Socio-ecological Niches for Minimum Tillage and Crop-residue Retention in Continuous Maize Cropping Systems in Smallholder Farms of Central Kenya

S.N. Guto, P. Pypers, B. Vanlauwe, N. de Ridder, and K.E. Giller*

ABSTRACT

Soil fertility gradients develop on smallholder farms due to preferential allocation of inputs. A multi-location on-farm trial was conducted in Meru South, Central Kenya whose overall aim was to test minimum tillage and crop-residue retention practices in socio-ecological niches across heterogeneous smallholder farms. We identified three soil fertility classes together with the farmers, namely: good, medium, and poor. In each soil fertility class, two tillage (minimum or regular) and two crop residue (removed or retained) practices were tested for four consecutive seasons. Maize (*Zea mays* L.) grain yields in the good fields were above 2.5 Mg ha^{-1} across cropping seasons and cumulated yields were not influenced by tillage or crop residue management. The grain yields in the medium fields ranged between 1.3 and 5.4 Mg ha^{-1} and were greater with crop residue retention. In the poor fields, grain yield was <3.6 Mg ha^{-1} and minimum tillage resulted in yield decrease while crop residue addition did not affect yields. Regular tillage and crop residue removal resulted in largest gross benefits in the good fields ($5376 ha^{-1}) while in the medium fields, minimum tillage with residue retention was most profitable ($3214 ha^{-1}). Retention of crop residues will give improved maize performance in the medium fields and the prevailing prices favor minimum tillage and crop residue retention. In the poor fields, the emphasis should be on the rehabilitation of soil physical and chemical attributes because none of the tillage and crop residue practices was profitable.

Continuous cropping and use of inappropriate farming practices has led to decline in soil fertility, accelerated soil erosion, and degradation of arable lands in East Africa. Minimum tillage and maintaining permanent soil cover are two approaches that can mitigate the effects of soil degradation. Minimum tillage can moderate soil surface conditions (Govaerts et al., 2009; Blanco-Canqui et al., 2010), improve crop yields (Bescansa et al., 2006) and increase net farm benefits due to reduced production costs (Chikoye et al., 2006; Sánchez-Girón et al., 2007). With permanent soil cover, diurnal soil temperature variations are dampened (O'Connell et al., 2004), surface runoff controlled (Biamah et al., 1993), soil drying slowed (Chakraborty et al., 2008), and crop rooting enhanced (Gill et al., 1996). Smallholder farmers can generate soil cover by growing cover crops, but foregoing food crops may not be attractive to the farmers (Giller, 2001). Crop residues from annual crops such as maize provide alternative sources of mulch but competing demands for their use as fodder provides a ready market for maize stover as feed (Bebe et al., 2002). This is particularly true in high rainfall areas of Kenya due to the dynamic and expanding smallholder dairy milk sector (Ndambi et al., 2007). Smallholder farmers thus face the challenge of producing sufficient crop residue biomass to cater for all of the competing demands on the farm.

The need to mitigate soil degradation while addressing on farm production constraints such as shortage of labor in smallholder farms open windows of opportunity for new approaches such as minimum tillage and permanent soil cover. But local conditions in smallholder farming systems that affect the performance of such technologies (Erenstein, 2003; Vanlauwe et al., 2006; Zingore et al., 2008) need to be considered (Knowler and Bradshaw, 2007) and deliberate adaptation efforts made. Local conditions are site-specific and depend on either the biophysical environment such as seasonal variability in rainfall, and inherent soil fertility status or socio–economic environments (labor and capital constraints). Giller et al. (2009) stressed the need to identify specific local conditions based on the concept of the socio-ecological niche (Ojiem et al., 2006) where such practices may be feasible within the diverse and heterogeneous smallholder farming systems of sub-Saharan Africa.

The effect of tillage and crop residue practices on maize performance on smallholder farms in Kenya is poorly studied. Previous investigations have focused on erosion control (Fox and Bryan, 1992), mitigation of greenhouse gases (Baggs et al., 2006), and water conservation in the marginal rainfall zones (Gicheru et al., 2004; Ngigi et al., 2006). We studied the effects of minimum tillage and mulching with crop residues on maize crop yield across heterogeneous smallholder farms within the subhumid agroecological zone of central Kenya. Our guiding hypothesis was that properly targeted tillage and crop residue practices can improve soil productivity but are feasible only in some socio-ecological niches within heterogeneous smallholder farms. The specific objectives were to: (i) identify different soil fertility classes for the

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Abbreviations: SOC, soil organic carbon.

Table 1. Characteristics of the different soil fertility classes in smallholder farms of Meru South District, Murugi Location of Central Kenya.

Field characteristics	Fertility class		
	Good	Medium	Poor
Distance from the homestead, m	<35	35–70	>70
Field slope, %	<5	5–12	>12
Average maize yield in the last two seasons, Mg ha^{-1}	Large (>3)	Medium (2–3)	Small (<2)
Cultivation intensity in the last 5 yr	High (fallow for <2 seasons)	Medium (fallow for 2–3 seasons)	Low (fallow for >3 seasons)
Infestation with weeds (proportion of plot area)	≤10%	10–20%	≥20%
Planting date	Early (dry-planted before onset of rains)	expected (within 1 wk after onset of rains)	Delayed (later than 1 wk after onset of rains)
Manure application rate, kg ha^{-1}	High (>100)	Low (<100)	None
Basal fertilizer application rate, kg ha^{-1}	High (>45)	Low (<45)	None
Use of anti stalk borer Dust, kg ha^{-1}	High (>5)	Low (1–5)	None

assessment of tillage and crop residue practices in smallholder farms, (ii) assess the impact of tillage and crop residue practices on soil productivity in different soil fertility classes and cropping seasons, (iii) determine cumulative costs and benefits from tillage and crop-residue practices for the different soil fertility classes, and (iv) match tillage and crop residue practices to socio-ecological niches in the smallholder farming systems.

MATERIALS AND METHODS

The Study Area

The study was conducted in Murugi Location, Meru South District in Central Kenya. The area has a high population density (800 people km^{-2}) and small farm sizes averaging between 0.5 and 3 ha per household (Jaetzold et al., 2006). Land is individually owned and smallholder mixed farming predominates. Maize and beans (*Phaseolus vulgaris* L.) are the most common food crops while coffee (*Coffea arabica* L.) or tea (*Camellia sinensis* L.) are the major cash crops. Majority of the farmers keep cattle (*Bos taurus*), sheep (*Ovis aries*), goats (*Capra hircus*) and poultry. There is no communal grazing for livestock and stall-feeding (zero-grazing) is common (Tittonell et al., 2010).

The soils are deep, well-drained Humic Nitisols with moderate to good inherent soil fertility (FAO, 1991) and a clayey texture (de Meestester and Legger, 1988) whose estimated water holding capacity is 175 mm m^{-1} depth for the upper 1.5 m of the soil (Landon, 1991). Mean annual rainfall is 1500 mm with a bimodal distribution: the long rains commence in mid-March and end in May, while the short rains start in mid-October and end in late November (Jaetzold et al., 2006). Mid-season drought spells commonly occur in both seasons and pose a risk to crop production. Daily rainfall was measured at strategic points in farmers' fields next to the experimental areas using rain gauges.

Experimental Design and Management

To understand spatial variability in soil fertility within smallholder farms in the study area and identify farmers to be involved in the experiment, we performed exploratory visits, reviewed secondary literature and interviewed key informants. An initial group of 30 farms was randomly drawn from a list of 100 farmers identified by the key informants. Farms were visited to assess suitability of the 30 preselected farms based on their willingness to participate in setting up, monitoring, and eventual evaluation of experiments. Subsequently, we identified 21 farms and revisited them to gather specific information on management of different fields within the farm to allow identification of fields for further experimentation. We deliberately timed the second farm visits to coincide with maize crop harvesting in the long rains 2007 season to observe crop performance in the different fields and discuss the cause(s) to the variations in crop performance with the farmers.

Three soil classes based on crop performance were delineated in consultation with the farmers that represented the spatial variability in soil fertility, namely: good, medium, and poor (Table 1). Good fields were closest to the homestead (<35 m), hence well-managed and most fertile as they received the bulk of the farm inputs. On the contrary, poor fields were furthest from the homestead (>70 m) and least fertile due to poor past management. The medium fields were intermediate in both distance from the homestead and management status. Fields in the good class had substantial amounts of soil organic matter, available P, favorable soil pH, and CEC (Table 2). The fields in the poor class had the least soil organic C, available P, CEC, and were more acid.

Farm fields representing the identified soil fertility classes distributed across 16 farms were selected for setting up the experiments. A 2 × 2 × 3 full factorial experiment was

Table 2. Initial selected soil chemical properties of the topsoil (0–15 cm) for the three soil fertility classes (n = 6).

Fertility class	Organic C	Total N	Available P	Soil pH	CEC	Texture		
						Clay	Silt	Sand
	%		mg P kg^{-1}		cmol$_c$ kg^{-1}		g kg^{-1}	
Good	2.18	0.22	31.9	5.94	15.50	37.0	41.0	22.0
Medium	2.06	0.21	17.3	5.59	13.17	35.5	42.1	22.4
Poor	1.54	0.17	10.8	4.85	11.00	36.3	41.0	22.7
SED	0.30*	0.02*	6**	0.18*	1.4*	1.4^{ns}†	2.8^{ns}	0.8^{ns}

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
*** Significant at $P \leq 0.001$.
† LSD: ns, not significant.

established comparing two tillage (minimum or regular) and two crop residue (removed or retained) practices across three soil fertility classes (good, medium, and poor). A split-plot design was used whereby the soil fertility classes were replicated six times in main plots while tillage and crop residue practices were replicated four times in subplots within each of the main plots. A field within a farm was the main plot while plots demarcated within the field were subplots. The trial was maintained for four consecutive seasons (short rains 2007 to long rains 2009) but crop residue practices were only compared after the first season when residues had been generated.

The trials were established jointly with farmers in the short rains 2007 to expose farmers to the technology for their evaluation. Thereafter, the only operation performed by the farmers was tillage using a hand hoe on the tillage treatment plots. A field assistant and three casual workers performed all other field operations (herbicide application, planting, weeding, and top-dressing) across the different fields to ensure consistent management across the experiment.

At the onset of each season, in the plots under minimum tillage, a postemergent application of glyphosate (500 g L^{-1} active ingredient) at the rate of 1.5 to 2 L ha^{-1} was used to control early season weeds. Control of mid- to late-season weeds was done manually with minimal soil disturbance and weeds left on the soil surface. Land preparation in plots with tillage was by forked hoe (10–15-cm depth). Maize (Dekalb variety 8031) was grown at an inter-row spacing of 75 cm and an intra-row spacing of 25 cm (5.3×10^4 plants ha^{-1}). Weeding was done twice with a machete (5–7-cm depth). Fertilizer was applied in all plots [30 kg P ha^{-1} as triple superphosphate (TSP) at planting and 50 kg N ha^{-1} as urea in two equal splits after the first and second weeding)].

DATA COLLECTION

Soil Data

Before trial establishment, composite soil samples were taken from 0- to 15-cm depth in all experimental fields for field characterization. In the last season soil samples were taken separately from each treatment in the 0- to 6-cm depth and soil C measured (corrected for bulk density).

Bulk density, penetration resistance, and infiltration rate were determined in the last season of the trial (long rains 2009) in four fields selected randomly from the six fields in each class. Topsoil bulk density was determined by clearing plant residues and weeds from the soil surface, and gently pushing duplicate cores (5.7-cm depth, 121 cm^3) into the soil in each plot. The soil samples were dried for 48 h at 105°C and bulk density calculated.

Soil water infiltration was determined in the last season (long rains 2009) in triplicate for each plot using a single plastic ring (19 cm diam. and 29 cm height), inserted 2 cm into the soil. Fresh water (3 L) was released into the plastic ring and infiltration time measured at 1 cm (water column) intervals initially, and at 0.5-cm intervals later (subject to intensity of infiltration). Measurements were repeated until all the water had infiltrated or a steady-state rate was reached.

Topsoil (0–10-cm depth) penetration resistance was measured in the last season (long rains 2009) using a hand ring cone penetrometer (Type 1b) (0.05 cm cone diam. and 1.0 kg cm^{-2} spring) in three positions within each plot. The moveable penetrometer ring was adjusted to zero and the cone pushed at a constant speed into the soil. A reading was taken showing maximum compression of the spring and penetration resistance determined using the equation $PR = D \times F/d$ where PR = penetration resistance (kg cm^{-2}), D = Penetrometer sliding distance (cm), F = Spring kilogram force (kg cm^{-2}) and d = Cone diameter (cm). Gravimetric soil water content was measured simultaneously when the penetration distance measurements were performed to the same depth (0–10 cm) and used to adjust the soil strength measurements in case the two parameters were significantly correlated.

Crop Data

Maize grain was harvested in each plot, weighed, and corrected for moisture content by a multi-grain moisture meter (Dickey John multi-grain moisture tester, Dickey John Corp., Auburn, IL). Yield is reported on a dry matter basis. Maize stover was harvested in each plot and weighed and subsamples oven-dried (65°C) for 48 h to correct stover yields for moisture content.

In experimental plots with crop residues retained, residue cover was determined every 2 wk in the short rains 2008 and long rains 2009 using the line transect method (Laflen et al., 1981) modified to suit the small plots. A 5 m long nonelastic cord with marks at intervals of 25 cm was randomly placed across the plots thrice. The number of cord marks that touched crop residue on the soil was counted each time. Residue cover was calculated as the ratio between the counted cord marks and total markings.

Economic Data

Farm gate input and output prices were obtained from a survey of 25 farmers in the experimental area (Table 3). For labor (nonpurchased input), estimates were based on direct observations on work rates by casual workers in the fields, but corroborated with information gathered from neighboring farmers and confirmed with key informants before use in economic analysis. Field costs of labor for specified field operations were based on the prevailing field labor price (Table 3). Labor and non-labor input costs were summed up to obtain treatment total variable costs. Treatment gross benefits were calculated by multiplying the market prices with corresponding treatment yields.

Data Analysis

Effects of soil fertility class, tillage, and crop residue practice on maize grain and stover yield, residue cover, soil physical attributes, and the economic parameters (total variable costs, gross benefits, and benefit/cost ratio) were determined by ANOVA using the linear mixed model in Genstat Discovery 3 statistical package. Soil fertility class, tillage, and crop residue practices were the fixed parameters and plots nested within fields were random parameters. The protected LSD mean separation procedure at $P \le 0.05$ was used to compare treatment means. The benefit/cost ratio analysis (CIMMYT, 1988, p. 63–71) was used to assess the profitability of the tillage and crop residue practices (ratio's ≥2 were profitable).

RESULTS

Grain Yields

The maize crop stand ranged between 80 and 95% of the targeted maize population (5.3×10^4 plants ha^{-1}) for all the experimental fields and was satisfactory across the four cropping seasons. There was effective early season control of most annual and perennial weeds in minimum tillage plots following postemergent

Table 3. Input and output items, amounts used and prevailing average item prices.

Products	Item	Purpose	Unit	Amount	Price
				ha^{-1}	U.S.$
Inputs					
	Touch-down	Weed control	liter	1–3	17 (4.5)†
	Bull-dock powder	Anti-stalk borer dust	kilogram	8–12	1.13 (0.01)
	Triple superphosphate	Basic fertilizer	kilogram	30	0.96 (0.21)
	Urea	Top dress fertilizer	kilogram	60	0.63 (0.06)
	Dekalb 8031	Maize planting seed	kilogram	20–25	2.00 (0.50)
	Labor		hour		0.29 (0.11)
		Tillage		94–126	
		Spraying		34–44	
		Planting		220–252	
		First weeding		90–157	
		Second weeding		50–75	
		First top-dress		63–94	
		Second top-dress		63–94	
		Harvesting		152–214	
		Crop residue cutting/collection		157–180	
		Crop residue chopping		126–150	
Outputs					
	Maize grain	Food	kilogram		0.32 (0.12)
	Maize residue	Feed	kilogram		0.02 (0.003)

† Numbers in parentheses are the standard error of the mean.

application of the herbicide (glyphosate). Some tolerant perennial weeds (e.g., *Commelina* sp.) were controlled manually.

The first season (short rain 2007) was the wettest season (Fig. 1) and the rainfall distribution even without periods of drought. Mean seasonal grain yields were 2.6 Mg ha^{-1} across soil fertility classes, tillage, and residue practices and decreased steadily from the good to poor fields (Table 4). The harvest index ranged from 36 to 39% across soil fertility classes and tillage and crop residue practices (data not shown). Being the first season, there were no crop residue effects to test. Soil fertility class and tillage practices had significant interactive effects on crop yield (Table 4). Fields in the good and medium classes had greater yields with regular tillage than under minimum tillage but tillage practice did not affect yield in the poor fields.

The crop suffered mid-season moisture stress for 5 wk during the long rain 2008 season which was the driest season (Fig. 1). Mean maize yield was 1.7 Mg ha^{-1} across soil fertility classes,

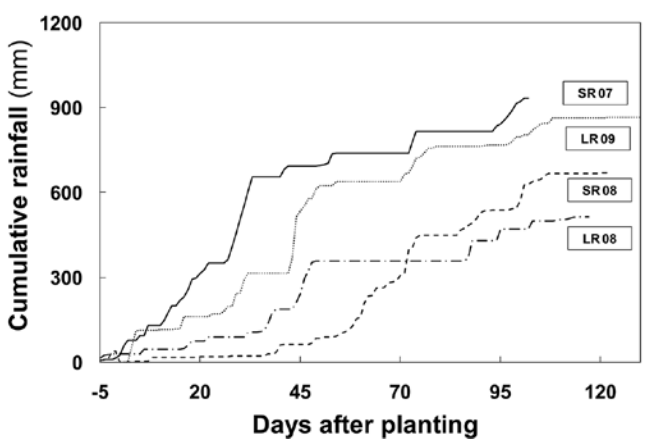

Fig. 1. Cumulative rainfall (mm) for the four consecutive seasons (short rains 2007–long rains 2009) in the experimental area.

tillage and crop residue practices. The harvest index ranged widely between 36 and 48% across the experimental treatments (data not shown). There were significant ($P < 0.01$) soil fertility class and tillage interactive effects on crop yields (Table 4). Fields in the good class had significantly greater yields under minimum tillage than with tillage and vice-versa for those in the poor soil fertility class. The grain yields for the fields in the medium class were similar across tillage and crop residue practices.

There was inadequate rainfall after maize planting in the short rain 2008 season (Fig. 1) but the crop recovered from this early setback to attain a mean grain yield of 2.7 Mg ha^{-1} with an average harvest index of 36% (data not shown) across soil fertility classes, tillage, and crop residue practices. There were no significant differences in average grain yield between the good and medium fields across tillage and residue practices (Table 4). Soil fertility class had significant interactive effects with either tillage or crop residue practice (Table 4). There were greater grain yields in the good and medium fields with minimum tillage and retention of crop residue whereas in the poor class, minimum tillage gave strongly reduced yields.

Rainfall during the long rains 2009 season was evenly distributed without intraseasonal drought and an average grain yield of 4.3 Mg ha^{-1} was attained across soil fertility classes, tillage and residue practices. The crop stand in the good fields under minimum tillage and residue retention had slower early season growth with symptoms of N deficiency (yellow leaves with a score of 3–4 on an ordinal scale of 0–10), which translated into a substantial yield reduction.

The three-way interaction between soil fertility class, tillage, and crop residue practice was significant (Table 4). In the good fields, maize under minimum tillage gave 1.2 Mg ha^{-1} less grain yield with crop residue retention as opposed to removal, while the same treatment combination in the medium fields increased grain yield by 0.6 Mg ha^{-1}. As in the previous season

Table 4. Seasonal grain yields as affected by soil fertility classes (n = 6), tillage and crop residue practices (n = 24) for four seasons (short rains 2007–long rains 2009).

Fertility class	Tillage	Residue	Grain yield			
			Short rains 2007	Long rains 2008	Short rains 2008	Long rains 2009
			Mg ha^{-1}			
Good	With	Removed	4.51	2.33	2.99	6.55
		Retained	–	2.12	3.20	6.25
		Mean	4.51	2.23	3.10	6.40
	Minimum	Removed	3.78	2.57	3.27	6.15
		Retained	–	2.94	3.84	4.97
		Mean	3.78	2.76	3.56	5.56
	Mean		4.15	2.49	3.33	5.98
Medium	With	Removed	2.70	1.28	2.76	5.26
		Retained	–	1.63	2.67	5.48
		Mean	2.70	1.46	2.72	5.37
	Minimum	Removed	2.27	1.14	2.93	5.20
		Retained	–	1.22	3.43	5.79
		Mean	2.27	1.18	3.18	5.50
	Mean		2.49	1.32	2.95	5.43
Poor	With	Removed	1.09	1.42	2.09	4.28
		Retained	–	1.38	2.11	3.89
		Mean	1.09	1.40	2.10	4.09
	Minimum	Removed	1.14	0.96	1.24	3.03
		Retained	–	1.01	1.38	3.07
		Mean	1.14	0.99	1.31	3.05
	Mean		1.12	1.19	1.71	3.57
SED						
Fertility class (F)			0.34***	0.36***	0.52***	1.12**
F × Tillage (T)			0.44*	0.40**	0.28***	0.40***
T × Residue (R)			–	1.00	0.24*	1.96
F × T × R			–	2.18	3.00	0.56*
Cumulative rainfall, mm			933	514	670	866
Rainfall distribution			Even	5 wk of mid-season drought	2 wk of early season drought	Even

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
*** Significant at $P \leq 0.001$.

(short rains 2008), there were no significant differences in average yield between fields in the good and medium classes across tillage and crop residue practices (Table 4).

The cumulative grain yields across the four seasons were significantly affected by the three-way interaction of soil fertility class, tillage, and crop residue practice (Fig. 2). The overall responses for all the treatment combinations in the good fields were similar whereas the best crop performance in the medium fields was with crop residue retention, and regular tillage in the poor fields enhanced crop performance.

Residue Cover

The initial residue cover increased linearly with increase in stover yields (Fig. 3) and the relationship was strong and significant (R^2 = 0.95**) across soil fertility classes and tillage practices. The amount of residue cover declined at a faster rate early in the season (2.03– 3.72% wk^{-1}) than toward the end of the season (0.063–0.097% wk^{-1}) in all of the soil fertility classes (Fig. 4).

In the medium and good soil fertility classes, there was a carryover of 6 to 24% residue cover in short rains 2008 and 12 to 44% in long rains 2009, with greater residue quantities under minimum tillage than with tillage. There was no residue cover in the poor fields by the 10th week after planting in short rains 2008 and the 12th week after planting for the long rains 2009 with tillage. At the end of both seasons, a lower soil cover (1–4%) remained in the poor fields under minimum tillage (Fig. 4).

Soil Chemical and Physical Attributes

The soil organic carbon (SOC) in the last season in the surface 6 cm increased from the poor to the good fields across the tillage and crop-residue practices (Table 5). Across crop residue practices, SOC stocks were larger under minimum tillage in the good soil fertility class but independent of tillage in the medium soil fertility class while it was smaller with minimum tillage in the poor soil fertility class. Across tillage practices, retaining crop residue increased SOC by about 1.5 Mg ha^{-1} in the good and medium soil fertility classes over the four seasons whereas in the poor fields, residue retention had a marginal effect on SOC.

The soil bulk density increased significantly from the good to the poor soil fertility classes (Table 5) across tillage and crop residue practices while infiltration rate increased in the opposite direction. The bulk density was significantly greater under minimum tillage than with tillage while the infiltration rate was greater with tillage than under minimum tillage independent of the soil fertility classes.

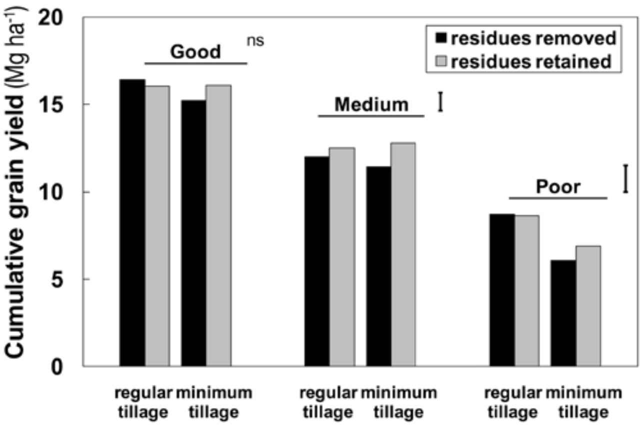

Fig. 2. Cumulative maize grain yields for four seasons (short rains 2007-long rains 2009) as affected by soil fertility class, tillage, and crop residue practices. Error bars represent LSDs for effects of tillage and crop residue practice in the "medium" and "poor" class, respectively at $P \leq 0.05$.

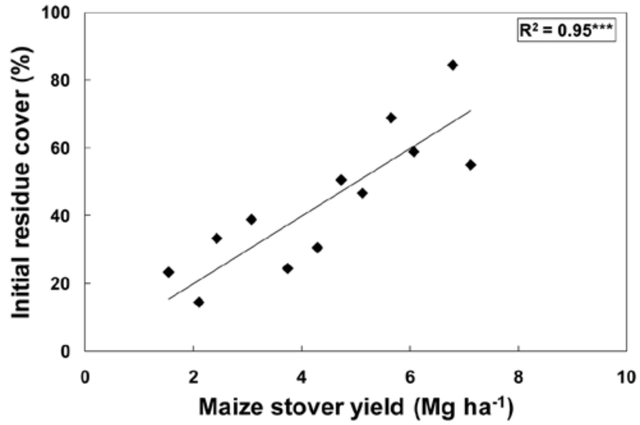

Fig. 3. Relationship between initial crop residue cover at the onset of the cropping season and stover yields for the preceding season [Data for long rains 2008– short rains 2008 (stover) and, short rains 2008– long rains 2009 (% crop residue cover)].

There was no significant relationship between penetration resistance and soil moisture content and penetration resistance ranged between 1.2 and 2.4 kg cm^{-2} across soil fertility classes, tillage, and crop residue practice. The penetration resistance increased from the good to the poor fields (Fig. 5) but was greater with minimum tillage for the fields in the poor class. Residue retention reduced the penetration resistance for fields in the medium class, but penetration resistance for the fields in the good class was independent of either tillage or crop residue practice.

Total Variable Costs, Gross Benefits, and Benefit/Cost Ratios

Across field classes and tillage practice, the removal of crop residues required \$1335 ha^{-1} labor costs while \$1278 ha^{-1} was spent on labor if crop residues were retained (Table 6). Across field classes and crop residue practices, labor costs were \$1195 and 1418 ha^{-1} for minimum and regular tillage, respectively. The total variable costs across field classes and crop residue practice were \$2050 for minimum and 2193 ha^{-1} for regular tillage. Further, between crop residue practices but across field classes and tillage practice, the total variable costs were \$2141 and 2103 ha^{-1} for crop residue retention and removal practices, respectively.

Across tillage and crop residue practices, the gross benefits reduced gradually from the good to the poor fields. The benefit/cost ratio differed significantly between soil fertility classes, tillage, and crop residue practices (Table 6). Benefit/cost ratios were above 2 in the good fields for all tillage and crop residue practices while in the medium fields, only minimum tillage with crop residue retention had its ratio above 2. In the poor fields, all the tillage and crop residue practices had benefit/cost ratios below 2.

DISCUSSION

Effects of Tillage and Crop Residue Practices on Grain Yields

There were positive effects of minimum tillage on grain yield in good fields during the long rains 2008, while in the short rains 2008 there were positive interactive effects between minimum tillage and crop-residue retention in both good and medium fields. The maize crop experienced mid-season drought in the long and short rain seasons of 2008 (Fig. 1) and since fertilizer application rates were constant across the soil fertility classes, it is likely that improved water availability caused the positive minimum tillage and crop residue retention effects. Minimal soil disturbance coupled with the increased soil cover resulting from retention of crop residues may have decreased direct evaporation of water from the soil surface, as shown elsewhere (Thierfelder and Wall, 2009). Rockstrom et al. (2009) have reported yield improvements under minimum tillage with decrease in rainfall across East and Southern Africa.

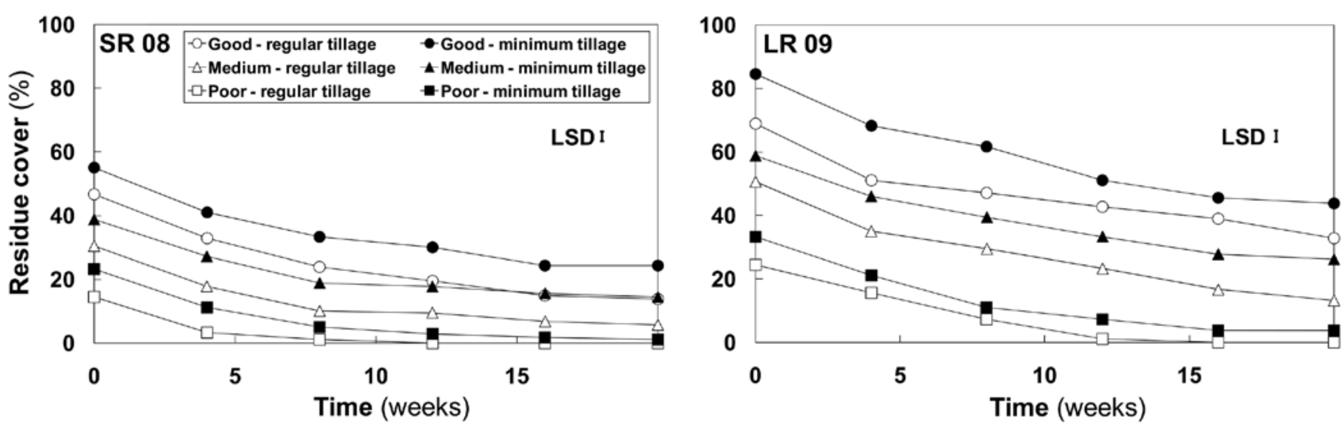

Fig. 4. Percent crop residue cover for the short rains 2008 and long rains 2009 as affected by soil fertility class and tillage practice. Error bars represent LSDs for the interactive effect of soil fertility class, time and tillage practice at $P \leq 0.05$.

Table 5. Top-soil (0–6 cm) means of soil organic carbon, bulk density, infiltration and pore space as affected by soil fertility classes (*n* = 4), tillage and crop residue practices (*n* = 16) at the end of the long rains 2009 season.

Fertility class	Tillage	Infiltration	Pore space	Bulk density	Soil organic C: Residue removed	Soil organic C: Residue retained	Soil organic C: Mean
		mm h^{-1}		g cm^{-3}		Mg ha^{-1}	
Good	With	126	0.51	1.12	16.1	17.4	16.7
	Minimum	107	0.52	1.14	17.8	19.5	18.7
	Mean	117	0.52	1.13	17.0	18.4	17.7
Medium	With	76	0.50	1.24	15.3	17.1	16.2
	Minimum	71	0.50	1.25	15.8	17.3	16.5
	Mean	73	0.50	1.25	15.6	17.2	16.4
Poor	With	64	0.49	1.30	9.95	12.0	11.0
	Minimum	37	0.49	1.33	12.3	12.7	12.5
	Mean	50	0.49	1.32	11.1	12.3	11.7
LSD							
Fertility class	(F)	18***	0.012***	0.022***		0.86**	
Tillage	(T)	16*	0.01^{ns}	0.018**		0.64**	
Residue	(R)	18^{ns}†	0.01^{ns}	0.018^{ns}		0.64*	
F × T		28^{ns}	0.018^{ns}	0.030^{ns}		1.16*	
F × R		28^{ns}	0.018^{ns}	0.030^{ns}		1.16*	
F × T × R		40^{ns}	0.024^{ns}	0.044^{ns}		1.60*	

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
*** Significant at $P \leq 0.001$.
† LSD: ns, not significant.

Maize yields in the poor fields were greater with regular tillage (Table 4). This is in line with results from other studies (e.g., Rieger et al., 2008; Verch et al., 2009), although these authors attributed poor crop performance with zero tillage to reduced plant density, which was not the case in our experiments. Franzluebbers (2004) suggested that not tilling the soil can result in compaction immediately below the surface during initial seasons. In the poor fields, penetration resistance was much stronger with minimum tillage (Fig. 5), the soils were poor in organic matter (Table 2) and there was sparse residue cover (Fig. 3)—much less than the minimum 30% recommended (Hobbs et al., 2008) that can lead to soil degradation and yield reduction (Govaerts et al., 2009). Under these conditions, maize yielded much better with regular tillage, presumably due to the loosening of the soil, which increases soil water infiltration, stimulates mineralization of N from the soil organic matter and creates a more favorable environment for root growth.

In the long rains 2009, minimum tillage and residue retention gave the smallest yields in the good fields but the greatest yields in the medium fields. Among the three soil fertility classes, the largest quantity of residue carryover from the previous season occurred in the good fields (Fig. 3). The large amounts of cereal crop residues with a high C/N ratio may have induced N immobilization in the good fields leading to less available N for the maize crop (Palm et al., 2001). Minimal soil disturbance (with minimum tillage) coupled with the good rains may have led to excess soil moisture that can accelerate loss of nutrients by leaching or denitrification. In medium fields, residue quantities were lower and both residue retention and minimum tillage had positive effects on yields. The benefits could have been due to reduced

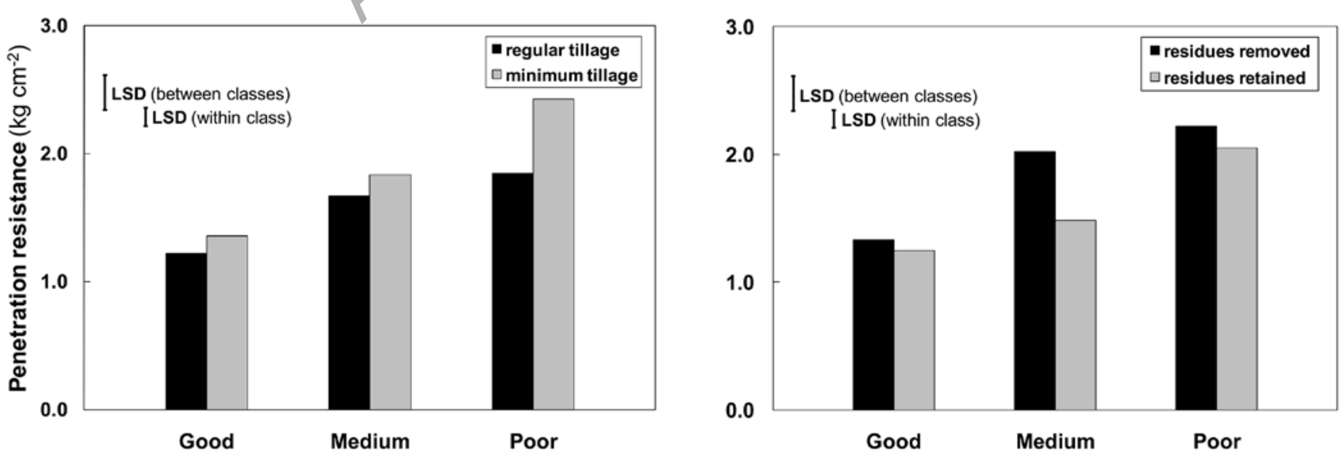

Fig. 5. Penetration resistance (kg cm^{-2}) for different soil fertility classes as affected by tillage and crop residue practices at the end of the long rains 2009 season. Error bars represent LSDs of tillage or crop residue practice effects between or within soil fertility classes at $P \leq 0.05$.

Table 6. Cumulative costs and benefits as affected by soil fertility classes (*n* = 6), tillage and crop residue practices (*n* = 24) for four seasons (short rains 2007 to long rains 2009).

Fertility class	Tillage	Residue	Labor	Labor costs	Non-labor costs)	Total costs	Gross benefits	Benefit/cost ratio
			h ha^{-1}	$ ha^{-1}				
Good	With	Removed	4950	1435	772	2207	5963	2.7
		Retained	4843	1404	773	2177	5336	2.5
	Minimum	Removed	4194	1216	843	2059	5528	2.7
		Retained	3917	1136	860	1996	5521	2.8
	Mean		4476	1298	812	2110	5587	2.7
Medium	With	Removed	4969	1441	769	2210	3985	1.8
		Retained	4761	1381	799	2180	3671	1.7
	Minimum	Removed	4219	1223	837	2060	3942	1.9
		Retained	4106	1191	884	2075	4090	2.0
	Mean		4514	1309	822	2131	3922	1.8
Poor	With	Removed	5050	1465	769	2234	3332	1.5
		Retained	4761	1381	772	2153	2808	1.3
	Minimum	Removed	4231	1227	848	2075	2690	1.3
		Retained	4055	1176	862	2038	2451	1.2
	Mean		4525	1312	813	2125	2820	1.3
Means								
	With		4889	1418	776	2193	4183	1.9
	Minimum		4120	1195	856	2050	4037	2.0
		Removed	4602	1335	806	2141	4240	2.0
		Retained	4407	1278	825	2103	3980	1.9
LSD								
Fertility class		F	100$^{\text{ns}}$†	29$^{\text{ns}}$	10$^{\text{ns}}$	21$^{\text{ns}}$	266**	0.012***
Tillage		T	81**	24***	8***	17***	217$^{\text{ns}}$	0.095$^{\text{ns}}$
Residue		R	81***	24**	8*	17**	217$^{\text{ns}}$	0.095$^{\text{ns}}$
		F × T × R	199$^{\text{ns}}$	58$^{\text{ns}}$	10$^{\text{ns}}$	41$^{\text{ns}}$	532$^{\text{ns}}$	0.233**

* Significant at $P \leq 0.05$.
** Significant at $P \leq 0.01$.
*** Significant at $P \leq 0.001$.
† LSD: ns, not significant.

run-off losses, resulting in increased plant-available water that improved fertilizer use efficiency.

Across tillage and crop residue practices but within each of the soil fertility classes, grain yield increased across the four seasons (Table 4). There were no significant yield differences between the good and medium fields in the third and fourth seasons. The poor fields had consistently smaller yields compared with the medium and good fields. The most probable cause for reduced performance in the poor fields was the poor soil organic matter status and low soil cover that affects soil structure, soil moisture evaporation, and nutrient availability.

The cumulative grain yields varied significantly between soil fertility classes and cropping seasons, but were either independent of tillage and crop residue practice in the good fields or marginally influenced by tillage and crop residue practice in the medium and poor soil fertility classes (Fig. 2). Cropping season differences and inherent soil fertility status had a strong influence on the effects of tillage and crop residue practices on maize performance. Franzluebbers (2004) and Monneveux et al. (2006) have reported lack of consistent tillage practice effects on crop performance. Our results indicate that the inherent soil fertility status of the fields has a strong influence on the effects of tillage and crop residue practice on crop yield and this provides insight into the inconsistent effects reported in the literature.

Tillage and Crop Residue Practice Effects on Soil Properties

The SOC in the surface layer (0–6-cm depth) was greater with minimum tillage across the soil fertility classes (Table 5). Minimum tillage can increase soil organic matter in the soil surface by better conservation of organic residues within the field, greater physical protection of residues due to lack of erosion and reduced soil mixing. The rates of soil organic matter storage under minimum tillage in this study maybe overstated because the entire plow depth was not considered. Govaerts et al. (2009) in a review report increased soil organic matter for some soils under minimum tillage in the upper soil layers rather than the entire soil profile.

The positive effects of crop residues on crop growth appear not to have been necessarily linked to N supply but rather to positive effects on soil structure by increased soil porosity and water infiltration (Table 5), ease of root penetration (Fig. 5) and reduced soil surface evaporation (Schwartz et al., 2010). These tallies with the observations made by de Ridder and van Keulen (1990). The lack of overall positive effects of minimum tillage in good fields maybe due to the inherently high initial SOC such that the soils are not likely to obtain additional benefits with adoption of minimum tillage because inherent soil characteristics were already good.

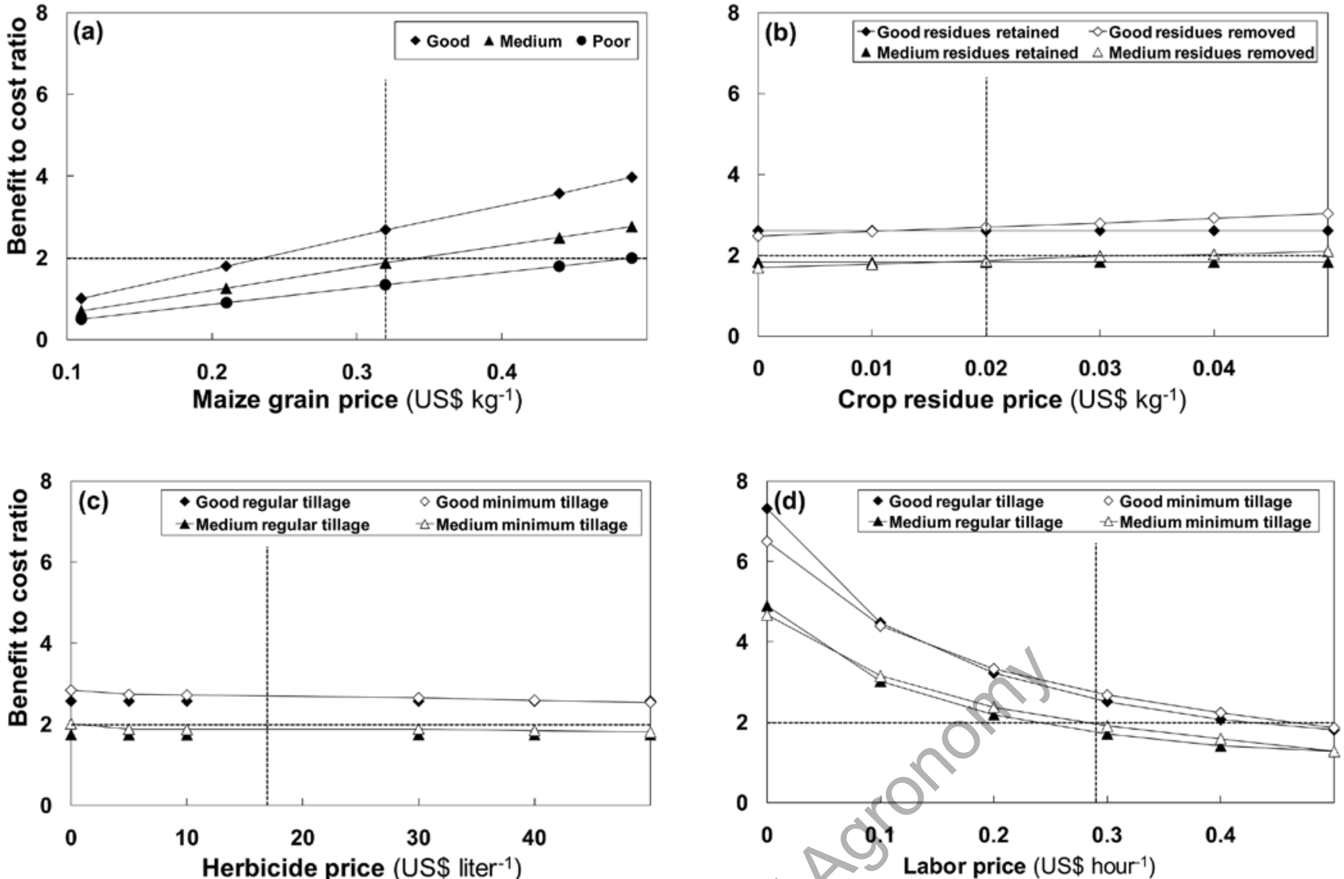

Fig. 6. Sensitivity of benefit/cost ratios to the price of (a) maize grain, (b) crop residues, (c) herbicide, and (d) labor. The dotted vertical lines indicate the prevailing prices for the items while horizontal lines represent the lowest profitable benefit/cost ratio.

Soil Fertility Class and Tillage Practice Effects on Crop Residue Cover

Across the soil fertility classes and seasons (short rains 2008 and long rains 2009), initial residue cover increased linearly with increased stover yields (Fig. 3). Other studies have reported an asymptotic positive relationship (e.g., Steiner et al., 2000). The difference would be because of a delay between crop harvesting and the time of initial residue cover measurement (1–3 mo; longer for the long rain seasons) during which some of the residue decomposes as livestock are not allowed to graze in cropping fields in the study area. Bationo et al. (1999) reported that 21 to 39% of the stover production at harvest time is available as mulch at the onset of subsequent season in the Sahel region of West Africa, where livestock graze freely, a much larger reduction in soil cover than that we observed in central Kenya. Besides, Kihara et al. (2008) report faster rates of crop residue depletion due to termite activity in the semiarid Western Kenya, which was rare in our experiments.

Residue cover was greater under minimum tillage than with tillage across the soil fertility classes (Fig. 4). Tillage involves soil movement that incorporates crop residues, though the degree of incorporation was limited in this study because of the implements used (a forked hand-hoe and machete). In poor fields with low crop residue yields, soil disturbance was sufficient to incorporate a greater fraction of the crop residues and maintaining adequate soil cover was difficult. Inadequate soil cover in the poor fields would increase water loss and create unfavorable conditions for crop growth and development.

The SOC in the soil surface was greater with residues retained compared with removal (Table 5) in the good and medium soil fertility classes. Removal of the crop residues has implications for soil organic matter dynamics as it represents a loss of carbon input to the soil resulting in a decline in soil organic matter compared with crop residue retention (Kapkiyai et al., 1999). In the poor soil fertility class, there was a modest change in surface SOC (Table 5) regardless of the crop residue practice due to the small amounts of crop residues generated.

Economic Performance of The Tillage and Crop Residue Practices

Across field classes and tillage practices, crop-residue removal required 4% more labor compared with retention (Table 6). Removal of crop residues required more manual labor for cutting and collecting crop residues as opposed to chopping the residues when retained (Table 3). Across field classes and crop residue practices, minimum tillage had 28% less labor requirement over regular tillage while non-labor costs were 7% higher for minimum tillage over regular tillage. Regular tillage required more labor for manual land preparation and hand weeding (Table 3) while greater non-labor costs were incurred with minimum tillage for the purchase of herbicides. In an assessment of improved tillage and crop residue practices in Zambia and Zimbabwe households, Mazvimavi and Twomlow (2009) attributed similar decreased costs to less weed density due to accumulation of crop residues and acquisition of experience in the technology. By contrast, Rockstrom et al. (2009) found a 30% increase in weeding costs with minimum tillage due to weed management problems even though herbicides were used.

Across tillage and crop residue practices, gross benefits were greatest in the good fields, least in the poor fields but intermediate for medium fields (Table 6). All the tillage and crop residue practices were profitable in the good fields since the benefit/cost ratios were above two (Table 6). In the medium fields, only minimum tillage with crop residue retention was profitable. For the poor fields, none of the tillage and crop residue practices were profitable. The benefit/cost ratio was more sensitive to changes in the price of labor and maize grain but less sensitive to herbicide and crop residue prices (Fig. 6). The economic benefits in this study are comparable to those previously obtained in the region by Mucheru-Muna et al. (2010).

Identification of Socio-Ecological Niches for Tillage and Crop Residue Practices

Socio-ecological niches can be identified because none of the tillage and crop residue practices was consistently efficient for the different cropping seasons across soil fertility classes. Maize grain is a staple food in the study area and the farm gate prices varied widely (Table 3). Across tillage and crop residue practices, maize grain from the good fields will be profitable if the price is above \$0.26 kg^{-1} whereas in the medium fields, the price should be above \$0.37 kg^{-1} (Fig. 6). For the poor fields, maize production was not profitable even with the highest projected farm gate prices in the study area. Minimum tillage and crop residue retention cannot be therefore implemented in the poor fields before investments in rehabilitation of soil attributes for better crop performance. Options to do this could be crop residue transfer from the good to the poor fields (taking into consideration competing on-farm uses: Giller et al., 2006; Tittonell et al., 2009) or use of legume cover crops (Baijukya et al., 2005) that involve substantial investment of scarce labor without immediate returns.

In the good fields, the choice between crop residue retention and removal will depend on the amount of N fertilizer the farmers can afford to apply. This is because enhancement of crop performance by crop residue retention was smaller in seasons with unfavorable rainfall compared with yield reduction due to N immobilization when rainfall was adequate. Farmers should therefore retain crop residues in the good fields on the condition that they apply sufficient N fertilizer. In addition, the choice will depend on the profitability from sale of crop residues influenced by the prevailing prices. Crop residues can be retained if the prevailing local price is below \$0.012 kg^{-1} (Fig. 6). The choice between regular and minimum tillage will depend on the price of labor (Fig. 6). Minimum tillage can be adopted if prevailing labor price is above \$0.14 h^{-1} (Fig. 6). Since the prevailing local prices for labor and crop residues are above the identified margins (Table 3), retaining crop residues and minimum tillage may not be economically attractive under the present conditions in the good soil fertility class.

In the medium soil fertility class, crop residue retention gave significantly greater yields across the different tillage practices (Fig. 3). Considering income from selling crop residues, residues can be retained if their price is below \$0.016 kg^{-1} (Fig. 6). The decision as to whether to combine it with minimum or regular tillage will depend on the price of labor. Minimum tillage may be economically attractive in the medium fields provided labor price is above \$0.06 h^{-1} (Fig. 6). Crop performance and, the prevailing prices of crop residues and labor (Table 3) make retention of crop residues and minimum tillage feasible in the medium soil fertility class.

CONCLUSIONS

The effects of tillage and crop residue practices on maize performance varied strongly across soil fertility classes and cropping seasons. We can therefore formulate differentiated recommendations for tillage and crop residue practices across socio-ecological niches found on smallholder farms. Minimum tillage will be an unsuitable tillage practice for the good and poor soil fertility classes because regular tillage has comparatively greater economic benefits. In addition, the prevailing prices of crop residues make retention of crop residues in the good and poor soil fertility classes less economically beneficial. Also, in the poor soil fertility class, none of the tillage and crop residue practices was profitable and the emphasis should be on the rehabilitation of their soil physical and chemical attributes. Retention of crop residues will give improved maize performance in the medium fields, and the prevailing crop residue, herbicide and labor prices make crop residue retention and minimum tillage beneficial.

Our research contributes to a better understanding of where modified tillage practices and mulching, two key components of conservation agriculture, may play a role in raising agricultural productivity under the conditions of smallholder farming in sub-Saharan Africa.

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