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Utilisation of *Zai* pits and soil fertility management options for improved crop production in the dry ecosystem of Kitui, Eastern Kenya

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This study sought to address challenges faced by smallholder farmers in the drylands of Eastern Kenya including soil fertility decline and low profitability resulting from poor soil and water conservation measures. An experiment was set up at Kabati, Kitui County, Kenya in the year 2018/2019 seasons to evaluate the effects of the interaction of *zai* pits, cattle manure and fertilizer inputs on soil nutrients, sorghum yield and economic returns over two seasons. The field trials were set up in a randomized complete block design (RCBD). Eight treatments were replicated thrice with sorghum *gadam* variety as the test crop. The results indicated that total nitrogen significantly (p<0.05) reduced at the end of the two cropping seasons. Organic carbon significantly (p<0.05) reduced in conventional method without input, *zai* with fertilizer and *zai* with manure and fertilizer treatments. Soil electrical conductivity significantly (p<0.05) increased in *zai* with fertilizer, *zai* with manure and *zai* with manure and fertilizer treatments. Available phosphorous significantly (p<0.05) increased in conventional with manure, *zai* with fertilizer and *zai* with manure. Sorghum grain yields were significantly (p<05) higher in all *zai* treatments with fertility inputs compared to their conventional counterparts during the SR2018 season. During the SR2018 season, return to labour was significantly higher (p=0.0269, p=0.0252, p=0.0379, respectively) in *zai* treatments with fertility inputs compared to their conventional counterparts. The findings of this research study highlight the importance of using *zai* pits and the use of manure with mineral fertilizer supplements to improve soil fertility, enhancing crop yields and profitability.

Key words: *Zai,* soil fertility, soil chemical properties, integrated soil fertility management, cost-benefit analysis.

INTRODUCTION

The world is currently facing food insecurity resulting from soil fertility decline, water scarcity and frequent prolonged

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drought (Leonard et al., 2010; Ali and Erenstein, 2017; Ouda and Zohry, 2020). The drought events are often associated with climate variability negatively affecting crop production in the arid and semi-arid lands (Tumushabe, 2018). The arid and semi-arid lands (ASALs) are characterized with low and poorly distributed rainfall within the growing period, degraded soils that are crusted and low in nutrients negatively affecting crop production (Zougmoré et al., 2014). The drylands of Eastern Kenya generally record low crop yields resulting from poor degraded soils and water scarcity due to low and unreliable rainfall (Joshi et al., 2009; Mganga et al., 2015). The small holder farmers in the Eastern Kenya region generally depend on rainfall for crop production which is a limiting factor during the growing season threatening their livelihood (Kiboi et al., 2017; Ogada et al., 2020). As a result of high dependence on rain-fed agriculture by the farmers, this subjects them to vulnerable climate change impacts (Adimassu and Kessler, 2016; Kogo et al., 2021).

Soil fertility and water scarcity problem has driven more innovative approaches in agriculture to strengthen subsistence and food security especially among agricultural small holder farmers through adoption of the suitable technologies (Nyang'au et al., 2021). To curb the problem of water scarcity and low crop yields, soil and water conservation strategies, irrigation, planting trees and improved crop seeds have been used as remedies of climate change (Gebru et al., 2020; Wawire et al., 2021). The small holder farmers in the drylands of Kenya have used various strategies to improve soil fertility, soil water availability and overall crop yield hence improving the economic returns (Mati, 2006; Kimaru-Muchai et al., 2020). This involves the use of soil and water conservation practices to improve livelihood and reduce vulnerability to drought (Sawadogo, 2011; Funk et al., 2020). Water harvesting technologies such as pitting is a form of water conservation strategy used to improve water supply for agricultural use and reduce vulnerability in an event of prolonged drought (Liang and Van Dijk, 2011; Patle et al., 2020). Pitting increases the moisture content in the soil and restores productivity in areas where rainfall is insufficient (Biazin et al., 2012; Kimaru-Muchai et al., 2020; Ndeke et al., 2021).

Zai pit a form of soil and water conservation technique harvests rainwater in small pits with manure buried in the pits to improve soil fertility as well as conserve soil moisture (Danjuma and Mohammed, 2015; Danso-Abbeam et al., 2020). The pits are best suited in areas that have low annual rainfall ranging from 300 to 800 mm (Motis and Lingbeek, 2013; Mwangi, 2020). In Africa, the *zai* pit system has been used in Mali, Niger and Burkina Faso with studies indicating that they improve soil fertility over time (Zougmoré et al., 2003; Danso-Abbeam et al., 2020). In Kenya, the most common type is the "five by nine" pit system with the *zai* pit system being promoted in the arid and semi-arid lands (ASALs) (Mati, 2006). The *zai* pit system has been practiced in Eastern Kenya which has been proved successful (Kathuli and Itabari, 2014; Kimaru-Muchai et al., 2020).

Declining soil fertility also remains a major biophysical challenge in crop production among the smallholder farmers in the drylands of Eastern Kenya. This is a result of high rates of soil erosion, continuous cultivation without adequate addition of fertility inputs and the removal of crop residues from the field (Njeru et al., 2011; Aniah et al., 2019; Sarkar et al., 2020). Integrated soil fertility management (ISFM) technologies are used to enhance agricultural productivity through maximizing and efficient use of the applied nutrients (Vanlauwe et al., 2010; Bayu, 2020). The ISFM technologies include; use of organic matter, inorganic fertilizers, use of improved germplasm and adaptation to the local conditions to improve the soil properties and the overall crop yield (Ejigu et al., 2021; Mucheru-Muna et al., 2021). The small holder farmers in the drylands of Kenya commonly use crop residues, mineral fertilizers, farmyard manure and composts for short-term supply of nutrients with most farmers believing that the use of inorganic fertilizers is the quickest and surest method to supply nutrients (Mucheru-Muna et al., 2021).

Challenges facing small holder farmers arid and semi-arid lands (ASALs) of Kenya include soil fertility decline, water scarcity, low crop yields and low economic returns. To address the challenges, a trial was set up in Kabati, Kitui County with the aim of assessing the effects of *zai* pits combined with ISFM technologies on soil nutrients, sorghum yields and the economic feasibility of using *zai* pits combined with integrated soil fertility management technologies on sorghum production within the study area.

MATERIALS AND METHODS

Description of the study area

The experiment was conducted in Kabati, Kitui County Kenya (1°14'13.0"S 37°54'52.2"E) (Figure 1). The area experiences unreliable rainfall ranging from 250 to 1050 mm per annum. The rainfall pattern is bimodal with the short rains (SR) occurring between October and December and the long rains (LR) being experienced between March and May. The rest of the year is dry. The hot months are July-September and January-February with high temperatures ranging between 14 and 34°C.

The topography of the area is described as hilly rugged uplands and lowlands. The general landscape of the area is flat with plains gently rolling down towards the east where the altitudes are as low as 400 m above sea level.

The soils found at Kabati are lixisols consisting of strongly weathered, leached and finely textured materials with high base saturation (Nezomba, 2016). As described by IUSS WG WRB (2015), a publicly available 30-m Soil Information System of Africa, lixisols are classified as oxic subgroups of Alfisols with principal qualifiers including, gleyic, stagnic, ferralic, nudiargic, lamellic, albic, ferric, rhodic/chromic, xanthic, gypsic, calcic, fractic, skeletic and haplic. The supplementary qualifiers include abruptic, albic, ferric, geric, humic, hyperochric, lamellic, profondic, and stagnic. The soils

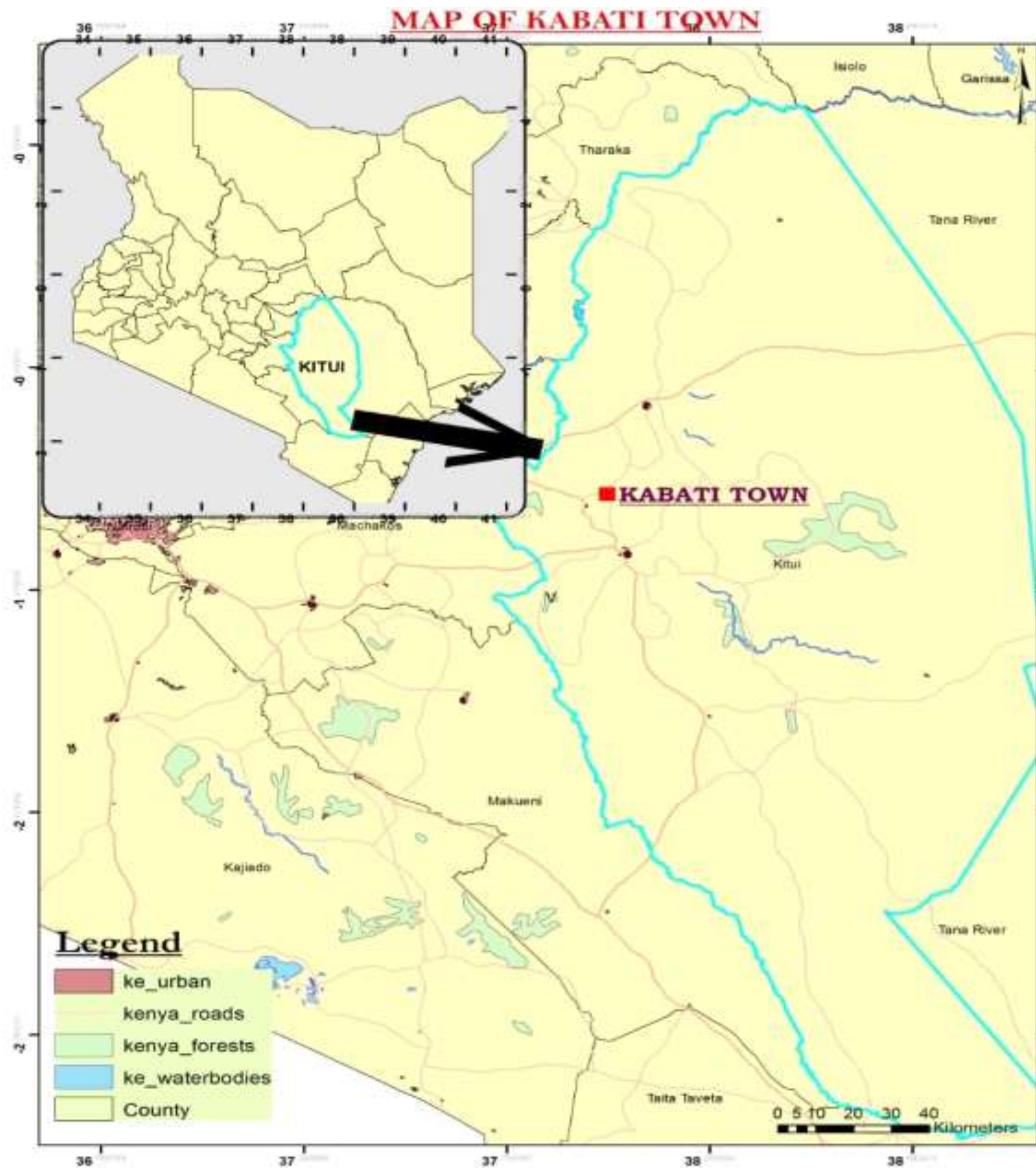

Figure 1. Map of the study area.
Source: Arch GIS (2020).

are formed due to chemical weathering and are found in subtropical to warm climate with a pronounced dry season. They are thin and brown with low levels of available nutrients and low organic carbon levels. The surface soils have low aggregate stability prone to erosion and slaking when exposed to raindrops. Tillage and erosion measures to control erosion include mulching, use of cover crops and terracing to conserve them.

Kabati is in the upper midland 3-4 (semi-arid farming zone) with various natural resources including forests, rivers, hills and wildlife. The semi-arid zone has good agricultural potential used for agricultural production but frequent crop failures are recorded. The main socio-economic practices in the area include crop, livestock production, fish production and tourism. The main food crops grown in the area include legumes such as green grams (*Vigna radiata*), cowpeas (*Vigna unguiculata*), pigeon peas (*Cajanus cajan*) and beans (*Phaseolus vulgaris*). Cereals include maize (*Zea mays*), sorghum (*Sorghum bicolor*) and millet (*Pennisetum glaucum*) with tuber crops being cassava (*Manihot esculenta*) and sweet potatoes (*Ipomoea batatas*). Fruits include avocado (*Persea americana*), watermelon (*Citrullus lanatus*), pawpaw (*Carica papaya*) and mangoes (*Mangifera indica*).

Rainfall trend over the experimental period

The two growing seasons (SR2018 and LR2019) received varying amounts of rainfall with the total seasonal amount of rainfall recorded being 382.3 and 116.3 mm, respectively (Figure 2).

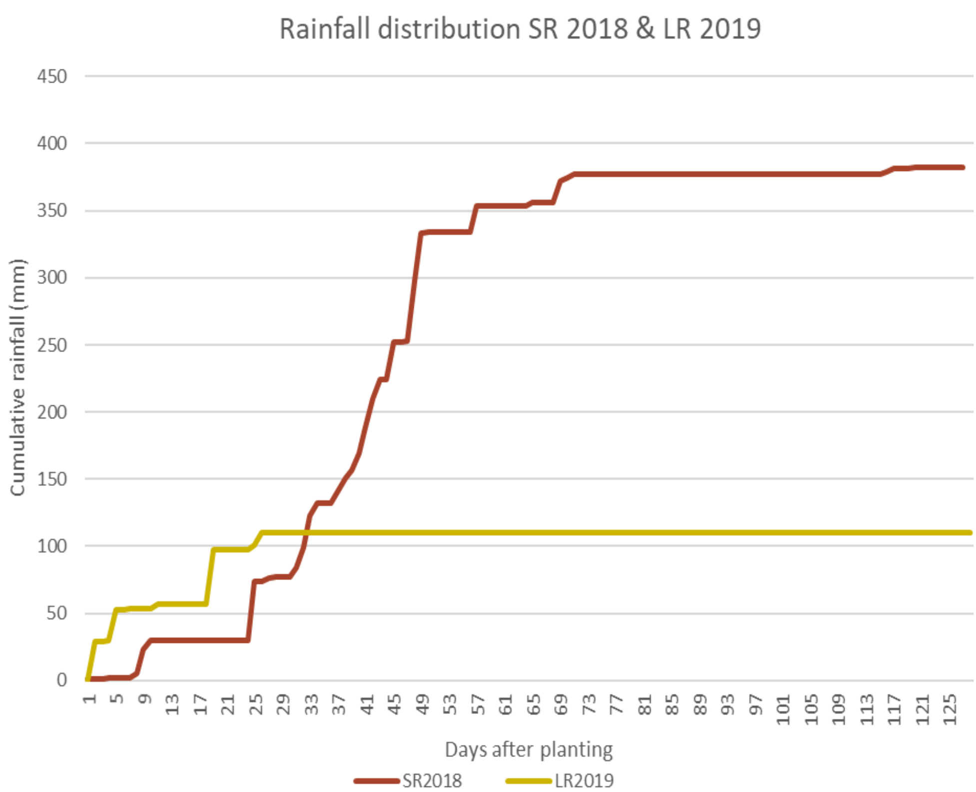

Figure 2. Rainfall distribution during the SR2018 and LR2109 seasons at Kabati, Kitui County, Kenya.
Source: KMD (2020).

Table 1. Treatment combinations of the experiment at Kabati, Kitui County, Kenya.

Treatments	N from manure (kg ha^{-1})	N and P from Inorganic fertilizer (kg ha^{-1})
Zai pits + Manure	60	0
Zai pits + Inorganic fertilizer	0	60 N and 60 P
Zai pits+ Manure+ Inorganic fertilizer	30	30 N and 30 P
Zai pits +No inputs	0	0
Conventional + Manure	60	0
Conventional +inorganic fertilizer	0	60 N and 60 P
Conventional+Manure +inorganic fertilizer	30	30 N and 30 P
Conventional + No inputs	0	0

SR2018 season (October-December, 2018) received more rainfall compared to LR2019 (March-May, 2019) which experienced less rainfall. The rains in the SR2018 growing season were uniformly distributed with the LR2019 experiencing rain in only 10 days of the growing period with the rest of the season being dry.

Experimental layout and management

The experiment was laid out as a randomized complete block design (RCBD) with eight (8) treatments replicated thrice (Table 1). The plot size measured 6 by 4.5 m, a spacing of 1 m between the plots and 1 m for the guard zone. The *zai* pits were made by digging out the topsoil to make 60 cm wide, 60 cm long and a depth of 30 cm (Danso-Abbeam et al., 2020). The topsoil was then refilled to a level of 15 cm before the fertility amendments were added. Sorghum gadam variety a drought-tolerant crop was planted at a spacing of 75 and 20 cm inter and intra-row, respectively and two sorghum plants were planted per hill. Weeding was done twice during the planting period by use of a hand hoe. No diseases were observed on the sorghum during the experimental period. Six out of the eight treatments, had three external fertility amendments inputs in both *zai* and conventional planting (1) Cattle manure (60 kg N ha^{-1}), (2) Cattle manure (30 kg N ha^{-1}) + 30 kg N ha^{-1} / 30 kg P ha^{-1}, and (3) 60 kg N ha^{-1} / 60 kg P ha^{-1} were applied at the beginning of every season to give an equivalent of 60 kg N ha^{-1} and 60 kg P ha^{-1} the KARLO recommended rate of N and P for sorghum totalling to six treatments (Karanja et al., 2014). The seventh and eight

Table 2. Initial soil characteristics of Kabati, Kitui County, Kenya.

Parameter	Min	Max	Mean
Sand (%)	52	70	61
Silt (%)	5	11	8
Clay (%)	23	37	30
Bulk density (g/cm^3)	1.15	1.29	1.22
Soil aggregate stability (MWD) mm	1.20	2.42	1.81
TN (%)	0.31	0.46	0.39
EC (S)_dS/m	183.8	249.8	216.8
pH (H_2O)	5.40	5.59	5.50
OC (%)	1.07	1.45	1.26
Phosphorous (mg kg^{-1})	6.37	12.75	9.56

Min=Minimum values of each parameter, Max=Maximum value of each parameter, Mean=Average of each parameter.

treatments were absolute control in both conventional and *zai* planting where no external fertility inputs were applied (Table 1).

Data collection

Soil sampling and laboratory analysis

Soil sampling was done before setting up the experiments at the field in the SR2018 season and at the end of the LR2019 season in all the plots at a depth of 0 to 15 cm by use of a soil auger. The soil samples were collected from five different spots within the plot then bulked to one sample which was then analysed for total nitrogen (TN), soil pH, phosphorus, electrical conductivity, and organic carbon.

Soil laboratory analysis

Soil chemical properties

The soil samples from the field were delivered to the laboratory, air-dried and ground to pass through a 2 mm sieve. All the laboratory analyses on the chemical properties of the soil were performed using the standard methods for analysing soils as described by Motsara and Roy (2008). Total nitrogen was analysed using the Kjeldahl method as described by Bremner (1960), available phosphorus (P) was measured using the Brays method, potassium (K) was estimated with a flame photometer, soil pH was measured by an electronic pH meter, the electric conductivity of the soil was measured by electric conductivity meter, and organic carbon (OC) was measured by the ignition method (Motsara and Roy, 2008).

Soil physical properties

Soil aggregate stability (dry sieving) was determined as described by Ekwuea et al. (2018), soil particle size was determined using the hydrometer method and soil bulk density was determined by core sampling method described by Motsara and Roy (2008). Table 2 shows the averages for the initial soil chemical and physical properties at Kabati, Kitui County.

Sorghum yields

Sorghum heads were harvested at maturity from the net area of each plot and weighed. The sorghum heads were then sundried, threshed and the dry weight recorded as well. Grain moisture was determined using a moisture meter and the grain weight was adjusted to 12.5% moisture content after sun drying.

Rainfall measurement

Rainfall data was collected using a simple rain gauge calibrated in millimetres. Daily rainfall was measured and recorded with monitoring visits done to ensure the accuracy of the rainfall.

Economic analysis

To evaluate the economic returns of using *zai* pits and integrated soil fertility management (ISFM) technologies on sorghum production, partial budgeting was used to compare the costs and financial benefits of each treatment. The benefits and costs with each treatment were evaluated using the different ISFM technologies with *zai* pits. The costs included fertility-enhancing inputs (manure and inorganic fertilizer), pitting and labour with benefits being increased sorghum yield. The inputs and outputs prices derived from the prevailing market prices in the area and values used in economic analysis are shown in Table 3.

Detailed data on the labour requirements were collected in the two seasons for all the various field operations (land preparation, manure and fertilizer application, weeding, harvesting and pitting) and time taken for each activity was recorded using a stopwatch. Labour was valued at the local wage rate (USD man day^{-1}; USD 3.532) per working day (8 h). Net benefit, return to labour and benefit-cost ratio were used as the economic tools in assessing profitability. The net benefit, return to labour and benefit-cost ratio were calculated using the following formulas:

Net benefits=Total benefits-Total costs
Return to labour=Net benefits/Labour costs
Benefit cost ratio=Net benefits/Total Cost

Data analysis

Data on sorghum yield, soil chemical properties and economic return were subjected to analysis of variance (ANOVA) using the proc procedure in SAS 9.2 software and means separated using standard error of differences (SED) at $p<0.05$. To compare the effects of each treatment on sorghum yield, conversion of relative increases compared to the control were done. Changes in yield were compared between the two seasons using t-test. Comparisons on soil nutrients from soil samples collected at the beginning and

Table 3. Parameters used in cost-benefit analysis.

Parameter	Cost (US Dollars)
Cost of NPK (per kg)	0.67
Labour cost (man/day ha^{-1})	3.532
Cost packet of sorghum seeds (2 kg)	3.36
Price of sorghum grains (per kg)	0.76
Cost of cattle Manure (tonnes)	5.775

"Official exchange rate (September 2019)"; 1USD=Ksh.103.9.

the end of the experiments were analysed using t-test.

RESULTS

Interaction effects of pits, cattle manure and mineral fertilizers on selected soil chemical properties

The treatments significantly (*p*=0.0214) reduced total nitrogen at the end of the experiment with electrical conductivity and available phosphorous increasing significantly (*p*=0.0097, *p*=0.0005, respectively) over the same period. Under the *zai* tillage system nitrogen content reduced significantly (*p*=0.0390, *p*=0.0310, *p*=0.0005, respectively) in *zai* pit with manure and half rate mineral fertilizer, *zai* with sole manure and *zai* without input treatments (Table 4). Under the conventional tillage system nitrogen content decreased significantly (*p*=0.0212, *p*=0.0198, *p*=0.0007, respectively) in conventional with manure and fertilizer, conventional with sole manure and conventional with mineral fertilizer treatments. *Zai* with fertilizer had the highest percentage reduction (-65.22%) and conventional with manure recording the lowest percentage reduction (-38.71%).

Under the conventional tillage system, electrical conductivity significantly (*p*=0.0037, *p*=0.0415, *p*=0.0180, respectively) increased in conventional with fertilizer, conventional with manure and fertilizer and conventional without input. Under the zai tillage system, electrical conductivity significantly (*p*=0.0010, *p*=0.0175, *p*=0067, respectively) increased in *zai* with fertilizer, *zai* with sole manure and *zai* with manure and mineral fertilizer (Table 4). Soil organic carbon (SOC) significantly (*p*=0.0015, *p*=0.0109, *p*=0.0146, respectively) reduced in conventional without inputs, *zai* with manure and mineral fertilizer and *zai* with mineral fertilizer treatments. Available phosphorous significantly (*p*=0.0258, *p*=0.0114, *p*=0.0266, respectively) increased in z*ai* planting with sole manure, *zai* planting with full-rate fertilizer and conventional planting with sole manure treatments (Table 4).

Zai pits, cattle manure and mineral fertilizers interaction effects on sorghum yields

Variation of grain and stover yields due to seasons, tillage systems (*zai* and conventional) and the different fertility inputs were observed over the study period. During the SR2018 season, sorghum grain and stover yields were significantly (*p*<0.0001, *p*=0.0005, respectively) influenced by *zai* pits and ISFM technologies (Table 5). During the LR2019 season the stover yields were significantly (*p*=0.0007) influenced by *zai* pits and ISFM technologies.

The highest grain and stover yields (4.37 and 12.71 t ha^{-1}), respectively were recorded during the short rains (SR2018) season while the lowest grain (0.06 t ha^{-1}) and stover (1.29 t ha^{-1}) yields were recorded during the long rains (LR2019) season (Table 5). The average grain and stover yields were higher under *zai* planting compared to conventional planting in both the SR2018 and LR2019 seasons. During the SR2018 season, grain yield was highest in *zai* planting with manure and fertilizer (4.37 t ha^{-1}) and lowest in conventional without inputs (2.06 t ha^{-1}) treatments. During the LR2019, the highest grain yield (Table 5) was recorded in *zai* planting with fertilizer (0.28 t ha^{-1}) and the lowest grain yield recorded in conventional with manure and mineral fertilizer treatment (0.06 t ha^{-1}).

During the SR2018 season, significant higher grain yields were recorded in *zai* with mineral fertilizer, *zai* planting with sole manure and *zai* with manure and fertilizer (*p*=0.0027, *p*=0.0036, *p*=0.0116, respectively) compared to conventional with fertilizer, conventional with sole manure and conventional with manure and mineral fertilizer. During the same season, stover yields were significantly higher (*p*=0.0009) in *zai* planting with manure and mineral fertilizer as compared to conventional planting with manure and mineral fertilizer. During the LR2019 season, significantly higher stover yields (*p*=0.0498, *p*=0.0390, respectively) were recorded in *zai* planting with mineral fertilizer and *zai* with sole manure as compared to conventional with mineral fertilizer and conventional with sole manure (Table 5).

Economic returns

During the SR2018 the highest net benefit was recorded in *zai* planting with manure and mineral fertilizer (2690.51 USD ha^{-1}) and the lowest recorded in *zai* planting without input (1228.99 USD ha^{-1}) in the same season (Figure 2). In the LR2019 season the net benefits recorded a negative change (Table 6) with the highest net benefit

Table 4. Soil chemical properties (0-15 cm) at the beginning of SR2018 and end of LR2019 seasons at Kabati, Kitui County, Kenya.

Soil Parameter	**Total Nitrogen (%)**			**Soil pH (H_2O)**			**Electrical conductivity (dS/m)**			**Organic Carbon (%)**			**Available Phosphorous (ppm)**		
Treatments	**Beg**	**End**	**t-test *p***	**Beg**	**End**	**t-test *p***	**Beg**	**End**	**t-test *p***	**Beg**	**End**	**t-test *p***	**Beg**	**End**	**t-test, *p***
CF60	0.40^{a}	0.15^{a}	0.0007	5.43^{a}	5.40^{a}	0.7607	192.3^{a}	288.3^{a}	0.0037	1.28^{a}	1.17^{a}	0.0596	6.37^{a}	18.68^{a}	0.1508
CM60	0.31^{a}	0.19^{bc}	0.0198	5.58^{a}	5.76^{a}	0.1836	194.1^{a}	311.1^{a}	0.2710	1.35^{a}	0.82^{a}	0.2602	7.11^{a}	21.03^{ad}	0.0266
CMF30	0.38^{a}	0.21^{b}	0.0212	5.53^{a}	5.63^{a}	0.5950	234.8^{a}	384.3^{b}	0.0415	1.44^{a}	0.59^{a}	0.0631	15.30^{a}	37.70^{bd}	0.0773
CNO	0.31^{a}	0.16^{a}	0.0737	5.44^{a}	5.50^{a}	0.7098	183.8^{a}	289.5^{a}	0.0180	1.07^{a}	0.32^{a}	0.0015	8.83^{a}	20.02^{a}	0.1142
ZF60	0.46^{a}	0.16^{a}	0.1196	5.49^{a}	5.48^{a}	0.9018	210.7^{a}	352.4^{b}	0.0010	1.37^{a}	0.87^{a}	0.0146	10.20^{a}	61.30^{c}	0.0114
ZM60	0.38^{a}	0.18^{ab}	0.0390	5.59^{a}	5.87^{a}	0.0909	209.9^{a}	342.4^{b}	0.0175	1.45^{a}	0.51^{a}	0.1055	11.02^{a}	26.62^{abd}	0.0258
ZMF30	0.39^{a}	0.19^{ac}	0.0310	5.59^{a}	5.66^{a}	0.5648	200.2^{a}	318.3^{a}	0.0067	1.36^{a}	0.58^{a}	0.0109	8.46^{a}	37.47d	0.0632
ZNO	0.37^{a}	0.19^{bc}	0.0005	5.40^{a}	5.36^{a}	0.4557	249.8^{a}	303.3^{a}	0.2257	1.33^{a}	0.43^{a}	0.1047	12.75^{a}	14.54^{ad}	0.1387
SED	0.0483	0.0112		0.1071	0.1313		18.4474	16.658		0.1729	0.1897		2.0173	5.6397	
***P* value**	0.4011	0.0214		0.812	0.1511		0.2677	0.0097		0.8296	0.0974		0.0971	0.0005	

CMF30=Conventional + Cattle Manure+30 kg N ha^{-1}, CNO= Conventional with no inputs, CM60=Conventional+Manure, CF60=Conventional+ 60 kg N ha^{-1}, ZNO=*zai* with no inputs, ZMF30=*zai*+ Cattle manure+ 30 kg N ha^{-1}, ZM60=*zai* + Manure, ZF60=*zai*+ 60 kg N ha^{-1}. Means followed by a different letter are not significantly different p<0.05, Standard Error of Difference (SED).

Table 5. Sorghum grain and stover yield during the SR2018 and LR2019 seasons at Kabati, Kitui County, Kenya.

Treatment	**Grain yield (t ha^{-1})**		**Stover yield (t ha^{-1})**	
	SR2018	**LR2019**	**SR2018**	**LR2019**
Conventional + Fertilizer	2.54^{b}	0.24^{a}	6.35^{c}	2.18^{bcd}
Conventional + Manure	2.88^{b}	0.10^{a}	7.34^{c}	1.49^{cd}
Conventional + Manure + Fertilizer	3.13^{b}	0.06^{a}	5.95^{c}	1.85^{cd}
Conventional + No inputs	2.06^{b}	0.11^{a}	6.75^{c}	1.29^{d}
Zai +Fertilizer	4.38^{a}	0.28^{a}	7.81^{bc}	3.62^{a}
Zai +Manure	3.86^{a}	0.18^{a}	10.37^{ab}	2.98^{ab}
Zai + Manure + Fertilizer	4.37^{a}	0.20^{a}	12.71^{a}	2.33^{bc}
Zai +No inputs	3.06^{b}	0.14^{a}	6.74^{c}	1.97^{cd}
***P* value**	<.0001	0.1209	0.0005	0.0007
SED $_{(0.05)}$	0.2908	0.0547	0.8613	0.2926

Means followed by a different letter are not significantly different p<0.05; Standard Error of Difference (SED).

recorded in *zai* with fertilizer (27.11 USD ha^{-1}) and the lowest recorded in conventional with manure and fertilizer (-199.71 USD ha^{-1}). During the SR2018 season, the highest return to labour was recorded in *zai* with sole manure treatment (22.60 USD ha^{-1}) and the lowest recorded in conventional with fertilizer treatment (7.41 USD ha^{-1}). In the LR2019 season the highest return to labour was recorded in *zai* with fertilizer treatment (0.19 USD ha^{-1}) and the lowest in conventional with manure and fertilizer (-0.96 USD ha^{-1}). BCR was highest in *zai* with sole manure (17.09 USD ha^{-1}) and lowest

Table 6. Economic returns (USD) of the different treatments during the SR2018 and LR2019 seasons.

Treatment	Labour cost SR2018	Labour cost LR2019	Total cost SR2018	Total cost LR2019	Total benefit SR2018	Total benefit LR2019	Net benefit SR2018	Net benefit LR2019	Return to labour SR2018	Return to labour LR2019	BCR SR2018	BCR LR2019
CF60	225.09[c]	225.09[a]	258.58[d]	258.58[a]	1930.16[b]	182.16[a]	1671.58[bc]	-76.42[ab]	7.41[d]	-0.34[ab]	6.44[d]	-0.31[a]
CM60	141.13[e]	141.12[c]	168.85[f]	168.83[de]	2163.70[b]	71.28[a]	1994.85[abc]	-97.54[ab]	14.13[bcd]	-0.69[b]	11.81[abc]	-0.58[a]
CMF30	207.56[d]	207.52[b]	241.48[e]	241.48[b]	2533.33[b]	41.77[a]	2291.86[ab]	-199.71[b]	11.03[cd]	-0.96[b]	9.48[cd]	-0.83[a]
CNO	141.89[e]	141.89[c]	141.89[g]	141.89[f]	2171.43[b]	81.43[a]	2029.54[abc]	-60.46[ab]	14.29[bcd]	-0.43[ab]	14.29[abc]	-0.43[a]
ZF60	1128.42[a]	147.3[c]	1168.61[a]	187.50[c]	3482.23[a]	214.61[a]	2313.62[ab]	27.11[a]	15.67[abc]	0.19[a]	12.31[abc]	0.15[a]
ZM60	1094.78[b]	113.28[d]	1129.20[a]	154.39[ef]	3693.64[a]	135.71[a]	2564.44[a]	-18.68[a]	22.60[a]	-0.16[ab]	16.92[a]	-0.12[a]
ZMF30	1125.08[a]	143.96[c]	1163.65[a]	182.54[cd]	3854.16[a]	151.93[a]	2690.51[a]	-30.61[ab]	18.92[ab]	-0.21[ab]	15.00[ab]	-0.17[a]
ZNO	1094.27[b]	113.15[d]	1094.27[c]	113.15[g]	2323.25[b]	108.67[a]	1228.99[c]	-4.49[a]	10.87[cd]	-0.02[ab]	10.87[bcd]	-0.02[a]
P	<.0001	<.0001	<.0001	<.0001	<.0001	0.1202	0.0049	0.0393	0.0001	0.0889	0.0039	0.1088
SED $_{(0.05)}$	3.809	3.2578	6.0487	6.0916	226.7482	42.9366	227.866	42.8921	1.5772	0.2532	1.5147	0.2229

CMF30=Conventional + Cattle Manure+30 kg N ha^{-1}, CNO= Conventional with no inputs, CM60=Conventional+Manure, CF60=Conventional+ 60 kg N ha^{-1}, ZNO=*zai* with no inputs, ZMF30=*zai*+ Cattle manure+ 30 kg N ha^{-1}, ZM60=*zai* + Manure, ZF60=*zai*+ 60 kg N ha^{-1}. Means followed by a different letter are not significantly different p<0.05; Standard Error of Difference.

in conventional with fertilizer (6.34 USD ha^{-1}) during the SR2018 season. During the LR2019 season, BCR was highest (Table 6) in *zai* with fertilizer (0.15 USD ha^{-1}) and lowest in conventional with manure and fertilizer (-0.83 USD ha^{-1}).

The three economic tools, that is, the net benefits, return to labour and benefit cost ratio (BCR) were significantly (p=0.0048, p=0.0001, p=0.0039, respectively) influenced by *zai* pits and ISFM technologies during the SR2018 season. During the SR2018 season, return to labour was significantly higher (p=0.0269, p=0.0252, p=0.0379, respectively) in *zai* with fertilizer, *zai* with manure and *zai* with manure and fertilizer as compared to conventional with fertilizer, conventional with manure and conventional with manure and fertilizer (Table 6).

DISCUSSION

The incorporation of fertility inputs negatively influenced total nitrogen with electrical conductivity and available phosphorous positively influenced by the end of LR2019 cropping season. The addition of manure and mineral fertilizer significantly reduced total nitrogen by the end of the two cropping seasons and this could be because the application of fertility inputs makes nitrogen readily available for plant uptake hence the reduction of total nitrogen in the soil. The reduction of total nitrogen could also be attributed to loss through volatilization, nitrous oxide emission, leaching, erosion and oxidation of nitrogen as reported by Pal et al. (2020). These results corroborated by Pasley et al. (2019) who noted that an increase in nitrogen fertilizer application increased nitrogen uptake by crops reducing its availability in the soil. Similarly, Omara et al. (2019) reported that the efficiency of nitrogen uptake by crops was accelerated by manure and fertilizer application. However, other studies recorded a significant increase in total nitrogen in the soil. For instance, Bedada et al. (2014) noted that a combination of compost and nitrogen, phosphorous (NP) fertilizer increased the stock of total nitrogen 0-10 cm compared to the control experiment and nitrogen phosphorous (NP) fertilizer alone treatments. Similarly, Mattuso et al. (2014), Yegon et al. (2016), Kihara et al. (2016) and Liu et al. (2020) reported that the addition of manure and mineral fertilizer increased total nitrogen in the soil.

The application of sole manure increased the electrical conductivity of soil. This could be attributed to the high amounts of dissolved salts in manure. Soil electrical conductivity increases as a result of manure application is related to the high amounts of dissolved salts that is beneficial in supplying a pool of nutrients and ions into the soil. Similar findings have also been reported by Carmo et al. (2016a, b) and Miller et al. (2016) who indicated that electrical conductivity increased with manure application.

Conversely, soil organic carbon reduced in all the treatments by the end of the two cropping seasons. This could be attributed to the slow changes in soil organic carbon in compacted, poorly drained soils and clayey soils compared to sloping and coarse-textured soils. Tillage also speeds up the loss of soil organic carbon by increasing its mineralization and loss by erosion. This is because mixing of soils with litter favours bacteria and promotes the rapid breakdown process of organic carbon. Tillage induced erosion of soils is also the cause of severe loss of soil organic carbon more especially in upland landscapes. Similar results have also been reported by Liu et al. (2003), Blanco-Canqui et al. (2013) and Corsi et al. (2012) who indicated that soil organic carbon declined significantly in the first five years of cultivation. Long-term experiments are required to detect changes in soil organic carbon because it responds slowly to changes in agricultural management. Therefore, this means that the changes may require a long period of time to be detected and quantify the effect of the management activities (Haddaway et al., 2015). A similar study on the changes of soil organic carbon in an established plantation in northern China recorded an initial decrease in soil carbon (Lei et al., 2019). This could be attributed to the loss of carbon through decomposition which outweighed gains of carbon from litter.

Available phosphorous increased in treatments that had sole manure in *zai* and conventional tillage systems an indication that manure could have contributed to the increase in phosphorous in the soil. The current trend of results is in consonance with findings of Ali et al. (2019) who noted that manure application as an amendment in agricultural soils improved the soil physiochemical properties and cycling of nutrients through enhancing enzyme and soil microbial activities leading to improved phosphorous bioavailability for crop uptake. Buckley and Makortoff (2004) reported that manure contains about 45 to 90% of inorganic orthophosphates a form in which phosphorous is taken up by plants which makes it a rich supplier of phosphorous into the soil.

On average, the LR2019 season recorded lower grain and stover yields compared to the SR2018 season. This could be associated with the dry spells and prolonged meteorological drought that was experienced in the planting (LR2019) season where the cumulative rainfall declined (Figure 2) affecting the growth and production of sorghum. Similar results were also reported by Rockström (2010), Ibrahim et al. (2011) and Nyakudya and Stroosnijder (2011) who noted that low yields experienced were as a result of water stress which is often experienced by the smallholder farmers in the arid and semi-arid regions.

Zai pits as a water harvesting technique increased the grain yields in SR2018 and this could be attributed to their ability to retain soil moisture and improve nutrient efficiency. These results were similar with Amede et al. (2011) and Wouterse (2017) who noted that the *zai* pit technology was an intervention used by smallholder farmers to increase agricultural productivity through improving precipitation capture, reduction of runoff, increase water infiltration and water evaporation from the soil. The current trend of results also corroborated by Kathuli and Itabari (2014) who reported that the use of *zai* pits significantly increased sorghum grain yield. Similarly, Mazvimavi and Twomlow (2008) noted higher yields in pitting technology compared to the conventional tillage system.

During the SR2018 season, grain yields were significantly higher in *zai* with full-rate fertilizer compared with *zai* without input an indication that mineral fertilizer significantly increased the grain yields. This could be because mineral fertilizer improves soil chemical and physical properties by increasing the availability of nutrients in the soil and promoting the growth of crops.

During the same season grain yields were significantly higher in *zai* with sole manure and *zai* with manure and mineral fertilizer compared to the control. This was also attributed to the ability of the combination to enhance release of nutrients and uptake by crops. Tittonel et al. (2008), Kihara et al. (2017) and Mi et al. (2018) attributed the increase of grain yield to the use of fertilizer and manure. Matusso et al. (2014) linked the significant increase in grain yield to the ability of the combination to enhance the nutrient release and uptake. Amede et al. (2011) also reported that *zai* pits and a combination of fertilizer additions increased the yield of potatoes by 500 to 2000% and bean yield by 250%. The application of manure alone or in combination with mineral fertilizer increased crop yield and this could be associated with the increase in the supply of the nutrients in the soil as well as the ability of the combination to enhance release of nutrients hence increase in nutrient availability. Chen et al. (2018) reported that the application of organics alone or a combination with mineral fertilizers led to increased crop yield compared to the sole mineral fertilizers. Elsewhere, Chivenge et al. (2011) reported an increase in maize yield in treatments that had a combination of organic resources and fertilizers (114%) and sole organic resources (60%). Biazin et al. (2012), Dunjana et al. (2012) and Kar et al. (2013) also noted that rainwater harvesting in combination with the use of both inorganic and organic inputs increases the nutrients in the soil improving crop productivity.

The significant difference in the economic parameters between the seasons, with SR2018 performing much better than the LR2019 season could be as a result of the low grain yields recorded in LR2019 due to the prolonged dry spell. Ray et al. (2018) noted that drought causes significant reduction in yields and economic returns in both irrigated and rainfed crops because of the reduction of water and moisture available for crop growth. The SR2018 season had higher benefits in treatments that had a combination of manure and fertilizer in both conventional and zai tillage systems compared to the control. This was an indication that the combined use of organics and mineral fertilizers was economically viable to the small-holder farmers. Hobbs et al. (2011) and Kebede (2020) attributed the high net benefits with soil fertility amendments and water conservation techniques used in crop production. This generally explains the higher net benefit results in the SR2018 season that on average the combination of cattle manure and mineral fertilizers had higher net benefits than the recommended rate of fertilizer (Olarinde et al., 2012; Girma et al., 2020).

The net benefits, return to labour and BCR were higher in *zai* treatments compared to conventional treatments with similar fertility inputs. This could be attributed to the water conservation and fertility technologies in the *zai* treatments which increased the overall net benefits. Hobbs et al., (2011) reported that *zai* pits has been used as an intervention to increase productivity by improving water availability and nutrient efficiency. Higher net benefits, return to labour and BCR were recorded in treatments that had a combination of manure and mineral fertilizer in both *zai* and conventional planting. This could be attributed to the increased supply of nutrients hence high productivity. Similar results have been reported by Mutegi et al. (2012) that on average, the combined use of organic inputs and mineral fertilizers had higher net benefit and BCR compared to the sole application of mineral fertilizers. Kearney et al. (2012), Ojiem et al. (2014), Matusso et al. (2014) and Thimmaiah et al. (2016) noted that greater net benefits were recorded in a combined application of inorganics and mineral fertilizers compared with the application of sole inorganics and sole mineral fertilizer.

During the SR2018 season, BCR was greater than one in all the treatments compared with the LR2019 season whereby the BCR was less than one in all the treatments. If the BCR is greater than one, it shows that the technologies can be beneficial as Shively and Galopin (2013) reported. Higher BCR was recorded in *zai* planting with manure and *zai* with manure and mineral fertilizer compared to their conventional counterparts in the two cropping seasons. This could be a consideration because it is more economical and a feasible alternative available for nutrient supplementation compared to the high costs of purchasing inorganic fertilizers (Mucheru-Muna et al., 2007). The combined use of fertilizer and inorganics can be practiced by small-holder farmers in the study area to supplement nutrient deficiencies due to the limited purchasing power of the farmers.

Conclusion

Cattle manure an amendment used to improve soil fertility increased soil pH in both *zai* pit and conventional planting. The application of cattle manure and mineral fertilizer improved the soil electrical conductivity and available phosphorous. Total nitrogen and organic carbon significantly reduced at the end of the LR2019 cropping season due to losses. There were also beneficial effects in *zai* planting as compared to conventional planting and combined application of manure and mineral fertilizer relative to applying sole fertilizer in terms of sorghum grain yields and economic benefits. Grain and stover yields were higher in *zai* planting compared to their conventional counterparts with the same fertility inputs. Higher net benefits, return to labour and BCR were also observed in treatments that had a combination of manure and mineral fertilizer. Rainfall variability in amount and distribution greatly affected sorghum yields across the seasons. The installation of *zai* pits is more labour intensive but the economic returns are higher in subsequent cropping systems compared to the conventional tillage system. Therefore, there is a need to integrate organic and inorganic fertilizer as a viable option and use of *zai* pits by the small holder farmers to enhance crop production and profitability.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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