



Research article

Optimizing interaction between crop residues and inorganic N under zero tillage systems in sub-humid region of Kenya



Kinyua Michael^{a,b,*}, Mucheru-Muna Monicah^b, Bolo Peter^{a,b}, Kihara Job^a

^a Alliance of Bioversity International and the International Center for Tropical Agriculture, c/o International Centre of Insect Physiology and Ecology (ICIPE), Duduville Campus Off Kasarani Road, P.O. Box 823-00621, Nairobi, Kenya

^b Kenyatta University, Department of Environmental Sciences and Education, P.O. Box 43844-00100, Nairobi, Kenya

ARTICLE INFO

Keywords:

Soil aggregation
Tillage systems
Inorganic fertilizers
Carbon stock
Crop residues
Nitrisols

ABSTRACT

Conservation agriculture practices involving zero tillage and residue retention are promising nutrient management strategies for soil health restoration. Despite their potential positive impact on soil fertility, improved crop yields and increased revenues for smallholder farmers; their effect on nitrogen inputs and crop growth is not clearly understood. This may limit their potential as a nutrient management strategy that may remedy soil degradation and boost crop yields for farmers. This study investigated how different tillage practices, crop residues and inorganic nitrogen (N) options affect maize production, soil fertility and economics of smallholder farming systems. The study was conducted in a short-term (2 years) on-station trial, under randomized complete block design with three replications in a maize monocrop system. Six treatments, involving three different rates of maize stover residue (0, 3 and 5 t ha⁻¹) and inorganic N (0, 3 and 5 t ha⁻¹) inputs, respectively, were assessed under conventional and zero tillage systems. Mineral N and organic C were assessed at four depths (0–10 cm, 10–30 cm, 30–60 cm and 60–90 cm) whereas soil aggregate distribution was assessed at 0–5 cm, 5–10 cm, 10–15 cm and 15–20 cm depths. Application of inorganic N as the only input increased ($p \leq 0.05$) grain yield (with the yields doubling in the short rains (SR) of 2015 and increasing by 1.4 times in long rains (LR) of 2016) compared to unfertilized control treatment. Treatment, soil depth and the time of sampling significantly affected soil mineral N concentration ($p \leq 0.05$). Soil organic C reduced significantly ($p \leq 0.05$) with sampling depths, but no differences were observed across treatments. At 0–5 cm depth, the proportion of large macroaggregates in zero tillage increased (48%; $p \leq 0.05$) after application of crop residues at 5 t ha⁻¹ relative to 3 t ha⁻¹. Zero tillage treatment with application of 5 t ha⁻¹ of residue and 80 kg N ha⁻¹ was the most dominant and most profitable compared to the other treatments. This treatment had a benefit cost ratio (BCR) of 2.9 (in the short rains season of 2015) and 3.0 (long rains of 2016 seasons). Its marginal rate of return (MRR) was 368% (in the 2015 short rains season) and 416% (in the 2016 long rains season). This makes it a good nutrient management strategy with potential of optimizing maize yields.

1. Introduction

Inappropriate utilization of intensive farming methods has led to degradation of majority of agricultural lands (Zhang et al., 2017). Climate change associated vulnerabilities have worsened the situation, leading to progressive decline in crop yields, with a consequentially food insecure smallholder farmers (Rusinamhodzi et al., 2011; Choudhury et al., 2014). Nutrient management practices in majority of smallholder

systems are characterized by underutilization of organic resources and lack of site-specific fertilizer N recommendations (Mucheru-Muna et al., 2014; Vanlauwe et al., 2014). The decline in soil N can be attributed to specific field management practices employed (i.e., tillage type, fertilizer blends applied and intensity of their application), prevailing weather conditions and bio-physical characteristics of the soil. Integrated soil fertility management (ISFM) and conservation agriculture are two major strategies being promoted to mitigate the declining N stock in majority of

* Corresponding author.

E-mail address: m.kinyua@cgiar.org (K. Michael).

<https://doi.org/10.1016/j.heliyon.2021.e07908>

Received 22 February 2021; Received in revised form 24 June 2021; Accepted 30 August 2021

2405-8440/© 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

arable lands of Kenya (Kitonyo et al., 2018). However, N use efficiencies in soils, including humic Nitisols of Embu County, are still low, thus threatening food security (Mugwe et al., 2011).

Soil disturbance through tillage in most smallholder conventional tillage systems in sub-Saharan Africa (SSA) cannot be overlooked as a main cause of soil organic matter (SOM) loss and structural destruction (Govaerts et al., 2014). Under these systems, residue removal after crop harvest results in nutrient mining and compromises the nutrient cycling role of soil biota leading to declining C stock (Ayuke et al., 2019). Incorporation of crop residues helps to improve soil properties such as aeration and soil water infiltration. However, tillage associated disturbances cause disintegration of soil aggregate particles (Morlue et al., 2021). This exposes SOM preserved within macroaggregates and increase their vulnerability to microbial attack, consequently increasing N mineralization and leaching (Sheehy et al., 2015).

Conservation agriculture (CA) is actively promoted as a promising strategy for enhancing climate resilience and managing soil nutrient losses in SSA. The practice entails three principles namely zero tillage, maintaining at least 30% soil cover and cultivating diverse crops under rotation or intercropping (Kihara et al., 2020). Zero tillage systems laid with surface residues can buffer soils from effects of climate extremes, build N and C stocks, improve soil structure, and stabilize crop yields (Govaerts et al., 2014). However, utilizing low quality residues, characterized by slow mineralization of N, may result in prolonged immobilization that may lead to crop nutrient deficiency especially during early stages of growth (Masvaya et al., 2018). There is emerging debate on whether to include N fertilization (Vanlauwe et al., 2014) or exclude it (Sommer et al., 2014) as a fourth principle of conservation agriculture. However, utilizing appropriate rates and timing of inorganic fertilizers in zero tillage applied with high C:N residues would reduce effects of prolonged N immobilization (Leitner et al., 2017). The most critical concern, however, is an existing research gap on what could be the most appropriate site-specific crop nutrient recommendations for zero tillage systems. Generally, in most conservation agricultural practices, nutrient recommendations for conventional tillage are being utilized under zero tillage systems (Tambang et al., 2008).

A sustainable nutrient management system should not only minimize nutrient losses but also match its supply to meet crop demands. Zero tillage systems can meet this credential if right residue quantities and site-specific N fertilizer rates are properly understood. This is because surface mulch regulates soil moisture and temperatures as well as optimizing soil microbial action. In addition, applying surface mulch results in N lock-up that reduces plant nutrient loss and accelerates C sequestration (Giller et al., 2011; Wang et al., 2019). The site-specific nutrient recommendations for zero tillage systems and their economics within smallholder systems characterized by complex integration of crops and livestock production need to be established. Therefore, this study aimed at examining how soil fertility and maize yield respond to different inorganic N and crop residue options and the associated economics in both conventional and zero tillage systems of Embu County in Kenya.

2. Materials and methods

2.1. Study site

Trials were established at Kenya Agricultural and Livestock Research Organization (KALRO) station in Embu County during the short rains (SR) season of 2015 (between October and December) and long rain (LR) season of 2016, (occurring from March through May). The site lies between latitude 0° 33' 18" S and longitude 37° 53' 27" E and at an altitude of 1420 m above sea level. Mean annual temperatures range between 14 °C and 21 °C and a bimodal rainfall of 1250 mm per annum. The soils are deep (>2.5 m) humic Nitisols with low exchangeable bases and high P sorption rates, a common characteristic of soils in the upper (UM) and lower (LM) midland ecological zones of Central Highlands of Kenya (Jaetzold et al., 2006). Besides, the soils are less fertile due to recurrent

intensive cultivation and sub-optimal nutrient replenishments (Mucheru-Muna et al., 2007). The area has a complex integration of crops and livestock management, practiced in approximately 1.2 ha sizes, within individual smallholder farmer setup.

2.2. Experimental design

The experiment was laid out in a randomized complete block design with three replicates in plots measuring 6 m × 4.5 m. Treatments comprised of combined application of three rates of maize stover residue and inorganic N fertilizer, respectively, under both conventional and zero tillage systems. Retaining some level of crop residues coupled by a substantial amount of N is recommended for conventional systems in the study area (Kiboi et al., 2017). Moreover, retaining stover with no fertilizer N has been reported to reduce crop growth rate by up to 10% and 23% lower shoot biomass (Kitonyo et al., 2018). Hence, this was not considered as a good treatment option during this study. The common nutrient rates (0 t ha⁻¹ residues +0 N and up to 0 t ha⁻¹ of residues +80 kg N ha⁻¹) applied in conventional systems of the study area were integrated and cumulatively built on to derive the six treatments (Table 1). Combined application of 3 t ha⁻¹ of residues and 80 kg N ha⁻¹ was considered as the optimal nutrient rate that resource constrained farmers, within an area characterized by intensive competition for residue by the livestock component, would be willing to invest in their conventional systems. Moreover, labor cost saving under zero tillage was considered to compensate for the investment on 5 t ha⁻¹ residues and 120 kg N ha⁻¹. Maize was grown as test crop under rain-fed conditions.

2.3. Field management

Tillage and crop residue application were conducted two weeks before planting and the process was repeated per season. In conventional tillage, maize stovers were chopped into approximately 5 cm long pieces before incorporating into the soil using hand-hoes during land preparation. In zero tillage systems, residues were spread uniformly on soil surface. In both tillage systems, planting hills were made using hand hoes at a 25 cm × 75 cm spacing. Two maize seeds (var. DeKalb 8031) were sown per hill and later thinned to one. Phosphorus (P), in form of triple super phosphate (TSP), was applied in all plots at a uniform rate of 26 kg P ha⁻¹ during sowing (V0). One-third of N fertilizer was applied in form of urea at V6 (six fully expanded leaves) and two thirds at V12 stages (twelve expanded leaves). Control treatments had no nutrient amendments. In zero tillage treatments, weeds were controlled by spraying 1.5 L ha⁻¹ of Weedall 480 SL (before planting) and 2, 4 D-Amine herbicides (at V6 and V11). Weeding in conventional tillage system was conducted using hand hoes.

2.4. Measurements

Daily rainfall and temperatures were recorded in an automated meteorological station located within the station, about 200 m from the experimental trial. Soils were sampled on four randomly selected points, per replicate; and at a depth of 0–20 cm for nutrient characterization.

Table 1. Treatments used to assess the effects of tillage, crop residues and inorganic N application during the SR 2015 and LR 2016 seasons in Embu County, Kenya.

Tillage	Residues (t ha ⁻¹)	Inorganic N (kg N ha ⁻¹)
Conventional tillage	0	0
Conventional tillage	0	80
Conventional tillage	3	80
Zero tillage	3	80
Zero tillage	5	80
Zero tillage	3	120

Collected soil samples were mixed to ensure homogeneity, taken to laboratory for oven drying (60 °C), ground through 2-mm sieve, coned and quartered before analysis. Soil extractable P was determined by Mehlich 3 extraction procedure (Mehlich, 1984), K using flame photometer while exchangeable Ca and Mg using atomic absorption spectrophotometry. Cation exchange capacity was assessed using NH₄-acetate leaching whereas soil pH was determined in 1:2 soil:water. Total C and N were assessed by Duma's type of combustion using Elemental Vario Max Cube.

Initial soil characterization showed that the soils of the study area contained low soil total N (<0.2%), moderate SOC levels (<2.0%) and P (>30 mg kg⁻¹). Additional information on soil chemical characteristics of the trial is illustrated in Table 2.

Analysis of soil nitrate and ammonium N (herein referred to as soil mineral N) was done using Kjeldahl method (Kjeldahl, 1883). Briefly, soil sampling was conducted four times in the LR 2016 season i.e., at sowing, when maize had developed eight leaves (V8), ten leaves (V10) and at dough stage (R4). Samples were collected at 0–10 cm, 10–30 cm, 30–60 cm and 60–90 cm depths at three randomly selected points per plot. The soil samples were thoroughly mixed, stored in cooler box, transported to the laboratory and stored at 4 °C until analysis. For ammonium-N determination, 2.0 ml supernatant was added into a test tube, followed by addition of 5 ml of N1 reagent (containing 68 g sodium salicylate +50 g sodium citrate +50 g sodium tartrate + deionized water made up to 1500 ml) and 5.0 ml of N2 reagent (containing 60 g NaOH +0.24 g sodium nitroprusside). Absorbance was read at 655 nm wavelength using spectrophotometer. For nitrate-N assessment, absorbance was read at 540 nm (Doane and Horwath, 2003). Soil sampling for SOC assessment was conducted at V10 stage in the LR 2016 season. Collected samples were air dried, ground, passed through a 2 mm mesh-sized sieve, and analyzed using Walkley method (Walkley, 1947).

Soil sampling for aggregate fractionation was done in the LR 2016 season at 0–5, 5–10, 10–15 and 15–20 cm depths at maize physiological maturity. In each plot, a pit (measuring about 15 cm in length, 15 cm width and 30 cm deep) was dug, a slice of soil carefully cut, labelled, packed and transported to the laboratory for processing. Dry soil samples were passed through 8 mm sieve and oven dried at 60 °C for 24 h. In each dry soil sample, 32 g was weighed, put in wet sieving apparatus (Eijkamp 08.13) for 5 min and repeatedly passed (for 3 min) through 2 mm sieve to obtain large macroaggregates, 250 µm for small macroaggregates, and 53 µm for microaggregates. Mean weight diameter (MWD) was calculated as illustrated in equation (i):

$$MWD = \sum XiWi \quad (i)$$

where Xi is the diameter of i^{th} sieve size and Wi = proportion of total aggregates in i^{th} fraction.

Geometric mean diameter (GMD) was calculated using equation (ii):

$$GMD = \left(\frac{\sum Wi \ln Xi}{\sum Wi} \right) \quad (ii)$$

where: Wi is the weight of aggregates in size class i and Xi is the mean diameter of class size.

Leaf chlorophyll was measured fortnightly from V6 to tasseling stage using Soil Plant Analysis Development (SPAD-502) meter. This was done

in the middle part of fully expanded leaf blades of ten randomly selected plants at plot level.

Maize was harvested from net plots measuring 19 square meters and fresh weights of stovers and cobs recorded. A sample of five random cobs were selected and weighed (Kihara et al., 2016). Five plants were randomly sampled from each net plot, chopped, thoroughly mixed, sub-sampled and fresh weights recorded. In the laboratory, cobs were shelled, oven dried together with stover samples at 60 °C for 24 h and dry weights recorded. Grain and stover biomass yield in t ha⁻¹ were calculated as described by Mupangwa et al. (2007).

2.5. Data analyses

Pooled means for variables recorded on multiple times were run through repeated measures analysis of variance (ANOVA) using GenStat 14th edition. Variates were maize grain yield, stover yield, soil mineral N and chlorophyll. Time was considered as either season or growth stages when sampling was done. Factors were Treatments and Treatments × Depth interaction (for mineral N) i.e., *Treatment* = *Factor1* * *Depth* and *Blocking structure* = *Reps*. A two-way ANOVA was used to assess the effects of treatment on soil aggregate fractions and SOC. Where models were significant, means were separated using least significant difference (LSD) at $p \leq 0.05$.

2.6. Economic analysis

Partial economic analysis was performed to assess the profitability of tillage systems under trial. Total variable cost (TVC) was the cumulative expenses incurred during land preparation, cost of fertilizers, herbicides, maize stubble residues, top dressing, spraying, residue application and weeding. Prices of nutrient and chemical inputs were sourced from local agro-dealer outlets. Price of one kg of urea was \$0.59, TSP (\$0.64), one liter each of Weedall herbicide (\$5.34) and 2-4-D herbicide (\$7.29), and labor cost per man day (1-man day = 8 h) at \$1.98. In the study area, maize stubble is locally utilized as cattle feed and was valued at \$19.4 per ton. Prices of maize grain for the two seasons were retrieved from National Farmers Information Service, 2020 (<http://www.nafis.go.ke/category/market-info/>) where a 90 kg bag traded at \$ 25.7 in January 2015 and \$ 27.6 in September 2016. Original prices on the website were recorded in Kenya shillings, where 1\$ was trading at Kes 101.3 at the end of second season (LR 2016). Before performing any economic computation, plot level yields were reduced by 10% to adjust for high yields in researcher-managed trials and another 5% reduction conducted to adjust for small plot size effect (CIMMYT, 1988).

Gross incomes (GI; \$ ha⁻¹) were computed by multiplying maize grain and stubble yield by their respective unit prices. Net revenue (NR; \$ ha⁻¹) was computed by subtracting TVC (\$ ha⁻¹) from GI. Profitability of using different fertilizer rates in maize production was assessed using value to cost ratio (VCR; \$ \$⁻¹), benefit to cost ratio (BCR; \$ \$⁻¹) and marginal rate of return (MRR; %). Value to cost ratio was computed as the ratio of GI of a treatment and cost of basal and top-dressing fertilizers applied. Benefit to cost ratio was NR divided by TVC while MRR was ratio of difference in NR between one treatment and another treatment with lower variable cost and the difference in their TVC (CIMMYT, 1988). Dominance analysis was performed to identify treatments dominated by others, having lower NR and higher TVC. Treatment elimination criterion

Table 2. Soil chemical characteristics before the establishment of the trial during SR 2015 season at KALRO station in Embu, County Kenya.

Depth (cm)	pH (1:2.5 soil:H ₂ O)	Total N (g kg ⁻¹)	SOC (%) [†]	P (mg kg ⁻¹)	K (mg kg ⁻¹)	Mg (mg kg ⁻¹)	Ca (ppm)	CEC (meq/100 g)
0–15	4.7	1.9	2.0 [‡]	36.3	5.8	2.4	2.4	17
15–30	4.6	1.5	1.9 [‡]	30.1	5.2	2.3	2.3	16

Note: [†] shows SOC was assessed at different depths, [‡] represents soil sampled at 0–10 cm; [§] represents soil sampled at 10–15 cm.

applied by Kihara et al. (2010) was applied to determine the best bet technologies to recommend to smallholder farmers in the study area.

Economic data was analyzed using one-way ANOVA by GenStat 14th edition. In the model, the different economic parameters were considered as variates, factors were treatments under test while blocking structure was the three replicates.

3. Results

3.1. Weather data

The cumulative seasonal rainfall was 384 mm for the SR 2015 and 285 mm for the LR 2016 seasons. The SR 2015 season received 26% more rainfall than amount experienced in the LR 2016 season. In both seasons, high rainfall (i.e., 357 mm in the SR 2015 and 240 mm in the LR 2016 season) was experienced within the first 50 DAS followed by a decline during the later period of crop growth. Minimum and maximum temperatures ranged between 17–33 °C in the SR 2015 and 10–29 °C in the LR 2016 seasons (Figure 1).

3.2. Grain and stover biomass yield

In both seasons, maize grain yields were significantly affected by treatments ($p \leq 0.01$). Significant treatment effects on stover yield occurred only during the SR 2015 season (Table 3). Application of inorganic N as the only nutrient input doubled ($p \leq 0.05$) maize grain yield in SR 2015 season and increased it by 47% during the LR 2016 season when compared to the control. The same treatment had 22% higher ($p \leq 0.05$) stover yield during the SR 2015 and 10% in the LR 2016 seasons than the control treatment. Application of equivalent rates of inputs (i.e., 3 t ha⁻¹ of residue and 80 kg N ha⁻¹) resulted in significantly higher grain yields in conventional than in zero tillage treatments during both the SR 2015 and LR 2016 seasons. In the SR 2015 season, stover yield increased ($p \leq 0.05$) in conventional tillage relative to zero tillage when equivalent input rates were applied, a case not observed during the LR 2016 season. When grain production was compared under zero tillage systems, increasing the amount of residues from 3 t ha⁻¹ to 5 t ha⁻¹ enhanced ($p \leq 0.05$) grain yield by 17% during the SR 2015 and 23% in the LR 2016 season.

3.3. Leaf chlorophyll

Leaf chlorophyll content was significantly affected by the interaction between inorganic N application and sampling time ($p \leq 0.05$). Averaged

Table 3. Maize grain and stover yield as influenced by tillage system, nitrogen and residue application during SR 2015 and LR 2016 in Embu County.

Treatments	Grain yield (t ha ⁻¹)		Stover yield (t ha ⁻¹)	
	SR 2015	LR 2016	SR 2015	LR 2016
Conventional tillage + 0R + 0N (control)	2.48 ^c	3.18 ^c	4.33 ^c	4.55 ^b
Conventional tillage + 0R + 80N	5.03 ^a	4.57 ^{ab}	5.57 ^a	5.07 ^{ab}
Conventional tillage + 3R + 80N	5.16 ^a	5.04 ^a	5.60 ^a	5.12 ^{ab}
Zero tillage + 3R + 80N	4.20 ^b	3.98 ^{bc}	5.20 ^b	5.14 ^{ab}
Zero tillage + 3R + 120N	4.40 ^b	4.63 ^{ab}	5.27 ^b	6.55 ^a
Zero tillage + 5R + 80N	4.92 ^a	4.88 ^a	5.50 ^a	5.36 ^{ab}
P-value	0.01	0.01	0.01	0.22
LSD	0.28	0.83	0.14	1.62
s.e.	0.09	0.26	0.04	0.51
s.e.d.	0.13	0.37	0.06	0.73

Note: values of means in a column followed by similar superscripts are not significantly different; R = crop residues (t ha⁻¹); N = nitrogen (kg ha⁻¹); LR = Long rains season; SR = Short rains season.

across sampling periods, leaf chlorophyll ranged between 49.4 SPAD units in the control and 56.6 SPAD units in zero tillage system where 120 kg N ha⁻¹ was applied (Table 4). Top dressing maize with 80 kg N ha⁻¹ enhanced leaf chlorophyll at growth periods around 46 DAS and 58 DAS relative to the control. However, this was in exemption of zero tillage system with 5 t ha⁻¹ of residues where leaf chlorophyll was low i.e., 41.1 SPAD units, during the early growth stages followed by a subsequent increase (>60 SPAD units) as the season progressed.

3.4. Soil mineral N concentration

Soil mineral N was significantly affected by treatment ($p < 0.001$), depth ($p < 0.001$), sampling period ($p < 0.001$) and interaction between treatments and sampling period ($p < 0.01$). However, there were no significant difference of soil mineral N within treatment \times depth and treatment \times depth \times growth stage interactions. When assessed across the sampling periods, the mean soil mineral N content ranged from 6.7 kg ha⁻¹ in the control to 8.4 kg ha⁻¹ where N was applied as the only nutrient input (Figure 2a, here). However, there were no significant differences between treatments \times depth interaction. The concentration of soil mineral N was in the order of 0–10 cm > 10–30 cm > 30–60 cm \geq 60–90 cm i.e., 10.4 kg ha⁻¹ > 8.3 kg ha⁻¹ > 5.9 kg ha⁻¹ \geq 5.3 kg ha⁻¹. At sowing, soil mineral N content at 0–10 cm and 10–30 cm (20.1 kg ha⁻¹ and 13.3 kg ha⁻¹, respectively) was significantly higher than in the period before 40 DAS (8.5 kg ha⁻¹ and 8.1 kg ha⁻¹, respectively). In addition, application of N as the only nutrient input at the period before 40 DAS increased (95.6%) the amount of soil mineral N, at 0–10 cm depth, relative to that of the control. Interestingly, at 40 DAS, mineral N concentration was significantly ($p < 0.05$) higher both at 30–60 cm and 60–90 cm soil depths compared to the upper depths (Figure 2b, here).

3.5. Aggregate fractionation, Mean Weight Diameter and Geometric Mean Diameter

Both aggregates MWD and GMD were significantly affected by depth and treatment \times depth interaction (Table 5). Sampling depth had significant influence on the distribution of large macroaggregates, small macroaggregates and silt + clay (Table 6). However, only the large macroaggregate fraction was significantly affected by interaction between treatment \times depth. No significant differences were observed when equal rates of residue i.e., 3 t ha⁻¹, were applied in both conventional and zero tillage systems. At 0–5 cm depth, application of 5 t ha⁻¹ resulted in 69% and 135% higher large macroaggregates fraction compared to when 3 t ha⁻¹ was applied in zero tillage system and conventional tillage, respectively. Though not significantly different, the level of microaggregates and silt + clay at 0–5 cm depth was higher in conventional tillage + 3R + 80N (45% and 42%, respectively) and zero tillage + 3R + 80N (34% and 26%, respectively) relative to that of zero tillage + 5R + 80N. Across the soil depth, no significant differences were observed in conventional systems with and without crop residue application.

3.6. Soil organic carbon

Soil organic carbon was significantly affected by sampling depths ($p \leq 0.01$). However, SOC was not affected by treatment and treatment \times depth interaction (Table 7). Soil organic C ranged from a mean of 1.61% in Zero tillage + 3R + 120N to 1.91% in Conventional tillage + 3R + 80N. Conventional tillage + 3R + 80N had significantly higher SOC content than the rest of the treatments. While no significant differences were observed between 0–10 cm (2.0%) and 10–30 cm (1.9%) across the tillage treatments, significant SOC reduction was recorded in the lower soil depths i.e., 1.7% in 30–60 cm and 1.2% in 60–90 cm. However, variability in SOC content increased with increase in soil depth (Figure 3, here).

Table 4. Treatment effects on leaf chlorophyll at different stages of maize growth during the LR 2016 season in Embu County.

Treatments	Chlorophyll levels per growth stage (SPAD units)						Average ^ε
	33 DAS	46 DAS	52 DAS	58 DAS	65 DAS	71 DAS	
Conventional tillage + 0R + 0N	41.7	44.5 ^c	51.5 ^c	51.7 ^c	54.1 ^c	52.7 ^c	49.4 ^c
Conventional tillage + 0R + 80N	41.9	53.5 ^{ab}	55.6 ^{ab}	57.7 ^b	58.7 ^{ab}	55.3 ^{abc}	53.8 ^b
Conventional tillage + 3R + 80N	43.8	52.6 ^{ab}	55.4 ^{ab}	57.2 ^b	55.5 ^{bc}	54.9 ^{bc}	53.2 ^b
Zero tillage + 3R + 80N	45.4	54.9 ^{ab}	55.3 ^{ab}	58.0 ^b	59.0 ^{ab}	55.8 ^{abc}	54.7 ^b
Zero tillage + 3R + 120N	45.2	57.8 ^a	56.8 ^a	61.3 ^a	60.3 ^a	58.0 ^{ab}	56.6 ^a
Zero tillage + 5R + 80N	41.1	49.9 ^{bc}	53.5 ^{bc}	57.2 ^b	60.5 ^a	59.1 ^a	53.6 ^b
p-value	0.26	0.01	0.01	0.01	0.02	0.04	0.01
LSD		6.09	2.45	2.37	3.69	3.75	1.79
s.e.		1.93	0.78	0.75	1.17	1.19	1.47
s.e.d.		2.74	1.10	1.06	1.66	1.68	0.81

Note: R = maize stover residues (t ha⁻¹); N = nitrogen (kg ha⁻¹); DAS = Days after sowing; ^ε is the average SPAD across the sampling periods. The superscript letter represents the average SPAD across the sampling periods. This means the average SPAD measurement from 33 DAS to 71 DAS.

Table 5. Treatment effects on aggregates Mean Weight Diameter and Geometric Mean Diameter during the LR 2016 season in Embu.

Treatments	Mean Weight Diameter (mm)				Geometric Mean Diameter (mm)			
	0–5 cm	5–10 cm	10–15 cm	15–20 cm	0–5 cm	5–10 cm	10–15 cm	15–20 cm
Conventional tillage + 0R + 0N	1.6 ^{abc}	1.9	1.6 ^{ab}	1.2	0.8 ^{ab}	1.0	0.8 ^{ab}	0.8
Conventional tillage + 0R + 80N	1.2 ^c	1.5	1.6 ^{ab}	1.5	0.6 ^b	0.8	0.8 ^{ab}	0.9
Conventional tillage + 3R + 80N	1.4 ^{bc}	1.4	1.6 ^{ab}	1.4	0.7 ^{ab}	0.7	0.9 ^{ab}	0.8
Zero tillage + 3R + 80N	1.5 ^{abc}	1.3	2.0 ^a	1.3	0.8 ^{ab}	0.7	1.1 ^a	0.7
Zero tillage + 3R + 120N	1.9 ^{ab}	1.6	1.2 ^b	1.2	1.0 ^{ab}	0.9	0.7 ^b	0.7
Zero tillage + 5R + 80N	2.0 ^a	1.7	1.8 ^a	1.5	1.1 ^a	0.9	0.9 ^{ab}	0.8
p-value	0.03	0.37	0.06	0.17	0.05	0.59	0.18	0.69
LSD	0.61		0.49		0.40		0.31	
s.e.	0.19		0.15		0.13		0.10	
s.e.d.	0.27		0.22		0.18		0.14	

Note: Values of means within columns followed by similar superscripts are not significantly different ($p \leq 0.05$).

Table 6. Effect of tillage and crop residue application on soil aggregate distribution during the LR 2016 in Embu County.

Treatment	Large macroaggregates (%) (≥ 2 mm)				Small macroaggregates (%) (≥ 250 μm ≤ 2 mm)				Microaggregates (%) (≥ 53 μm ≤ 250 μm)				Silt + Clay (%) (≤ 53 μm)			
	Depth (cm)															
	0–5	5–10	10–15	15–20	0–5	5–10	10–15	15–20	0–5	5–10	10–15	15–20	0–5	5–10	10–15	15–20
CT + 0R + 0N	15.0 ^{abc}	22.6	15.1 ^{ab}	5.5 ^b	54.4	50.5	54.6	66.8 ^a	27.3 ^{ab}	23.7	28.19	25.9	2.7 ^{ab}	2.5 ^{ab}	1.8	1.7
CT + 0R + 80N	9.1 ^c	13.6	16.7 ^{ab}	12.0 ^a	52.2	52.8	51.9	60.4 ^{ab}	34.8 ^a	30.7	28.9 ^a	24.4	3.3 ^a	2.8 ^a	2.3	1.8
CT + 3R + 80N	10.7 ^{bc}	11.4	15.5 ^{ab}	11.1 ^{ab}	55.9	55.6	57.5	60.6 ^{ab}	30.4 ^{ab}	30.5	24.2 ^{ab}	26.1	2.7 ^{ab}	2.4 ^{ab}	2.2	2.2
ZT + 3R + 80N	14.9 ^{abc}	9.0	25.7 ^a	8.8 ^{ab}	53.3	58.8	62.6	61.1 ^{ab}	28.2 ^{ab}	28.9	19.3 ^b	26.8	2.4 ^{ab}	2.4 ^{ab}	2.1	2.0
ZT + 3R + 120N	23.1 ^{ab}	15.9	6.4 ^b	5.0 ^b	51.3	54.9	51.9	64.1 ^{ab}	22.5 ^b	26.7	27.4 ^{ab}	27.9	2.2 ^{ab}	2.0 ^b	2.3	2.2
ZT + 5R + 80N	25.2 ^a	17.9	20.9 ^a	13.1 ^a	51.5	54.2	54.0	58.1 ^b	21.0 ^b	24.9	22.8 ^{ab}	26.7	1.9 ^b	2.4 ^{ab}	1.6	1.6
P-value	0.12	0.36	0.09	0.08	0.83	0.50	0.37	0.34	0.10	0.50	0.16	0.95	0.19	0.46	0.50	0.96
LSD	13.62		12.60	6.74				8.59	10.11		8.23		1.17	0.76		
s.e.	4.32		3.94	2.14				2.73	3.21		2.57		0.37	0.24		
s.e.d.	6.11		5.57	3.03				3.85	4.54		3.64		0.53	0.34		

3.7. Cost benefit analysis

During the SR of 2015 and the LR of 2016, gross income, net revenues, benefit cost ratios and value cost ratios were significantly ($p \leq 0.001$) affected by tillage system and not by cropping seasons or the interaction between the two factors (Table 8). Gross incomes ranged from USD 672 ha⁻¹ to USD 1343 ha⁻¹ in the SR 2015 season and USD 869 ha⁻¹ to USD 1338 ha⁻¹ in the LR 2016 season in the control treatment and conventional tillage + 3R + 80N, respectively. Contrary to GI, NR

ranged from USD 454 ha⁻¹ to USD 952 ha⁻¹ in the SR 2015 season and USD 651 ha⁻¹ to USD 957 ha⁻¹ in the LR of 2016 in the control and zero tillage + 5R + 80N, respectively. Application of 80 kg N ha⁻¹ as the only nutrient input resulted in a 49% (in SR 2015) and 19% (in LR 2016) increase in NR compared to that of the control. This led to an equal BCR between the two treatments in SR 2015 and a 1.1 increment in the BCR of the control in LR 2016 relative to the N applied treatment. When equal rates of N and residues were applied, zero tillage systems had significantly higher BCR (i.e., 33% in SR 2015 and 37% in LR 2016) and lower

Table 7. Interactive effect of treatment and depths on soil organic carbon content.

Treatment	Soil organic carbon (%)			
	0–10 cm	10–30 cm	30–60 cm	60–90 cm
Conventional tillage + 0R + 0N	2.02	1.96	1.63 ^{abc}	1.01 ^b
Conventional tillage + 0R + 80N	2.03	1.91	1.58 ^{bc}	1.14 ^{ab}
Conventional tillage + 3R + 80N	2.22	2.05	1.90 ^a	1.48 ^a
Zero tillage + 3R + 80N	1.9	1.9	1.74 ^{abc}	1.23 ^{ab}
Zero tillage + 3R + 120N	1.94	1.82	1.48 ^c	1.23 ^{ab}
Zero tillage + 5R + 80N	2.03	1.76	1.81 ^{ab}	1.24 ^{ab}
<i>p</i> -value			0.1	0.27
LSD			0.31	0.39
s.e.			0.1	0.12
s.e.d.			0.14	0.17

VCR (i.e., 18% for both seasons) compared to conventional tillage systems ($p \leq 0.05$). Within the zero tillage systems, a combined application of 3 tons of residue and 120 kg N ha⁻¹ was not superior to 3 tons of residue and 80 kg N ha⁻¹. Application of 5 t ha⁻¹ of residues resulted in 15% increment in net revenues in the SR 2015 season and 23% in the LR 2016 compared to retaining 3 t ha⁻¹ of residues under zero tillage. All treatments had BCR > 1 and VCR > 2 in both seasons. Zero tillage + 5R + 80N had the greatest BCR in both SR 2015 (2.9) and the LR 2016 (3.0) seasons. Despite having the lowest BCR (≤ 1.8), conventional tillage treatment with + 3R + 80N had the highest VCR (≥ 7.1) in both SR 2015 and LR 2016 seasons ($p \leq 0.05$).

Zero tillage + 3R + 80N and zero tillage + 5R + 80N dominated over other treatments with marginal rate of return of 465% and 368% in the SR 2015 season and 241% and 416% in the LR 2016, respectively.

4. Discussions

4.1. Effects of seasonal weather patterns, tillage, inorganic N and crop residue application on soil mineral N and yields

This study represents zero tillage systems where the effect of N application influences systems' profitability, soil nutrient availability and structural response to organic residues application. The amount and distribution of rainfall under the rain-fed smallholder farming systems also played a key role in shaping maize production during the two

seasons. The amount of rainfall received during the study period was sufficient to sustain crop growth. However, 93% of total rainfall in the SR 2015 and 84% in LR 2016 season was experienced within 50 DAS, depicting poor rainfall distribution. This undesirable rainfall distribution pattern caused dry spells (also reported by [Kisaka et al., 2005](#)) which might have significantly affected maize production ([Ngetich et al., 2014](#)) in fields around the study area.

Maize yield increment when 80 kg N ha⁻¹ was applied as the only nutrient input is an indication of N deficiency in soils of this environment. Improved yields and soil N content after N application indicate that soils around the site are responsive to N application. Results from different agro-ecologies have also indicated that application of fertilizer N and organic amendments such as manure and crop residues (i.e., retained partially or fully after crop harvest) are important for restoring crop nutrients thus influencing the amount of attainable yields in a cropping system ([Mucheru-Muna et al., 2007](#); [Rusinamhodzi et al., 2011](#)). Leaf chlorophyll content also increased following N application, which implies the need for N fertilization to improve crop productivity. Application of appropriate N amounts would not only enhance its availability but also improve utilization efficiency of the applied P because of the synergistic relationship between the two nutrients during crop uptake ([Bojórquez-Quintal et al., 2017](#)).

Soil mineral N variability during crop growth was attributed to rapid N flush through birch effect following a dry-wetting cycle. Previous studies from Eastern ([Mucheru-Muna et al., 2009](#)) and Southern Africa ([Masvaya et al., 2018](#)) have reported similar observations. [Leitner et al. \(2017\)](#) attributed N spike to high microbial activities within the upper soil depths. The successive decline in soil mineral N amount after initial N spike points to a potentially combined loss through nitrous oxide emission, leaching, reduced nitrifier activities, N being incorporated in microbial biomass and utilization by actively growing crops. Findings from this study also concur with [Mtambanengwe et al. \(2006\)](#) who reported high N concentration at the upper soil depth during the first 21 days of crop growth followed by a corresponding N deposition in the lower depths.

The N management benefits accrued from practicing zero tillage are critical for soils that are vulnerable to nutrient losses following extreme weather conditions and at growth stages when roots are unable to optimize N uptake. Immobilization of N, which is attributed to retention of low-quality residues under zero tillage, probably minimized leaching of N to the lower depths ([Musyoka et al., 2019](#)). Similar nitrogen management benefits associated with N lock-up and the synchrony in N release which corresponds to plant nutrient demand under zero tillage

Table 8. Economic analysis of different nutrient management options under conventional and zero tillage systems during the SR 2015 and LR 2016 in Embu County.

Treatments	SR 2015					LR 2016				
	GR (\$ ha ⁻¹)	NR (\$ ha ⁻¹)	BCR (\$ \$ ⁻¹)	VCR (\$ \$ ⁻¹)	MRR (%)	GR (\$ ha ⁻¹)	NR (\$ ha ⁻¹)	BCR (\$ \$ ⁻¹)	VCR (\$ \$ ⁻¹)	MRR (%)
Conventional tillage + 0R + 0N	672 ^c	454 ^e	2.0 ^b			869 ^c	651 ^c	3.0 ^a		
Conventional tillage + 0R + 80N	1311 ^a	890 ^{ab}	2.1 ^b	7.0 ^a	d	1222 ^{ab}	800 ^{abc}	1.9 ^{bc}	6.5 ^{ab}	d
Conventional tillage + 3R + 80N	1343 ^a	855 ^{bc}	1.8 ^c	7.2 ^a	d	1338 ^a	850 ^{abc}	1.7 ^c	7.1 ^a	d
Zero tillage + 3R + 80N	1103 ^b	808 ^{cd}	2.7 ^a	5.9 ^b	465	1074 ^{bc}	780 ^{bc}	2.7 ^{ab}	5.8 ^b	242
Zero tillage + 3R + 120N	1153 ^b	767 ^d	2.0 ^b	6.2 ^b	d	1256 ^{ab}	870 ^{ab}	2.3 ^{abc}	6.7 ^{ab}	d
Zero tillage + 5R + 80N	1285 ^a	952 ^a	2.9 ^a	6.9 ^a	368	1330 ^a	997 ^a	3.0 ^a	7.1 ^a	416
LSD	70.6	70.6	0.19	0.40		214.2	214.2	0.80	1.2	
s.e.	22.4	22.4	0.06	0.12		67.0	67.0	0.25	0.35	
s.e.d.	31.7	31.7	0.08	0.17		94.7	94.7	0.35	0.50	
ANOVA of variables (p-values)	Treatments		Season		Treatment × Season					
GR	<0.001		0.205		0.180					
NR	<0.001		0.205		0.180					
BCR	<0.001		0.124		0.117					
VCR	<0.002		0.730		0.430					

Note: GI = gross income; NR = net revenue; BCR = benefit cost ratio; VCR = value cost ratio; MRR = marginal rate of return; d = treatments dominated by other treatments; Means with similar superscript letters within same column denote no significant differences between treatments.

were also reported by Masvaya et al. (2017). The short-term porosity resulting from soil disturbance in conventional tillage systems and over 80% of rainfall being received within the first 50 DAS could have eased N translocation to lower soil depths as also reported by Memon et al. (2013).

Studies have reported conflicting results following residue application in enhancing crop yields, where increases (Kitonyo et al., 2018) and decreases (Rusinamhodzi et al., 2011) respectively, have been previously reported in Kenya and Zimbabwe. Residue mulch in zero tillage systems experiencing reduced breakdown and comminution by soil fauna (as was the case in this study) would help to conserve moisture in moisture-constrained seasons. However, soil water saturation effect under high rainfall seasons may result in waterlogging which negatively impacts the attainable yields. Reduced leaf chlorophyll following application of 5 t ha⁻¹ under zero tillage system can be attributed to elevated N immobilization. However, a subsequent mineralization of N during later growth stages demonstrated a potential of averting nutrient losses after applying the high residue rates (Masvaya et al., 2017). Yield differences that emanated from applying equivalent rates of inputs was an indication that nutrient recommendations in conventional tillage do not apply for zero tillage systems. Improved chlorophyll content when nitrogen was increased from 80 kg N ha⁻¹ to 120 kg N ha⁻¹ is attributed to luxurious consumption of N. Conversely, the high chlorophyll does not always translate to increased yields (as observed during this study) or nutrient use efficiency (Kitonyo et al., 2018).

4.2. Tillage, inorganic N and crop residue application effects on soil C and aggregate distribution

Practicing zero tillage is considered as a good strategy for C sequestration and a key process for improving soil C stock (Wang et al., 2019; Li et al., 2020). Unfortunately, lack of treatment effects on SOC indicate that 2 years of zero tillage practice is not adequate to fully detect changes under Nitisols of this region. Low macrofauna activity involved in comminution of residues has been reported in soils within (Ayuke et al., 2019) and around (Ayuke et al., 2009) the study site which might have reduced residue decomposition rates. In addition, anecdotal evidence during this study also indicated residues applied during one season were still intact on soil surface in the consecutive season. Existing literatures also contradict on the rate of SOC recovery after introduction of improved management practices. For example, while results from this study support findings by Cotrufo et al. (2013) that applying low quality residues do not necessarily increase SOM due to their slower decomposition rate (resulting in lower SOM accumulation in the soil), other studies have alluded the possibility of high-quality residues offering enhanced accumulation of stable SOC (Knicker, 2011; Sarker et al., 2018). Soil organic carbon accumulation benefits have been reported in long-term zero tillage systems by Sommer et al. (2017) in Ferralsols, Gao et al. (2019a) in Cambisols as well as other soil types (Sheehy et al., 2015). On the contrary, Gentile et al. (2013) observed that applying low quality residues did not influence SOC stabilization in the long-term since all residues would eventually get decomposed. Moreover, while Norton et al. (2012) indicated that 12 years was a suitable time for SOC recovery, Halvorson et al. (2016) reported insignificant SOC recovery after 18 years of improved management practices.

Variability in SOC with increasing soil depth was an indication that utilizing fallow periods and planting crops to homogenize the soil may not be sufficient to eliminate soil heterogeneity. Existence of variability is attributed to complexity of soil C sequestration processes as influenced by several factors including the historical management practices, existing climatic conditions, and the associated soil biophysical and chemical properties (Morlue et al., 2021). Results from this study agree with Ellert et al. (2008) and Kravchenko and Robertson (2011) who reported existence of high soil variability with increasing soil depths, which may complicate detection of differences even when they may exist. Farmlands in this region were established after clearing mountain forests (Kenya

Land Commission, 1934) which hosted huge trees. Owing to their deep rooting system, carbon from their extensive root might have been sequestered into lower soil depths.

Retention of surface residue cover under zero tillage systems improved soil structural development by cushioning soil aggregates from biophysical disturbances that induce disintegration. The 5 tons ha⁻¹ of residues provided a good environment for binding together of clay, SOM and microaggregate particles into large macroaggregate fractions relative to application of lower residue rates. Moreover, conventional tillage systems expose macroaggregate particles to factors inducing their disintegration into microaggregates and silt + clay (Gao et al., 2019a). Such factors include extreme weather conditions (i.e., wet-drying cycles) and reduction in glomalin, arbuscular mycorrhizal spores and length of active hyphae (Luo et al., 2011). Higher macroaggregate turnover was also reported by Choudhury et al. (2014), Zhang et al. (2017) and Gao et al. (2019b) and was attributed to reduced organic matter preservation efficiency in conventional systems after creation of more aerobic environment that increases SOM decomposition. Soil aggregate disturbances may also alter critical soil functions such as bioavailability of aggregate associated organic matter, vital microbial activities and availability of other important plant nutrients (Zhang et al., 2014).

4.3. Effect of tillage, inorganic N and residues application on cropping system economics

Utilizing the right rates of organic and inorganic inputs under zero tillage system is viable in improving the profitability of smallholder farming systems. The high net revenue in zero tillage systems can be associated with savings from extra labor required for land preparation and the multiple weeding regimes under conventional systems. The economic advantage of utilizing zero tillage systems was also reflected in the significantly higher BCR than those of conventional systems. This signifies that a unit of investment under zero tillage results in higher yield return than in conventional systems. Farmers applying at least 80 kg N ha⁻¹ of synthetic N fertilizers in their fields have the potential of earning more GR and NR than their counterparts who do not utilize fertilizer during crop production. However, application of synthetic fertilizers does not necessarily guarantee higher BCR due to the high costs of fertilizers and the associated labor costs. Therefore, initiating government programs to offer fertilizer subsidies would help to generate more income for resource constrained farmers in the study area.

The technologies under test had VCR >4 which indicates potential for systems' profitability after investing in fertilizer inputs (Niyuhire et al., 2017). Indeed, applying nutrient resources can help farmers to accommodate risks attributed to weather vulnerability and fluctuation of produce prices (Masso et al., 2017). The higher VCR under conventional than zero tillage system when equal amounts of residues were applied signifies that within the second year of practicing zero tillage, farmers might get more satisfactory financial incentive by utilizing fertilizers under conventional than zero tillage systems. Results also point to the little possibility of recovering the financial incentive lost under zero tillage by increasing fertilizer investment from 80 kg N ha⁻¹ to 120 kg N ha⁻¹ but rather by increasing amount of surface residues from 3 t ha⁻¹ to 5 t ha⁻¹ at the same unit of fertilizer (80 kg N ha⁻¹). Furthermore, the performance of zero tillage + 5R + 80N indicates the importance of integrating residues and inorganic fertilizers for increased crop production. Overall, two zero tillage options (i.e., zero tillage + 3R + 80N and zero tillage + 5R + 80N) had the best performance during the study period. The MRR levels of the two technologies (i.e., >346% in the SR 2015 season and >242% in the LR 2016 season) are beyond the 100% level used to determine the allowable rate of return for technology uptake by target farmers (CIMMYT, 1998). Furthermore, it was above the 200% level applied by Kihara and Njoroge (2016) to determine P recommendations for soils in Western Kenya. However, considering the significantly higher maize grain yields (i.e., 300–750 kg ha⁻¹), net revenues (\$144–\$162 ha⁻¹) and VCR (1–1.3 \$ \$⁻¹) under zero tillage + 5R +

80N during the two cropping seasons, this system can be recommended as the best-bet technology. This is because this technology is not only risk averse but also offers increased economic net returns for the smallholder farmers in the study area. The idea guiding this recommendation is that the profitability of a technology influences its adoption by farmers, however, both risk and uncertainty inspire farmers' decision making (Chianu et al., 2002).

5. Conclusions and recommendations

Combined application of crop residues and inorganic N enhanced maize grain yield compared to applying N as the only nutrient input in conventional tillage. Input rates recommended for conventional tillage (i.e., sole application of 80 kg N ha⁻¹ or combined application of 3 t ha⁻¹ of residues and 80 kg N ha⁻¹), result in reduced yields and are not fit for zero tillage systems. Rather at 80 kg N ha⁻¹, application of 5 t ha⁻¹ of residues in zero tillage produced similar maize grain yields as incorporation of 3 t ha⁻¹ under conventional tillage. Retention of crop residues under zero tillage reduced the amount of N leached at 30–60 cm and 60–90 cm soil depths, with 5 t ha⁻¹ of residues having the highest macroaggregation. The results from this study also revealed zero tillage + 5R + 80N as the most promising alternative for smallholder farmers in the study area because of the high net economic returns, risk averseness and potential of meeting food security demands through improved yields.

Declarations

Author contribution statement

Kinyua Michael: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mucheru-Muna Monicah: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Bolo Peter: Analyzed and interpreted the data; Wrote the paper.

Kihara Job: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Analyzed and interpreted the data; Wrote the paper.

Funding statement

This work was supported by the Sustainable Intensification of Maize-Legume Cropping Systems for Food Security in Eastern and Southern Africa (SIMLESA) project. The work is aligned to the CGIAR Research Program on Water, Land and Ecosystems (WLE) with support from CGIAR Fund Donors including: the Australian Center for International Agricultural Research (ACIAR); Bill and Melinda Gates Foundation; Netherlands Directorate General for International Cooperation (DGIS); Swedish International Development Cooperation Agency (Sida); Swiss Agency for Development Cooperation (SDC); and the UK Department of International Development (DIFD). WLE funding supported staff time for some of the authors.

Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at <https://doi.org/10.1016/j.heliyon.2021.e07908>.

Acknowledgements

The authors would like to acknowledge Joshua Mutua for logistical support during the study, the field technical assistance by Alfonse Muriuki and Dority Muthoni and laboratory support by Evonne Oyugi, Francis Mung'ethu and Margaret Muthoni. Many appreciations to Collins Odhiambo who also helped to review the manuscript.

References

- Ayuke, F.O., Karanja, N.K., Muya, E.M., Musombi, B.K., Mungatu, J., Nyamasyo, G.H.N., 2009. Macrofauna diversity and abundance across different land use systems in Embu, Kenya. *Trop. Subtrop. Agroecosyst.* 11 (2), 371–384.
- Ayuke, F.O., Kihara, J., Ayaga, G., Micheni, A.N., 2019. Conservation agriculture enhances soil fauna richness and abundance in low input systems: examples from Kenya. *Front. Environ. Sci.* 7, 97.
- Bojórquez-Quintal, E., Escalante-Magaña, C., Echevarría-Machado, I., Martínez-Estévez, M., 2017. Aluminum, a friend or foe of higher plants in acid soils. *Front. Plant Sci.* 8, 1767.
- Chianu, J.N., Akintola, J.O., Kormawa, P.M., 2002. Profitability of cassava-maize production under different fallow systems and land-use intensities in the derived Savanna of Southwest Nigeria. *Exp. Agric.* 38 (1), 51–63.
- CIMMYT, 1988. From Agronomic Data to Farmer Recommendations: an Economics Workbook. D.F.: CIMMYT, Mexico.
- CIMMYT, 1998. From Agronomic Data to Farmer Recommendations: an Economics Workbook. Completely Revised Edition. CIMMYT, Mexico D.F.
- Choudhury, S.G., Srivastava, S., Singh, R., Chaudhari, S.K., Sharma, D.K., Singh, S.K., Sarkar, D., 2014. Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice-wheat cropping system under reclaimed sodic soil. *Soil Tillage Res.* 136, 76–83.
- Cotrufu, M.F., Wallenstein, M.D., Boot, C.M., Deneff, K., Paul, E., 2013. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: do labile plant inputs form stable soil organic matter? *Global Change Biol.* 19 (4), 988–995.
- Doane, T.A., Horváth, W.R., 2003. Spectrophotometric determination of nitrate with a single reagent. *Anal. Lett.* 36 (12), 2713–2722.
- Ellert, B.H., Janzen, H.H., VandenBygaart, A.J., Bremer, E., 2008. Measuring change in soil organic carbon storage. *Soil Sampl. Meth. Anal.* 2, 25–38.
- Gao, L., Wang, B., Li, S., Han, Y., Zhang, X., Gong, D., Ma, M., Liang, G., Wu, H., Wu, X., Cai, D., Degré, A., 2019a. Effects of different long-term tillage systems on the composition of organic matter by ¹³C CP/TROSS NMR in physical fractions in the Loess Plateau of China. *Soil Tillage Res.* 194, 104321.
- Gao, L., Wang, B., Li, S., Wu, H., Wu, X., Liang, G., Gong, D., Zhang, X., Cai, D., Degré, A., 2019b. Soil wet aggregate distribution and pore size distribution under different tillage systems after 16 years in the Loess Plateau of China. *Catena* 173, 38–47.
- Gentile, R.M., Vanlauwe, B., Six, J., 2013. Integrated Soil Fertility Management: aggregate carbon and nitrogen stabilization in differently textured tropical soils. *Soil Biol. Biochem.* 67, 124–132.
- Giller, K.E., Corbeels, M., Nyamangara, J., Triomphe, B., Affholder, F., Scopel, E., Tittonell, P., 2011. A research agenda to explore the role of conservation agriculture in African smallholder farming systems. *Field Crop. Res.* 124, 468–472.
- Govaerts, B., Verhulst, N., Castellanos-Navarrete, A., Sayre, K.D., Dixon, J., Dendooven, 2014. Conservation agriculture and soil carbon sequestration: between myth and farmer reality. *Crit. Rev. Plant Sci.* 28, 97–122.
- Halvorson, J.J., Liebig, M.A., Archer, D.W., West, M.S., Tanaka, D.L., 2016. Impacts of crop sequence and tillage management on soil carbon stocks in South-Central North Dakota. *Soil Sci. Soc. Am. J.* 80, 1003–1010.
- Jaetzold, R., Schmidt, H., Hornet, Z.B., Shisanya, C.A., 2006. Farm Management Handbook of Kenya-Natural Conditions and Farm Management Information, second ed., 11/C. Central Kenya (Eastern and Central provinces) Ministry of Agriculture /GTZ, Nairobi, Kenya.
- Kenya Land Commission, 1934. Kenya Land Commission Evidence, 1. HMSO, London.
- Kiboi, M.N., Ngetich, K.F., Diels, J., Mucheru-Muna, M., Mugwe, J., Mugendi, D.N., 2017. Minimum tillage tied ridging and mulching for better maize yield and yield stability in the Central Highlands of Kenya. *Soil Tillage Res.* 170, 157–166.
- Kihara, J., Vanlauwe, B., Waswa, B., Kimetu, J.M., Chianu, J., Bationo, A., 2010. Strategic phosphorus application in legume-cereal rotations increases land productivity and profitability in Western Kenya. *Exp. Agric.* 46 (1), 35.
- Kihara, J., Njoroge, S., 2016. Phosphorus agronomic efficiency in maize-based cropping systems: a focus on western Kenya. *Field Crop. Res.* 1–8.
- Kihara, J., Nziguheba, G., Zingore, S., Coulbaly, A., Esilaba, A., Kabambe, V., Njoroge, S., Palm, C., Huisin, J., 2016. Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. *Agric. Ecosyst. Environ.* 229, 1–12.
- Kihara, J., Bolo, P., Kinyua, M., Nyawira, S., Sommer, R., 2020. Soil health and ecosystem services: lessons from sub-Saharan Africa (SSA). *Geoderma* 370, 114342.
- Kisaka, M.O., Mucheru-Muna, M., Ngetich, F.K., Mugwe, J.N., Mugendi, D., Mairura, F., 2005. Rainfall variability, drought characterization, and efficacy of rainfall data reconstruction: case of Eastern Kenya. *Adv. Meteorol.* 16.
- Kitonyo, O.M., Sadras, V.O., Zhou, Y., Denton, M.D., 2018. Nitrogen fertilization modifies maize yield response to tillage and stubble in a sub-humid tropical environment. *Field Crop. Res.* 223, 113–124.
- Kjeldahl, C., 1883. A new method for the determination of nitrogen in organic matter. *Z. Anal. Chem.* 22, 366.

- Knicker, H., 2011. Soil organic N - an under-rated player for C sequestration in soils? *Soil Biol. Biochem.* 43 (6), 1118–1129.
- Kravchenko, A.N., Robertson, G.P., 2011. Whole-profile soil carbon stocks: the danger of assuming too much from analyses of too little. *Soil Sci. Soc. Am. J.* 75 (1), 235–240.
- Leitner, S., Minixhofer, P., Inselsbacher, E., Keiblinger, K.M., Zimmermann, M., Zechmeister-Boltenstern, S., 2017. Short-term soil mineral and organic nitrogen fluxes during moderate and severe drying–rewetting events. *Appl. Soil Ecol.* 114, 28–33.
- Li, S., Lu, J., Liang, G., Wu, X., Zhang, M., Plougonven, E., Wang, Y., Gao, L., Abdelrhman, A.A., Song, X., Liu, X., Degre, A., 2020. Factors governing soil water repellency under tillage management: the role of pore structure and hydrophobic substances. *Land Degrad. Dev.* 1–14.
- Luo, Y.J., Wang, Z.F., Gao, M., Wei, C.F., 2011. Effects of conservation tillage on organic carbon, nitrogen and enzyme activities in a hydric anthrosol of Chongqing, China. *Energy Proc.* 5, 30–36.
- Masso, C., Nziguheba, G., Mutegi, J., Galy-Lacaux, C., Wendt, J., Butterbach-Bahl, K., et al., 2017. Soil fertility management in sub-Saharan Africa. In: *Sustainable Agriculture Reviews*. Springer, pp. 205–231.
- Masvaya, E., Nyamagara, J., Descheemaeker, K., Giller, K.E., 2017. Tillage, mulch and fertilizer impacts on soil nitrogen availability and maize production in semi-arid Zimbabwe. *Soil Tillage Res.* 168, 125–132.
- Masvaya, E.N., Nyamangara, J., Giller, K.E., Descheemaeker, K., 2018. Risk management options in maize cropping systems in semi-arid areas of Southern Africa. *Field Crop. Res.* 228, 110–121.
- Mehlich, A., 1984. Mehlich 3 soil test extractant: a modification of Mehlich 2 extractant. *Commun. Soil Sci. Plant Anal.* 15 (12), 1409–1416.
- Memon, S.Q., Mirjat, M.S., Mughal, A.Q., Amjad, N., 2013. Effect of conventional and non-conventional tillage practices on maize production. *J. Agric. Agric. Eng. Vet. Sci.* 29 (2), 155–163.
- Morloe, B., Kamau, S., Ayuke, F., Kironchi, G., 2021. Land use change, but not soil macrofauna, affects soil aggregates and aggregate-associated C content in central highlands of Kenya. *J. Soil Sediment* 21 (3), 1360–1370.
- Mucheru-Muna, M., Mugendi, D., Kung'u, J., Mugwe, J., Bationo, A., 2007. Effects of organic and mineral fertilizer inputs on maize yield and soil chemical properties in a maize cropping system in Meru South District, Kenya. *Agrofor. Syst.* 69, 189–197.
- Mucheru-Muna, M., Mugendi, D., Mugwe, J., Kung'u, J., Merckx, R., Vanlauwe, B., 2009. Soil mineral N dynamics in a maize crop following different soil fertility amendments in different soil fertility status in sub-humid and semi-arid regions in Central Kenya. *Res. J. Agric. Biol. Sci.* 5 (6), 978–993.
- Mucheru-Muna, M., Mugendi, D., Pypers, P., Mugwe, J., Kung'u, J., Vanlauwe, B., Merckx, R., 2014. Enhancing maize productivity and profitability using organic inputs and mineral fertilizer in central Kenya small-hold farms. *Exp. Agric.* 50 (2), 250–269.
- Mugwe, J., Mugendi, D.N., Mucheru-Muna, M., Kung'u, J., 2011. Soil inorganic N and N uptake by maize following application of legume biomass, tithonia, manure and mineral fertilizer in Central Kenya. In: Bationo, A., Waswa, B., Okeyo, J.M., Maina, F., Kihara, J.M. (Eds.), *Innovations as Key to the green Revolution in Africa: Exploring the Scientific Facts*. Springer Science & Business Media, pp. 605–612.
- Mupangwa, W., Twomlow, S., Walker, S., Hove, L., 2007. Effect of minimum tillage and mulching on maize (*Zea mays* L.) yield and water content of clayey and sandy soils. *Phys. Chem. Earth* 32 (15), 1127–1134.
- Musyoka, M.W., Adamtey, N., Bunemann, E.K., Muriuki, A.W., Karanja, E.N., Mucheru-Muna, M.W., Fiaboe, K.K.M., Cadisch, G., 2019. Nitrogen release and synchrony in organic and conventional farming systems of the Central Highlands of Kenya. *Nutr. Cycl. Agroecosyst.* 113, 283–305.
- Mtambanengwe, F., Mapfumo, P., Vanlauwe, B., 2006. Comparative short-term effects of different quality organic resources on maize productivity under two different environments in Zimbabwe. *Nutr. Cycl. Agroecosyst.* 76, 271–284.
- National Farmers Information Service (NAFIS), 2020. <http://www.nafis.go.ke/category/market-info/>. (Accessed 12 January 2021).
- Ngetich, K.F., Diels, J., Shisanya, C.A., Mugwe, J.N., Mucheru-Muna, M., Mugendi, D.N., 2014. Effects of selected soil and water conservation techniques on runoff, sediment yield and maize productivity under sub-humid and semi-arid conditions in Kenya. *Catena* 121, 288–296.
- Niyuhire, M.C., Pypers, P., Vanlauwe, B., Nziguheba, G., Roobroeck, D., Merckx, R., 2017. Profitability of diammonium phosphate use in bush and climbing bean-maize rotations in smallholder farms of Central Burundi. *Field Crop. Res.* 212, 52–60.
- Norton, J.B., Mukhwana, E.J., Norton, U., 2012. Loss and recovery of soil organic carbon and nitrogen in a semi-arid agroecosystem. *Soil Sci. Soc. Am. J.* 76, 505–514.
- Rusinamhodzi, L., Corbeels, M., Van Wijk, M.T., Rufino, M.C., Nyamangara, J., Giller, K.E., 2011. A meta-analysis of long-term effects of conservation agriculture on maize grain yield under rain-fed conditions. *Agron. Sustain. Dev.* 31, 657–673.
- Sarker, J.R., Singh, B.P., Cowie, A.L., Fang, Y., Collins, D., Dougherty, W.J., Singh, B.K., 2018. Carbon and nutrient mineralization dynamics in aggregate-size classes from different tillage systems after input of canola and wheat residues. *Soil Biol. Biochem.* 116, 22–38.
- Sheehy, J., Regina, K., Alakukku, L., Six, J., 2015. Impact of no-till and reduced tillage on aggregation and aggregate-associated carbon in Northern European agroecosystems. *Soil Tillage Res.* 150, 107–113.
- Sommer, R., Thierfelder, C., Titttonell, P., Hove, L., Mureithi, J., Mkomwa, S., 2014. Fertilizer use should not be a fourth principle to define conservation agriculture: response to the opinion paper of Vanlauwe et al. (2014) 'A fourth principle is required to define conservation agriculture in sub-Saharan Africa: the appropriate use of fertilizer to enhance crop productivity'. *Field Crop. Res.* 169, 145–148.
- Sommer, R., Paul, B.K., Mukalama, J., Kihara, J., 2017. Reducing losses but failing to sequester carbon in soils—the case of Conservation Agriculture and Integrated Soil Fertility Management in the humid tropical agro-ecosystem of Western Kenya. *Agric. Ecosyst. Environ.* 254, 82–91.
- Tambang, Y.G., Svensson, M., G.E., 2008. Low external input strategies for sustainable small-scale farming in Kenya: a systems dynamic approach. In: 26th International Conference of the System Dynamics Society, pp. 1–22.
- Vanlauwe, B., Wendt, J., Giller, K.E., Corbeels, M., Gerard, B., Nolte, C., 2014. A fourth principle is required to define conservation agriculture in sub-Saharan Africa: the appropriate use of fertilizer to enhance crop productivity. *Field Crop. Res.* 155, 10–13.
- Walkley, A., 1947. A critical examination of a rapid method for determining organic carbon in soils—Effect of variations in digestion conditions and of inorganic soil constituents. *Soil Sci.* 63 (4), 251–264.
- Wang, B., Gao, L., Yu, W., Wei, X., Li, J., Li, S., Song, X., Liang, G., Cai, D., Wu, X., 2019. Distribution of soil aggregates and organic carbon in deep soil under long-term conservation tillage with residual retention in dryland. *J. Arid Land* 11 (2), 241–254.
- Zhang, H., Ding, W., He, X., Yu, H., Fan, J., Liu, D., 2014. Influence of 20-year organic and inorganic fertilization on organic carbon accumulation and microbial community structure of aggregates in an intensively cultivated sandy loam soil. *PLoS One* 9, e92733.
- Zhang, X., Xin, X., Zhu, A., Zhang, J., Yang, W., 2017. Effects of tillage and residue managements on organic accumulation and soil aggregation in sandy loam soil of the North China Plain. *Catena* 156, 176–183.