger millet, (*Eleusine coracana)* (Smucker and Wisner, 2008).

2.2. Experimental layout and management

The experiment was set up in a Randomized Complete Block Design (RCBD), involving 12 soil management treatments as shown in Table 1 with three replications per block. The field experiment was conducted during the short rains 2013 (SR13), Long rain 2014 (LR14) and short rain 2014 (SR14) seasons using treatments shown in Table 1. The crop under investigation was sorghum Gadam variety. Plot dimensions were 4.5 m × 6 m. For Zai pits, the holes were dug 0.6 m deep 0.6m wide and 0.6m long at a spacing of 0.75 m and 0.6 m as inter- and intra-row, respectively while for conventional planting, the holes were dug at a depth of 0.1 m deep at a spacing of 0.75 m by 0.2 m, inter- and intra-row, respectively (Clottey et al., 2015). The average nutrient composition of the organic inputs that were incorporated in the three seasons is shown in Table 2. *Tithonia diversifolia* was harvested from river bank bushes near the site and cattle manure was harvested from cattle sheds on the farm. All organic (Cattle manure and *Tithonia diversifolia)* and inorganic inputs (Table 1) were applied to give an equivalent amount of 30 or 60 kg N ha^{-1} as per treatment.

Five holes (four near each corner of the pit and one at the centre) were made in every Zai pit, and three seeds were sown per hole and thinned two weeks after emergence to two plants.

Tithonia diversifolia had the highest levels of N, K and Mg while cattle manure had the highest amounts of P and ash Table 2. Calcium content was also high in *Tithonia diversifolia* as compared to cattle manure.

Various observations were made routinely in the course of each season which included: daily rainfall, time of germination, plant population at harvest, grain and biomass yields. The edge effect was minimised using guard rows. The sorghum grain heads were separated from the stover, dried and hand-threshed. After threshing, moisture meter was used to determine the moisture content of the grains and grain weights adjusted to 12.5% moisture content.

To determine the economic feasibility of sorghum production using the different treatments, various variables were evaluated. The variables were: the cost of the seeds and inputs; labour costs (in land preparation, Cutting and tansportation of *Tithonia diversifolia, application of the fertilisers,* planting, weeding, harvesting and spraying); quantities of sorghum grain harvested and their value; amounts of sorghum biomass harvested and their monetary value (Table 3). To calculate the benefits, grains and stovers yields from each treatment were reduced by 10% to adjust to realistic values if the experiment was to be managed by a farmer (CIMMYT, 1988).

Table 1. Experimental treatments during SR13, LR14 and SR14 and Nitrogen sources in kg ha^{-1} in Ciakariga, Tharaka Nithi County, Kenya.

Soil water conservation Technique	N from Organics	N inorganic Fertilizer
Zai pits + Cattle manure	60	0
Zai pits + *Tithonia diversifolia*	60	0
Zai pits + Mineral fertilizer (60 kg N ha^{-1})	0	60
Zai pits + Cattle manure + fertilizer (30 kg N ha^{-1})	30	30
Zai pits + *Tithonia* + fertilizer (30 kg N ha^{-1})	30	30
Zai pits	0	0
Conventional + Cattle manure	60	0
Conventional + *Tithonia diversifolia*	60	0
Conventional + Mineral fertilizer (60 kg N ha^{-1})	60	0
Conventional + Cattle manure + fertilizer (30 kg N ha^{-1})	30	30
Conventional + *Tithonia* + fertilizer (30 kg N ha^{-1})	30	30
Control	0	0

Table 2. Average nutrient composition (%) of organic materials applied in the soil during the SR13, LR14 and SR14 experimental periods in Ciakariga, Tharaka Nithi County, Kenya.

Nutrients	Cattle manure		*Tithonia diversifolia*	
	Average	SD	Average	SD
Nitrogen	1.5	0.06	3.0	0.53
Potasium	1.9	0.04	2.9	0.13
Magnesium	0.4	0.05	0.7	0.21
Phosphorous	0.2	0.08	0.3	0.06
Calcium	1.0	0.10	2.1	0.10
Ash	46.3	0.12	13.2	0.25

2.3. Data analysis

Sorghum yield data were subjected to analysis of variance (ANOVA) using Proc ANOVA procedure in SAS 9.2 software (SAS Institute, 2004) to obtain an F value of the effect of the model. Pair-wise comparison of yields between treatments was analysed using t-test. Differences between treatment means were examined using the least significance difference (LSD) at $p = 0.05$.

The gross margin analysis was used to estimate the economic feasibility of sorghum production under different treatments. Gross margin model used was as shown in Eq. (1):

$$GM = TR\text{-}TVC \qquad \text{Equation 1}$$

where: GM is gross margin (US$ ha^{-1}); TR is total revenue or the total value of output from the sorghum enterprise (US$ ha^{-1}) both grain and biomass (it is the product of the average output per hectare multiplied by the market price); TVC is the total variable cost or the costs that are specific in producing (sorghum) output ((US$ ha^{-1})). TVC varied according to output and were incurred on variable inputs. It included the cost of inputs like seeds, fertiliser, and harvesting, labour cost (hired which will vary as per treatment).

Benefit-cost ratio was calculated using Eq. (2).

$$BCR = TR/TVC \qquad \text{Equation 2}$$

All the biophysical data were subjected to analysis of variance using the ANOVA Procedure to obtain an F value of the effect of the model for each treatment. To test for the treatment effect differences the means were separated using Least Significant differences (LSD) at the 5% level of significance.

Table 3. Parameters used to estimate the economic returns of sorghum production during the SR13, LR14 and SR14 in Ciakariga, Tharaka Nithi County.

Parameter	Actual values (*US$ kg^{-1})
1 kg N	1.63
Labour cost 8 h	0.28
Price of 1 kg sorghum grain	0.31
Price of 1Kg sorghum stover	0.026

* Exchange rate KES 101 = 1 US$ (January 2018).

3. Results

3.1. Rainfall distribution during the SR13, LR14 and SR14 in Ciakariga, Tharaka Nithi County

The three growing seasons received varying amounts of rainfall. The total seasonal rainfall recorded during the SR13, LR14 and SR14 growing season was 342.3 mm 249.7 mm and 461 mm, respectively (Figure 2). During the LR14 growing season, rainfall was only experienced in 12 days while SR13 and SR14 had 25 and 16 rain days respectively. Out of the 12 rain days of LR14, 9 days had received less than 14 mm rainfall while the others were 20.4 mm, 44 mm and 120 mm, sequentially.

The total daily rainfall recorded during the SR13 growing season ranged between 2.6 mm to 60 mm while it ranged between 2 mm and 120 mm for the LR14 and between 2.8 mm and 123 mm during the SR14 growing season. The SR14 growing season recorded the highest rainfall event of 123 mm and 110 mm on the 24th and 17th day after planting while the highest daily rainfall event for SR13 was on 33rd and 24th after planting for LR14. Dry spells were experienced after 57th day, 28th day and 46th day after planting during the SR13, LR14 and SR14 growing seasons, respectively.

3.2. Effects of Zai pit on sorghum production

The grain yields were mainly higher in those treatments with Zai pit regardless of the soil fertility amendments except during the LR14 season when conventional planting with *Tithonia diversifolia* was higher than Zai pits with *Tithonia diversifolia* although not statistically different at $p < 0.05$ (Table 4). During the SR13 season, Zai pit with *Tithonia diversifolia* treatment resulted in highest yields (4.3 Mg ha^{-1}) followed by Zai pit with cattle manure treatment (4.23 Mg ha^{-1}). During the LR14 season, the treatment with Zai pit with cattle manure and Zai pit with *Tithonia diversifolia* plus half rate NPK had the highest grain yields of 0.34 Mg ha^{-1} and 0.25 Mg ha^{-1}, respectively (Table 4). Zai pits with cattle manure (4.18 Mg ha^{-1}) and Zai pits with full rate NPK (4.17 Mg ha^{-1}) had the highest yields compared to other treatments in the SR14 season (Table 4). It is important to point out that grain yields and stover yields were lowest during the LR14 (Table 4). The highest grain and sorghum yields for LR14 were lower than the control for both SR13 and SR14 cropping season (Table 4).

Zai pit with *Tithonia diversifolia* plus half rate NPK treatment had the highest stover yields of 12.53 Mg ha^{-1} followed by Zai pit plus *Tithonia diversifolia* with 9.57 Mg ha^{-1} during the SR13. In LR14 season, all stover yields for Zai pit and conventional practices with amendments were significantly higher than the control at $p = 0.05$. During the SR14 season, stover yields for Zai pit with *Tithonia diversifolia* plus half rate NPK and Zai pit plus *Tithonia diversifolia* treatments were significantly higher with 12.53 Mg ha^{-1} and 11.29 Mg ha^{-1}, respectively (Table 4), compared to all other treatments.

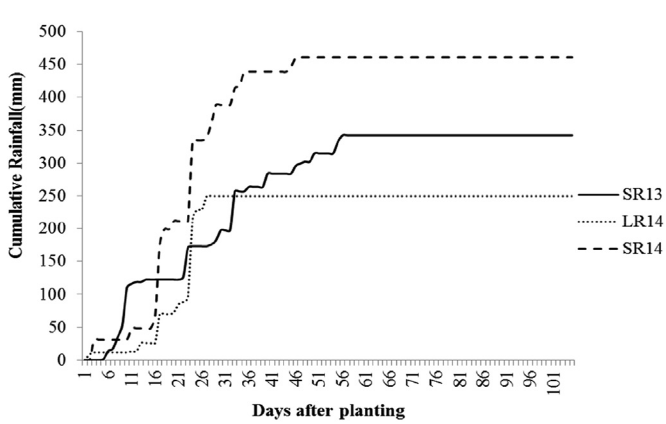

Figure 2. Distribution of rainfall at different days after planting during SR13, LR14 and SR14 in Ciakariga, Tharaka Nithi County.

Table 4. Grain and stover yields for Zai pits and conventional practices for SR13, LR14 and SR14 seasons in Ciakariga Tharaka County.

Treatment	Grain yields Mg/ha			Stover yields Mg/ha		
	SR13	LR14	SR14	SR13	LR14	SR14
ZT	4.30^{a}	0.21^{bc}	3.78^{ab}	9.57^{b}	1.73^{ba}	11.30^{a}
ZC	4.23^{ab}	0.34^{a}	4.18^{a}	8.15^{b}	1.96^{a}	8.89^{b}
ZT30	3.96^{ab}	0.25^{b}	3.30^{bcd}	12.53^{a}	1.79^{ab}	12.53^{a}
ZC30	3.92^{ab}	0.19^{bc}	3.57^{abc}	8.02^{bc}	1.54^{abc}	9.26^{b}
ZF60	3.48^{ab}	0.18^{bc}	4.17^{ab}	9.01 ^{b}	1.30^{bc}	9.01^{b}
ZNO	1.96^{c}	0.03^{d}	1.00^{e}	4.75^{d}	0.21^{d}	4.75^{c}
CT	3.75^{ab}	0.24^{b}	3.76^{abc}	5.93^{cd}	1.66^{ab}	6.11^{c}
CCM	3.71^{ab}	0.18^{bc}	2.72^{d}	7.78^{bc}	1.67^{ab}	8.33^{b}
CT30	3.79^{b}	0.24^{b}	3.11^{cd}	8.70^{b}	1.63^{ab}	8.64^{b}
CC30	3.71^{ab}	0.18^{bc}	3.57^{abc}	7.84^{bc}	1.4^{bc}	8.46^{b}
CF60	3.32^{ab}	0.14^{c}	3.82^{ab}	8.09^{bc}	1.11^{c}	8.09^{b}
CNO	1.76^{c}	0.03^{d}	0.79^{e}	4.63^{d}	0.19^{d}	4.62^{c}
F value	6.51	11.23	12.90	6.68	10.26	14.47
p	0.001	<0.001	<.001	<.001	<.001	<.001

Same superscript letters in along the column denote no significant difference between treatments at p = 0.05.
ZC = Zai pits + cattle manure, ZT = Zai pits + *Tithonia*, ZF60 = Zai pits +60 kg N ha^{-1}, ZC30 = Zai pits + Cattle manure +30 kg N ha^{-1}, ZT30 = Zai pits + *Tithonia* +30 kg N ha^{-1}, ZNO = Zai pits with no inputs, CCM = Conventional planting + cattle manure, CT = Conventional planting + *Tithonia*, CF60 = Conventional planting + NPK 60 kg N ha^{-1}, CC30 = Conventional planting + Cattle manure +30 kg N ha^{-1}, CT30 = Conventional planting + *Tithonia* +30 kg N ha^{-1},CNO = Conventional planting with no inputs.

3.3. The economic potential of Zai pits utilisation in combination with selected ISFM on sorghum production

Zai pit with *Tithonia diversifolia* treatments recorded the highest labour costs significantly at ($p < 0.001$) followed by conventional planting with *Tithonia diversifolia* with labour cost of US$2561.43 ha^{-1} and US$2053.12 ha^{-1}, respectively (Table 5). The total labour cost for Zai pit with cattle manure was 139% significantly higher than conventional planting with cattle manure while Zai pit without input labour cost was 167% higher than conventional planting without input (Table 5). There was a significant difference ($p < 0.001$) of 40.1% labour cost between Zai pit with *Tithonia diversifolia* plus half rate NPK and conventional planting with *tithonia* plus half rate NPK (Table 5). The labour cost for conventional planting with *Tithonia diversifolia*, conventional planting with cattle manure plus half rate NPK, conventional planting with cattle manure and conventional planting with full rate NPK was 503%, 54.4%, 29.9 % and 27.7%, respectively, higher than conventional planting without input (Table 5). Conventional planting without inputs had the lowest labour cost of U$340.46 ha^{-1}.

In all the three seasons total costs were recorded highest on the Zai planting with *Tithonia diversifolia* treatments followed by conventional planting with *Tithonia diversifolia*. Zai pit with *Tithonia diversifolia* treatment was significantly higher ($p < 0.001$) by 23.7% than conventional planting with *Tithonia diversifolia* treatment (Table 5).

The total cost for conventional planting with cattle manure plus half rate NPK, conventional planting with cattle manure and conventional planting with full rate NPK was 74.5%, 58% and 50%, respectively, higher than conventional planting without inputs (Table 5). The total cost for Zai pit with tithonia plus half rate NPK, Zai pit with cattle manure, Zai pit with cattle manure plus half rate NPK and Zai pit plus full rate NPK was 93.4%, 29.8%, 25.5% and 17.1%, respectively, higher than Zai pit without inputs (Table 5).

Table 5. Economic analysis on labour cost, total cost, total benefit, net benefit and BCR for three seasons SR13, LR14, SR14 in Tharaka Nithi County.

Treatment	Labour Cost(US$)	Total Cost(US$)	Total Benefit(US$)	Net Benefit(US$)	BCR
CCM	442.41[j]	680.03[k]	2123.55[c]	1443.52[ab]	3.12[b]
CC30	525.73[i]	749.69[j]	2365.40[abc]	1615.70[a]	3.15[b]
CF60	434.82[j]	645.12[l]	2317.10[bc]	1671.98[a]	3.58[a]
CNO	340.46[k]	429.57[m]	839.50[d]	409.93[ef]	1.95[cd]
CT	2053.12[b]	2142.23[b]	2363.61[abc]	221.20[fg]	1.10[f]
CT30	1270.99[e]	1420.69[e]	2295.89[bc]	875.14[cd]	1.62[de]
ZC	1058.75[f]	1296.37[f]	2743.49[a]	1447.11[ab]	2.12[c]
ZC30	1029.43[f]	1253.39[g]	2444.17[abc]	1190.78[bc]	1.95[cd]
ZCT	1877.62[c]	2041.00[c]	2321.38[bc]	280.38[efg]	1.14[f]
ZF60	958.89[g]	1169.19[h]	2511.27[abc]	1342.08[ab]	2.15[c]
ZNO	909.28[h]	998.39[i]	983.94[d]	-14.44[g]	0.99[f]
ZT	2561.43[a]	2650.54[a]	2680.49[ab]	29.95[fg]	1.01[f]
ZT30	1781.22[d]	1930.93[d]	2558.05[ab]	627.12[de]	1.32[ef]
LSD	37.098	37.098	468.62	450	0.4096

Same superscript letters in the same column denote no significant difference between treatments at p = 0.05.

ZC = Zai pits + cattle manure, ZT = Zai pits + *Tithonia diversifolia*, ZF60 = Zai pits +60 kg N ha^{-1}, ZC30 = Zai pits + Cattle manure +30 kg N ha^{-1}, ZT30 = Zai pits + *Tithonia diversifolia* +30 kg N ha^{-1}, ZNO = Zai pits with no inputs, CCM = Conventional planting + cattle manure, CT = Conventional planting + *Tithonia diversifolia*, CF60 = Conventional planting + NPK 60 kg N ha^{-1}, CC30 = Conventional planting + Cattle manure +30 kg N ha^{-1}, CT30 = Conventional planting + *Tithonia diversifolia* +30 kg N ha^{-1},CNO = Conventional planting with no inputs.

The Zai pit with *Tithonia diversifolia* and that with cattle manure treatments' recorded significantly ($p < 0.001$) higher total benefits than all the other treatments in the three seasons (Table 5). The total benefits for Zai pit with cattle manure was 29.2% significantly higher ($p < 0.001$). A significant difference ($p < 0.001$) of 178.8% was recorded between the total benefits for Zai pit with cattle manure and that without inputs while Zai pit with *Tithonia diversifolia* recorded a difference of 172.4% with Zai pit without inputs (Table 5. The total benefits for conventional planting combined with *Tithonia diversifolia* and conventional planting combined with cattle manure were significantly ($p < 0.001$) higher than conventional planting without inputs by 181.6% and 153%, respectively (Table 5). The total benefits for Zai pit combined with *Tithonia diversifolia*, and half rate NPK were 204% higher than conventional planting without inputs while conventional planting combined with *Tithonia diversifolia* and half rate NPK was 173% higher than conventional planting without input (Table 5). Conventional planting without inputs total benefits were significantly ($p < 0.001$) the lowest followed by Zai pit without inputs although they were not significantly different at ($p <$ 0.001). The observed trend was that during the three consecutive experimental seasons, total benefits were high under the Zai treated plots with amendments but low in both the planting techniques without amendments.

During the three seasons, the highest significant ($p < 0.001$) net benefit was recorded by the conventional planting with full rate NPK followed by the conventional planting with cattle manure plus half rate NPK with net benefits of US$1671.98 ha^{-1} and US$ 1615.70 ha^{-1}, respectively (Table 5). The net benefits for Zai pit with cattle manure plus half rate NPK were significantly lower than conventional planting with cattle manure plus half rate NPK by 26.3% ($p < 0.001$) (Table 5). Among the Zai treatment technique, Zai pit with full rate NPK had the highest significant net benefit of US$1342.08 ha^{-1} followed by Zai pit with cattle manure plus half rate NPK with net benefit of US$1190.78 ha^{-1} and the lowest was Zai pits without inputs with negative net benefit of US$-14.44 ha^{-1} (Table 5). This implied that the total cost for the treatment of Zai without inputs was higher than the benefits.

Conventional planting with mineral fertilizer had the highest significant ($p < 0.001$) BCR of 3.58 followed by conventional planting with cattle manure plus half rate NPK with a BCR of 3.15 (Table 5). The BCR for conventional planting with full rate NPK was 66% lesser than for conventional planting plus cattle manure (Table 5). Zai pit without input recorded BCR of 0.99 which was 98.2% lower than conventional planting without input (Table 5). Conventional planting with cattle manure was significantly higher ($p < 0.001$) than Zai pit with cattle manure by 47.9% while conventional planting with *Tithonia diversifolia* was insignificantly higher than Zai pit plus *Tithonia diversifolia* by 9.1%.

Labour was highest in Zai pits combined with *Tithonia diversifolia* treatment but lowest in convention planting with no input. Total benefits were highest in Zai pits combined with cattle manure treatment but lowest in convention planting with no input. Among the Zai treatment technique, Zai pit with full rate NPK had the highest significant net benefit of US$1342.08 ha^{-1} followed by Zai pit with cattle manure plus half rate NPK with a net benefit of US$1190.78 ha^{-1}. Zai pits without inputs had the lowest net benefit of US$-16.2 ha^{-1}. This implied that the total cost for the treatment of Zai without inputs was higher than the benefits.

4. Discussion

The dry spell coincided with the flowering stage of the sorghum resulting in low production and almost a complete crop failure during LR14 growing season. Dry spells occurring during the cropping period are a characteristic feature of semi-arid areas of Southern Africa (Araujo et al. (2016), West Africa (Froidurot and Diedhiou, 2017) and East Africa (Kisaka et al., 2015). Sorghum grain yield can be significantly affected by climatic changes, especially drought and high temperature (Prasad et al., 2015; Jabereldar et al.,2017). Rainfall recorded during the three seasons also exhibited the poor distribution of rainfall during the growing season which contributes to negative effects of crop yields (Kyei-Mensah et al., 2019). The varying total rainfall in different seasons agrees with other observations that populations in Eastern Kenya relies on October, November and December rains which are presumed to be dependable and can be forecasted with a high level of accuracy. This is because of the relatively higher rainfall amount recorded during short rains (Barron et al., 2003) than long rains season. According to Mulat et al. (2004) the amount and sequential distribution of rainfall is generally the one of the most important determinant of inter annual variations in national crop production levels. Simmilar observation were noted by Novella and Thiaw (2016) who reported that seasonal rainfall frequency and the chronological distribution of rains are significant because for adequate crop development to be achieved a high number of rain days are required.

Grain yields and stover yields for Zai pits with organic amendments were consistently higher for the three consecutive cropping seasons in comparison to Zai pit combined with sole inorganic or combination of organic and inorganic fertiliser. The increased grain and stover yields from Zai pits with amendments (Zai pit plus cattle manure and Zai pit plus *Tithonia diversifolia*) could be as a result of the applied amendments as well as from enhanced soil water retention following breakage of surface crust and subsequently higher water penetration. Zai pits tend to upsurge water accessibility in the root zone (Fatondji et al., 2011) while soil fertility amendments influence soil fertility (Cellier et al., 2014). Ncube et al. (2009) observed that Zai pits increased grain yield of cowpeas by eight-fold while in South Africa, the planting basins improved by more than four-fold. According to a study by Magombeyi and Taigbenu (2008), chololo pits (a variation of Zai pits) resulted in the highest yield in comparison to conventional treatments. In Masinga, Machakos county in Kenya, Zai pit without application of soil fertility ammendments significantly ($p < 0.05$) increased sorghum grain yields by ten times more than conventional treatments with no amendments (Kathuli and Itabali, 2015).

In all the three seasons, grain yields of conventional planting with amendments were higher than Zai pit with no amendments. This implies that the benefits of Zai pits are increased when combined with soil fertility amendments. The results agree with Fatondji et al. (2009) findings which reported that Zai and conventional with amendments performed better than without amendments. This also concurs with previous studies (Kihara et al., 2009) that yield responses to fertility amendments are much higher than the response to the water harvesting technologies alone. Combination of water management and soil fertility improvement as in the case of the use of micro-dosing of N fertiliser with tied ridges in Mozambique (Wall and Thierfelder, 2009) and Zai pits with organic manures in Niger (Fatondji et al., 2009) has resulted to significant yields (Ouattara et al., 2017).

Higher yields obtained on treatments under Zai pits with cattle manure in comparison to conventional planting with cattle manure imply that there was better interaction between Zai pit and cattle manure than conventional planting with cattle manure and hence more increment in grain yields. The increase in yields was most likely because cattle manure conserves soil moisture content, as well as the high levels of N realised from cattle manure (Onduru et al., 2008; Eckhardt et al., 2018). This is in agreement with Graham et al. (2010) who reported that application of cattle manure provided a significant yield increase of grain amaranth of 58.6% with the addition of cattle manure in comparison to control plots. According to Muhereza et al. (2014), most of the farmers in Kampala attribute the usage of cattle manure to increased yields. A study by Cai et al. (2019) recommended that manure application increases soil organic carbon, water storage, soil nutrients, and soil pH and subsequently increases crop productivity.

The results demonstrate that mineral fertilisers also contributed to an increase in yields on both zai pit and conventional planting techniques. A study on basin tillage system (a variation Zai pits), showed that basins gave higher yields than the conventional system with application of nitrogen fertiliser (Ncube et al., 2009). The use of inorganic fertilisers and other soil amendments is critical in enhancing crop production. In additional to improving crop yields, inorganic fertilisers increases crop residues used as livestock feed or as soil organic inputs (Bationo et al., 2006). Use of inorganic fertilisers containing major nutrients contribute to increase in yields under many intensified systems (Liverpool-Tasie et al., 2017). Guo et al. (2007) noted that inorganic fertilisers released their nutrient rather fast for the plants to utilise (Baghdadi et al., 2018). Simulation results using the Agricultural Production Systems Simulator (APSIM) model (Keating et al., 2003) for a 1951–1999 rainfall period in southern Zimbabwe, recommended that farmers could enhance their average yields by 50–100% by applying as little as 9 kg N ha^{-1}. The results imply that combined organic and inorganic have a positive effect on the yields. A research study by Tolera et al. (2018) and Baghdadi et al. (2018) indicated that combinations of organic and inorganic fertilizers result in higher crop yields compared with sole organic or sole inorganic fertilizers. This is also in agreement with Kimetu et al. (2004) who reported a general yield increase after combined application of *Tithonia diversifolia* with nitrogen fertilizers compared with sole *Tithonia diversifolia*. Other studies have shown that combinations of organic fertilizers and inorganic fertilizers result in higher crop yields compared to application of organic fertilizers aone or inorganic fertilizers alone Mutegi et al. (2012). This is as a result of positive interactions and complementarities between the organics and inorganic fertilizers (Jeannin, 2012; Biratu et al., 2018). Incorporation of organic and inorganic nutrient sources has been shown to result in synergy and improved synchronisation of nutrient release and uptake by plants leading to higher yields (Ngetich et al., 2012). According to Timsina (2018) fertiliser use efficiency is enhanced when inorganic and organic nutrient inputs are combined increases and hence a more balanced supply of nutrients to the crop.

Lack of significant differences between Zai pit without amendments and conventional planting without amendment is an indication that soil nutrient content was insufficient such there was a need to boost soil nutrient by application of soil fertility amendments despite the use of water harvesting technique. Addition of amendments restores soil quality for plant growth by balancing pH, source of nutrients, increasing water holding capacity, adding organic matter, restoring soil microbial activity, and reducing compaction (Allen et al., 2007; García et al., 2017). The observations made in this study indicate that Zai pits in combination with organics/inorganics yield better than conventional planting with similar amendments. Nonetheless, the uses of conventional planting in combination with soil fertility amendments also have a positive influence on yields. Therefore, in addition to utilisation of Zai pits as a water harvesting strategy, application of soil fertility inputs have a significant role in the yield increments.

Labour is the primary capital input in the construction of Zai pits and application of soil fertility amendments. The observed trend in the three seasons was that the labour costs for Zai treatments were higher ($p < 0.001$) than for conventional planting techniques with the same soil fertility amendments. This could be attributed to the labour invested in the digging of Zai pits. These results confirm observations of other studies which report that Zai technique is labour intensive (Nyamekye et al., 2018). In addition, tithonia treatement were found to have had high labour costs due to the time spent on cutting and chopping of the biomass. According to Jama et al. (2000) and Mango and Hebinck (2016) it takes about 4 min to collect 1 kg of fresh *Tithonia diversifolia* biomass from off-farm resources. Past research has shown that application of the optimum amount of 5 t ha^{-1} of *Tithonia diversifolia* requires 370 work-days per hectare while application of animal manure takes only 1–7 man-days per hectare (Jama et al., 2000). Report by Mucheru-Muna et al. (2007) indicated that inorganic fertiliser gave the highest (USD12.5) return to labour while *Tithonia diversifolia* alone gave the lowest (USD 4.0). Elsewhere, Jama et al. (2000) observed that the labour required for gathering, transportation and incorporation is a major challenge to the use of huge quantities of *Tithonia diversifolia* biomass. Also, production of *Tithonia diversifolia* on an extra land has been cited as a disincentive for the adoption of *Tithonia diversifolia* as green manure (Opala et al., 2015).

The high total benefits obtained from Zai pit technique are as result of high grain and stover yields obtained from Zai pits with amendment due to higher nutrient and water availability compared to the conventional planting technique. This implies that high total benefits from Zai pits would only be experienced when water harvested by Zai pits is in combination with improved nutrient management. The high total benefits give economic motivation as they portray high incomes for the farmers who practice these technologies. Lack of significant difference in total benefits between Zai pit and conventional planting technique with no amendments indicate that digging of Zai pits will not add any monetary value without amendments. This is in agreement with observations by Moswetsi et al. (2017) who stated that interactions of water harvesting technologies with organic or inorganic sources of nutrients may enhance crop production and hence be lucrative to farmers.

In the three seasons, high net benefits were experienced among planting techniques with amendments except those that had been combined with *Tithonia diversifolia*. This implied that the total cost for this treatment was low and the yields were relatively high compared to other planting techniques. Results of the economic analysis by Mucheru-Muna et al. (2007) indicated that *Tithonia diversifolia* with half recommended rate of inorganic fertiliser treatment yielded the highest net benefit (USD 787 ha^{-1}) while control was the lowest (USD 272 ha^{-1}).

The benefit-cost ration was strongly affected by the labour value for the different technologies. In general, during the three seasons, the BCR for Zai treatments were lower than for conventional planting techniques with the same soil fertility amendments. This could be attributed to the labour invested in the digging of Zai pits. At the same time, *Tithonia diversifolia* treated techniques had also low BCR compared to other soil fertility amendment due to the labour used on cutting and chopping of the biomass. The results of this study are contrary to Achieng et al. (2010) who observed there is near to nil investment cost on the use of *Tithonia diversifolia*. On the contrary, Mutegi et al. (2012) reported that *Tithonia* *diversifolia* alone and cattle manure treatment had the highest benefit-cost ratio, respectively. The results indicate that the yield increase with Zai pits or *Tithonia diversifolia* input is not adequate to payoff for the substantial investment on labour invested in the digging of Zai pits and application of *Tithonia diversifolia*. This contradicts Amede et al. (2011) report that the income earned by farmers from Zai pit application was up to 20-times more than the labour costs needed to prepare them. From the results, it can be observed that feasibility of Zai pits is determined by the amendments applied. However, conventional planting in combination with organic/inorganic amendments is more profitable than Zai pits with similar organics or in inorganic.

5. Conclusion

Application of soil fertility ammendments in zai pits and conventional planting improved stover and grain yields and consequently increased economic viability of sorghum production. Zai pit in combination with *Tithonia diversifolia* amendment had the highest grain yields while conventional planting with no input had the lowest yields. Grain and stover yields were observed to be significantly higher in Zai pits in combination with organic amendments than conventional practice with similar amendments. In all the three seasons the stover and grain yields for both Zai and conventional practices without amendments were not statistically different. In conclusion, Zai pits increase water availability in the root zone while amendments impact on soil fertility hence an increase in yields when combined. Additionally, control of soil erosion and low input application are also regarded as being important factors in adoption of zai pits.

Conventional planting with full rate NPK had the highest BCR while Zai pit without input had the least BCR. Conventional planting without input had a relatively higher BCR but may not be suitable in terms of attainment of food sufficiency due to the low grain yields. Zai pits with other amendments other than *Tithonia diversifolia* had high returns to investment and could, therefore, be more economical to farmers with complimentary labour such as family labour to achieve food sufficiency. Large scale farmers may be disadvantaged in adoption of Zai pits as it is difficult to use animal traction. Nonetheless, the study recommends economic benefit analysis of the technologies that not only takes into consideration the worth of the grain and stovers but also other long term effects of the technologies, such as soil conservation and improvement in soil fertility conditions.

Declarations

Author contribution statement

Serah W. Kimaru-Muchai: Conceived and designed the experiments; Wrote the paper.

Felix K. Ngetich: Performed the experiments.

Monica W. Mucheru- Muna; Mary Baaru: Conceived and designed the experiments.

Funding statement

This work was supported by the National Commission for Science, Technology and Innovation (NACOSTI/RCD/ST&I 5th Call).

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

Achieng, J.O., Ouma, G., Odhiambo, G., Muyekho, F., 2010. Effect of farmyard manure and inorganic fertilizers on maize production on Alfisols and Ultisols in Kakamega, western Kenya. Agric. Biol. J. N. Am. 1 (4), 430–439.

Allen, H.L., Brown, S.L., Chaney, R.L., Daniels, W.L., Henry, C.L., Neuman, D.R., Toffey, W., 2007. The Use of Soil Amendments for Remediation, Revitalization and Reuse. US Environmental Protection Agency, Washington, DC. EPA 542-R-07-013. 350 Bioavailability, Risk Assessment and Remediation.

Amede, T., Tarawali, S., Peden, D., 2011. Zai improves nutrient and water productivity in the Ethiopian highlands. (Special Issue: improving water productivity of crop-livestock systems in drought-prone regions. Exp. Agric. 47 (Suppl. 1), 7–20, 2011.

Araujo, J.A., Abiodun, B.J., Crespo, O., 2016. Impacts of drought on grape yields in Western Cape, South Africa. Theor. Appl. Climatol. 123 (1-2), 117–130.

Baghdadi, A., Halim, R.A., Ghasemzadeh, A., Ramlan, M.F., Sakimin, S.Z., 2018. Impact of organic and inorganic fertilizers on yield and quality of silage corn in intercropped system with soybean. PeerJ. Preprints 6, e26905v1.

Baptista, I., Fleskens, L., Ritsema, C., Querido, A., Tavares, J., Ferreira, A., Varela, A., 2015. Soil and water conservation strategies in Cape Verde (Cabo Verde in Portuguese) and their impacts on livelihoods: an overview from the Ribeira Seca Watershed. Land 4 (1), 22–44.

Barron, J., Rockström, J., Gichuki, F., Hatibu, N., 2003. Dry spell analysis and maize yields for two semi-arid locations in East Africa. Agric. For. Meteorol. 117, 23–37.

Bationo, A., Waswa, B., Kihara, J., Kimetu, J., 2006. Advances in integrated soil fertility management in sub-Saharan Africa: challenges and opportunities. Nutrient Cycl. Agroecosyst. 76.

Biratu, G.K., Elias, E., Ntawuruhunga, P., Sileshi, G.W., 2018. Cassava response to the integrated use of manure and NPK fertilizer in Zambia. Heliyon 4 (8), e00759.

Cai, A., Xu, M., Wang, B., Zhang, W., Liang, G., Hou, E., Luo, Y., 2019. Manure acts as a better fertilizer for increasing crop yields than synthetic fertilizer does by improving soil fertility. Soil Tillage Res. 189, 168–175.

Cellier, A., Gauquelin, T., Baldy, V., Ballini, C., 2014. Effect of organic amendment on soil fertility and plant nutrients in a post-fire Mediterranean ecosystem. Plant Soil 376 (1/2), 211–228.

CIMMYT, 1988. From Agronomic Data to Farmer Recommendation: an Economic Training Manual. CIMMTY, Mexico, p. 78.

Clottey, V., Wairegi, L., Bationo, A., Mando, A., Kanton, R., 2015. Sorghum-and Millet-Legume Cropping Systems. Africa Soil Health Consortium, Nairobi.

Danjuma, M.N., Mohammed, S., 2015. Zai pits system: a catalyst for restoration in the dry lands. J. Agricult. Veterin. Sci. 8, 1–4.

Eckhardt, D.P., Redin, M., Santana, N.A., Conti, L.D., Dominguez, J., Jacques, R.J.S., Antoniolli, Z.I., 2018. Cattle manure bioconversion effect on the availability of nitrogen, phosphorus, and potassium in soil. Rev. Bras. Ciência do Solo 42.

Evans, R.G., Sadler, E.J., 2008. Methods and technologies to improve efficiency of water use. Water Resour. Res. 44 (7).

Fatondji, D., Martius, C., Vlek, P., Bielders, C., Bationo, A., 2011. Effect of zai soil and water conservation technique on water balance and the fate of nitrate from organic amendments applied: a case of degraded crusted soils in Niger. In: Bationo, A., Waswa, B., Okeyo, J., Maina, F., Kihara, J. (Eds.), Innovations as Key to the Green Revolution in Africa. Springer, Dordrecht.

Fatondji, D., Martius, C., Bielders, C., Vlek, P., Bationo, A., Gérard, B., 2006. Effect of planting technique and amendment type on pearl millet yield, nutrient uptake, and water use on degraded land in Niger. Nutrient Cycl. Agroecosyst. 76, 203–217.

Fatondji, D., Martius, C., Bielders, C.L., Koala, S., Vlek, P.L.G., Zougmore, R., 2009. Decomposition of organic amendment and nutrient release under the Zai technique in the Sahel. Nutrient Cycling in Agroecosystems. Nutrient Cycl. Agroecosyst. 85, 225–239.

Froidurot, S., Diedhiou, A., 2017. Characteristics of wet and dry spells in the West African monsoon system. Atmos. Sci. Lett. 18 (3), 125–131.

García, C., Hernández, T., Coll, M.D., Ondoño, S., 2017. Organicamendments for soil restoration in arid and semi-arid areas: a review. AIMS Environmental. Science. 4, 640–676.

Gichangi, E.M., Njiru, E.N., Itabari, J.K., Wambua, J.M., Maina, J.N., Karuku, A., 2007. Assessment of improved soil fertility and water harvesting technologies through community-based on-farm trials in the ASALs of Kenya. In: Batiano, A. (Ed.), Advances in Integrated Soil Fertility Management in Sub-saharan African: Challenges and Opportunities. 2007 Springer, pp. 759–765.

Graham, E., Grandy, S.S., Thelen, M., 2010. Manure Effects on Soil Organic Matter and Soil Quality. Michigan State University Extension. Emerging Issues in Animal Agriculture, Michigan. USA, p. 6.

Guo, S.W., Zhou, Y., Goa, Y.X., Li, Y., Shen, Q.R., 2007. New insights into the nitrogen form effect on photosynthesis and photorespiration. Pedosphere 17, 601–610.

Jabereldar, A.A., El Naim, A.M., Abdalla, A.A., Dagash, Y.M., 2017. Effect of water stress on yield and water use efficiency of sorghum (Sorghum bicolor L. Moench) in semi-arid environment. Int. J. Agric. For. 7 (1), 1–6.

Jaetzold, R., Schmidt, H., Hornet, Z.B., Shisanya, C.A., 2006. Farm management handbook of Kenya. Natural conditions and farm information. In: Eastern Province. Ministry of Agriculture/GTZ, Nairobi, Kenya, second ed., 11/C

Jama, B., Palm, C.A., Buresh, R.J., Niang, A., Gachengo, C., Nziguheba, G., Amadalo, B., 2000. Tithonia diversifolia as a green manure for soil fertility improvement in western Kenya: a review. Agrofor. Syst. 49, 201–221.

Jeannin, M., 2012. Agricultural Innovation in Africa: from Soil Fertility to Market Integration. A Case Study from Benin. Master's thesis. Norwegian University of Life Sciences, Ås.

Kaboré, D., Reij, C., 2004. The emergence and spreading of an improved traditional soil and water conservation practice in Burkina Faso. In: EPTD Discussion Paper No. 114. International Food Policy Research Institute, Washington, DC.

Kathuli, P., Itabari, J.K., 2015. In situ soil moisture conservation: utilization and management of rainwater for crop production. In: Adapting African Agriculture to Climate Change. Springer International Publishing, pp. 127–142.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288.

Kihara, J., Bationo, A., Waswa, B., Okeyo, J., 2009. Tillage, residue management and fertilizer application effects on crop water productivity in western Kenya. In: Humphreys, E., Bayot, R.S. (Eds.), *Increasing The Productivity and Sustainability of Rainfed Cropping Systems of Poor Smallholder Farmers.* Proceedings of the CGIAR Challenge Program on Water and Food International Workshop on Rainfed Cropping Systems, Tamale, Ghana, 22-25 September 2008. The CGIAR Challenge Program on Water and Food, Colombo, Sri Lanka.

Kimetu, J.M., Mugendi, D.N., Palm, C.A., Mutuo, P.K., Gachengo, C.N., Bationo, A., Nandwa, S., Kung'u, J.B., 2004. Nitrogen fertilizer equivalencies of organics of differing quality and optimum combination with inorganic nitrogen source in central Kenya. Nutrient Cycl. Agroecosyst. 68, 127–135.

Kisaka, M.O., Mucheru-Muna, M., Ngetich, F.K., Mugwe, J.N., Mugendi, D., Mairura, F., 2015. Rainfall variability, drought characterization, and efficacy of rainfall data reconstruction: case of Eastern Kenya. Adv. Meteorol. 2015.

Kyei-Mensah, C., Kyerematen, R., Adu-Acheampong, S., 2019. Impact of rainfall variability on crop production within the worobong ecological area of fanteakwa district, Ghana. Adv. Agricult. 2019.

Liverpool-Tasie, L.S.O., Omonona, B.T., Sanou, A., Ogunleye, W.O., 2017. Is increasing inorganic fertilizer use for maize production in SSA a profitable proposition? Evidence from Nigeria. Food Pol. 67, 41–51.

Magombeyi, M.S., Taigbenu, A.E., 2008. Crop yield risk analysis and mitigation of smallholder farmers at quaternary catchment level: case study of B72A in Olifants river basin, South Africa. Phys. Chem. Earth 33, 744–756.

Mango, N., Hebinck, P., 2016. Agroforestry: a second soil fertility paradigm? A case of soil fertility management in Western Kenya. Cogent Social Sciences 2 (1), 1215779.

Mango, N., Makate, C., Tamene, L., Mponela, P., Ndengu, G., 2017. Awareness and adoption of land, soil and water conservation practices in the Chinyanja Triangle, Southern Africa. Int. Soil Water Conserv. Res. 5, 122–129.

Mekuriaw, A., Heinimann, A., Zeleke, G., Hurni, H., 2018. Factors influencing the adoption of physical soil and water conservation practices in the Ethiopian highlands. Int. Soil Water Conserv. Res. 6 (1), 23–30.

Moswetsi, G., Fanadzo, M., Ncube, B., 2017. Cropping systems and agronomic management practices in smallholder farms in South Africa: constraints, challenges and opportunities. J. Agron. 16, 51–64.

Mucheru-Muna, M., Mugendi, D., Kung'u, J., Mugwe, J., Bationo, A., 2007. Effects of organic and mineral fertilizer inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya. Agrofor. Syst. 69 (3), 189–197.

Muhereza, I., Pritchard, D., Murray-Prior, R., 2014. Utilisation of cattle manure and inorganic fertiliser for food production in central Uganda. J. Agricult. Environ. Int. Develop. 108 (2), 135–151.

Muindi, E.M., Semu, E., Mrema, J.P., Mtakwa, P.W., Gachene, C.K., Njogu, M.K., 2016. Soil acidity management by farmers in the Kenya highlands. J. Agricult. Ecol. Res. Int. 5 (3), 1–*11*.

Mulat, D., Fantu, G., Tadele, F., 2004. Agricultural Development in Ethiopia: Are There Alternatives to Food Aid? Department of Economics, Addis Ababa University www.sarpn. org.za/documents/d0001583/FAO2005_Casestudies_Ethiopia.pdf.

Muriu-Ng'ang'a, F.W., Mucheru-Muna, M., Waswa, F., Mairura, F.S., 2017. Socio-economic factors influencing utilisation of rainwater harvesting and saving technologies in Tharaka South, Eastern Kenya. Agric. Water Manag. 194, 150–159.

Mutegi, E.M., Kungu, J.B., Mucheru-Muna, M., Pieter, P., Mugendi, D.N., 2012. Complementary effects of organic and mineral fertilizers on maize production in the smallholder farms of Meru south district, Kenya. Agric. Sci. 3 (2), 221–229.

Mutunga, K., 2001. Water conservation, harvesting and management (WCHM)—Kenyan experience. In: Sustaining the Global Farm. 10th International Soil Conservation Organization Meeting. Purdue University and the USDA-ARS National Soil Erosion Research Laboratory, pp. 1139–1143.

Muyekho, F.N., Cheruiyot, D.T., Kapkusum, G., 2000. Effects of the "Tumbukiza" method of planting Napier grass (*Pennisetum purpureum*) on the quantity and quality of forage on smallholder farms in Kenya. In: Murethi, Gachene, Muyekho, Onyengo, Mose, Magenya (Eds.), Participatory Technology Development for Soil Management by Smallholders in Kenya. Proceedings of the 2nd Scientific Conference of the Soil Management and Legume Research Network Projects June 2000. Mombasa, Kenya, p. 551.

Mwadalu, R., Mwangi, M., 2013. The potential role of sorghum in enhancing food security in semi-arid eastern Kenya: a review. J. Appl. Biosci. 71, 5786–5799.

Ncube, B., Dimes, J.P., van Wijk, M.T., Twomlow, S.J., Giller, K.E., 2009. Productivity and residual benefits of grain legumes to sorghum under semi-arid conditions in south-western Zimbabwe: unravelling the effects of water and nitrogen using a simulation model. Field Crop. Res. 110 (2), 173–184.

Ngetich, F.K., Shisanya, C.A., Mugwe, J., Mucheru-Muna, M., Mugendi, D., 2012. The potential of organic and inorganic nutrient sources in Sub-Saharan African crop farming systems. In: Soil Fertility Improvement and Integrated Nutrient Management-A Global Perspective, pp. 135–156.

Nicol, A., Langan, S., Victor, M., Gonsalves, J. (Eds.), 2015. Water-smart Agriculture in East Africa. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Research Program on Water, Land and Ecosystems (WLE); Kampala, Uganda: Global Water Initiative East Africa (GWI EA).

Novella, N.S., Thiaw, W.M., 2016. A seasonal rainfall performance probability tool for famine early warning systems. J. Appl. Meteorol. Climat. 55 (12), 2575–2586.

Nyamekye, C., Thiel, M., Schönbrodt-Stitt, S., Zoungrana, B., Amekudzi, L., 2018. Soil and water conservation in Burkina Faso, West Africa. Sustainability 10 (9), 3182.

Onduru, D.D., Snijders, P., Muchena, F.N., Wouters, B., DeJager, A., Gachimbi, L., Gachini, G.N., 2008. Manure and soil fertility management in sub-humid and semi-arid farming systems of sub-saharan Africa: experiences from Kenya. Int. J. Agric. Res. 3 (3), 166–187.

Opala, P.A., Kisinyo, P.O., Nyambati, R.O., 2015. Effects of Tithonia diversifolia, farmyard manure and urea, and phosphate fertiliser application methods on maize yields in western Kenya. J. Agric. Rural Dev. Tropics Subtropics 116 (1), 1–9.

Ouattara, K., Serme, I., Bongoungou, S., Zombre, P., 2017. Soil and water conservation, and soil fertility management effects on rain water productivity of maize hybrid in Burkina Faso. Afr. J. Agric. Res. 12 (12), 1014–1021.

Prasad, P.V.V., Djanaguiraman, M., Perumal, R., Ciampitti, I.A., 2015. Impact of high temperature stress on floret fertility and individual grain weight of grain sorghum: sensitive stages and thresholds for temperature and duration. Front. Plant Sci. 6, 820.

Rao, K.P.C., Ndegwa, W.G., Kizito, K., Oyoo, A., 2011. Climate variability and change: farmer perceptions and understanding of intra-seasonal variability in rainfall and associated risk in semi-arid Kenya. Exp. Agric. 2 (47), 267–291.

SAS Institute, 2004. SAS State User's Guide. Version 9.1. SAS Institute, Cary, NC.

Smucker, T., Wisner, B., 2008. Changing household responses to drought in Tharaka, Kenya: persistence, change, and challenge. Disasters 32 (2), 90–215.

Timsina, J., 2018. Can organic sources of nutrients increase crop yields to meet global food demand? Agronomy 8 (10), 214.

Tolera, A., Tufa, T., Midega, T., Kumbi, H., Tola, B., 2018. Effect of integrated inorganic andOrganic fertilizers onYield and yield components of barley in Liben Jawi district. Int. J. Agron. 2018 (7).

Umesh, A., Nejadhashemi, A.P., Woznicki, S.A., 2015. Climate change and eastern Africa: a review of impact on major crops. Food Energy. *Security*. 4 (2), 110–132.

Van Beek, C., Herold, N., Kessler, A., Vonk, R., 2017. The quest for improving soil fertility: why an integrated approach is needed. SAGE 46, 289–294.

Vohland, K., Barry, B., 2009. A review of in situ rainwater harvesting (RWH) practices modifying landscape functions in African drylands. Agric. Ecosyst. Environ. 131 (3-4), 119–127.

Wall, P., Thierfelder, C., 2009. Some experiences with conservation agriculture in southern Africa. In: Humphreys, E., Bayot, R.S. (Eds.), *Increasing The Productivity and Sustainability of Rainfed Cropping Systems of Poor Smallholder Farmers.* Proceedings of theCGIAR Challenge Program on Water and Food International Workshop on RainfedCropping Systems, Tamale, Ghana, 22-25 September 2008.