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The response of soil physicochemical properties to tillage and soil fertility resources in Central Highlands of Kenya

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Abstract

To attain agricultural sustainability, use of soil resources and tillage requires equal consideration for chemical and physical components of soil fertility. We assessed responses of selected soil physical and chemical properties to tillage and soil fertility amending resources. The study was carried out in Meru South and Kandara sub-counties located in the Central Highlands of Kenya for four cropping seasons. The experimental design was split-plot with tillage as the main factor - conventional (D_{15}) - and minimum (D_0) tillage and soil fertility resources (SFR) as sub-factors - mineral fertilizer (F), crop residues + fertilizer (RF), residues + fertilizer + animal manure (RFM), residues + *Tithonia diversifolia* + manure (RTiM), residues + *Tithonia diversifolia* + phosphate rock (Minjingu) (RTiP), residues + manure + legume intercrop (RML) and control (no input). Compared with control, aggregate stability was significantly higher on average under SFRs with sole organics by 19% in Meru South. Total N and available P were higher under integration of fertilizer and organics in both sites. Calcium increased under sole organic or integration with fertilizer in Meru South and under sole organics in Kandara. Magnesium significantly increased under all SFRs compared with control in Kandara. Soil organic carbon significantly (P=0.02) increased under D_0 by 6% compared to D_{15} in 0-5 cm depth in Kandara. Application of RTiM had the highest SOC in all depths' at Meru South. SOC significantly increased under RTiP and RML by 11% in 0-5 cm depth and under RML by 13% in 5-10 cm depth at Kandara. Mineral-N (NO_3^--N and NH_4^+-N) was higher under D_0 at planting compared with D_{15} in Meru South. In Kandara, NO_3^--N and NH_4^+-N were significantly higher by 17% and 30%, respectively under D_0 compared with D_{15} at planting during SR16 season. Higher mineral N was recorded under F application on the 30th and 45th days in both sites. The highest mineral-N content was on the 45th day after planting during SR16 season and on the 30th day during LR17 season at Meru South. In Kandara, NO_3^--N and NH_4^+-N were highest on the 45th day and 30th day, respectively, during SR16 season. During LR17 season, mineral-N was highest on the 30th day in Kandara. The study highlights that minimal soil disturbance and organic inputs use or integration with fertilizers are feasible alternatives for improving soil fertility in the *Nitisols* of Central Highlands of Kenya.

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Introduction

Soil nutrient management is a significant challenge for food production worldwide, sub-Saharan Africa (SSA) (Powlson *et al*., 2011) and in the Central Highlands of Kenya (Okeyo *et al*., 2014). Conventional soil tillage, indiscriminate use of agro-chemicals and continuous cropping significantly contribute to degradation in the physical, chemical and biological properties of the soil (Mariangela and Francesco, 2010; Wyngaard *et al*., 2012). Continuous soil tillage leads to degraded soil with low organic matter content and a fragile physical structure, which leads to low crop yields and low fertilizer use efficiency (Wang *et al*., 2007). Conversely, conservation tillage is known to improve soil fertility (Busari *et al*., 2015). Fertilization is also a critical factor in soil fertility restoration and maintenance (Cai *et al*., 2019). Limited application of soil external nutrients exacerbates soil degradation and jeopardizes soil's productivity in small-hold farms of SSA and the study area (Mucheru-Muna *et al*., 2014). Addition of soil nutrients through the application of manures, green manuring and intercropping improves organic carbon content which in turn enhances soil physical-chemical properties. Mandal *et al*. (2003) reported that green manure increased soil organic matter (SOM), total nitrogen concentration, bulk density and mean weight diameter aggregate, which increased crop growth. Inorganic fertilizers may also be applied however they accelerate decomposition of organic residues and potentially reduce aggregate stability (Mäder *et al*., 2002). In the Central Highlands of Kenya, continuous soil tillage coupled with low or non-use of soil fertility resources is a significant constraint to crop production (Kiboi *et al*., 2018). Use of readily available organic inputs (animal manure, biomass transfer) or their combination with mineral fertilizers could be used to build up soil organic carbon (SOC), meet the N requirements of annual crops, for example, Maize (*Zea Mays* L.) and improve soil physical properties in the study area.

Fertilization and conservation tillage systems are management practices that counteract soil degradation (Dalal *et al*., 2011). Conventional agriculture that uses extensive tillage without application of soil fertility inputs can cause degradation in soil chemical fertility (Tiritan *et al*., 2016). Conventional tillage depletes the chemical properties of soil (Mangalassery *et al*., 2015; Nivelle *et al*., 2016), while conservation tillage improves them (Divito, 2012). Conservation tillage has been reported to increase extractable P, and exchangeable Ca, Mg, and K, in the surface of the soil (Ismail *et al*., 1994). Application of soil fertility resources has also been shown to improve soil structure and chemical properties (Scotti *et al*., 2013). In their review, Mariangela and Francesco (2010) confirmed that numerous organic inputs applications enhanced soil available potassium, extractable phosphorous and organic carbon content. Ghosh *et al*. (2012) reported increased amounts of available N, P, and K in soils that received both organic and inorganic inputs. Leite *et al*. (2010) found that a combination of conservation tillage with organic inputs or with organic and inorganic fertilizers resulted in higher total N stocks. Thus, implementation of effective tillage and application of soil nutrient inputs can enhance soil properties.

Soil organic carbon, which can be affected by soil management practices, is a critical soil quality and health indicator, widely used as an index of SOM (Abraham, 2013). Soil organic matter in agricultural soils plays an essential role in the improvement of all soil properties and nutrient supply to crops (Yang *et al*., 2012). Continuous soil tillage which is widely practiced in the Central Highlands of Kenya (Kiboi *et al*., 2017), promotes soils carbon depletion and reduced productivity (Baker *et al*., 2007). Conversely, SOC content increases under minimum tillage compared to conventional tillage methods (Sun *et al*., 2011). Nitrogen fertilizers affect SOC levels but, the influence of this effect depends on management and the soil type (Jagadamma *et al*., 2007). Greater clay concentrations may stabilize the organic matter and improve productivity in finer textured soils (Bechtold and Naiman 2006). Many farmers in SSA and the study area have limited access and affordability of mineral fertilizers (Vanlauwe *et al*., 2011). Thus, the use of the available organic inputs would increase SOC content. According to Korodjouma *et al*. (2006), SOM increased on manured plots compared to non-manured plots. Garcia-franco *et al*. (2015) reported that reduced tillage combined with green manure increased SOC concentrations.

Nitrogen is an essential soil nutrient for crop growth. Conversely, it is often the most limiting nutrient for crop production (Lobell, 2007) in most agricultural systems. Some of the pathways that facilitate N lose include harvesting of crops, leaching, volatilization/gaseous losses, runoff and erosion (Rufino *et al*., 2006). Agricultural systems require surplus N additions to produce desired yields (Drinkwater, 2004). Changes in soil management practices such as tillage, litter input, and quality may significantly affect soil N content (Peichl and Leava, 2012). Tillage promotes soil organic N mineralization, which can lead to N_2O production from nitrification and denitrification (Estavillo *et al*., 2002). Inorganic or organic fertilizers could be used to improve N availability to crops. However, much of the N in organic inputs is organically bound and must be mineralized to make it available to crops (Balkcom *et al*., 2009). Combination of mineral fertilizers and organic inputs accelerates N mineralization (Chivenge *et al*., 2011b). Ghosh *et al*. (2012) reported that soils receiving both inorganic and organic amendments consistently showed significantly higher amounts of available N due to the mineralization and release of N contained in the organics on their decomposition. Intercropping of cereal crops and legumes could also be used to increase potential N mineralization and available N (Sakala *et al*., 2000). To manage short and long-term N availability to crops from soil inputs, N release patterns need to be understood.

Soil physical properties such as aggregation and porosity indirectly influence plant growth through their effects on soil water content and mechanical impedance which affects root development and seedling emergence (Gomez *et al*., 2001). Excessive tillage may lead to reduced soil physical fertility. Conservation tillage has been found to improve aggregation (Mellek *et al*., 2010) and hydraulic conductivity (Abolanle *et al*., 2015) compared to tilled soils. Application of soil fertility resources such as animal manure, biomass transfer could also be used to increase soil physical fertility. Organic resources result in enhanced soil physical fertility, mainly by improving aggregate stability (Mariangela and Francesco, 2010). Mellek *et al*. (2010) found that dairy liquid manure led to a decrease in bulk density and increased aggregation. Application of manure and minimum tillage led to increased soil aggregation (Gicheru *et al*., 2004). However, the use of organic inputs in combination with mineral fertilizers and effective tillage practices for soil physical fertility improvement in the study area remains low leading to degraded soils which result in decreased crop yields. We hypothesized that minimum tillage combined with organic and inorganic soil fertility resources could be viable options that can produce beneficial effects on soil physical and chemical properties that can lead to soil fertility degradation arrest. Therefore, the objective of this study was to assess the effect of tillage practices and soil fertility resources on selected soil physical and chemical properties, SOC and mineral N dynamics under tropical sub-humid agro-ecological conditions.

Materials and methods

Site description

The experiment was conducted at Kangutu primary school farm (00° 98'S, 37° 08'E) in Meru South sub-county and Kenya Agricultural and Livestock Organization (KALRO) farm (00° 20'S, 37° 41'E) in Kandara sub-county. In both sites, the predominant soil type is *Nitisols*, a typically deep, weathered, well-drained, dusky red to dark reddish-brown, friable clay with acidic *humic* topsoil and moderate to high fertility (Jaetzold *et al*., 2007). The initial soil properties are shown in Table 1. Maize is the predominant annual crop in the two sub-counties. The rainfall pattern is bimodal in the two sub-counties with long rains season (LR) lasting from March to June and short rains season (SR) from late October to December, hence two cropping seasons per year (Jaetzold *et al*., 2007). The sub-counties are in the sub-humid region and receive average annual rainfall ranging from 400 mm to 1400 mm and a mean annual temperature of 20.7°C (Jaetzold *et al*., 2007).

During the study period, distinctions in cumulative rainfall amount and distribution in the cropping seasons were observed in each site (Figure 1). Meru South received total rainfall amounts of 879 mm during LR16, 385 mm during SR16, 341 mm during LR17, 571 mm during SR17 and 145 mm during off-seasons (Figure 1A). In Kandara, rainfall received during LR16 was 329 mm, 243 mm during SR16, 206 mm during LR17, 491 mm during SR17 and 95 mm during off-seasons (Figure 1B).

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Both sites experienced meteorological droughts and dry spells in all cropping seasons. Meru South site experienced a meteorological drought of 33 days and dry spells of 16 and 13 days while Kandara site had a meteorological drought of 31 and dry spells of 18, 10 and 24 days during the LR16 season. A dry spell of 10 days was experienced in Meru South at the beginning of the SR16 season and a meteorological drought of 31 days towards the end of the season (Figure 1A). In Kandara, there were dry spells of 17 and 14 days at the onset of the SR16 season and a meteorological drought of 36 days towards the end of the season (Figure 1B). During LR17 season, Meru South had a dry spell of 21 days at the beginning of the season and a meteorological drought of 31 days towards the end of the season while Kandara site experienced dry spells' of 17, 10 and 16 days and a meteorological drought of 31 days at the end of the season. In the SR17 season, Meru South experienced dry spells' of 17, 15 and 27 days while Kandara had two dry spells of 10 days each and a meteorological drought of 43 days (Figure 1).

Field experiments

The experimental design was a split-plot implemented in a randomized complete block arrangement with four replications (Kiboi *et al*., 2018). Tillage was the main factor at two levels (minimum and conventional tillage) while soil fertility resources were the sub-factors at six levels (sole mineral fertilizer, crop residues + mineral fertilizer, crop residues +mineral fertilizer + animal manure, crop residues+*Tithonia diversifolia* + phosphate rock (Minjingu), crop residues+ animal manure+ legume intercrop (*Dolichos lablab*) and crop residues + *Tithonia diversifolia* + animal manure and a control treatment (no input applied). Both tillage and soil fertility resources factors resulted in 14 combinations/treatments. Animal manure and *Tithonia diversifolia* were incorporated into the soil two weeks to the onset of the cropping season, during land preparation. Incorporation in the minimum tillage plots was limited to the planting rows. Maize (*Zea Mays* L.) was the test crop. Soil fertility resources were applied to give an equivalent amount of 60 kg N ha^{-1} to meet maize nutrient requirements in the two study areas (FURP, 1987). Maize crop residue was uniformly (5 Mg ha^{-1}) applied in five treatments under each tillage practice after crop emergence. Soil organic carbon was determined during LR16 and SR17 season while mineral N was determined during the SR16 and LR17 seasons.

Soil sampling

Soils were sampled during the trials' establishment (LR16 season) and at the end of the study period (LR17 season). For the physical characteristics (texture, bulk density, hydraulic conductivity, and aggregate stability), undisturbed soils were sampled at 0-5 cm depth using core rings measuring 50 mm by 50 mm, diameter and height, respectively. Composite samples for selected soil chemical properties (pH water, total N, available P, potassium, and exchangeable Ca and Mg) were sampled from each experimental plot at 0-20 cm depth using Edelman auger. For soil organic carbon

Table 1. Soil properties (0-20 cm) at Meru South and Kandara sub-Counties study sites (Source Kiboi *et al.*, 2018).

Parameter	Meru South	Kandara
Soil texture		
Clay (%)	70	80
Silt (%)	16	10
Sand (%)	14	10
Textural class	Clay soil	Clay soil
pH 4.85	5.49	
Total N (%)	0.14	0.14
Total C (%)	1.48	1.38
Available P (g/kg)	0.02	0.02
Exch.* K+ (cmol+/kg)	0.45	1.15
Exch. Ca+ (cmol+/kg)	2.53	4.15
Exch. Mg+ (cmol+/kg)	1.17	1.38

*Exch, exchangeable.

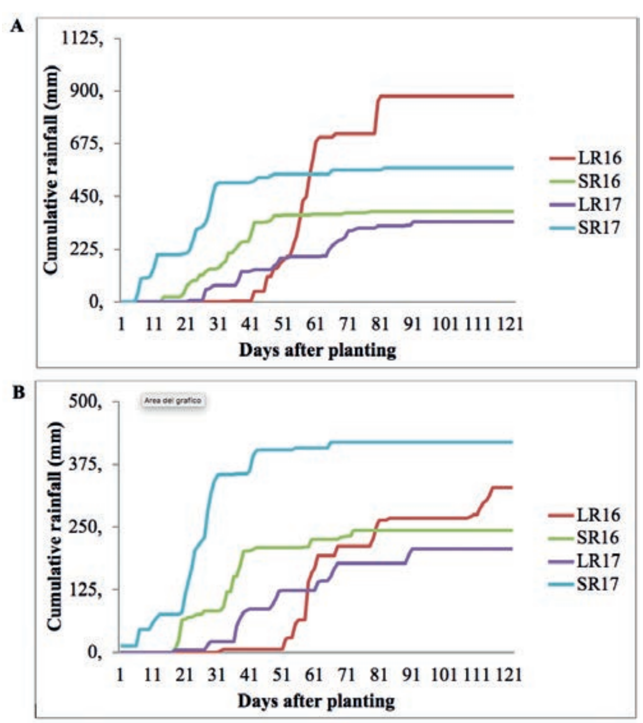

Figure 1. Cumulative rainfall amount received in Meru South (A) and Kandara (B) experiment sites during long rains 2016, short rains 2016, long rains 2017 and short rains 2017 seasons.

samples, undisturbed soil sampling was done using Eijkelkamp Gouge Auger at depths of 0-5 cm, 5-10 cm, 10-20 cm, and 20-40 cm.

Mineral nitrogen

To determine mineral N content (NO_3^--N and NH_4^+-N), soil samples were collected at 0-20 cm depth using Eijkelkamp Gouge Auger during planting (0), 30, 45, 60, and 90 days after sowing. Sampling was done in between plants within the rows since the incorporation of the soil fertility resources in the minimum tillage plots was limited to planting rows. The soil samples were transported to the laboratory in cool boxes and refrigerated at 4°C pending processing. Moist samples were passed through 8 mm sieve, and subsamples of 30 g picked. Crop residues and other debris (>2 mm) were manually removed from the subsamples. A 15 g portion of the subsample was oven-dried at 105°C to gravimetrically determine soil moisture content. The remaining 15 g was extracted with 50 ml 0.5M KCL by shaking on a reciprocal shaker for 1 hour and filtered through a Whatman No. 42 ashless filter paper.

Laboratory analyses

Laboratory analyses (both physical and chemical parameters for soil characterization) were done following the standard methods of soil analysis described by Ryan *et al*. (2001). Soil pH water (1:1, soil: water) was measured using pH meter; nitrogen by the Kjeldahl method, available phosphorus by Mehlich 3 method (Mehlich, 1984); potassium by a flame photometer and exchangeable calcium and magnesium by atomic absorption spectrophotometry and organic carbon by modified Walkley and Black wet oxidation method.

Soil texture by hydrometer method, bulk density was determined gravimetrically; hydraulic conductivity by constant-head method (Klute and Dirksen, 1986) and aggregate stability by Rotary dry sieving method (Lyles *et al*., 1970). The mean weight diameter was calculated using Eq. (1) Kemper and Rosenau (1986).

$$MWD = \sum_{i=1}^{8} \bar{x}_i w_i$$

where *MWD* is mean weight diameter (mm), w_i is total weight fraction of aggregates in the size class *i* with a diameter $\bar{x}_i$.

Statistical analyses

The data were subjected to analysis of variance (ANOVA) using the Mixed Procedure Model in SAS 9.3 software (SAS Institute, 2011) to obtain an F value of the model effect. Differences between treatment means were examined using Tukey's Kramer HSD (Honestly significant difference) at P=0.05.

Results

Soil physical properties

The soil physical properties (soil texture, bulk density, aggregate stability, and hydraulic conductivity) were not significantly different between the treatment plots at the beginning of the experiment period in both sites (Table 2). At the end of the study period, bulk density was not significantly different between the treatments in Meru South. Aggregate stability declined in all the treatments in Meru South; nevertheless, it was significantly (P=0.01) higher under RML by 24% compared with the control (Table 2). Hydraulic conductivity declined under all the treatments except RF at the end of the study period.

In Kandara, bulk density was significantly higher under mini-

Table 2. Soil physical properties in Meru South and Kandara study sites at the beginning (LR16) and end (LR17) of the study period.

Treatment	Meru South BD g cm^{-3}		Meru South MWD mm		Meru South K_{sat} cm		Kandara BD hr^{-1}		Kandara MWD g cm^{-3}		Kandara Ksat mm	
Tillage	LR16	LR17	LR16	LR17	LR16	LR17	LR16	LR17	LR16	LR17	LR16	LR17
D_{15}	0.93^{a}	0.93^{a}	1.07^{a}	0.61^{a}	16.57^{a}	13.83^{a}	1.05^{a}	1.01^{b}	0.70^{a}	0.85^{a}	18.21^{a}	15.06^{a}
D_0	0.96^{a}	0.95^{a}	1.04^{a}	0.56^{a}	17.06^{a}	16.56^{a}	1.07^{a}	1.05^{a}	0.71^{a}	0.80^{a}	15.70^{a}	13.60^{a}
Soil fertility resources												
Control	0.99^{a}	0.94^{a}	1.02^{a}	0.55^{bc}	15.09^{a}	13.79^{a}	1.04^{a}	1.05^{a}	0.70^{a}	0.87^{ab}	21.87^{a}	14.26^{b}
F	0.95^{a}	0.96^{a}	1.12^{a}	0.48^{c}	12.77^{a}	10.29^{a}	1.14^{a}	1.04^{a}	0.71^{a}	0.86^{ab}	13.41^{a}	11.55^{b}
RF	0.97^{a}	0.91^{a}	1.04^{a}	0.64^{ab}	13.95^{a}	20.50^{a}	1.05^{a}	1.05^{a}	0.72^{a}	0.78^{b}	17.80^{a}	15.78^{ab}
RFM	0.95^{a}	0.99^{a}	1.05^{a}	0.58^{abc}	18.61^{a}	15.64^{a}	1.05^{a}	1.04^{a}	0.68^{a}	0.97^{a}	17.07^{a}	11.09^{b}
RML	0.92^{a}	0.93^{a}	10.4^{a}	0.68^{a}	17.99^{a}	13.92^{a}	1.03^{a}	1.03^{a}	0.85^{a}	0.76^{b}	15.73^{a}	22.46^{a}
RTiM	0.94^{a}	0.94^{a}	1.09^{a}	0.63^{ab}	20.64^{a}	13.77^{a}	1.09^{a}	1.00^{a}	0.65^{a}	0.79^{b}	16.41^{a}	13.97^{b}
RTiP	0.93^{a}	0.95^{a}	1.01^{a}	0.59^{ab}	18.66^{a}	18.45^{a}	1.04^{a}	1.03^{a}	0.64^{a}	0.78^{b}	16.39^{a}	11.24^{b}
Effect												
Tillage	ns	ns	ns	ns	ns	ns	ns	0.02	ns	ns	ns	ns
SFR	ns	ns	ns	0.05	ns	ns	ns	ns	ns	0.05	ns	0.04
Tillage * SFR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Tr, treatment; D_{15}, conventional tillage; D_0, minimum tillage; LR16, long rains 2016 season; LR17 , long rains 2017 season; F, mineral fertiliser, RF, crop residue + mineral fertiliser; RFM, crop residue + mineral fertiliser + animal manure; RML, crop residue + animal manure + legume intercrop; RTiM, crop residue + *Tithonia diversifolia* + animal manure, RTiP, crop residue + *Tithonia diversifolia* + phosphate rock; ns, not significant; SFR, soil fertility resources. [a,b]Different letters indicate significant differences of the post hoc Tukey's HSD test performed in case effects of the model was significant (P≤0.05).

mum tillage (D_0) by 4% compared with conventional tillage (D_{15}). There was an increase in aggregate stability at the end of the study period under all the implemented treatments but no significant difference between the treatments compared with the control (Table 2). Hydraulic conductivity significantly (P=0.04) increased under RML by 57% compared with the control at the end of the study period (Table 2). The interactions had no significant influence on soil physical properties at the end of the study period in both sites (Table 2). Generally, soils in Kandara had a higher bulk density (ranging from 1.00 to 1.14 g cm^{-3}) than in Meru South site (ranging from 0.93 to 0.99 g cm^{-3}) (Table 2).

On average, bulk density and hydraulic conductivity were not significantly different between the soil fertility resources compared with the control at the end of the study period in both sites (Table 3). Aggregate stability (MWD) was significantly higher under treatments with sole organic inputs (Org) by 19% compared with the control in Meru South site but was not significantly influenced by the SFR in Kandara site (Table 3).

Soil chemical properties

Soil pH, total N, available P, K, Ca and Mg were not statistically different between the treatment plots at the beginning of the study in both sites (LR16) (data not shown). At the end of the study period, tillage had no significant influence on the measured soil chemical properties in both sites (Table 4). Conversely, soil pH, P, K and Ca were significantly influenced under soil fertility resources (SFR) at both sites. In Meru South, soil pH was significantly higher under RTiM and RML by 8% compared with the control (Table 4). Available P was significantly higher under RtiP, RFM, RF, and F by 223, 204, 153 and 139% compared with the control. Still, in Meru South, K was significantly higher under RtiM, RML, and RtiP by 164, 96 and 78% compared with the control. Calcium significantly increased under RtiM, RML, RFM, and RtiP by 17, 14, 7 and 5% compared with the control (Table 4). Total N and Mg were not statistically different between SFRs at the end of the study period in Meru South. The interactions had no significant influence on the soil chemical properties at Meru South site. In Kandara, soil pH significantly increased under RtiM, RML, RFM, and RtiP by 17, 14, 7 and 5% respectively, compared with the control (Table 4). Total N was not significantly different between SFR in Kandara. Phosphorous was significantly (P=0.002) influenced under all the SFR compared with the control

Table 3. Average of soil physical properties under soil fertility resources in Meru South and Kandara study sites at the end of study period (LR17).

Treatment	Meru South			Kandara		
SFR	BD g cm^{-3}	MWD mm	Ksat cm hr^{-1}	BD g cm^{-3}	MWD mm	Ksat cm hr^{-1}
Control	0.94^{a}	0.54^{b}	13.78^{a}	1.05^{a}	0.86^{a}	14.25^{ab}
Fert	0.93^{a}	0.55^{b}	15.39^{a}	1.04^{a}	0.82^{a}	13.66^{ab}
Fert + Org	0.96^{a}	0.58^{ab}	17.04^{a}	1.03^{a}	0.87^{a}	11.16^{b}
Org	0.93^{a}	0.65^{a}	13.84^{a}	1.01^{a}	0.77^{a}	18.21^{a}
P value	ns	0.05	ns	ns	ns	ns

SFR, soil fertility resources; Control, no fertiliser; Fert, mineral fertiliser; Fert+Org, mineral fertiliser plus organic inputs; Org, organic inputs; BD, bulk density; MWD, aggregate mean weight diameter, Ksat, hydraulic conductivity, ns, not significant; ns, not significant. [a,b]Same superscript letters in the same column denote no significant difference between the treatment means at a given site at P=0.05.

Table 4. Soil chemical properties in Meru South and Kandara sites at the end of study period (LR17).

Treatment	Meru South						Kandara					
Tillage	pH	Total N %	P g/kg	K Exchangeable cmol+/kg	Ca Exchangeable cmol+/kg	Mg Exchangeable cmol+/kg	pH	Total N %	P g/kg	K Exchangeable cmol+/kg	Ca Exchangeable cmol+/kg	Mg Exchangeable cmol+/kg
D_{15}	4.96^{a}	0.17^{a}	28.33^{a}	0.39^{a}	4.98^{a}	0.15^{a}	4.98^{a}	0.15^{a}	31.92^{a}	1.04^{a}	2.57^{a}	2.13^{a}
D_0	4.98^{a}	0.17^{a}	30.37^{a}	0.46^{a}	4.89^{a}	0.16^{a}	4.89^{a}	0.16^{a}	29.52^{a}	1.03^{a}	2.52^{a}	2.02^{a}
Soil fertility resources												
Control	4.89^{bc}	0.16^{a}	13.75^{c}	0.28^{dc}	4.69^{c}	0.15^{a}	4.69^{c}	0.15^{a}	16.25^{c}	0.82e	2.44^{b}	1.55^{c}
F	4.51^{d}	0.16^{a}	32.97^{b}	0.23^{d}	4.49^{cd}	0.16^{a}	4.49^{cd}	0.16^{a}	27.50^{b}	0.78e	2.39^{b}	1.96^{b}
RF	4.72^{cd}	0.16^{a}	34.81^{ab}	0.28^{dc}	4.48^{d}	0.15^{a}	4.48^{d}	0.15^{a}	35.00^{ab}	0.78e	2.36^{b}	2.10^{ab}
RFM	4.93^{bc}	0.17^{a}	41.87^{ab}	0.43^{bc}	5.04^{b}	0.16^{a}	5.04^{b}	0.16^{a}	40.63^{a}	1.04^{d}	2.46^{b}	2.28^{a}
RML	5.28^{a}	0.17^{a}	20.00^{c}	0.55^{b}	5.39^{a}	0.17^{a}	5.39^{a}	0.17^{a}	33.13^{ab}	1.28^{b}	2.70^{ab}	2.27^{a}
RtiM	5.29^{a}	0.18^{a}	17.50^{c}	0.74^{a}	5.53^{a}	0.16^{a}	5.53^{a}	0.16^{a}	28.61^{b}	1.41^{a}	2.88^{a}	2.23^{ab}
RtiP	5.16^{ab}	0.18^{a}	44.54^{a}	0.50^{b}	4.93^{b}	0.15^{a}	4.93^{b}	0.15^{a}	33.96^{ab}	1.15^{c}	2.58^{ab}	2.15^{ab}
Effects												
Tillage	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
SFR	<.0001	ns	<.0001	<.0001	<.0001	ns	<.0001	ns	0.002	<.0001	0.05	<.0001
Tillage * SFR	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	0.02

D_{15}, Conventional tillage; D_0, Minimum tillage; F, mineral fertiliser; RF, crop residue + mineral fertiliser; RFM, crop residue + mineral fertiliser + animal manure; RML , crop residue + animal manure +legume intercrop; RTiM, crop residue + *Tithonia diversifolia* + animal manure; RTiP, crop residue + Tithonia diversifolia + phosphate rock; ns, not significant; SFR, soil fertility resources. [a,b,c,d]Different letters indicate significant differences of the post hoc Tukey's HSD test performed in case effects of the model was significant (P≤0.05).

(Table 4). Potassium significantly increased under RtiM, RML, RtiP, and RFM by 72, 56, 40 and 27% compared with the control. Calcium was only significantly higher under RtiM compared with the control (Table 4). Application of RML, RFM and RtiP showed slightly high Ca content compared with the control in Kandara. Magnesium was significantly different under RFM, RML, RtiM, RtiP, RF and F by 47, 46, 43, 38, 35 and 26% compared with the control. On average, the application of sole mineral fertilizer led to lower pH compared with the control at both sites (Table 5). In Meru South, soil pH significantly increased ($p<.0001$) under sole organic treatments (Org) by 10% in Meru South compared with the control (Table 5). Total N was significantly higher under the integration of fertilizer and organic inputs (Fert + Org) compared with the control in Meru South. Phosphorous was significantly higher under Fert+ Org treatment by 214% while Ca significantly increased under Org and Fert+ Org by 101and 76%, respectively compared with the control in Meru South.

In Kandara, pH significantly increased ($P<0.0001$) under Org 17% compared with the control. Phosphorous was significantly higher under Fert+ Org treatment by 129% compared with the control (Table 5). While Ca significantly increased under Org by 15% compared with the control, magnesium significantly increased under Org, Fert+ Org and Fert by 46, 43 and 32% compared with the control in Kandara (Table 5).

Soil organic carbon

At the beginning of the study, there were no significant differences in soil organic carbon (SOC) between the treatment plots at both sites (data not shown). At the end of the study (four cropping seasons), tillage had no significant influence on SOC in all the sampled depths' at Meru South site. However, D_0 showed slightly higher values compared to D_{15} (Table 6), but these changes were not significant (Figure 2A). Soil fertility resources significantly influenced SOC at Meru South site in the sampled depths' except in the 5-10 cm depth. This was also indicated by the recorded significant changes (Figures 2A and 3A-B). Application of RTiM led to the highest SOC increase in all depths' at Meru South site (Table 6). In the 0-5 cm depth, SOC significantly increased under RTiM, RTiP, RML, RF, and RFM by 47, 35, 33, 33 and 29% compared with the control in Meru South (Table 6). Despite the SFRs' not significantly influencing SOC in the 5-10 cm depth in Meru South, there was a similar trend with that observed in the 0-5 cm depth (Table 6). In the 10-20 and 20-40 cm depths' all the SFRs' significantly increased SOC compared with the control. SOC changes under control showed a decline in the first three sampled depths at Meru South site (Figures 2A-B and 3A).

In Kandara, D_0 significantly ($P=0.02$) increased SOC by 6% compared with D_{15} at 0-5cm depth (Table 6 and Figure 2A). Minimum tillage also showed slightly higher SOC values in the other depths compared to conventional tillage in Kandara. Soil fertility resources significantly influenced SOC in the first two sampled depths' and showed an increasing trend in the last two sampled depths' compared with the control (Table 6). In the 0-5 cm depth, SOC significantly increased under RTiP and RML by 11% and under RML by 13% in the 5-10 cm depth compared with the control. The control showed a decrease in SOC in the last two sampled depths in Kandara site (Figure 3A and B). The interactions had no significant influence on SOC in all sampled depths in both study sites (Table 6).

Soil mineral nitrogen

The bulk of soil mineral N content found in the soil on all sam-

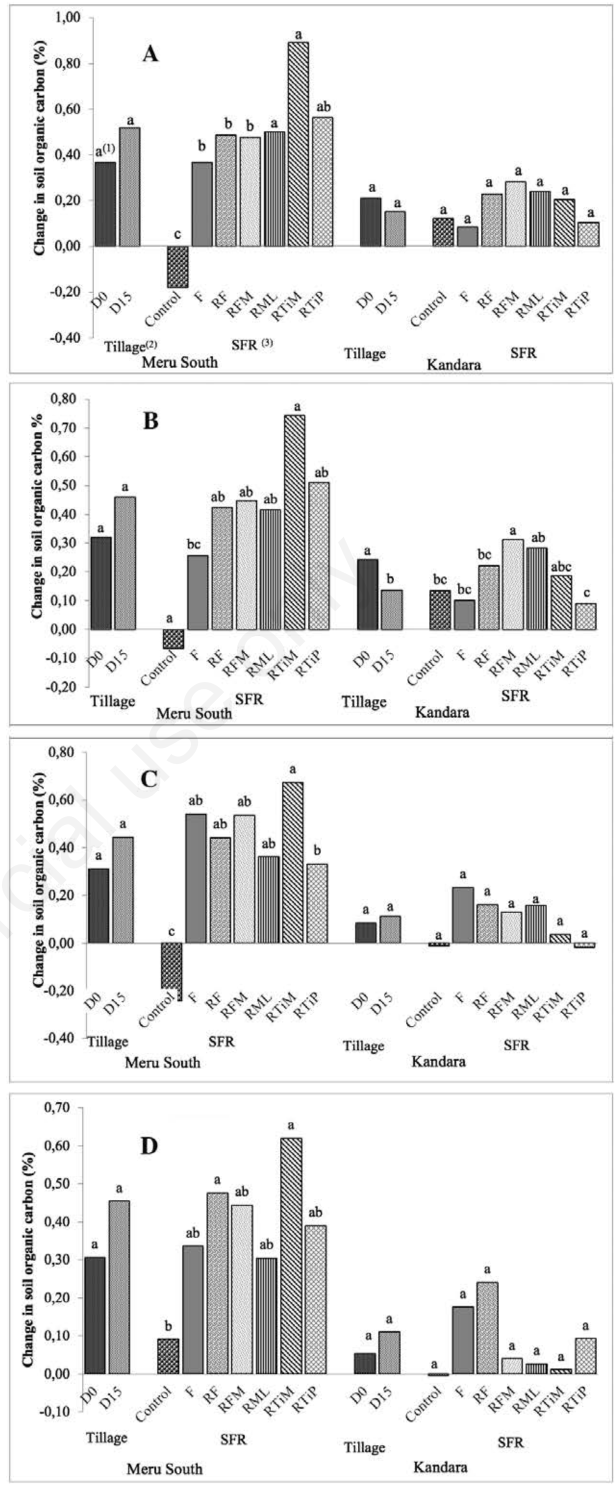

Figure 2. Changes in soil organic carbon (%) in the A) 0-5, B) 5-10, C) 10-20, D) 20-40 cm depths' at Meru South and Kandara sites. (1)Different letters indicate significant differences in the post hoc Tukey's HSD test performed in case effects of the model was significant ($P\leq0.05$). (2)Tillage abbreviations D_{15}=Conventional tillage, D_0=Minimum tillage. (3)SFR=Soil fertility resources abbreviations, Control=No input, F=Mineral fertiliser, RF=Crop residue + mineral fertiliser, RFM=Crop residue + mineral fertiliser + animal manure, RML=Crop residue + animal manure +legume intercrop, RTiM=Crop residue + *Tithonia diversifolia* + animal manure, RTiP=Crop residue + *Tithonia diversifolia* + phosphate rock.

pling dates was in the form of Nitrate-N (NO_3^--N) at both sites. In Meru South, NO_3^--N was significantly different under tillage at planting and 45 days after planting during SR16 season (Figure 3A). At planting NO_3^--N was significantly (P<0.0001) higher under minimum tillage (D_0) by 74% compared with the conventional tillage (D_{15}). On the 45th day, NO_3^--N significantly (P=0.02) decreased under D_0 by 77% compared with the D_{15} in Meru South. Ammonium-N content was not significantly influenced by tillage during SR16 season in Meru South (Figure 3B). From the 30th day after planting, mineral N was higher under D_{15} compared with the D_0 (Figure 3A and 4B). Under soil fertility resources, soil NO_3^--N was significantly different at planting, 30 and 90th day after planting during SR16 season in Meru South. On the 30th day, NO_3^--N was significantly (P=0.003) higher under mineral fertilizer (F) by 39%, compared with the control (C) (Figure 4A). On the 90th day, NO_3^--N was significantly (P=0.02) different between the various SFRs but not significantly higher than the control. Ammonium-N content under SFRs was significantly (P=0.03) different on the 90th day during SR16 season. It was significantly higher under RTiP and RTiM by 23 and 16% respectively, compared with the control (Figure 4B). The interactions significantly influenced NO_3^--N on the 30th (P<0.0001) and 90th (P=0.03) day after planting at Meru South site during SR16 season (Table 7). On the 30th day, only minimum tillage*fertilizer (D_0*F) was significantly higher than the control and greatly decreased on the 45th day (Table 7). Nitrate-N content was least under all the interactions on the 90th day during SR16 season with the D_{15}*RFM, D_0*RTiM and D_{15}*RF being significantly higher than the control. Ammonium-N was significantly (P=0.02) different between the interactions on the 30th day during SR16 season. The highest mineralization of mineral N during SR16 season occurred on the 45th day after planting under tillage, soil fertility resources and interactions in Meru South.

During LR17 season, NO_3^--N was not significantly different between the tillage systems on all the sampling days in Meru South (Figure 3C) while NH_4^+-N was significantly different on the 60th day after planting (Figure 3D). Ammonium-N was significantly higher under D_{15} by 46% compared with the D_0 on the 60th day (Figure 3D). At planting, 30 and 45th days, mineral N content was higher under D_0 compared with the D_{15} while on the 60th and 90th days it was higher under D_{15} (Figure 3C and D). Under soil fertility

Table 5. Average soil chemical properties under soil fertility resources in Meru South and Kandara study sites at the end of study period.

Treatment SFR	Meru South pH	%	Total N g/kg	P	K (Exchangeable cmol+/kg)	Ca	Mg	Kandara Total N g/kg	P	K (Exchangeable cmol+/kg)	Ca	Mg
Control	4.80^b	0.16^b	13.75^c	0.28^c	2.27^b	1.49^{ab}	4.68^c	0.15^a	16.25^b	0.82^c	2.43^b	1.54^b
Fert	4.61^c	0.16^b	33.89^b	0.25^c	2.46^b	1.44^b	4.48d	0.16^a	31.25^a	0.77^c	2.37^b	2.03^a
Fert + Org	5.04^{ab}	0.18^a	43.21^a	0.46^b	4.00^a	1.57^a	4.98^b	0.15^a	37.29^a	1.09^b	2.52^{ab}	2.21^a
Org	5.28^a	0.17^{ab}	18.75^c	0.65^a	4.57^a	1.61^a	5.46^a	0.15^a	30.87^a	1.34^a	2.79^a	2.25^a
P value	<.0001	0.04	<.0001	<.0001	<.0001	0.01	<.0001	ns	0.001	<.0001	0.03	<.0001

SFR, soil fertility resources; Control, no fertiliser; Fert, mineral fertiliser; Fert+Org, mineral fertiliser plus organic inputs; Org, organic inputs; ns, not significant. a-c Same superscript letters in the same column denote no significant difference between the treatment means at a given site at P=0.05.

Table 6. Soil organic carbon (%) concentration in different depths (cm) at Meru South and Kandara study sites.

Treatment	Meru South 0-5	5-10	10-20	20-40	Kandara 0-5	5-10	10-20	20-40
Tillage	0-5	5-10	10-20	20-40	0-5	5-10	10-20	20-40
D_{15}	1.65^a	1.60^a	1.54^a	1.47^a	1.49^b	1.52^a	1.40^a	1.36^a
D_0	1.66^a	1.60^a	1.57^a	1.50^a	1.59^a	1.57^a	1.51^a	1.44^a
Soil Fertility Resources								
Control	1.28^b	1.40^b	1.29^b	1.22^c	1.46^b	1.47^b	1.30^a	1.26^a
F	1.61^a	1.50^{ab}	1.57^a	1.48^{ab}	1.47^b	1.48^b	1.47^a	1.39^a
RF	1.71^a	1.65^{ab}	1.64^a	1.63^{ab}	1.49^{ab}	1.48^b	1.44^a	1.44^a
RFM	1.66^a	1.63^{ab}	1.65^a	1.41^{bc}	1.52^{ab}	1.54^{ab}	1.50^a	1.40^a
RML	1.71^a	1.62^{ab}	1.55^a	1.47^{ab}	1.62^a	1.67^a	1.53^a	1.37^a
RTiM	1.89^a	1.74^a	1.65^a	1.65^a	1.57^{ab}	1.55^{ab}	1.43^a	1.47^a
RTiP	1.73^a	1.68^{ab}	1.53^a	1.57^{ab}	1.63^a	1.62^{ab}	1.53^a	1.47^a
Source of variation								
Tillage	ns	ns	ns	ns	0.02	ns	ns	ns
SFR	0.01	ns	0.05	0.01	0.05	0.05	ns	ns
Tillage* SFR	ns	ns	ns	ns	ns	ns	ns	ns

D_{15}, conventional tillage; D_0, minimum tillage; F, mineral fertiliser; RF, crop residue + mineral fertiliser; RFM, crop residue + mineral fertiliser + animal manure, RML, crop residue + animal manure + legume intercrop, RTiM, crop residue + *Tithonia diversifolia* + animal manure, RTiP, crop residue + Tithonia diversifolia + phosphate rock; ns, not significant; SFR, soil fertility resources. a,b,c Different letters indicate significant differences of the post hoc Tukey's HSD test performed in case effects of the model was significant (P≤0.05).

resources, NO_3^--N was significantly (P=0.03) different at planting under RML, F and RF by 69, 68 and 60% compared with the control during LR17 season (Figure 4C).On the 30th day, NO_3^--N significantly (P<0.0001) increased under RF, RFM, RTiP, and RTiM by 231, 205, 91 and 90% compared with the control. On the 60th day, NO_3^--N was significantly higher under RF and RTiM by 115 and 78%, respectively compared with the control (Figure 4C). NH_4^+-N was significantly different at planting, the 30th and 45th day after planting compared with the control (Figure 4D). At planting, NH_4^+-N was significantly different under F application by 104% compared with the control. On the 30th day, NH_4^+-N was significantly higher under RFM and F by 155 and 131%, respectively, compared with the control during LR17 season (Figure 4D). On the 45th day, NH_4^+-N was significantly higher under RML and RFM compared with the control. In the LR17 season, NO_3^--N was significantly (P=0.02) different under the interactions on the 60th and 90th day after planting while NH_4^+-N was significantly different only at planting (Table 7). Mineral N (NO_3^--N and NH_4^+-N) was highest on the 30th day after planting under tillage, SFR and the interactions during LR17 season in Meru South.

In Kandara, Nitrate-N was significantly (P<0.0001) higher under D_0 by 17% at planting and by 73% on the 30th day compared with D_{15} during SR16 season (Figure 5A). Ammonium-N was significantly (P=0.01) higher under D_0 by 30% at planting and 30th day after planting compared with D_{15} (Figure 5B). Under soil fertility resources, soil NO_3^--N was significantly (P<0.0001)

Table 7. Mineral-N response under tillage* soil fertility resources interactions in the 0-20 cm depth on different sampling dates during short rains 2016 season at Meru South site.

		Sampling days after planting (SR16 season)									
		Nitrate-N (ppm/100g)					Ammonium-N (ppm/100g)				
Tillage	SFR	0	30	45	60	90	0	30	45	60	90
Conventional* (D_{15})	C	9.50^{a}	16.87^{g}	40.42^{a}	14.54^{a}	7.39^{ef}	4.03^{a}	14.36^{d}	22.39^{a}	15.49^{a}	13.22^{a}
	F	16.65^{a}	19.42^{fg}	22.76^{a}	22.22^{a}	8.76^{de}	9.60^{a}	15.68^{cd}	25.10^{a}	29.39^{a}	4.89^{a}
	RF	8.46^{a}	29.13^{cd}	45.64^{a}	9.90^{a}	10.21^{cd}	4.85^{a}	27.37^{a}	23.26^{a}	16.04^{a}	18.66^{a}
	RFM	19.63^{a}	38.36^{b}	43.36^{a}	15.06^{a}	17.04^{a}	9.92^{a}	15.05^{d}	24.14^{a}	24.78^{a}	12.17^{a}
	RML	14.34^{a}	25.97^{d}	40.02^{a}	12.22^{a}	4.83^{g}	14.98^{a}	8.85^{e}	24.60^{a}	22.84^{a}	22.33^{a}
	RTiM	10.36^{a}	25.86^{de}	31.14^{a}	11.33^{a}	12.38^{b}	5.44^{a}	17.65^{cd}	26.35^{a}	27.02^{a}	26.83^{a}
	RTiP	5.97^{a}	23.74^{e}	36.88^{a}	15.02^{a}	7.67^{ef}	5.52^{a}	20.39^{bc}	24.72^{a}	17.83^{a}	24.60^{a}
Minimum* (D_0)	C	27.32^{a}	37.22^{b}	26.31^{a}	2.83^{a}	9.78^{d}	5.77^{a}	15.43^{d}	23.68^{a}	2.49^{a}	6.84^{a}
	F	24.40^{a}	56.01^{a}	18.91^{a}	16.10^{a}	9.81^{d}	8.03^{a}	19.97^{bc}	17.90^{a}	18.47^{a}	16.68^{a}
	RF	13.58^{a}	22.22^{ef}	34.15^{a}	16.67^{a}	5.30^{g}	16.97^{a}	25.69^{ab}	26.49^{a}	17.63^{a}	19.69^{a}
	RFM	17.84^{a}	16.82^{g}	22.36^{a}	11.83^{a}	6.53^{fg}	15.90^{a}	13.28^{d}	27.82^{a}	8.59^{a}	7.68^{a}
	RML	29.63^{a}	7.89h	24.83^{a}	10.51^{a}	5.40^{g}	8.91^{a}	27.84^{a}	23.95^{a}	27.19^{a}	14.02^{a}
	RTiM	15.97^{a}	31.36^{c}	29.18^{a}	10.99^{a}	11.81^{bc}	5.63^{a}	14.60^{d}	24.20^{a}	18.86^{a}	16.39^{a}
	RTiP	19.51^{a}	31.02^{c}	44.81^{a}	13.79^{a}	8.77^{de}	13.16^{a}	21.77^{b}	24.47^{a}	16.36^{a}	20.23^{a}
P		ns	<.0001	ns	ns	0.03	ns	0.02	ns	ns	ns

SFR, soil fertility resources abbreviations; F, mineral fertiliser; RF, crop residue + mineral fertiliser; RFM, crop residue + mineral fertiliser + animal manure; RML, crop residue + animal manure +legume intercrop; RTiM, crop residue + Tithonia diversifolia + animal manure; RTiP, crop residue + *Tithonia diversifolia* + phosphate rock; ns, not significant. a-gDifferent letters indicate significant differences in the post hoc Tukey's HSD test performed in case effects of the model was significant (P≤0.05).

Table 8. Mineral-N response under tillage* soil fertility resources interactions in the 0-20 cm depth on different sampling dates during long rains 2017 season at Meru South site.

		Sampling days after planting (LR17 season)									
		Nitrate-N (ppm/100g)					Ammonium-N (ppm/100g)				
Tillage	SFR	0	30	45	60	90	0	30	45	60	90
Conventional (D_{15})	C	9.70^{ab}	16.88^{a}	3.85^{a}	3.96h	4.14^{h}	6.84^{de}	28.12^{ab}	1.82^{f}	5.13^{a}	3.37^{a}
	F	23.25^{a}	23.34^{a}	8.65^{a}	7.93^{bcdef}	6.49^{bcdef}	22.13^{a}	40.60^{a}	15.56^{c}	5.31^{a}	3.45^{a}
	RF	23.57^{a}	63.32^{a}	8.41^{a}	16.04^{a}	11.29^{a}	5.24^{ef}	23.10^{ab}	4.07^{ef}	6.19^{a}	3.73^{a}
	RFM	17.67^{a}	51.69^{a}	8.97^{a}	7.83^{cdef}	6.43^{cdef}	4.65^{ef}	46.69^{a}	29.43^{b}	9.69^{a}	2.52^{a}
	RML	15.05^{a}	35.57^{a}	8.31^{a}	6.97^{efg}	5.92^{efg}	6.53^{def}	29.23^{ab}	10.86^{cd}	11.94^{a}	4.05^{a}
	RTiM	18.00^{a}	41.48^{a}	5.72^{ab}	9.50^{b}	7.42^{b}	4.62^{ef}	14.43^{ab}	12.43^{c}	15.34^{a}	5.22^{a}
	RTiP	14.11^{a}	33.04^{a}	2.73^{ab}	8.74^{bcd}	6.97^{bcd}	3.88^{f}	33.53^{a}	3.61^{ef}	12.37^{a}	3.92^{a}
Minimum (D_0)	C	16.37^{a}	17.58^{a}	1.90^{ab}	6.33^{fg}	5.54^{fg}	6.97^{de}	17.06^{ab}	3.06^{ef}	5.22^{a}	4.43^{a}
	F	20.73^{a}	37.42^{a}	5.29^{a}	8.28^{bcde}	6.70^{bcde}	6.12^{def}	51.61^{a}	5.32^{ef}	2.63^{a}	4.32^{a}
	RF	18.09^{a}	65.33^{a}	10.68^{a}	6.15^{g}	5.43^{g}	8.68^{cd}	16.77^{ab}	6.72^{de}	5.15^{a}	3.66^{a}
	RFM	13.60^{a}	57.17^{a}	12.03^{a}	8.52^{bcde}	6.84^{bcde}	8.36^{cd}	55.35^{a}	11.26^{cd}	5.70^{a}	4.40^{a}
	RML	29.15^{a}	28.16^{a}	10.15^{a}	7.47^{cdefg}	6.21^{cdefg}	10.06^{bc}	30.75^{a}	34.41^{a}	8.79^{a}	4.93^{a}
	RTiM	14.99^{a}	26.07^{a}	5.97^{ab}	8.82^{bc}	7.01^{bc}	6.48^{def}	32.39^{a}	10.84^{cd}	0.97^{a}	4.90^{a}
	RTiP	14.40^{a}	34.99^{a}	14.42^{a}	7.17^{defg}	6.03^{defg}	12.49^{b}	24.16^{ab}	2.40^{ef}	6.79^{a}	2.78^{a}
P		ns	ns	ns	0.02	0.02	0.006	ns	0.01	ns	ns

F, mineral fertiliser; RF, crop residue + mineral fertiliser; RFM, crop residue + mineral fertiliser + animal manure; RML, crop residue + animal manure + legume intercrop; RTiM, crop residue + *Tithonia* diversifolia + animal manure; RTiP, crop residue + *Tithonia diversifolia* + phosphate rock; ns, not significant. a-gDifferent letters indicate significant differences in the post hoc Tukey's HSD test performed in case effects of the model was significant (P≤0.05).

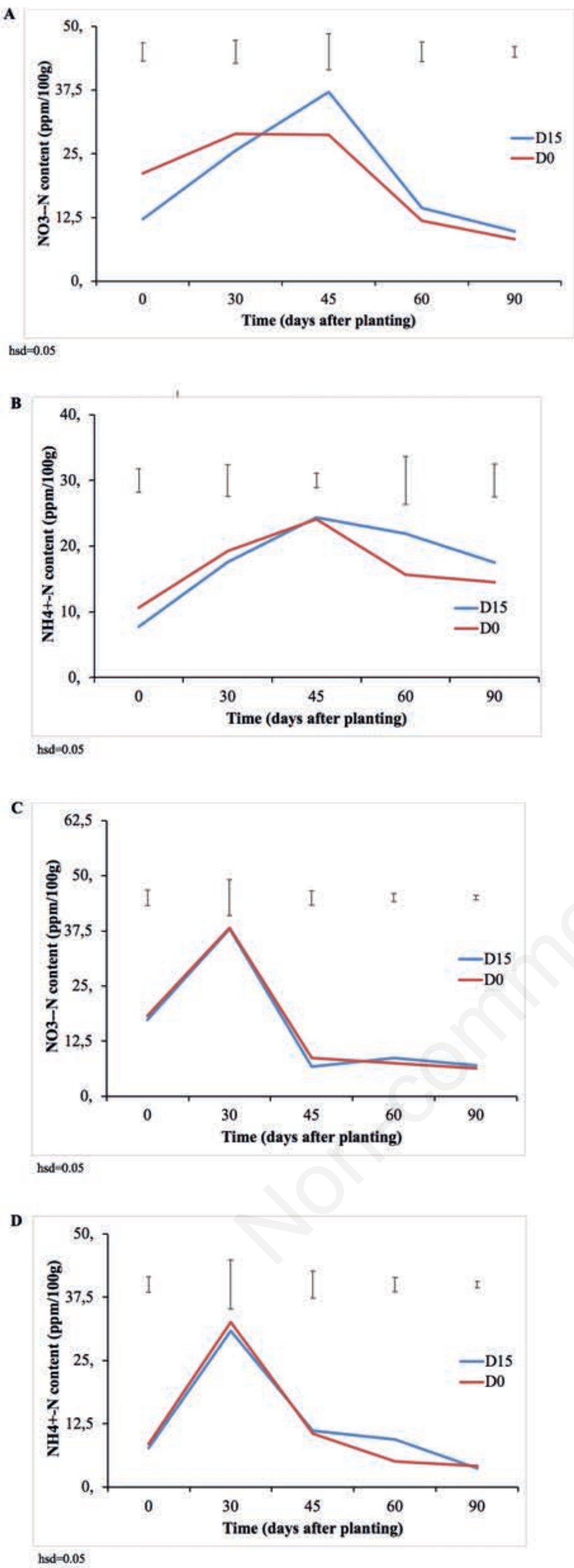

Figure 3. Mineral nitrogen response to different tillage systems in 0-20 cm depth during the short rain 2016 season: A) NO_3^--N and B) NH_4^+-N and long rain 2017; C) NO_3^--N and D) NH_4^+-N season at Meru South site; D_{15}, conventional tillage; D_0, minimum tillage. Significant differences of the post hoc Tukey's HSD test performed in case effects of the model was significant at P≤0.05.

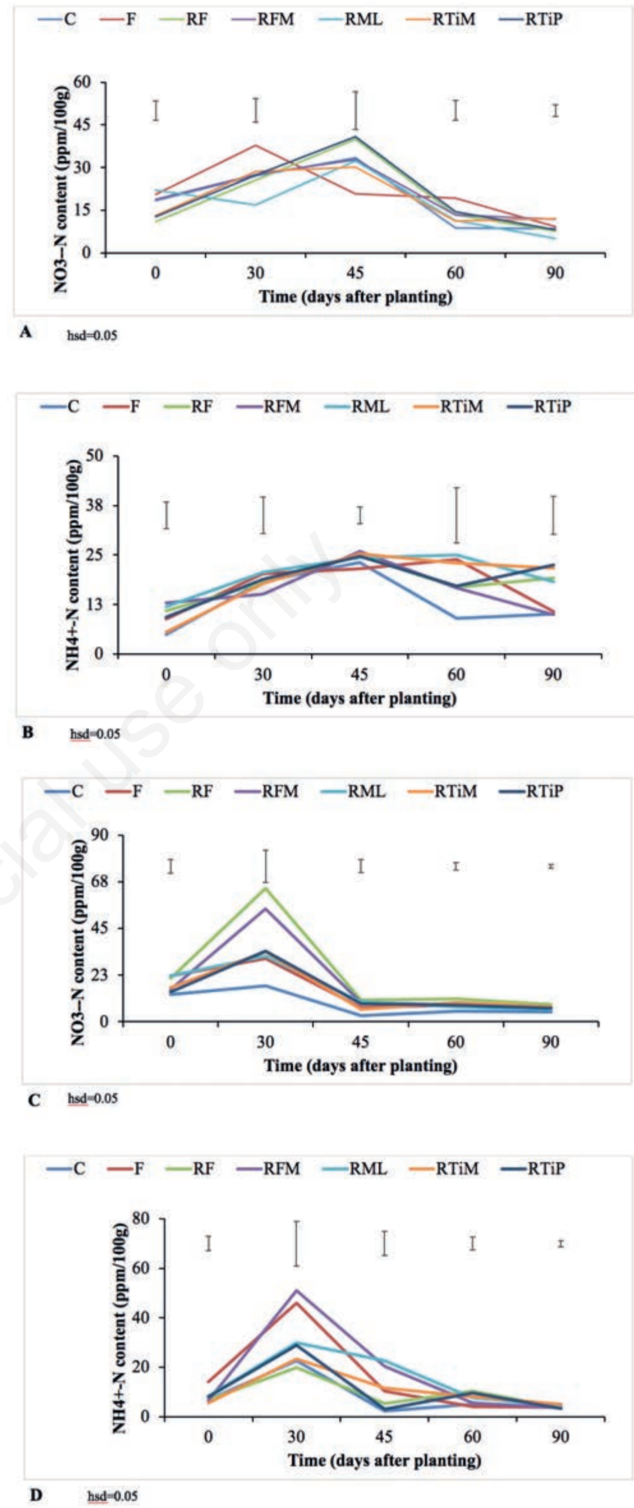

Figure 4. Mineral nitrogen response to various soil fertility resources during the short rain 2016 season: A) NO_3^--N and B) NH_4^+-N and long rain 2017; C) NO_3^--N and D) NH_4^+-N season in Meru South site. F, mineral fertiliser, RF, crop residue + mineral fertiliser, RFM, crop residue + mineral fertiliser + animal manure; RML, crop residue + animal manure +legume intercrop; RTiM, crop residue + *Tithonia diversifolia* + animal manure, RTiP, crop residue + *Tithonia diversifolia* + phosphate rock. Significant differences of the post hoc Tukey's HSD test performed in case effects of the model was significant at P≤0.05.

different on all the sampled days during SR16 season (Figure 6A). At planting NO_3^--N was significantly different under F, RF, RFM, and RML by 37, 26, 22 and 13% compared with the control during SR16 season (Figure 6A). On the 30th day, NO_3^--N was significantly higher under F, RF, RFM, and RML by 189, 136, 113 and 69% compared with the control. Application of RTiM and RF significantly increased NO_3^--N by 205 and 151%, respectively, compared with the control on the 45th day during SR16 season in Kandara. Ammonium-N was significantly different under SFR on all the sampling days except on the 90th day during SR16 season in Kandara (Figure 6B). NH_4^+-N was significantly higher under RTiM and RFM at planting by 91 and 55% and on the 30th day by 73 and 19%, respectively, compared with the control. On the 45th day, NH_4^+-N was significantly higher under F by 119% and under RTiM by 50% on the 60th day compared with the control during SR17 season (Figure 6B). Under the interactions, NO_3^--N was significantly different throughout the LR17 season on all the sampling dates (Table 9). At planting and on the 30th day after planting NO_3^--N was significantly highest under D_0*F interaction by 61 and 361%, respectively, compared with D_{15}*Control interaction (Table 9). On the 45th day, NO_3^--N was significantly highest under D_0*RTiM interaction by 213% compared with the D_{15}*Control interaction. Nitrate-N was significantly highest under D_0*RFM and D_{15}*RF on the 60th day and under D_{15}*RF on the 90th day compared with the control during SR16 season. Ammonium-N was highest under D0*RTiM interaction on the 30th day and under D_{15}*RF on the 90th day compared with the control. Nitrate-N was highest on the 45th day while NH_4^+-N was highest on the 30th day under tillage, SFR and under the interactions during SR16 season in Kandara site. During LR17 season, NO_3^--N was significantly higher under D_{15} on the 30th ($P=0.004$) and 60th ($P=0.02$) day after planting compared with the D_0 in Kandara (Figure 5C). Ammonium-N content was significantly ($P=0.01$) different between the tillage systems only at planting during LR17 season (Figure 5D). Under soil fertility resources, NO_3^--N was significantly higher under F, RFM, RF, RTiM, RML and RTiP 163, 159, 84, 70, 67 and 60% compared with the control on the 30th day during LR17 season (Figure 6C). On the 45th day, NO_3^--N was significantly higher under RFM and F by 296 and 260%, respectively, compared with the control. While on the 60th day, NO_3^--N was significantly higher under RFM and RML by 131 and 70%, respectively, compared with the control (Figure 6C). Compared with the control, NH_4^+-N was significantly different among SFR at planting and on the 45th day during LR17 season at Kandara site (Figure 6D). On the 45th day, NH_4^+-N was significantly higher under RTiP by 174% compared with the control. Under the interactions, NO_3^--N was significantly ($P=0.006$) different only on the 30th day during LR17 season (Table 10). Ammonium-N was significantly different at planting, on the 30th and 60th day in Kandara site during LR17 season (Table 10). Both NO_3^--N and NH_4^+-N was highest on the 30th day under tillage, SFR and the interactions during LR17 season in Kandara site.

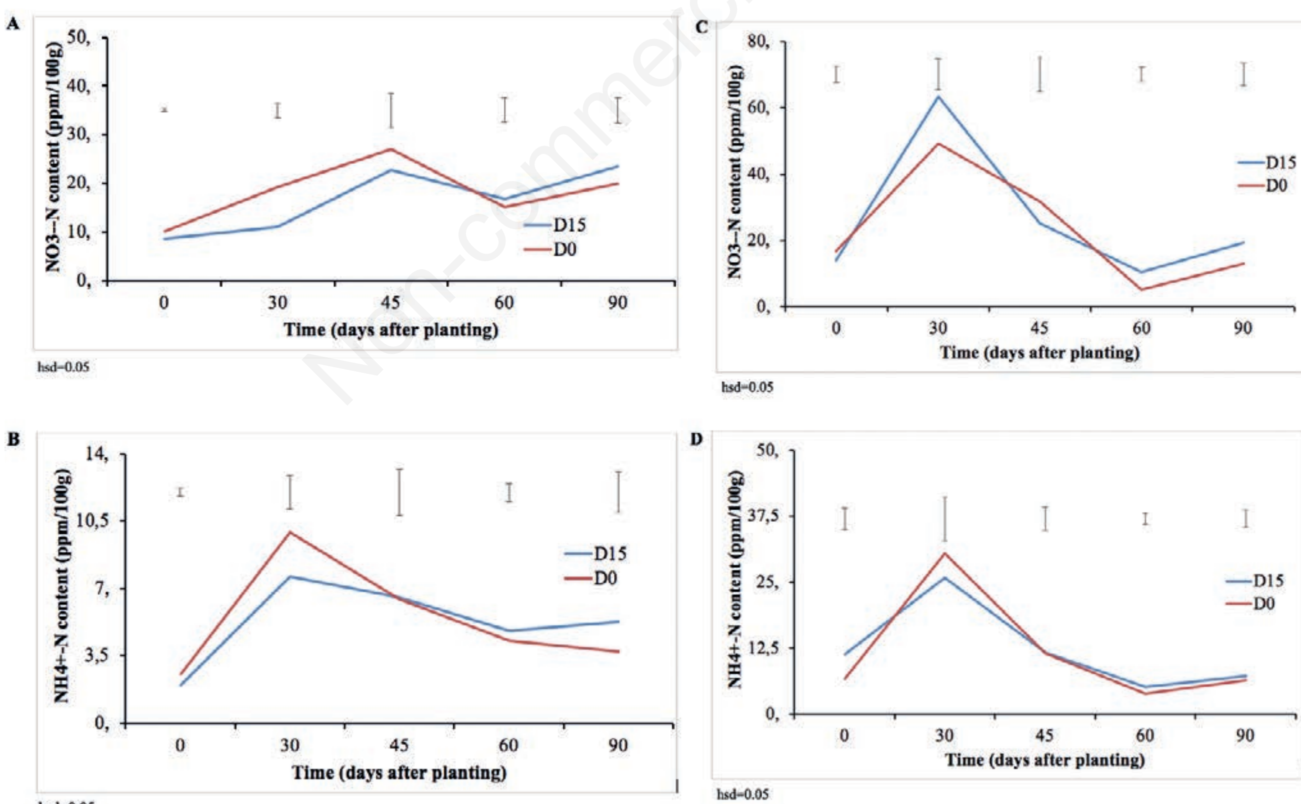

Figure 5. Mineral nitrogen response to different tillage systems in 0-20 cm depth during the short rain 2016 season: A) NO_3^--N and B) NH_4^+-N and long rain 2017; C) NO_3^--N and D) NH_4^+-N season in Kandara site; D_{15}=Conventional tillage; D_0=Minimum tillage; Significant differences of the post hoc Tukey's HSD test performed in case effects of the model was significant at $P\leq0.05$.

Discussion

Soil bulk density is a frequently measured soil quality parameter in tillage experiments (Logsdon and Karlen, 2004). In our study, tillage significantly influenced bulk density in Kandara site (Table 2). Ferreras *et al*. (2000) also reported greater soil bulk density under conservation tillage than conventional tillage. Bulk density was not significantly different between the minimum and conventional tillage systems at Meru South site. This corroborates with the findings of several authors like Antichi *et al*. (2011); Lou

Table 9. Mineral-N response under tillage* soil fertility resources interactions in the 0-20 cm depth on different sampling dates during short rains 2016 season at Kandara site.

		Sampling days after planting (SR16 season)									
		Nitrate-N (ppm/100g)					Ammonium-N (ppm/100g)				
Tillage	SFR	0	30	45	60	90	0	30	45	60	90
Conventional* (D_{15})	Control	7.83^{hi}	7.15^{j}	17.93^{gh}	5.96^{e}	7.50^{h}	0.79^{f}	6.94^{fg}	7.27^{cd}	4.48^{a}	3.34^{a}
	F	9.52^{e}	16.32^{e}	41.38^{b}	20.98^{c}	36.54^{b}	1.70^{e}	4.89^{h}	16.88^{a}	5.11^{a}	2.49^{a}
	RF	9.37^{e}	16.03^{e}	32.08^{d}	36.38^{a}	42.65^{a}	2.62^{bcd}	5.43^{gh}	3.68^{gh}	5.03^{a}	4.85^{a}
	RFM	7.90^{hi}	15.51^{e}	24.16^{fg}	16.59^{cd}	12.27^{fg}	1.80^{e}	8.83^{e}	3.06^{gh}	4.25^{a}	4.58^{a}
	RML	9.46^{e}	7.54^{ij}	11.24^{ij}	5.28^{e}	12.75^{fg}	2.43^{bcd}	9.91^{de}	3.99^{gh}	4.62^{a}	8.72^{a}
	RT^{i}M	8.53^{fg}	10.99^{gh}	23.82^{fg}	24.52^{bc}	43.56^{a}	2.00^{e}	8.82^{e}	6.29^{def}	5.05^{a}	5.29^{a}
	RT^{i}P	7.22^{j}	3.86k	7.86^{j}	7.33^{e}	8.89^{gh}	2.35^{bcde}	8.44^{ef}	4.44^{fgh}	4.91^{a}	7.56^{a}
Minimum* (D_0)	Control	8.33^{gh}	9.89^{hi}	22.62^{fg}	7.57^{e}	17.44^{e}	2.54^{bcd}	9.48^{de}	4.80^{efg}	2.63^{a}	1.93^{a}
	F	12.60^{a}	33.05^{a}	20.62^{fgh}	28.11^{b}	20.39^{de}	2.99^{b}	11.89^{bc}	9.66^{b}	5.32^{a}	3.32^{a}
	RF	11.08^{c}	12.71^{fg}	34.03^{c}	8.35^{e}	41.07^{ab}	1.60^{e}	6.38^{gh}	10.77^{b}	3.53^{a}	7.69^{a}
	RFM	11.82^{b}	24.83^{c}	14.98^{hi}	38.67^{a}	24.71^{cd}	1.97^{e}	10.64^{cd}	4.13^{gh}	4.28^{a}	3.28^{a}
	RML	8.85^{f}	28.83^{b}	15.00^{hi}	8.81^{e}	11.93^{fgh}	2.76^{bc}	6.66^{g}	6.64^{de}	4.89^{a}	2.22^{a}
	RT^{i}M	8.13^{gh}	8.77^{hij}	56.22^{a}	6.80^{e}	15.09^{ef}	4.40^{a}	19.55^{a}	2.59^{h}	5.61^{a}	4.46^{a}
	RT^{i}P	9.55^{de}	16.53^{de}	25.23^{ef}	7.05^{e}	9.28^{gh}	1.69^{e}	4.85^{h}	6.63^{de}	3.59^{a}	3.26^{a}
P		0.0004	0.0004	0.008	0.0003	0.003	0.0007	0.001	0.05	ns	ns

SFR, soil fertility resources; F, mineral fertiliser; RF, crop residue + mineral fertiliser; RFM, crop residue + mineral fertiliser + animal manure; RML, crop residue + animal manure + legume intercrop, RTiM, crop residue + *Tithonia diversifolia* + animal manure; RTiP = Crop residue + *Tithonia* diversifolia + phosphate rock; ns, not significant. a-jDifferent letters indicate significant differences in the post hoc Tukey's HSD test performed in case effects of the model was significant (P≤0.05).

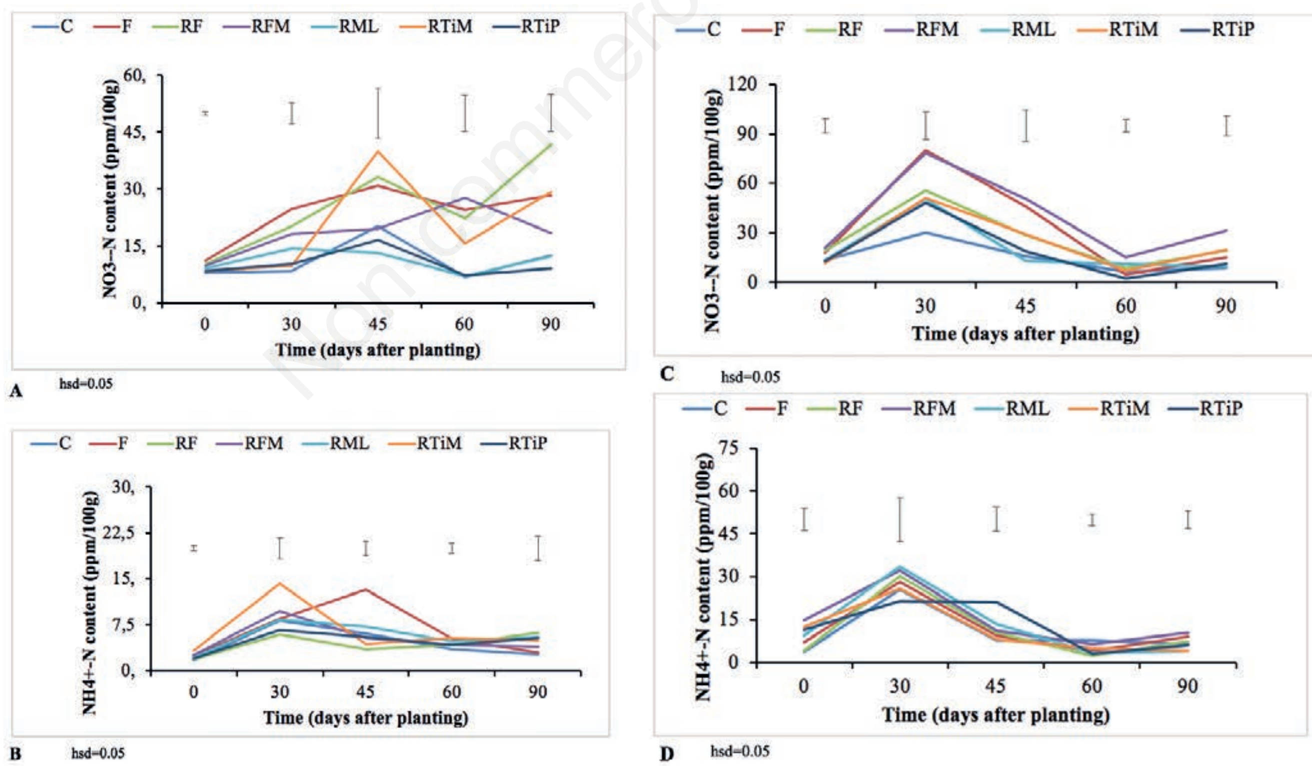

Figure 6. Mineral nitrogen response to various soil fertility resources during the short rain 2016 season: A) NO_3^--N and B) NH_4^+-N and long rain 2017; C) NO_3^--N and D) NH_4^+-N season in Meru South site. F, mineral fertiliser; RF, crop residue + mineral fertiliser; RFM, crop residue + mineral fertiliser + animal manure; RML, crop residue + animal manure + legume intercrop; RTiM, crop residue + *Tithonia diversifolia* + animal manure; RTiP, crop residue + *Tithonia* diversifolia + phosphate rock. Significant differences of the post hoc Tukey's HSD test performed in case effects of the model was significant at P≤0.05.

et al. (2012); Askari and Holden (2015). Implementing no-tillage and stubble mulch tillage, Baumhardt, and Jones (2002) found no significant difference in soil bulk density. Application of SFRs' had no significant influence on bulk density at both sites. Wyngaard *et al*. (2012) also found that fertilization had no significant effect on bulk density. After conducting trials for two years, Motavalli *et al*. (2003) also observed that application of organic amendment, turkey litter had no significant effect on soil bulk density. Peck *et al*. (2011) found no difference in bulk density under integrated and organic treatments. Furthermore, Willekens *et al*. (2014) found that neither tillage nor compost influenced bulk density.

A significant increase in aggregate stability under minimum tillage compared to conventional tillage has been reported in some studies, for instance, Gicheru *et al*. (2004) and Paul *et al*. (2013). Conversely, this was not the case in our study, and the none-response might be attributable to soils with high clay content in both sites. Interaction of clay with other soil properties such as SOC content and differences in the mineralogical structure of the different clay types and ionic composition could be responsible for the varying results (Saygin *et al*., 2015). Ghuman and Sur (2001) also found no significant differences in aggregation indices between the minimum and conventional tillage treatments. Increased aggregate MWD under RML in Meru South (Table 2) was attributed to increased SOC (Table 6) at 0-5 cm depth. Increased SOC content increases soil aggregation (Meena *et al*., 2015), while SOM maintains soil aggregation (Mulumba and Lal, 2008). Some authors have reported that increased biomass input in legume crops-based cropping systems increases SOM content (Vieira *et al*., 2007; Wood *et al*., 2015).

Soil aggregation controls hydrological properties such as water holding capacity and storage of SOC (Bronick and Lal, 2005). In our study, hydraulic conductivity increased under application of crop residue, animal manure and legume intercrop (RML). Improvement of soil physical structure with the application of organic resources more so increased hydraulic conductivity has been reported (Macci *et al*., 2012). We attributed the insignificant effects on soil physical properties of the other SFRs used in this study to the short duration the experiments were conducted. Mosaddeghi *et al*. (2000) observed that application of animal manure or other organic resources has effects on soil physical properties when applied in high rates or over several years.

Changes in soil chemical properties after the study period were variable under application of soil fertility resources perhaps due to differences in the inputs' quality. This was consistent with the findings of Mucheru-Muna *et al*. (2014) in a study conducted in Central Kenya. The pH increased under application of RTiM and RML in both sites and under RFM and RTiP in Kandara site. This could be due to the organic acids and ligands that are produced during decomposition of organics enhancing the increase in soil pH (Hue, 1992). The increase in pH under SFR with organic resources could also be as a result of increased base-forming cations (Ca and K in both sites and also Mg in Kandara) contained in organic resources thus decreasing soil acidity (Brady, 1990; Melero *et al*., 2007). Increase in soil pH as a result of using organic resources has been observed by several authors (Agbede, 2010; Mijangos and Garbisu, 2010).

On average, total N increased under the combination of mineral fertilizer and organic inputs. This could be due to complete uptake of the readily available N from the mineral fertilizer by the crop and partial uptake of N from the organic inputs. Phosphorous increased under soil fertility resources with mineral fertilizers; F, RF, RFM, and RTiP in both sites which was attributed to the readily available P in the mineral fertilizers' and the fact that it is also an immobile element with high residual effect. This finding was consistent with the results of Onwonga *et al*. (2015). Potassium increased in soils that received sole organic resources (RTiM, RML) and with the combination of mineral fertilizer (RFM, RTiP). The increase in potassium could be explained by the fact that animal manure and *Tithonia diversifolia* contain high and readily decomposable potassium (Jama *et al*., 2000). Generally, soil fertility resources with animal manure showed an increase in soil nutrients. Application of animal manure tends to surpass the crop nutrient requirements leading to nutrient accumulation in agricultural

Table 10. Mineral-N response under tillage* soil fertility resources interactions in the 0-20 cm depth on different sampling dates during long rains 2017 season at Kandara site.

		Sampling days after planting (SR17 season)									
		Nitrate-N (ppm/100g)					Ammonium-N (ppm/100g)				
Tillage	SFR	0	30	45	60	90	0	30	45	60	90
Conventional * (D_{15})	C	10.35^{a}	28.70^{f}	16.66^{a}	9.15^{a}	10.59^{a}	4.22^{d}	17.26^{de}	8.19^{a}	13.04^{a}	10.63^{a}
	F	13.18^{a}	78.84^{b}	43.58^{a}	4.21^{a}	18.76^{a}	2.98^{d}	21.05^{d}	9.26^{a}	2.37^{de}	6.84^{a}
	RF	17.98^{a}	59.03^{cd}	19.34^{a}	19.93^{a}	28.07^{a}	5.30^{d}	30.03^{c}	11.08^{a}	6.87^{b}	10.09^{a}
	RFM	24.23^{a}	95.84^{a}	32.29^{a}	19.22^{a}	27.43^{a}	15.74^{ab}	16.25^{de}	16.30^{a}	3.82^{d}	8.23^{a}
	RML	14.42^{a}	42.17^{e}	14.26^{a}	11.96^{a}	5.06^{a}	16.15^{a}	46.79^{a}	6.57^{a}	2.36^{de}	4.43^{a}
	RTiM	9.44^{a}	74.47^{b}	23.69^{a}	6.52^{a}	31.30^{a}	15.43^{b}	12.43^{eg}	10.52^{a}	3.84^{cd}	4.50^{a}
	RTiP	8.69^{a}	63.45^{c}	26.36^{a}	2.05^{a}	14.25^{a}	19.52^{a}	36.72^{bc}	19.79^{a}	4.05^{cd}	5.53^{a}
Minimum * (D_0)	C	16.27^{a}	31.54^{f}	13.92^{a}	3.76^{a}	6.66^{a}	3.40^{d}	33.53^{c}	7.19^{a}	2.47^{de}	2.51^{a}
	F	22.11^{a}	80.97^{b}	47.66^{a}	4.65^{a}	11.13^{a}	11.26^{bc}	35.29^{bc}	9.73^{a}	5.73^{bc}	11.13^{a}
	RF	20.27^{a}	52.17^{d}	36.85^{a}	9.99^{a}	9.58^{a}	2.87^{d}	30.20^{c}	9.56^{a}	5.72^{bc}	4.91^{a}
	RFM	16.86^{a}	60.41^{cd}	68.09^{a}	2.77^{a}	34.58^{a}	14.09^{b}	48.39^{a}	6.09^{a}	2.92^{de}	12.33^{a}
	RML	11.53^{a}	58.73^{cd}	11.06^{a}	4.65^{a}	13.31^{a}	2.58^{d}	20.33^{d}	20.59^{a}	2.59^{de}	3.89^{a}
	RTiM	13.84^{a}	27.66^{f}	34.51^{a}	7.53^{a}	8.23^{a}	9.48^{c}	39.19^{b}	5.49^{a}	6.48^{b}	3.38^{a}
	RTiP	17.14^{a}	32.99^{f}	10.78^{aa}	2.56^{a}	7.76^{a}	3.55^{d}	5.94^{g}	22.49^{a}	1.80^{e}	6.41^{a}
P		ns	0.006	ns	ns	ns	0.04	0.001	ns	0.02	ns

SFR, soil fertility resources; F, mineral fertiliser; RF, crop residue + mineral fertiliser; RFM, crop residue + mineral fertiliser + animal manure; RML, crop residue + animal manure + legume intercrop; RTiM, crop residue + *Tithonia diversifolia* + animal manure; RTiP, crop residue + *Tithonia* diversifolia + phosphate rock; ns, not significant. $^{a-g}$Different letters indicate significant differences in the post hoc Tukey's HSD test performed in case effects of the model was significant (P≤0.05).

soil (Nautiyal *et al*., 2010).

Minimum tillage showed a trend of increased SOC in all the sampled depths at the end of the study and significantly increased SOC content in the 0-5 cm depth in Kandara compared with conventional tillage (Table 6). This could be attributed to the higher physical protection of soil organic matter due to minimized soil disturbance under D_0. Increases in SOC are usually limited to the topmost soil layer of 0-5 cm (Poeplau and Don, 2013; Flávia *et al*., 2015). In a study conducted in China, on *Cambisols*, Lou *et al*. (2012) found that SOC significantly increased under conservation tillage compared to the traditional tillage system under 0-5 cm depth. Increase in SOC under conservation tillage practices has also been reported by several authors (Dalal *et al*., 2011; Powlson *et al*., 2012; Awale *et al*., 2013). Lack of significant differences in SOC concentrations in response to tillage in deeper depths might be due to the short duration the study was conducted (Geisseler and Horwath, 2009). Application of SFRs' led to positive changes in soil organic carbon.

Generally, use of SFRs with sole organic resources or in combination with mineral fertilizers led to an increment of SOC. Organic resources have a significant impact on increasing soil carbon directly (Mucheru-Muna *et al*., 2007). Soil fertility resources with animal manure led to increased SOC in our study. Manure application supplies different organic carbon compounds from organic residues to humus which includes the composition of all C fractions resulting in significantly increased root biomass that could return more C to the soil (Tong *et al*., 2014). Increase in SOC due to manure application has been reported (Mucheru-Muna *et al*., 2007). Soil organic carbon increased under RML compared with the control in both sites. The inclusion of legumes increases SOC active pools (Romanyà *et al*., 2012). Lablab has an extensive root system that aids in improving soil organic carbon (Sheahan, 2012.). Soils under organic management are widely reported to increase and maintain SOC (Chivenge *et al*., 2011b; Powlson *et al*., 2012; Lorenz and Lal, 2016). Increased SOC under inorganic fertilizer in Meru South could be due to higher root biomass accumulated over the cropping seasons than in the control plots (Rasool *et al*., 2008). Mineral fertilizers increase both crop yield and the return of plant residues to the soil and thus can also increase organic matter retention (Romanyà *et al*., 2012). Other studies have reported that addition of inorganic fertilizers significantly increases SOC stocks (Diekow *et al*., 2005; Zanatta *et al*., 2007). However, in the long-term use of mineral fertilizers alone has been shown not capable of increasing SOC compared to organic fertilizers (Triberti *et al*., 2008; Hai *et al*., 2010). Crop residue retention is known to enhance SOC, yet, in Kandara use of RF and RFM had no significant difference with the control. This would be attributed to the slow decomposition of maize stover residue and short-term period we conducted the study. In a meta-analysis by Chivenge *et al*. (2011a) insignificant SOC response under residue retention in clayey soils was also reported.

The bulk of mineral N found in the soil in all treatments during the two cropping season on all the sampling days was in the form of nitrate-N compared with ammonium-N at both sites. This was as a result of the fast conversion of ammonia to nitrate following mineralization of inputs in the soil as also found by (Shisanya *et al*., 2009). Mineral-N tended to be high under minimum tillage only at planting, then decreased but increased under conventional tillage as the season progressed. The decrease under minimum tillage could be attributed to reduced soil inversion while the increase under conventional tillage was due to regular soil disturbance that breaks down SOM thus inducing mineralization. Reduced soil disturbance under minimum tillage enhances the formation of stable aggregates that physically protect SOM hence reducing mineralization rates (Lichter *et al*., 2008). We also observed increased soil organic carbon under minimum tillage (Table 6). Continued lack of soil loosening during cropping season slows N mineralization in minimally tilled soils and promotes denitrification. Conventional tillage induces rapid mineralization of soil nutrients homogenizing distribution of nutrients to the depth of tillage (Johansen *et al*., 2012) and leading to potential loss of N from the soil (Abolanle *et al*., 2015).

The general pattern observed for soil mineral N content was that greater N release occurred on the 30th or 45th day after planting and declined on the 60th and 90th at both sites. This could be ascribed to the more rainfall events experienced (Figure 1) around the sampling days leading to increased soil moisture that favors microbial activities. Kaupa and Rao (2014) found that mineralization rates were significantly faster in the first 30 days; later, the rate of release was comparably slower. Soil moisture plays an important role in N mineralization (Qiu-hui *et al*., 2012). According to Dou *et al*. (1996), N mineralization shows a two-phase pattern, *i.e*., the rapid phase and the slow to steady phase. Soil microbes utilize easily decomposable organic N sources in short periods, leaving more recalcitrant organic matter progressively to be mineralized (Khalil *et al*., 2005) hence gradually slower rates of mineralization in the later phase. Reduced mineral-N on the last sampling dates (60th and 90th) was probably due to a reduction in microbial populations (Butterly *et al*., 2009) and a limitation of the solute diffusivity under limited soil moisture conditions (Manzoni *et al*., 2012). Generally, mineral N was higher during LR17 season compared with the SR16 season in both sites. This was attributed to better rainfall distribution during LR17 season than the SR16 season (Figure 1). Soil mineral N under the soil fertility resources varied and consequently did not show clear trends which could be attributed to uniform application of crop residues. Mineral N is readily available from inorganic fertilizers, hence higher mineral N recorded on first sampling days. Application of mineral N fertilizer leads to greater mineralization of soil N from SOM (Kaupa and Rao, 2014). Organic soil fertility resources with high N contents and low C:N ratios mineralize sufficient N to satisfy plant growth while those with lower N contents and higher C: N ratios can immobilize N (Masunga *et al*., 2016). Application of crop residues with a high C: N ratio (Palm *et al*., 2001) like maize crop residues, may counterbalance the effects of mineralization (Fan *et al*., 2014). Li *et al*. (2013) found that soils amended with residues had a lower cumulative N mineralization than the un-amended soils. Mineralization of N from crop residues on or near the surface of conservation tillage soils is slower, and N immobilization is higher than when the residues are incorporated by plowing (Van Den Bossche *et al*., 2009). Immobilization is also observed in soils with higher clay content (Sakala *et al*., 2000). Use of RML was not highly significant in mineral-N as expected. Murty *et al*. (2002) also found that inclusion of leguminous species in the organic system was not effective in adjusting the C/N ratio to the lower value for arable soil.

Conclusions

We evaluated the effect of tillage practices and soil fertility resources on selected soil physical and chemical properties, SOC and mineral N dynamics under tropical sub-humid agro-ecological conditions. The results highlighted that soil properties are affected by tillage and soil fertility resources. Unlike chemical properties, the physical properties were not prominently influenced by the treatments, probably due to the short period the study was conducted. Application of sole organic inputs or in combination with mineral fertilizer showed positive effects on chemical properties. Implementation of minimum tillage, as well as the application of organic soil inputs, showed significant positive effects on soil organic carbon and mineral nitrogen. During the study period, mineral nitrogen was significantly affected by the interactions. Thus our study highlighted that tillage, soil fertility resources application and their combination has effects on soil properties in clayey soils of high agricultural potential areas such as Central Highlands of Kenya. Therefore, we conclude that conservation agriculture practices can offer an opportunity for enhancing and maintaining soil fertility of smallholder agro-ecosystems of sub-Saharan Africa as soil conditions are improved and thus increase crop yields. However, longer-term experimentation would be required to determine the influence of tillage and soil fertility resources on soil physical properties.

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