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

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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 amendments. 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 rainwater 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
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 whereas 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 Illsela 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, Volland 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 typhoides), 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 x 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 by 0.2 m, 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.

Cutting and transportation of Tithonia diversifolia, application of the fertilizers, 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).

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):

\[ GM = TR - TVC \]

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\(^{-1}\)).

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, 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).

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

\[ BCR = TR/TVC \]

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 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 |
| Potassium | 1.9      | 0.04 | 2.9      | 0.13 |
| Magnesium | 0.4      | 0.05 | 0.7      | 0.21 |
| Phosphorus | 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 |

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 35th 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 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.

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 US$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%, 25.3% and 17.1%, respectively, higher than Zai pit without inputs (Table 5).

**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<sup>a</sup> | 0.21<sup>b</sup> | 3.78<sup>b</sup> | 9.57<sup>b</sup> | 1.73<sup>b</sup> | 11.30<sup>b</sup> |
| ZC        | 4.23<sup>ab</sup> | 0.34<sup>a</sup> | 4.18<sup>b</sup> | 8.15<sup>b</sup> | 1.96<sup>a</sup> | 8.89<sup>b</sup> |
| ZT30      | 3.96<sup>ab</sup> | 0.25<sup>b</sup> | 3.30<sup>c</sup> | 12.53<sup>a</sup> | 1.79<sup>b</sup> | 12.53<sup>a</sup> |
| ZC30      | 3.92<sup>ab</sup> | 0.19<sup>b</sup> | 3.57<sup>b</sup> | 8.02<sup>b</sup> | 1.94<sup>a</sup> | 9.26<sup>b</sup> |
| ZF60      | 3.48<sup>ab</sup> | 0.18<sup>b</sup> | 4.17<sup>b</sup> | 9.01<sup>b</sup> | 1.30<sup>ab</sup> | 9.01<sup>b</sup> |
| ZNO       | 1.96<sup>c</sup> | 0.03<sup>d</sup> | 1.00<sup>c</sup> | 4.75<sup>c</sup> | 0.21<sup>d</sup> | 4.75<sup>c</sup> |
| CT        | 3.75<sup>b</sup> | 0.24<sup>b</sup> | 3.76<sup>b</sup> | 9.53<sup>b</sup> | 1.66<sup>c</sup> | 6.11<sup>c</sup> |
| CCM       | 3.71<sup>b</sup> | 0.18<sup>b</sup> | 2.72<sup>b</sup> | 7.78<sup>b</sup> | 1.67<sup>ab</sup> | 8.33<sup>b</sup> |
| CT30      | 3.79<sup>b</sup> | 0.24<sup>b</sup> | 3.11<sup>b</sup> | 8.70<sup>b</sup> | 1.63<sup>b</sup> | 8.64<sup>b</sup> |
| CC30      | 3.71<sup>b</sup> | 0.18<sup>b</sup> | 3.57<sup>b</sup> | 7.84<sup>b</sup> | 1.4<sup>c</sup> | 8.46<sup>b</sup> |
| CF60      | 3.32<sup>ab</sup> | 0.14<sup>b</sup> | 3.82<sup>b</sup> | 8.09<sup>b</sup> | 1.11<sup>c</sup> | 8.09<sup>b</sup> |
| ZNO       | 1.76<sup>c</sup> | 0.03<sup>d</sup> | 0.79<sup>c</sup> | 4.63<sup>c</sup> | 0.19<sup>d</sup> | 4.62<sup>c</sup> |
| F value    | 6.51 | 11.23 | 12.90 | 6.68 | 10.26 | 14.47 |
| p         | 0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |

Same superscript letters in along the column denote no significant difference between treatments at \( p = 0.05 \).

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.**
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.

| Treatment   | Labour Cost(US$) | Total Cost(US$) | Total Benefit(US$) | Net Benefit(US$) | BCR |
|-------------|------------------|-----------------|-------------------|-----------------|-----|
| ZC          | 1058.75          | 1296.37         | 2743.49           | 1447.11         | 2.12|
| ZC30        | 1029.43          | 1253.39         | 2444.17           | 1190.78         | 1.62|
| ZCT         | 1877.62          | 2142.23         | 2321.38           | 221.20          | 1.01|
| ZF60        | 958.89           | 1169.19         | 2511.27           | 1342.08         | 2.15|
| ZNO         | 909.28           | 998.39          | 983.94            | -14.44          | 0.99|
| ZT          | 2561.43          | 2650.54         | 2680.49           | 29.95           | 1.01|
| ZT30        | 1781.22          | 1930.93         | 2558.05           | 627.12          | 1.32|
| LSD         | 37.098           | 37.098          | 468.62            | 450             | 0.4096|

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

**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.

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% lower than for conventional planting with 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 conventional planting with no input. Total benefits were highest in Zai pits combined with cattle manure treatment but lowest in conventional 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 (Ararui 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; Jabareldar 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 Mutal 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 Thiaiw (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 Taigebu (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 amendments significantly ($p < 0.05$) increased sorghum grain yields by ten times more than conventional treatments with no amendments (Kathuli and Itabali, 2015).

Fatondji et al. (2011) observed that Zai pit with cattle manure and Zai pit 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}$. This implied that the total cost for the treatment of Zai without inputs was higher than the benefits.
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 fertilizer with tied ridges in Mozambique (Walling 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 (Onyidi 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 fertilizers 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 addition 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 fertilizers released their nutrient rather fast for the plants to utilize (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 crops by application of inorganic fertilisers and other soil 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 treatment 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 sources. 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 fertilizer treatment yielded the highest net benefit (USD 787 ha⁻¹) while control was the lowest (USD 272 ha⁻¹).

The benefit-cost ratio was strongly affected by the labour value for the different technologies. Generally 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, Mutebi 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 pay off for the substantial investment on labour work 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 amendments 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.

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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.

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