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Tillage system and integrated soil fertility inputs improve smallholder farmers' soil fertility and maize productivity in the Central Highlands of Kenya

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Abstract

We designed and implemented an on-farm trial in Meru South and Gatanga sub-counties to understand the effects of integrated soil fertility management (ISFM) technologies on soil nitrogen (N), phosphorus (P), potassium (K), and maize productivity. The technologies included combinations of mineral fertiliser and maize stover (CrMf); crop residue, *Tithonia diversifolia* and rock phosphate (CrTiP); crop residue, *Tithonia diversifolia* and goat manure (CrTiMan); crop residue, inorganic fertiliser and goat manure (CrMfMan); crop residue, goat manure and *Dolichos lablab* (CrManLeg), and sole inorganic fertiliser (Mf) executed under conventional (ConC) and minimum (MinTill) tillage methods. We interviewed the farmers who participated in implementing the trials at the end of the study to understand the likelihood to uptake the technologies. We observed that the technologies increased soil N, P, K, and maize productivity compared to ConC (the control). There was a high likelihood of uptake of high-performing ISFM technologies. We recommend CrTiP for the two sub-counties for the short-term. However, a long-term experiment is needed to evaluate performances of CrTiMan, CrTiP, CrMfMan, and CrManLeg under the two tillage methods for site-specific recommendations taking into consideration rainfall variations.

Keywords: crop productivity, maize yield, *Nitisols*, tillage, *Tithonia diversifolia.*

1 Introduction

Agricultural land in sub-Saharan Africa (SSA) is under increased pressure to support roughly 950 million people which is expected to increase to 2.1 billion persons by 2050 (DESA, 2017). This population estimates negatively correlate with the ability of the land to sustain food provision because of continuous soil fertility degradation and climate change (Descheemaeker *et al.*, 2016; 2020). Soil fertility depletion in the Central Highlands of Kenya is further exacerbated by the fact that smallholder farmers practice crop-livestock farming on already degraded lands (Castellanos-Navarrete *et al.*, 2015). Consequently, these farmers continuously harvest low maize yields (usually less than 1.0 Mg ha^{-1}) against the 6.0–8.0 Mg ha^{-1} potential maize productivity (Kiboi *et al.*, 2019). This low productivity level is associated with low levels of soil nitrogen (N) and phosphorus (P) partly caused by unbalanced nutrient mining and low soil fertility amendments.

Integrated soil fertility management (ISFM) may be critical in solving food insecurity at both global and regional scales through enhanced soil fertility. Empirical evidence demonstrates the practicality of ISFM technologies in solving soil fertility decline in smallholder farms where farmers are often regarded as resource-poor and have limited ability to access inorganic fertilisers (Nezomba *et al.*, 2018). In fact, ISFM components like goat manure, legume intercrop, crop residue mulch and *Tithonia diversifolia* (green manure) have been shown to increase plant nutrients availability, soil

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microbial quality and improve soil physical properties (Serafim *et al.*, 2013; Schröder *et al.*, 2015; Kermah *et al.*, 2017) leading to increased crop yields.

Farmers in the Central Highlands of Kenya apply little to no soil fertility inputs such as inorganic fertilisers (Kiboi *et al.*, 2019). Furthermore, the region's specific fertiliser recommendations promoted by National and County governments' extension officers in Kenya may have failed to effectively manage on-farm soil fertility because soil fertility gradients greatly vary at farm and plot levels (Vanlauwe *et al.*, 2010). Farmers also differ in the timing of/and management practices. ISFM is designed to solve these problems as it takes into account variations at farm and plot levels and is adaptable to local conditions (Vanlauwe *et al.*, 2010). Continuous soil cultivation has also been blamed for the declining soil fertility in the Central Highlands of Kenya (e.g., Kiboi *et al.*, 2017, 2019). However, this is not adequately justifiable because of the inconsistencies related to the effect of tillage on soil quality parameters (Rowen *et al.*, 2020). We, therefore, hypothesized that the selected ISFM technologies executed under conventional and minimum tillage methods would significantly improve soil N, P, K, and maize productivity, and farmers' evaluation of the selected ISFM would increase the likelihood of their uptake.

2 Materials and methods

2.1 *Site description*

The field experiments were set up in Meru South and Gatanga sub-counties during long rains 2016 (LR2016) and short rains (SR2016). In Meru South, the field experiments were implemented in Gakuuni (0°20′18″ S and 37°40′8″ E), Gakweguni (0°20′25″ S and 37°40′23″ E), Kangutu (0°20′14″ S and 37°40′55″ E) and Kathunguni (0°20′12″ S and 37°41′6″ E) villages while in Gatanga they were in Githunguri (0°57′49″ S and 36°58′55″ E), Njabai (0°57′18″ S and 36°59′23″ E), Rwaitira (0°57′1″ S and 36°59′8" E) and Mithandukuini (0°57′55″ S and 37°0′7″ E) villages. The soils in the two sub-counties are predominantly *Nitisols* which are deep and highly weathered with moderate to high inherent fertility (Jaetzold *et al.*, 2007). Meru South lies at an altitude of 1500 m asl and receives an annual rainfall between 600 to 1200 mm while the mean annual temperature is 20 °C. Gatanga is located at an altitude ranging between 1520 to 2,280 m asl and annually receives rainfall between 900 to 1400 mm with a mean annual temperature of 18 °C. Soil samples were collected from 0–15 cm depth at the beginning of the experiment. Standard soil analysis methods as described by Ryan *et al.* (2001) were used to characterise soils in Meru South and Gatanga sub-counties (Table 1). The methods used were; Kjeldahl method for N; available P by Mehlich method; organic C by modified Walkley and Black wet oxidation method; exchangeable K by flame photometer; exchangeable Mg and Ca by atomic absorption spectrophotometry; and pH using pH meter. Rainfall pattern in both Meru South and Gatanga sub-counties is bimodal, with the long rains (LR) from March to May and short rains (SR) from October to December. Farmers predominantly practice livestock-crop farming system. Common livestock included both indigenous and improved breed of dairy goats, cattle and sheep. Maize (*Zea mays* L.) is the common staple annual food crop. Widespread poverty is one of the critical challenges facing developmental agendas in the two sub-counties (Jaetzold *et al.*, 2007).

2.2 *Farmers selection and informants' interviews*

Eighteen farmers per site were randomly selected from a list obtained from the Ministry of Agriculture extension officers from each sub-county, trained, and guided in choosing the technologies to implement. The selection of farmers was based on; willingness to implement the treatments, similarity of the farmers' fields in terms of tillage method and cropping during every cropping season annually, and nearness to an installed automatic rain gauge (maximum of 1 km radius). At the end of the experiment, these farmers were interviewed to assess their likelihood to take up the tested technologies. The interview schedule, had questions on the likelihood to continue implementing and recommending the technologies to other farmers. We also inquired whether other farmers visited the study farms to learn about the technologies. We used the results as proxies to evaluate the likelihood of farmers to uptake the implemented ISFM technologies.

2.3 *Experimental design*

The experiment was laid out in a randomised incomplete block design. It was implemented in the farms of 18 selected farmers. Fifteen farmers implemented 3 technologies while three (3) farmers implemented 4 technologies each. Of the total technologies implemented by each farmer, one was a control (Conventional tillage with no inputs). At the beginning of each season the farmers received fertilisers, maize seeds variety H516 and *Dolichos lablab* while they provided labour, *Tithonia diversifolia*, goat manure, and maize stover. N and P were applied at the rates of 60 kg N ha^{-1} and 90 kg P ha^{-1}, respectively. We used NPK 23:23:0 and Triple Super Phosphate (TSP) (0:46:0) and top-dressed using Calcium Ammonium Nitrate (CAN). The quantity of *Tithonia diversifolia* and goat manure applied were calculated based on the laboratory analysis to supply equivalent to 60 kg N ha^{-1} leading to application of 1.5 tons ha^{-1} and

Table 1: *Baseline chemical properties of topsoil (0 – 15 cm) at Meru South and Gatanga*

Parameter	*Meru South*	*Gatanga*
Total N %	0.10	0.10
Available P (mg kg^1)	43.00	42.00
Total organic C (%)	0.81	0.77
Exchangeable K (cmol kg K^{-1})	1.25	1.27
Exchangeable magnesium (Mg^+)($cmol^+$ kg^{-1})	1.46	1.39
Exchangeable calcium (Ca^+) ($cmol^+$ kg^{-1})	11.49	7.94
C/N ratio	8.10	7.70
pH water (1:1, soil:water)	5.84	5.32

Source: Authors (2016)

Table 2: *Technologies and their abbreviations used in the trials*

Tillage	*SFI**	*Combinations*	*n*
Conventional	Control	ConC	18
Conventional	Mf	ConMf	3
Conventional	CrMf	ConCrMf	3
Conventional	CrMfMan	ConCrMfMan	3
Conventional	CrTiP	ConCrTiP	3
Conventional	CrManLeg	ConCrManLeg	3
Conventional	CrTiMan	ConCrTiMan	3
Minimum	No inputs	MinTill	3
Minimum	Mf	MinMf	3
Minimum	CrMf	MinCrMf	3
Minimum	CrMfMan	MinCrMfMan	3
Minimum	CrTiP	MinCrTiP	3
Minimum	CrManLeg	MinCrManLeg	3
Minimum	CrTiMan	MinCrTiMan	3

SFI= soil fertility input; ConC= conventional tillage; MinTill= minimum tillage; Mf= inorganic fertiliser; CrMf= crop residues + inorganic fertiliser; CrMfMan= crop residues + inorganic fertiliser + goat manure; CrManLeg= crop residues + goat manure + legume intercrop; CrTiMan= crop residue + *Tithonia diversifolia* + goat manure; CrTiP= crop residue + *Tithonia diversifolia* + rock phosphate. Note: inputs application rates: Mineral fertiliser = 60 kg N ha^{-1}, 90 kg P ha^{-1}; Crop residues = 5 t ha^{-1}; *Tithonia diversifolia* = 1.5 t ha^{-1}; Goat manure = 2.86 t ha^{-1}. Rock phosphate 90 kg P ha^{-1}. Apart from crop residues, the rates were halved where the soil fertility inputs were combined.

2.86 tons ha^{-1}, respectively. Five tons ha^{-1} of crop residues as surface mulch was applied one week after seedling emergence. Rock phosphate (27:29 % P_2O_5, 36:38 % CaO) was applied at the rate of 90 kg P ha^{-1}. Tables 2 and 3 show the treatments and the laboratory-determined nutrients content of *Tithonia diversifolia* and goat manure.

Table 3: *Macro-and micro-nutrients contents of goat manure and Tithonia diversifolia*

	Percentage (%)					*mg kg^{-1}*			
Litter type	*N*	*P*	*K*	*Ca*	*Mg*	*Fe*	*Cu*	*Mn*	*Zn*
Goat manure	2.10	0.20	0.64	0.70	0.30	141.00	38.70	228.00	32.50
Tithonia diversifolia	3.90	0.30	2.56	0.96	0.30	626.30	27.70	110.0	59.00

Source: own analysis (2016)

Conventional tillage (ConC) plots were ploughed using hand hoe to a depth of 15 cm while minimum tillage (MinTill) plots were scrapped to a depth of 0-5 cm using a machete. Maize was planted at a spacing of 0.75 m x 0.50 m inter- and intra-row, respectively. *Tithonia diversifolia* and goat manure were incorporated two weeks before planting to a depth of 15 cm during ploughing under ConC, while for MinTill the inputs were placed in the planting holes. *Dolichos lablab* was planted a week after maize germination between maize rows. The farmers independently conducted the required agronomic practices as per the training.

2.4 *Data collection*

Soil samples were also collected at the end of the experiments using core rings at 0-15 cm depth for soil organic carbon while Eijkelkamp Gouge soil auger was used to collect soil samples for chemical parameters. The farmers recorded phenological data and together with the researchers they harvested and weighed crop yields. Maize grain and stover yields were harvested from net plots measuring 15.75 m^2 and 21 m^2 in Meru South and Gatanga, respectively. Stovers were separated from cobs during harvesting, samples taken, and air-dried under shade to a constant weight. The dried samples were used to correct stover weight. The cobs were air-dried and grains separated from the cobs through hand shelling. Grain moisture content was determined using Dickey-John MiniGAC® moisture meter. Grain weight was then corrected based on the determined moisture content to an equivalence of 12.5 %. Rainfall was collected using automated rain gauges installed near an on-station experimental site in the two sub-counties.

2.5 *Data analysis*

Data were subjected to a one-way analysis of variance using General Linear Model (GLM) in SAS version 9.2. For treatments with a significant difference, the means were separated using Duncan multiple range test at $p \leq 0.05$. To assess changes in the measured soil parameters over time, pairwise comparisons using student t-test at $p \leq 0.05$ were carried out. Qualitative data obtained from the interview schedules were coded and put in Microsoft Excel for descriptive analysis.

3 Results

3.1 *Rainfall characteristics*

Rainfall amounts received during the LR2016 season were 880 mm and 329 mm in Meru South and Gatanga, respectively (Table 4). Rainfall onset delayed during the LR2016 season in Meru South and Gatanga compared to the reported long-term observed onset dates of 15^{th} March (Ngetich *et al.*, 2014). The length of the LR2016 season was 79 and 63 days in Meru South and Gatanga, respectively. Meru South and Gatanga experienced five and three dry spells, respectively, during the LR2016 season. We defined a dry spell as five consecutive days without rainfall and then assessed the number of times a dry spell occurred within 5-10 and 11-15 days during a season. Meru South and Gatanga received rainfall amounts of 393 and 243 mm, respectively, during SR2016 season. There was a delay in rainfall onset in Meru South (Table 4). However, in Gatanga, the rains started early during the SR2016 season (6th October). There were six and three dry spells during the season in Meru South and Gatanga, respectively.

Table 4: *Rainfall onset dates, cessation dates, length of the season, cumulative rainfall and number of dry spells per season in Meru South and Gatanga during LR2016 and SR2016 seasons.*

	Season	
Rainfall characteristics	*LR2016*	*SR2016*
	Meru South	
Onset date	5th April	5th September
Cessation date	29th July	31st December
Length of the season (days)	79	116
Total rainfall (mm)	879.5	392.9
Dry spells:		
	2	4
5-10 days		
11-15 days	2	0
More than 15 days	1	2
	Gatanga	
Onset date	21st April	06th October
Cessation date	24th June	26th December
Length of the season (days)	63	108
Total rainfall (mm)	328.7	243.2
Dry spells:		
	1	1
5-10 days		
11-15 days	1	1
More than 15 days	1	1

3.2 *Soil properties*

Tillage method significantly affected soil N and P in Meru South and P and K in Gatanga (Table 5). Minimum tillage (MinTill) plots had 50 % more N than plots under conventional tillage (ConC), while ConC plots had over 120 % more P than MinTill plots in Meru South. In Gatanga, ConC plots significantly had more P and K (114 and 109 %, respectively)

Table 5: *Total soil N (%), available P (%) and K (g kg^{-1}) as affected by tillage and soil fertility inputs in Meru South and Gatanga.*

	Meru South			*Gatanga*		
Treatment	N	P	K	N	P	K
Tillage						
ConC	0.04^{b}	9.43^{a}	0.14^{a}	0.02^{a}	5.60^{a}	0.23^{a}
MinTill	0.06^{a}	-2.00^{b}	-0.02^{a}	0.02^{a}	-0.81^{b}	-0.02^{b}
Soil fertility inputs						
C	0.04^{a}	-6.33^{c}	-0.21^{bc}	0.02^{a}	-4.50^{abc}	-0.08^{a}
Mf	0.06^{a}	-10.33^{c}	-0.34^{c}	0.02^{a}	-2.83^{abc}	0.06^{a}
CrMf	0.04^{a}	-5.92^{c}	-0.12^{abc}	0.02^{a}	-10.50^{bc}	0.17^{a}
CrManLeg	0.05^{a}	14.67^{ab}	0.20^{ab}	0.02^{a}	14.67^{ab}	0.11^{a}
CrMfMan	0.05^{a}	5.00^{bc}	0.34^{a}	0.03^{a}	15.25^{ab}	0.11^{a}
CrTiMan	0.06^{a}	3.00^{bc}	0.24^{ab}	0.03^{a}	-14.00^{c}	0.10^{a}
CrTiP	0.05^{a}	26.00^{a}	0.30^{a}	0.03^{a}	18.67^{a}	0.24^{a}
*Source of variation**						
Tillage	0.0295	0.0229	0.1950	0.9727	0.0312	0.0049
SFI	0.5456	0.0035	0.0197	0.8376	0.0477	0.5357
SFI *Tillage	0.0276	0.3346	0.1210	0.345	0.7975	0.0048

* p values; means with the same letter(s) within a column are not significantly different at $p \leq 0.05$.

ConC= conventional tillage; MinTill= minimum tillage; C= control; Mf= inorganic fertiliser; CrMf= crop residues + inorganic fertiliser; CrMfMan= crop residues + inorganic fertiliser + goat manure; CrManLeg= crop residues + goat manure + legume intercrop; CrTiMan= crop residue + *Tithonia diversifolia* + goat manure; CrTiP= crop residue +*Tithonia diversifolia*+ rock phosphate.

than MinTill plots. There was a significant tillage-SFIs interaction effect on N in Meru South. Tillage method did not significantly affect K and N in Meru South and Gatanga, respectively. Soil fertility inputs (SFIs) significantly affected P and K in Meru South and P in Gatanga (Table 5). Compared to ConC, the application of CrTiP and CrManLeg increased P by 511 to 332 %, respectively, in Meru South. The other SFIs did not perform any differently as ConC. On the other hand, CrManLeg and CrTiP had a superior K increase of about 262 to 243 % relative to ConC. The other SFIs did not statistically differ with ConC in relation to K. It was observed that P significantly increased by 426 to 515 % when the soil was treated with CrManLeg, CrMfMan, and CrTiP compared to ConC. The other SFIs had the same effect on P as the ConC. However, SFIs did not record a significant effect in N in Meru South and N and K in Gatanga.

Source of soil nutrients (SoNs) significantly increased soil P and K in Meru South while no significant changes in N in Meru South and Gatanga was recorded (Fig 1). There were significant changes in P and K in Meru South (Fig. ß1b & c). Sole organic inputs and integration of inorganic and organic inputs increased P by 21 and 11 % from -6.33 % P, respectively, in Meru South. Similarly, integration of inorganic and organic inputs increased K by 0.46 g kg^{-1} .

3.3 Maize above-ground biomass yields

LR2016 cropping season in Gatanga (Table 6). Soil fertility inputs, tillage method, and interaction did not significantly influence maize grain yield in Meru South during the LR2016 season. However, SFIs increased mean maize yield by 30 to 52 % relative to ConC. Amending soil with SFI increased mean maize yield by about 22 to 72 %, with CrTiMan and CrTIP recording the highest maize grain yields, compared to when the soil is not amended with SFI. On the other hand, CrTiP had the highest maize grain yield increase of 3.61 Mg ha^{-1} up from 2.23 Mg ha^{-1} in Gatanga during LR2016 cropping season.

Similarly, the SFIs significantly influenced maize stover yield in Meru South during LR2016 and SR2016, and in Gatanga during LR2016 cropping seasons (Table 6). SFIs significantly increased maize stover except for Mf and CrManLeg in Meru South in the first season (LR2016). The inputs increased the stover yield by approximately 5.74 to 7.63 Mg ha^{-1} up from 5.59 Mg ha^{-1}, accounting for about 103 to 136 % increase as compared to the ConC. The SFIs significantly increased stover yield by between 0.34 to 4.19 Mg ha^{-1} compared to the control. In Gatanga, the SFIs; CrMfMan, CrTiMan, and CrTiP, significantly increased

Table 6: *Maize grain and stover yields (Mg ha-1) during LR2016 and SR2016 in Meru South and Gatanga cropping seasons.*

	Meru South				*Gatanga*	
	LR2016		*SR2016*		*LR2016*	
Treatment	*Grains*	*Stover*	*Grains*	*Stover*	*Grains*	*Stover*
Tillage						
MinTill	3.64^{a}	13.78^{a}	0.93^{a}	7.76^{a}	2.23^{a}	12.63^{a}
ConTill	3.25^{a}	14.37^{a}	0.82^{a}	7.36^{a}	1.85^{a}	11.56^{a}
Soil fertility inputs						
ConC	2.54^{a}	5.59^{c}	0.68^{e}	2.35^{e}	1.90^{c}	4.04^{c}
Mf	3.59^{a}	6.26^{c}	0.83^{cd}	2.79^{cd}	2.59^{b}	5.11^{cd}
CrMf	3.78^{a}	11.33^{b}	1.04^{bc}	3.35^{c}	2.37^{b}	7.24^{c}
CrMfMan	3.85^{a}	13.22^{a}	1.10^{b}	5.94^{ab}	3.48^{a}	10.00^{a}
CrManLeg	3.44^{a}	6.62^{c}	0.90^{cd}	2.69^{cd}	1.96^{c}	6.99^{cd}
CrTiMan	3.38^{a}	12.81^{a}	1.17^{a}	6.54^{a}	3.45^{a}	8.51^{ab}
CrTiP	3.30^{a}	11.59^{b}	1.17^{a}	5.94^{ab}	3.61^{a}	7.77^{ab}
*Source of variation**						
Tillage	0.2100	0.2816	0.1900	0.6640	0.1500	0.2391
Soil fertility inputs	0.8500	<.0000	0.0200	<.0000	<.0000	0.0400
Tillage*fertility inputs	0.9643	0.0042	0.8768	0.1505	0.7343	0.1009

* p values; means with the same letter(s) within a column are not significantly different at $p \leq 0.05$.
ConC= conventional tillage; MinTill= minimum tillage; C= control; Mf= inorganic fertiliser; CrMf= crop residues + inorganic fertiliser; CrMfMan= crop residues + inorganic fertiliser + goat manure; CrManLeg= crop residues + goat manure + legume intercrop; CrTiMan= crop residue + *Tithonia diversifolia* + goat manure; CrTiP= crop residue +*Tithonia diversifolia*+ rock phosphate.

stover yield compared to ConC by 3.73 to 5.96 Mg ha^{-1} up from 4.04 Mg ha^{-1}.

Tillage method and its interactions with SFI had no significant effect on maize grain and stover yields in the two study sites and across the two seasons. There was total crop failure in Gatanga in the second cropping season (SR2016) because of the erratic rainfall received in the site hence we did not record any maize yield data. SoNs significantly increased maize grain yield during LR2016 and SR2016 cropping seasons in Meru South and in the LR2016 cropping season in Gatanga (Fig. 2). A combination of inorganic and organic (Inorg+Orgn) sources of nutrients had superior maize grain performance during the two cropping seasons in the two sites. In the first season (LR2016), a combination of inorganic and organic and sole inorganic fertiliser increased maize grain yield by 38 and 33 %, respectively, compared to ConC in Meru South. Conversely, sole organic inputs did not differ with ConC. Similarly, in the second cropping season (SR2016), a combination of inorganic and organic inputs caused a 47 % increase in maize grain yield in relation to ConC, while sole application of either organic or inorganic inputs performed the same as ConC. We also found that Inorg+Orgn and sole organic inputs increased maize grain yield by 87 and 62 %, respectively, in Gatanga during LR2016 cropping season. However, sole application of inorganic fertiliser did not differ statistically with the other SoNs in Gatanga during the LR2016 cropping season.

Source of nutrients significantly affected maize stover yield during LR2016 and SR2016 cropping seasons in Meru South and LR2016 cropping season in Gatanga (Fig. 3). Organic, inorganic, and integration of inorganic fertilizer and organic inputs significantly increased maize stover yield by 18, 34, and 64 %, respectively, than ConC during LR2016 cropping season in Meru South. Likewise, inorganic, organic, and integration of inorganic fertiliser and organic inputs had superior maize stover yield performances of up to 9, 10, and 23 %, respectively in relation to ConC in the second cropping season (SR2016) in Meru South. On the other hand, the performance of integrated inorganic fertiliser and organic inputs and sole organic inputs statistically recorded higher maize stover yield by 66 and 42 % in reference to ConC in Gatanga in the LR2016 cropping season. Sole application of inorganic fertiliser performed the same as ConC.

The technologies significantly affected stover yields during the LR2016 (p =< 0.00) and SR2016 (p =< 0.00) in Meru South, and during LR2016 ($p = 0.04$) in Gatanga (Table 5). We observed 13.76 Mg ha^{-1} yield in the MinCrMfMan which was 77 % higher compared to ConC during the

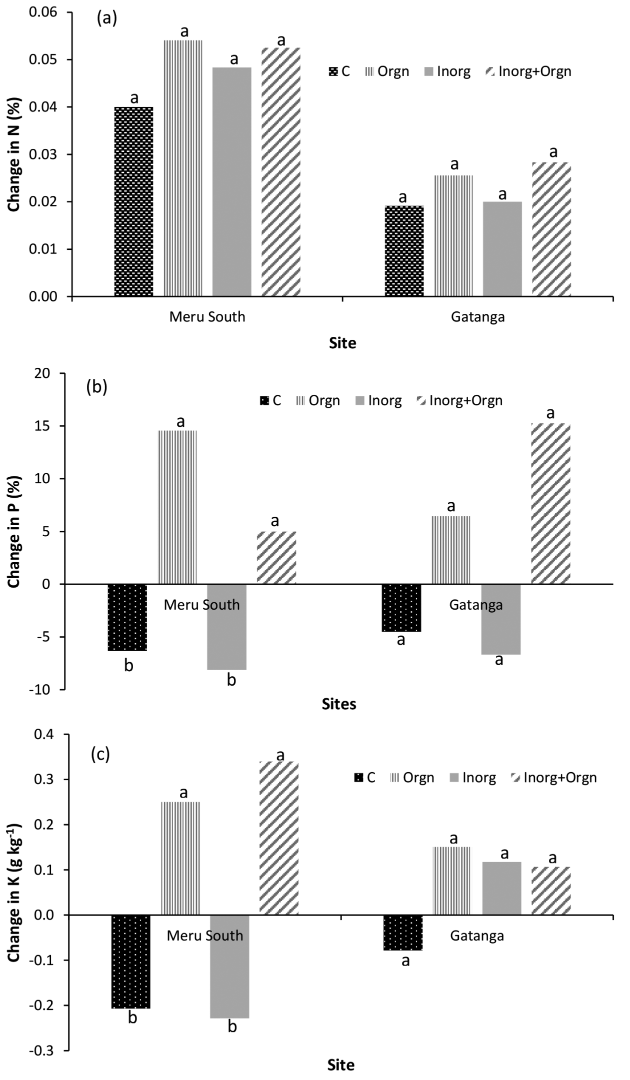

Fig. 1: *Change in (a) total soil N (%), (b) available P (g kg^{-1}), and (c) K (g kg^{-1}) in Meru South and Gatanga.*
Bars with the same letter are not significantly different at $p < 0.05$*. C = control; Orgn = organic; Inorg = inorganic; Inorg+Orgn = inorganic+organic.*

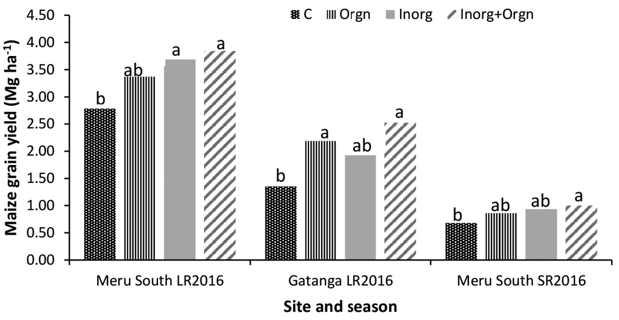

Fig. 2: *Maize grain yield (Mg ha-1) during (a) LR2016 and (b) SR2016 cropping seasons in Meru South and (c) LR2016 cropping season in Gatanga.*
Bars with the same letter are not significantly different at $p < 0.05$ *per sikte and season. C = control; Orgn = organic; Inorg = inorganic; Inorg+Orgn = inorganic+organic.*

LR2016 season in Meru South. The other treatments with significant increase in yields were ConCrMfMan, ConCrTiman, ConCrMf, MinMf, MinCrMf and ConCrTiP by 67, 60, 59, 53, 49 and 49 % compared to ConC. MinCrTiP had the highest yield during the SR2016 season amounting to 71 % compared to ConC. MinCrMfMan and MinCrTiMan significantly increased stover yield by 62 and 55 % compared to ConC. In Gatanga, MinCrTiMan, ConCrManLeg, MinCrMfMan, ConCrMfMan, MinCrTiP, MinMf, ConCrTiman, ConMf, MinCrMf, MinCrManLeg, ConCrTiP and ConCrMf increased stover yield by 161, 160, 154, 143, 138, 105, 62, 43, 42, 27, 22 and 12 % compared to ConC. There was total crop failure in the second season (SR2016) in Gatanga due to low amounts of rainfall with dry spell period occurring during maize grain filling stage hence no yield data was recorded.

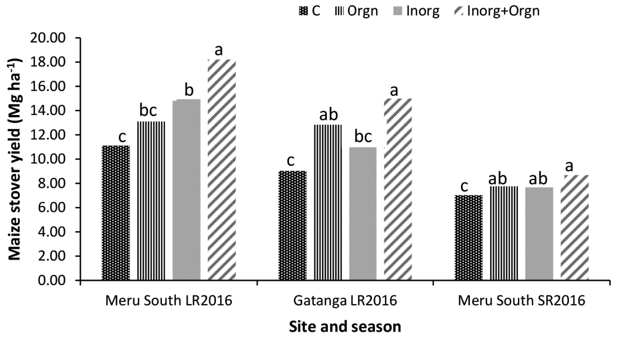

Fig. 3: *Maize stover yield (Mg ha^{-1}) during LR2016 and SR2016 cropping seasons in Meru South and LR2016 cropping season in Gatanga.*
Bars with the same letter are not significantly different at $p < 0.05$ *per sikte and season. C = control; Orgn = organic; Inorg = inorganic; Inorg+Orgn = inorganic+organic.*

3.4 Farmers' likelihood to uptake the implemented technologies

We found that, most farmers preferred technologies that integrated more than one soil fertility input, regardless of tillage method (Table 7). The most preferred technologies were CrMfMan, CrTiP, and CrTiMan. The farmers suggested that they preferred these technologies because the inputs were easily available, relatively easy to implement, and increased yields. Though farmers liked treatments with rock phosphate, their concern was that the input was not readily available in their immediate local markets. We observed that ConMf was preferred by a few farmers due to its ease of implementation but was unpopular among most farmers because of the acidifying effect and high cost of inorganic fertilisers.

4 Discussion

4.1 Effect of treatments on soil N, P and K

Total N was significantly higher under MinTill than in ConC in Meru South (Table 5) possibly due to decomposition and release of N. Incorporation of organic inputs could have enhanced soil microbial biomass (SMB) that catalysed mineralisation of organically-bound N into available form (Das *et al.*, 2018). Further, MinTill could have conserved soil moisture that favoured N mineralisation and build-up on the topsoil. Ability of MinTill to conserve soil moisture and the effect of soil moisture on SMB activities have been widely reported (Butcher *et al.*, 2020; Chen *et al.*, 2020; Fatumah *et al.*, 2020; Guo *et al.*, 2018).

Available P and exchangeable K were significantly higher under ConC than in MinTill in Meru South and Gatanga, which could be ascribed to the protection of the mineralised nutrients from inorganic and organic sources from run-off and leaching, respectively. Tilling the land could have accelerated the activities of acid-phosphomonoesterase that mineralised P as its biochemistry and biology respond rapidly to changes on the soil surface (Moreno *et al.*, 2021). This finding agrees with the results of Chen *et al.* (2020). Basal application on the planting holes at 0-15 cm could have led to the reported increase in the concentrations of P and K, as was in the case of a study by Yuan *et al.* (2020).

4.2 Effect of soil fertility inputs on primary soil nutrients

Tillage-SFIs interaction significantly increased N in Meru South, which could be attributed to increased water storage capacity under MinTill due to more water retention time and modification of soil surface with crop residues, which prevented soil loss through erosion with the findings of Nafi *et al.* (2020). The increased change caused by CrManLeg, CrMfMan, CrTiMan, and CrTiP on P and K in Meru South and P in Gatanga probably were because of the timing and application of the recommended fertiliser rates. Inorganic fertilisers were applied when the soil was moderately moist, which reduced the chances of losses through volatilisation and leaching due to exposure to sunlight (heat) and excessive rainfall, respectively. Further, the increase could be attributed to the high contents of P and K in *T. diversifolia* and goat manure that were readily mineralised. Manure and TSP fertiliser explained the significant increase in P in the two sites.

The soils in the two sites are acidic (Table 1); therefore, manure could have had a chelation effect by reacting with Al^{3+} liberating fixed P and made the applied P from TSP and soil exchange sites available. These results corroborate the findings of Serafim *et al.* (2013) on the short-term positive effect of manure on soil available P. It was, however, noted that P significantly declined under Mf and CrMf in Meru South and Gatanga, which could be explained by the low initial pH (Table 1) and mining through the harvested crop aboveground biomass (Table 6), in addition to crop residue which could have immobilised P. The finding of our study agrees with that of Cao *et al.* (2020), who found that soil Olsen-P declined under a treatment that combined maize stover and NPK fertiliser. Mucheru-muna *et al.* (2014) and Chatzistathis *et al.* (2020) also reported increased K as a result of *T. diversifolia* and goat manure application, respectively. Additionally, increased K under CrManLeg could be because of the high affinity of K by the legume crop and its enhanced solubilisation by rhizobacteria associated with leguminous crops, finding that agrees with Ghadam Khani *et al.*(2019); Solangi *et al.* (2019) and Wu *et al.* (2012).

Positive significant changes in P and K in Meru South and P in Gatanga observed under integrated sources of nutrients (ISFM) and sole application of organic inputs (Fig. 2b & c) could be because of differences in chemical compositions of goat manure and *Tithonia diversifolia* (Table 3) applied. An experiment conducted in Meru South by Mucheru-muna *et al.* (2014) intimated that *T. diversifolia* contained high P and K, reducing nutrient deficiencies in the soil. Moreover, mulching using maize stover (crop residue) could have also indirectly influenced P and K by moderating soil microclimate favourable for P and K mineralisation.

4.3 Maize grain and stover yields

The more grain yield during LR2016 than during SR2016 cropping season in Meru South was attributed to better rainfall amounts and distribution during LR2016 than SR2016 season (Table 4). A similar effect of rainfall amounts and distribution on seasonal maize grain yields was also reported by Mucheru-Muna *et al.* (2014) and Kiboi *et al.* (2017). Additionally, our findings concur with that of Okeyo *et al.* (2014), who in an on-station experiment conducted in Meru South (Kigogo), observed higher maize grain yields when rainfall was well distributed during vital maize growth stages.

The tillage method did not significantly affect maize grain and stover yield in the two sites across the two cropping seasons. This was probably due to the short experimentation period, which agreed with another short-term study that did not find a significant effect of the tillage method on maize yield (Idowu *et al.*, 2019). Conversely, there were higher

Table 7: *The number of farmers who responded positively to questions pertaining to their likelihood to continue practising the technologies they had implemented on their farms.*

	Would you continue implementing		*Have other farmers from the neighbourhood learnt from your field*		*Would you recommend the technology to other farmers?*	
Technologies	*Meru South*	*Gatanga*	*Meru South*	*Gatanga*	*Meru South*	*Gatanga*
ConMf	1	0	0	0	1	0
ConCrMf	2	1	0	0	1	1
ConCrMfMan	3	2	2	3	3	2
ConCrTiP	3	3	1	2	2	2
ConCrManLeg	2	2	0	4	3	3
ConCrTiman	3	3	3	1	3	3
MinTill	1	1	1	1	1	1
MinMf	1	0	0	0	1	0
MinCrMf	1	1	0	0	1	1
MinCrMfMan	3	2	2	2	3	2
MinCrTiP	3	3	3	2	3	3
MinCrManLeg	1	1	2	1	1	1
MinCrTiMan	3	2	1	3	3	2

ConC, conventional tillage (control); MinTill, minimum tillage (control); ConMf, minimum tillage + mineral fertiliser; ConCrMf, minimum tillage + crop residues + mineral fertiliser; ConCrMfMan, minimum tillage + crop residues + mineral fertiliser + goat manure; ConCrManLeg, minimum tillage + crop residues + goat manure + legume intercrop; ConCrTiman, minimum tillage + crop residue + *Tithonia diversifolia* + goat manure; ConCrTiP, minimum tillage + crop residues + *Tithonia diversifolia*+ rock phosphate; MinMf, minimum tillage + mineral fertiliser; MinCrMf, minimum tillage + crop residues + mineral fertiliser; MinCrMfMan, minimum tillage + crop residues + mineral fertiliser + goat manure; MinCrManLeg, minimum tillage + crop residues + goat manure + legume intercrop; MinCrTiMan, minimum tillage + crop residue + *Tithonia diversifolia* + goat manure; MinCrTiP, minimum tillage + crop residues + *Tithonia diversifolia* + rock phosphate.

grain and stover yields under MinTill except for maize stover yield in Meru South in the LR2016 cropping season, where ConC had more yields than MinTill. The finding of the current study could be a result of soil moisture retention under MinTill that enhanced the responsiveness of the applied inputs (Grabowski *et al.*, 2014; Lamptey *et al.*, 2020). The significant increase in maize stover yield under interaction between tillage and SFIs in Meru South during the LR2016 cropping season could be associated with increased soil moisture content and available plant nutrients from SFIs in soil solution as was in the case in the studies conducted by Haque *et al.* (2021) and Xu *et al.* (2020).

The higher maize yields under CrMfMan, CrTiMan, and CrTiP could be linked to readily available N (limiting in the two study sites) from inorganic fertilisers while the organic inputs could have released organic acids that complexed with Al^{3+} hence increased soil pH (Serafim *et al.*, 2013). This could have released the fixed P and made other nutrients available for crop uptake leading to increased maize yields, as was also reported by Mucheru-Muna *et al.* (2014). In addition to the effect of *Tithonia diversifolia*, rock phosphate could have slowly provided additional P leading to increased maize yield. Tao *et al.* (2015) also observed increased maize grain yields under crop residue, *Tithonia diversifolia*, and rock phosphates application.

The consistent superior maize yields under ISFM treatments (Fig. 2 & 3) could be because of the enhanced nutrient release through decomposition of organic inputs and increased nutrient use efficiency of inorganic fertilisers, a finding that agrees with the results of Kiboi *et al.* (2017, 2019) and Mutuku *et al.* (2020 b). The higher maize grain and stover yields in Meru South (Fig. 2 & 3) under sole inorganic fertiliser application could be associated with rapid release of readily available P and N that promoted root development and vegetative growth. Several studies have reported increased maize yields under sole application of inorganic fertilisers (Correndo *et al.*, 2021; Moretti *et al.*, 2020; Zhang *et al.*, 2021). We attributed the increased maize yields under sole application of organic inputs to improved water use efficiency, as was also reported by Zhao *et al.* (2021).

4.4 *Likelihood of uptake of the experimented ISFM technologies*

Almost all farmers who implemented ISFM (CrMfM, CrTiP, and CrTiMan) under both conventional and minimum tillage (Table 7) opined that not only would they continue using the various ISFM technologies but also will recommend these to other farmers. The fact that all those who implemented CrMfMan, CrTiP, and CrTiMan under both tillage methods favoured the technologies was an indicator of a high likelihood of the three technologies being taken up by farmers and was attributed to exemplary maize yield performances of those technologies (Table 6 and Fig. 2). These findings are consistent with those of Kiboi *et al.* (2017), where farmers preferred technologies that increased maize yields. Involving the farmers in the project design and implementation could also have influenced the farmers' decision for continued use of the various technologies. Farmers' participation in technology design and implementation was found to enhance the uptake of precision technology in sheep management by farmers (Kaler & Ruston, 2019). Farmers in the two sites typically practise conventional tillage; however, the willingness to uptake minimum tillage underpinned greater adaptability of the tillage method to a wide range of cropping systems, climatic and soil conditions (Derpsch *et al.*, 2010).

However, short-term threats to the uptake of technologies used in this study (Table 2) included the lack of willingness by farmers to engage in farmer-to-farmer learning. This is shown by the few numbers of neighbouring farmers who learned from the key informants (Table 7). Farmer-to-farmer learning plays a critical part in technology uptake by smallholder farmers (Nakano *et al.*, 2018). According to Wollni & Andersson (2014), uptake of ISFM can be enhanced through improved information availability within the neighbourhood and when the adopting farmers believe that their actions are meeting the expectations of their neighbours. On the other hand, though readily available, substituting maize stover for livestock feed was a potential barrier to the use of maize stover as soil input in both sites. The same finding was reported by Kiboi *et al.* (2017).

5 Conclusions

The technologies increased both soil nutrients (N, P, and K) and maize yields (grain and stover yields) compared to the control. However, even in the short-term, amending minimum tillage with integrated soil fertility management technologies was more efficient in increasing maize yields during low rainfall amounts than amending conventional tillage with the same technologies. Generally, integration of high levels of ISFM components led to the highest soil N, P, K, and maize yields. Based on maize performance and the fact that soils in the two studies are acidic and low in P, we recommend CrTiP as the most suitable technology for the two sub-Counties. A long-term study is, however, needed to evaluate performances of CrTiMan, CrTiP, CrMfMan, and CrManLeg under both tillage methods for site-specific recommendations taking into consideration rainfall variations.

Increased maize yields under various soil fertility amendments and farmers' participation in their implementation were critical in the high likelihood of CrTiMan, CrTiP, and CrMfMan being taken up by Meru South and Gatanga farmers. Participation in the execution of the treatments enhanced farmers' ability to evaluate the performance of these technologies and make an informed decision for continued use. However, to scale out these technologies, there is a need to strengthen the farmer-to-farmer learning institution. Using maize stover as livestock feed was the biggest limitation in the use of maize stover as a soil fertility amendment. Therefore, farmers should be trained on how to strike a balance between using maize stover as livestock feed and as a soil fertility input.

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Conflict of interest

Authors have declared that no competing interests exist.

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