Nutr Cycl Agroecosyst
https://doi.org/10.1007/s10705-021-10132-x

ORIGINAL ARTICLE

# Physico-chemical soil attributes under conservation agriculture and integrated soil fertility management

Eunice A. Mutuku · Bernard Vanlauwe · Dries Roobroeck · Pascal Boeckx · Wim M. Cornelis

Received: 14 August 2020 / Accepted: 8 March 2021


**Abstract** Conservation Agriculture (CA) and Integrated Soil Fertility Management (ISFM) have been promoted in Sub Saharan Africa as a means to improve soil quality. A four season research (March, 2017 to March, 2019) was conducted to evaluate CA-based treatment, no tillage with residue retention (NTR), ISFM-based treatment, conventional tillage with use of manure (CTM), a combination of CA + ISFM, no tillage with residue retention and use of manure (NTRM) and a control, (C) on soil quality attributes. In the two locations (sub-humid and semi-arid) the effect of soil fertility gradients (high and low) were considered. Trials were set out using a one farm one replicate randomized design. In either high or low fertility fields, soil chemical and physical properties were significantly different between the control and NTR, CTM and NTRM with no significant differences between NTR, CTM and NTRM. SOC was higher under NTR and NTRM practices, which consequently had higher hydraulic conductivity, air permeability, mean weight diameter and available phosphorus. For all the treatments and in both locations, the low fertility fields had significantly lower agronomic use efficiency (AUE) compared to the high fertility fields. In both soil types, plant available water capacity and relative water capacity values were below the recommended thresholds indicating low soil water uptake, suboptimal microbial activity and consequently low nutrient uptake which explains the observed low AUE.

**Keywords** Soil quality · Soil fertility gradients · Agronomic use efficiency · Physical soil quality indicators

E. A. Mutuku (✉) · W. M. Cornelis
Department of Environment, Ghent University, Ghent, Belgium
e-mail: anneunice24@yahoo.com

B. Vanlauwe · D. Roobroeck
Department of Natural Resource Management, International Institute of Tropical Agriculture, Nairobi, Kenya

P. Boeckx
Isotope Bioscience Laboratory-ISOFYS, Department of Green Chemistry and Technology, Ghent University, Ghent, Belgium

## Introduction

Sustainable intensification of agriculture is needed for areas where fallow periods are no longer possible. The said intensification is necessitated by the projected increase in world population to 9.1 billion by 2050 (FAO 2009). The increase is expected to come mostly from the developing world with Sub-Saharan Africa (SSA) highlighted on top of the list (Gerland et al. 2014). This creates a need for increased food production putting pressure on the natural resource base. As such, agricultural intensification has recently gained support, in part because of the growing recognition

Published online: 25 April 2021

that it enhances farm productivity as well as conserve the natural resource base, a major entry point to breaking the vicious cycle underlying rural poverty (Vanlauwe et al. 2011). Over the past years, food production increase in SSA has been achieved mainly through shifting cultivation with 92% of forest loss in this area related to this practice (Curtis et al. 2018). This practice is however not sustainable due to its related biodiversity loss and greenhouse gas emissions which will further worsen climate change effects (Van Ittersum et al. 2016). Insufficient use of mineral and organic fertilizer has led to nutrient mining thereby making plant nutrition a major limitation to crop production (Tittonell and Giller 2013; Wall et al. 2013). In Kenya, the situation is not different, where continuous cropping without addition of adequate organic and inorganic resources has caused soil fertility decline and reduced productivity (Mugendi et al. 1999). While these negative effects could be reversed by fallow periods, van Vliet et al. (2012) reported a decrease in fallow length related to population growth. As a consequence, smallholder farmers in Kenya are said "to have little choice but to better manage their soils" as a means to increase crop productivity (Kapkiyai et al. 1999).

Several land management practices to help intensify crop production in SSA have been developed, among them Conservation Agriculture (CA) and Integrated Soil Fertility Management (ISFM) (Sommer et al. 2018). CA is defined by three linked principles: continuous minimum mechanical soil disturbance, permanent organic soil cover using crops and/or crop residues, and diversification of crop species grown in sequence and/or association (FAO 2002). ISFM, on the other hand, is defined as a set of soil fertility management practices that necessarily include the use of fertilizers, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions (Vanlauwe et al. 2014). The effects of these practices on soil quality have not been studied sumptuously in Kenya, raising a need for that (Mutuku et al. 2020).

Soil quality is defined by Schjønning et al. (2004) as a measure of a soil's capacity to deliver ecosystem services and functions. To evaluate the effects of management practices on soil quality, measured parameters are used, for example, bulk density (BD), aggregate stability, and hydraulic conductivity as soil physical attributes. In addition to the measured soil physical properties, the importance of indirect soil physical quality indicators has been documented (Reynolds et al. 2002, 2008, 2009). A summary of such indicators that are directly influenced by land management is presented in Reynolds et al. (2007). These parameters are obtained from the soil water retention curve and for their usability, critical threshold values for optimal soil functioning have been determined (Reynolds et al. 2007, 2009). Calculated values falling outside the thresholds are an indication that the soils are physically limited.

While smallholder farmers generally believe that soil tillage is needed to maximise crop yield (Johansen et al. 2012), whether to till the land or not is a question that has gained a lot of research interests. Worldwide, most farmers till their land in preparation for sowing crops (Huggins and Reganold 2008). Soil tillage before sowing buries crop residues and troublesome weeds, aerates the soil and makes it easier for crop germination. But disturbing the soil in this way can also leave it vulnerable to erosion by wind and water, increased soil water loss via evaporation as well as cause soil organic carbon (SOC) losses through oxidation (Sithole et al. 2016). No tillage (NT) improves the physical and chemical characteristics of the soil by eliminating the negative effects of unsustainable intensive tillage (Derpsch et al. 2010). Nevertheless, ISFM-based practices, which involves soil tillage, have been promoted for their ability to relieve chemical and physical soil fertility constrains in the short run, thereby increasing crop productivity (Vanlauwe et al. 2014). The combined use of organic and inorganic nutrient sources under ISFM has been suggested as one of the effective ways of addressing soil fertility decline by resource constrained smallholder farmers who are unable to apply sufficient quantities of inorganic soil nutrients (Chivenge et al. 2011).

The shortages in the supplies of organic inputs and fertilizers have created soil fertility gradients within farms in SSA (Chianu et al. 2012) while resource endowments have contributed to between farm soil fertility gradients (Tittonell et al. 2005). With the majority of farmers in sub-humid and semi-arid regions being smallholders and resource strained, low availability of organic and inorganic resources has resulted in between and within farm soil fertility gradients (Vanlauwe et al. 2006). While information on the existence of soil fertility gradients between and within farms is present, there is scanty information on the influence of such gradients on the effectiveness of different soil fertility management practices.

In this study, we evaluated soil quality, nutrient agronomic use efficiency (AUE) and gross income analysis under CA-based, ISFM-based and a combination of the two practices and on smallholder farm fields on two contrasting sites (sub-humid and semi-arid) after four growing seasons. Gradients in soil fertility at farm scale were distinguished by the productivity of control trials. Specifically, the objectives of this study were to evaluate the short-term effects of CA-based practice (NTR), ISFM-based practice (CTM) and their combination (NTRM) on (i) top soil chemical properties on fields with high and low fertility status, (ii) top and sub soil physical properties and physical soil quality indicators, (iii) within and between planting row physical and chemical properties, (iv) agronomic efficiency in the high and low fertility fields and (v) to assess the economic viability of the practices.

## Materials and methods

### Study area and experimental design

This study was conducted in Embu county of Kenya which has contrasting agro-ecologies. Trials were set up in Kibugu (0° 26′ S and 37° 26′ E), classified as sub-humid and Machang'a (0° 46′ S and 37° 39′ E), classified as semi-arid. The locations lie at an altitude of 1543 m and 1106 m for Kibugu and Machang'a, respectively. The soils are classified as Nitisol with clay texture and Cambisol with sandy loam texture, in Kibugu and Machang'a, respectively (WRB 2006). Soil sampling was done in February, 2018 from rainfed trials with maize (*Zea mays* L.) as the test crop. The trials had been established on 10 farms in each of the locations in 2017 and were running for four consecutive seasons, i.e. long rains 2017 (LR17), short rains 2017 (SR17), long rains 2018 (LR18) and short rains 2018 (SR18). However, two farmers in Machang'a dropped out of the trials due to land subdivision reasons, leaving 18 farms at the end of the study. In each location, fields were selected representing a high and a low fertility status. Farms were selected firstly based on the willingness of the farmer to provide plots for the trials and secondly on whether farmers could identify fields of high and low fertility within their farms. The identification of high and low fertility fields was done based on past management and maize production history. After this classification, farms were later reclassified based on first season maize yield data from the control treatment which showed a clear distinction. After season four, farms were dropped to remain with two farms in each location where the trials were continued for another two seasons, LR and SR of 2018.

In addition to the fact that farmers in Africa start CA adoption with two principles, majority of farmers in the study area practiced maize-monocropping. Pittelkow et al. (2015) has also highlighted the need to investigate the effects of no tillage in the tropical environments. The trials were then designed in support of these, i.e., test no tillage and residues retention management systems on maize-monocropping. Therefore, in each field, the following treatments were laid down following a one-farm-one-replicate randomized design: (1) a conventional control with no inputs which depicts farmers practice in the study locations (C), (2) a CA-based treatment involving no tillage and residue retention (NTR), (3) an ISFM-based treatment involving conventional tillage and use of manure (CTM), and (4) a combination of the CA- and ISFM-based treatments involving no tillage, residue retention and use of manure (NTRM). It is important to note that rather than evaluating the individual components that constitute the tested treatments, such as tillage, residue retention, use of fertilizer and manure, the setup was designed to compare the alternative cropping systems.

Plots under tillage (C and CTM) were weeded by hand, hoeing up to 0.15 m, while plots under no tillage (NTR and NTRM) were sprayed with a selective herbicide (Tingatinga, Geneva agrochemical limited). Plots under NTR, CTM and NTRM were fertilized with 80 kg nitrogen (N) ha$^{-1}$ (urea) using split application of 40 kg N ha$^{-1}$ at planting and top-dressed at the same rate 6 weeks after planting, 30 kg phosphorus (P) ha$^{-1}$ (triple superphosphate) and 40 kg potassium (K) ha$^{-1}$ (muriate of potash) every growing season. Fully decomposed cow manure containing 2.1% N was applied at 2 t ha$^{-1}$ on plots under CTM and NTRM. Maize stover mulch was applied on the plots under NTR and NTRM at an application rate of 3 t stover ha$^{-1}$ to achieve ca. 30% soil cover. Plots under the farmer practice, C, received

0 kg N $ha^{-1}$, 0 kg P $ha^{-1}$, 0 kg K $ha^{-1}$, 0 t manure $ha^{-1}$ and 0% soil cover.

## Soil sampling and field measurements

Soils were sampled (0 to 0.15 m) in each farmer field before planting in season one. A composite sample was made from five points along an X shape covering the area where trials were to be established. At the end of season four, sampling was done using a similar sampling procedure. Composite soil samples were collected at 0–0.15 m since this is the depth where most of the maize roots were concentrated. Undisturbed soil samples were collected from 0 to 0.15 m and 0.15–0.30 m using Kopecky rings of 0.05 m inner diameter and 0.051 m height with a volume of 0.0001 $m^3$ for soil water retention curve analysis. In addition, disturbed soil samples for aggregate stability were collected from the same two depths. After season six, sampling was done to represent points within planting line and points between planting lines. During this sampling, two composite and three undisturbed samples per sampling point (within or between planting rows) were taken under each treatment. The soil samples were air-dried, 2 mm sieved and analysed for selected physico-chemical soil properties.

Hydraulic conductivity was determined in the field, in within and between planting points, using a tension disk infiltrometer (minidisk infiltrometer by Decagon, USA) at matric potentials of − 0.5 which eliminates water flow through macropores. The tension disk's bubble and reservoir chambers were filled with water and the matric potential adjusted to − 0.5 kPa. The disk was placed into contact with the soil after clearing the soil surface. The volume of the water in the tube was recorded at a time interval of 20 s for clay loam soils and 10 s for the sandy soils. After obtaining a constant volume at least five times in the selected time intervals, the run was stopped.

The hydraulic conductivity was calculated using the method proposed by Zhang (1997), Eqs. 1 and 2.

$$I = C1t + C2\sqrt{t} \tag{1}$$

where I is the cumulative infiltration, C1 and C2 are adjustable parameters related to hydraulic conductivity and soil sorptivity respectively.

The hydraulic conductivity (k) of the soil is computed from:

$$K = C1/A \tag{2}$$

where C1 is the slope of the curve of the cumulative infiltration versus the square root of time and A is a value relating to the matric potentials, soil type and radius of the tension disk infiltrometer.

Tillage practices induce soil structure degradation. Shear stress which is related to soil's ability to resist soil aggregate detachment can be used as an indicator to such structure degradation (Richard and Le 2004). As such, top soil with high SOC has low shear stress for soil particles are well cemented and can thus resist disintegration. Top soil and sub soil shear stress was measured in the field using a pocket vane tester with CL100 vane (Eijkelkamp Soil & Water, the Netherlands) with a measuring range of 0 to 250 kPa. To take measurements, the vane was placed on a pit wall. The meter was then turned by hand at a constant speed from zero in the direction of one until the head slipped back, leaving the arrow at the highest shear stress. To ensure constant meter turning speed, the measurements were done by one person.

## Laboratory analysis

Each intact 0.0001 $m^3$ core was used for several soil physical parameters analyses. First, the core was gradually saturated in a tray. It was then transferred to a permeameter (Eijkelkamp Soil & Water, type 09.02.01.05) for measuring hydraulic conductivity ($K_s$) using the constant head method. The water discharge was measured until a constant flux enabling calculation of $K_s$ (m $d^{-1}$) using Darcy's equation, Eq. 3.

$$K_s = \frac{Q_w L}{A \Delta H} \tag{3}$$

where $Q_w$ is the outflow of water through the soil core (m $d^{-1}$), L is the length of the soil core (m), A is the surface area of the soil core ($m^2$) and ΔH is hydraulic head difference (m $H_20$).

The core was then equilibrated at -100 hPa using the sand box apparatus (Eijkelkamp Soil & Water) after which the core was used for measuring air permeability ($K_a$) using a steady-state in-house made air permeameter proposed by Grover (1955) (Eq. 4).

$$K_a = \frac{Q_a \eta_{aL}}{A \Delta P} \tag{4}$$

where $Q_a$ is the outflow of air through the soil core (m $s^{-1}$), $\eta_a$ is the air viscosity (Pa s or kg $m^{-1}$ $s^{-1}$), $L$ is the length of the soil core (m), and $\Delta P$ is the pressure head difference across the sample (m).

After measuring $K_a$, the samples were subdivided into three sub samples for soil water content measurements at lower potentials of − 330 hPa, − 1000 hPa and − 15,000 hPa using pressure chambers (Soilmoisture Equipment, Santa Barbara CA, USA). As stipulated by Reynolds et al. (2007), water content at field capacity (FC) was taken at − 100 hPa, matric porosity (MatPor) at − 10 hPa and permanent wilting point (PWP) at − 15,000 hPa, while soil dry BD was determined at − 100 hPa during retention curve analysis.

Indirect soil physical quality indicators were calculated by Eqs. 5–8;

$$AC = \theta_s - \theta_{FC} \quad (5)$$

$$MacPor = \theta_s - MatPor \quad (6)$$

$$PAWC = \theta_{FC} - \theta_{PWP} \quad (7)$$

$$RWC = 1 - \frac{AC}{\theta_s} \quad (8)$$

where AC is air capacity, $\theta_s$, $\theta_{FC}$, and $\theta_{PWP}$ is the volumetric water content at saturation, field capacity and permanent wilting point, respectively, MacPor is macro porosity, plant available water capacity (PAWC) is plant available water content and relative water capacity (RWC) is relative water capacity.

MacPor is dependent on pore diameter and according to Jarvis (2007), it can be defined as pores having an equivalent cylindrical diameter larger than 0.3–0.5 mm, which is equivalent to a water entry pressure head of − 0.06 to − 0.1 m, according to the Young–Laplace equation (Eq. 9).

$$h = \frac{2\gamma cos(\theta)}{\rho g R} \quad (9)$$

where $h$ is the pressure head, $\gamma$ is the surface tension, $\theta$ is the contact angle between the two fluids, $\rho$ is the fluid density, $g$ is the gravitational acceleration, and $R$ is the radius of the capillary.

Aggregate stability was measured by the fast wetting procedure outlined by Le Bissonnais (1996). Fast wetting was chosen based on its ability to evaluate a large range of soils as affected by rapid wetting, appropriate for tropical areas that experience heavy rainstorms (Le Bissonnais 1996). To this effect, the soil materials were sieved through a column of sieves: 2000, 1000, 500, 200, 100 and 50 µm to determine fragment size distribution. The aggregate stability was expressed by mean weight diameter (MWD), which is the sum of the mass fraction of soil remaining on each sieve after sieving multiplied by the mean aperture of the adjacent mesh.

Total N and SOC were determined using an elemental analyzer (ANCA-SL, PDZ Europa, UK) coupled to an IRMS (20–22, SerCon, UK). Available P and exchangeable K were extracted using the resin and ammonium acetate method, respectively, and measured using the Inductively Coupled Plasma (ICP) method (Thermo scientific, iCAP 6000 SERIES, ICP spectrometer). pH-$H_2O$ (1:5) was measured using a HANNA PH + ISE Meter HI 5222. Texture analysis was done following the standard sieving and sedimentation techniques (Smith and Mullins 1991).

## Nutrient agronomic use efficiency

Agronomic use efficiencies of N, P or K were calculated using a formula given by Vanlauwe et al. (2011), Eq. 10.

$$AUE = \frac{(Y_F - Y_C)}{F_{appl}} \quad (10)$$

where $AUE$ (kg grain $kg^{-1}$ N, P or K) is defined as the increase in maize grain yield per unit of fertilizer N, P or K applied, $Y_F$ and $Y_C$ refer to grain yields (kg $ha^{-1}$) in the treatment where fertilizer N, P or K has been applied and in the control plot, respectively, and $F_{appl}$ is the amount of fertilizer N, P or K applied (kg $ha^{-1}$).

## Cost benefit analysis

The purpose of this analysis was to evaluate and compare the short-term economic returns of producing maize using under CA and ISFM-based practices. Maize productivity data has been presented earlier by Mutuku et al. (2020). Since the improved treatments did not show significant difference in soil quality, this analysis was important to help give an informed recommendation to smallholder farmers. In this analysis, fixed costs like land and tools were excluded hence results are presented as gross profit (Eqs. 11 and

12) (Kifuko et al. 2007). Maize yield was calculated as an average per treatment for the four seasons in Kibugu and three seasons in Machang'a (see Mutuku et al. 2020). Revenue from maize was calculated using farm gate prices. Parameters used for the calculation are presented in Table 1. The unit cost was based on prevailing retail prices during the study period. Labour costs include planting cost, fertilizer application, weeding, pesticide and herbicide application, manure application, mulching cost, harvesting and shelling costs. The information used for labour cost analysis was collected at the specific time of each activity in the course of the seasons. Labour calculations were based on the prevailing labour cost for casual workers and the number of days needed to accomplish any given activity.

$$\text{Gross profit} = \text{Revenue} - \text{costs} \tag{11}$$

$$\text{Revenue} = \text{Grain yield} \times \text{market price} \tag{12}$$

### Statistical analysis

All statistical computing and graphic designs were carried out in the R environment, version 3.4.2. (R Development Core Team 2016). The treatment effects on soil properties in each location and fertility level were evaluated through a linear mixed model using the packages 'lme4′ (Bates et al. 2015) and 'lmerTest' (Kuznetsova et al. 2017). The residual normal distribution and homoscedasticity of all models were ascertained by plotting residuals against quantiles and fitted values. Location, fertility level, treatment as well as interactions between these three factors were designated as fixed effects. The random intercepts of all mixed models were based on individual farm fields. The significance testing of main effects and their interactions for mixed models was performed through Type III analysis of variance with Satterthwaite approximation for degrees of freedom. In each location, seasons were taken as replicates for AUE data. Pairwise comparisons of means was made by least squares with confidence intervals and standard errors of difference using the 'lsmeans' package at a probability level of $p \leq 0.05$.

**Table 1** Values used for gross profit calculation

| Parameter | Unit | Unit cost (US$) |
|---|---|---|
| Inputs | | |
| Hybrid seeds | kg | 2.25 |
| Urea | 50 kg bag | 35 |
| Triple superphosphate | 50 kg bag | 35 |
| Muriate of potash | 50 kg bag | 35 |
| Pesticide | litre | 6 |
| Herbicide | litre | 12 |
| Manure | tonne | 10 |
| Labour cost | | |
| Labour | mandays | 4 |
| Revenue | | |
| Maize yield | kg | 0.2 |

Exchange rate of 1 USD = 100 Kenya shillings was used, USD is united states dollar and kg is kilogram

## Results

### Baseline soil properties

For maize crop, in our study locations, most roots were concentrated in the top 0.3 m. Visual evaluation of the soils showed a distinction between the top (0–0.15 m) and sub (0.15–0.3 m) soil layers. The top layer had a dark colour, an indication of higher soil organic matter thereby confirming its role in the supply of crop nutrients. For this reason, the top soil was considered in testing chemical soil quality while both top and sub soil were considered for physical soil quality.

Soils from Kibugu on average had significantly lower pH, higher SOC, higher total nitrogen (TN), higher total phosphorus (TP) and lower BD (bulk density) compared to soils from Machang'a (Table 2). In Kibugu, soils from high fertility fields had significantly higher pH, higher SOC, higher Resin-P and higher TP compared to low fertility fields. There were no significant differences in TN and exchangeable K between high and low fertility fields. On the other hand, soils from Machang'a high and low fertility fields showed no significant differences in the measured soil properties, though the high fertility fields had higher SOC, TN, resin-P and exchangeable K compared to the low fertility fields. Soils from Kibugu have significantly higher percentage of clay while those from Machang'a have a higher sand fraction.

**Table 2** Mean values of basic soil properties with standard deviations in parentheses at the start of the trial period for locations Kibugu and Machang'a and for soil fertility (SF) levels, high and low; pH (H2O), soil pH in water (1:5); soil organic carbon (SOC); total nitrogen (TN), Resin-P, available phosphorus; exchangeable potassium (Exch K); bulk density (BD); texture (clay, silt and sand), n = 10 and n = 8 for Kibugu and Machang'a, respectively

| Soil property | Kibugu | | | Machang'a | | |
|---|---|---|---|---|---|---|
| | High SF | Low SF | *p* value | High SF | Low SF | *p* value |
| pH-$H_2O$ | 5.7 (0.2)$^b$ | 5.0 (0.2)$^b$ | < 0.001 | 6.9 (0.6)$^a$ | 6.8 (0.5)$^a$ | 0.49 |
| SOC (g $kg^{-1}$) | 19.2 (4.3)$^a$ | 14.8 (9.3)$^a$ | 0.03 | 6.2 (3.8)$^b$ | 4.6 (0.4)$^b$ | 0.46 |
| TN (g $kg^{-1}$) | 2.2 (1.2)$^a$ | 1.7 (0.8)$^a$ | 0.06 | 0.7 (0.4)$^b$ | 0.5 (0.1)$^b$ | 0.61 |
| TP (g $kg^{-1}$) | 1.3 (0.2)$^a$ | 0.9 (0.3)$^a$ | < 0.001 | 0.1 (0.0)$^b$ | 0.1 (0.0)$^b$ | 0.48 |
| Resin-P (mg $kg^{-1}$) | 16.5 (21.4)$^a$ | 4.1 (4.9)$^a$ | 0.02 | 7.5 (9.6)$^a$ | 1.5 (2.4)$^a$ | 0.14 |
| Exch. K (mg $kg^{-1}$) | 0.4 (0.2)$^a$ | 0.4 (0.3)$^a$ | 0.51 | 0.7 (0.4)$^a$ | 0.4 (0.1)$^a$ | 0.17 |
| BD (Mg $m^{-3}$) | 0.9 (0.0)$^b$ | 0.9 (0.0)$^b$ | 0.98 | 1.5 (0.0)$^a$ | 1.5 (0.0)$^a$ | 0.97 |
| Clay (g $kg^{-1}$) | 747 (6.0)$^a$ | 811 (13.4)$^a$ | 0.06 | 134 (5.5)$^b$ | 112 (5.3)$^b$ | 0.19 |
| Silt (g $kg^{-1}$) | 158 (4.5)$^a$ | 135 (10.1)$^a$ | 0.18 | 125 (2.6)$^b$ | 152 (5.5)$^a$ | 0.15 |
| Sand (g $kg^{-1}$) | 88 (2.7)$^b$ | 54 (3.5)$^b$ | 0.01 | 747 (5.9)$^a$ | 737 (7.5)$^a$ | 0.58 |

*p* values show significant differences between high and low soil fertility (SF) fields per location. Per fertility level, values indicated with the same letter are not significantly different between kibugu and Machang'a for the same SF status

Treatment effects on soil chemical properties

At the end of season four, measured soil chemical properties were not significantly different between the improved management practices in either the low or high fertility fields of both locations (Table 3). They became, however, significantly higher compared to the farmer practice, i.e. control. In Machang'a, N, SOC, available P and exchangeable K were, as at the start of the study, not significantly different between the high and low fertility fields (Table 2). Similarly, after four seasons, these properties were not significantly different between the high and low fertility fields (Table 3). In the high fertility fields of Kibugu, total N was higher under NTRM with a value of 2.5 g $kg^{-1}$compared to NTR and CTM both with 2.3 g $kg^{-1}$. In the low fertility fields, the values were again higher in NTRM, 3.2 g $kg^{-1}$ compared to 3.0 and 2.8 g $kg^{-1}$ for CTM and NTR, respectively. In Machang'a, N trend was similar to Kibugu. In the high fertility fields, values of 0.8 g $kg^{-1}$ for NTRM and 0.7 g $kg^{-1}$ for both NTR and CTM while in the low fertility, values of 0.6 g $kg^{-1}$ for NTRM and 0.5 g $kg^{-1}$ for both NTR and CTM.

In Kibugu, SOC under NTR and NTRM was with values of 22.9 and 23.6 g $kg^{-1}$, respectively, higher compared to CTM with 21.7 g $kg^{-1}$ in the high fertility fields. In the low fertility fields, NTRM showed higher SOC than CTM, with values of 32.2 g $kg^{-1}$ and 29.0 g $kg^{-1}$, respectively, while NTR had the lowest with 27.7 g $kg^{-1}$. In Machang'a, SOC was as well higher under NTR and NTRM, with values of 7.4 g $kg^{-1}$ and 8.5 g $kg^{-1}$, respectively, compared to 6.7 g $kg^{-1}$ SOC in the high fertility fields under CTM. Also the low fertility fields exhibited higher SOC under NTR and NTRM with both showing values of 5.3 g $kg^{-1}$, compared to CTM with 4.6 g $kg^{-1}$ SOC. The general trend in SOC was NTRM > NTR > CTM.

In the low fertility fields of Kibugu and all the fields in Machang'a, no till resulted in higher resin-P as compared to conventional tillage (Table 3). Resin-P was 26.9 mg $kg^{-1}$ and 20.9 mg $kg^{-1}$ under NTR and NTRM, and 20.8 mg $kg^{-1}$ under CTM in the low fertility fields of Kibugu. In Machang'a, it was 45.1 mg $kg^{-1}$ under NTR and 54.5 mg $kg^{-1}$ under NTRM, and 36.2 mg $kg^{-1}$ under CTM in the high fertility fields. In the low fertility fields, values of 48.2 mg $kg^{-1}$ and 57.6 mg $kg^{-1}$ were observed under NTR and NTRM, respectively, and 31.7 mg $kg^{-1}$ under CTM. In the higher fertility fields of Kibugu, values of 31.5 mg $kg^{-1}$ for CTM and 21.0 and 25.2 mg $kg^{-1}$, for NTR and NTRM, respectively, were observed. Even though resin-P was mainly

**Table 3** Mean chemical data and standard deviations in parentheses after four treatment seasons for locations Kibugu and Machang'a and soil fertility levels (SF) levels, high and low

| Location | SF/Practice | C | NTR | CTM | NTRM |
|---|---|---|---|---|---|
| Kibugu | | | | | |
| TN (g $kg^{-1}$) | High | 2.3 (0.3)$^{Aa}$ | 2.3 (0.3)$^{Aa}$ | 2.3 (0.3)$^{Ab}$ | 2.5 (0.3)$^{Ab}$ |
| | Low | 2.7 (0.6)$^{Aa}$ | 2.8 (0.4)$^{Aa}$ | 3.0 (0.6)$^{Aa}$ | 3.2 (0.7)$^{Aa}$ |
| SOC (g $kg^{-1}$) | High | **17.8 (3.6)$^{Ba}$** | 22.9 (2.4)$^{Ab}$ | **21.7 (2.4)$^{Ab}$** | 23.6 (2.7)$^{Ab}$ |
| | Low | **14.5 (6.9)$^{Aa}$** | 27.7 (3.5)$^{Ba}$ | 29.0 (8.5)$^{Ba}$ | 32.2 (8.3)$^{Ba}$ |
| Resin-P (mg $kg^{-1}$) | High | 2.2 (2.4)$^{Ba}$ | 21.0 (23.9)$^{Aa}$ | 31.5 (22.9)$^{Aa}$ | 25.2 (25.0)$^{Aa}$ |
| | Low | 2.2 (2.8)$^{Ba}$ | 26.9 (21.4)$^{Aa}$ | 20.8 (13.9)$^{Aa}$ | 20.9 (31.8)$^{Aa}$ |
| Exch. K (mg $kg^{-1}$) | High | 0.1 (0.2)$^{Ba}$ | 0.5 (0.3)$^{Aa}$ | 0.7 (0.3)$^{Aa}$ | 0.8 (0.5)$^{Aa}$ |
| | Low | 0.3 (0.3)$^{Ba}$ | 0.4 (0.2)$^{Ba}$ | 0.5 (0.2)$^{Aa}$ | 0.7 (0.5)$^{Aa}$ |
| Machang'a | | | | | |
| TN (g $kg^{-1}$) | High | 0.6 (0.2)$^{Aa}$ | 0.7 (0.2)$^{Aa}$ | 0.7 (0.2)$^{Aa}$ | 0.8 (0.3)$^{Aa}$ |
| | Low | 0.4 (0.1)$^{Aa}$ | 0.5 (0.1)$^{Aa}$ | 0.5 (0.0)$^{Aa}$ | 0.6 (0.1)$^{Aa}$ |
| SOC (g $kg^{-1}$) | High | **5.0 (2.1)$^{Aa}$** | **7.4 (2.4)$^{Aa}$** | **6.7 (4.5)$^{Aa}$** | **8.5 (3.2)$^{Aa}$** |
| | Low | **3.8 (0.6)$^{Aa}$** | **5.3 (0.4)$^{Aa}$** | **4.6 (0.4)$^{Aa}$** | **5.3 (0.8)$^{Aa}$** |
| Resin-P (mg $kg^{-1}$) | High | 0.3 (0.4)$^{Ba}$ | 45.1 (20.8)$^{Aa}$ | 36.2 (19.0)$^{Aa}$ | 54.5 (14.4)$^{Aa}$ |
| | Low | 0.1 (0.0)$^{Ba}$ | 48.2 (26.1)$^{Aa}$ | 31.7 (27.8)$^{Aa}$ | 57.6 (13.7)$^{Aa}$ |
| Exch. K (mg $kg^{-1}$) | High | 0.2 (0.3)$^{Ba}$ | 0.3 (0.3)$^{Ba}$ | 0.4 (0.3)$^{Ba}$ | 0.5 (0.4)$^{Aa}$ |
| | Low | 0.2 (0.1)$^{Aa}$ | 0.3 (0.3)$^{Aa}$ | 0.3 (0.1)$^{Aa}$ | 0.4 (0.1)$^{Aa}$ |

C is control, NTR is no tillage with residue retention, CTM is conventional tillage with use of manure, NTRM is no tillage with residue retention and use of manure, TN is total nitrogen, SOC is soil organic carbon, Resin-P is available phosphorus, Exch. K is exchangeable potassium. Values in a row indicated with similar capital letters are not significantly different between the treatments for each fertility level. Under each management practice, values indicated with similar lower case letters are not significantly different between high and low fertility level for each soil property. SOC values in bold are below the suggested lower critical value of 23%

higher under NT practices compared to conventional tillage, very high variability between fields masked any significance difference.

Exchangeable K was higher under CTM with 0.7 mg $kg^{-1}$ and NTRM with 0.8 mg $kg^{-1}$ compared to NTR with 0.5 mg $kg^{-1}$ in the high fertility fields of Kibugu. In the low fertility fields, it was again higher under CTM with 0.5 mg $kg^{-1}$ and NTRM with 0.7 mg $kg^{-1}$ compared to NTR with 0.4 mg $kg^{-1}$. In Machang'a, the same trend was observed in the high fertility fields under CTM with 0.4 mg $kg^{-1}$ and NTRM with 0.5 mg $kg^{-1}$ having higher exchangeable K compared to NTR with 0.3 mg $kg^{-1}$. In the low fertility fields, exchangeable K was slightly higher under CTM and NTRM with both 0.4 mg $kg^{-1}$ compared to NTR with 0.3 mg $kg^{-1}$. Generally, the trend in exchangeable K was NTRM > CTM > NTR, an indication of a positive effect of manure application on exchangeable K.

### Treatment effects on soil physical properties

The improved management practices had no significant effect on measured soil physical properties in either the top or the sub soil in both the sub-humid Kibugu and the semi-arid Machang'a after four seasons since their introduction (Fig. 1). Unlike BD which did not show significant differences between top and sub soil, $K_s$, $K_a$, MWD and shear stress in Kibugu were significantly different, with the top soil showing better values. In the semi-arid Machang'a, only shear stress showed significant differences between top and sub soil. Nevertheless, the other parameters were better in the top soil as compared to the sub soil. That lack of significant differences in physical properties could be attributed to their high spatial variability. This spatial variability is said to be inherent in nature because of geological and pedological factors (Wang and Shao 2013). In this study, it was

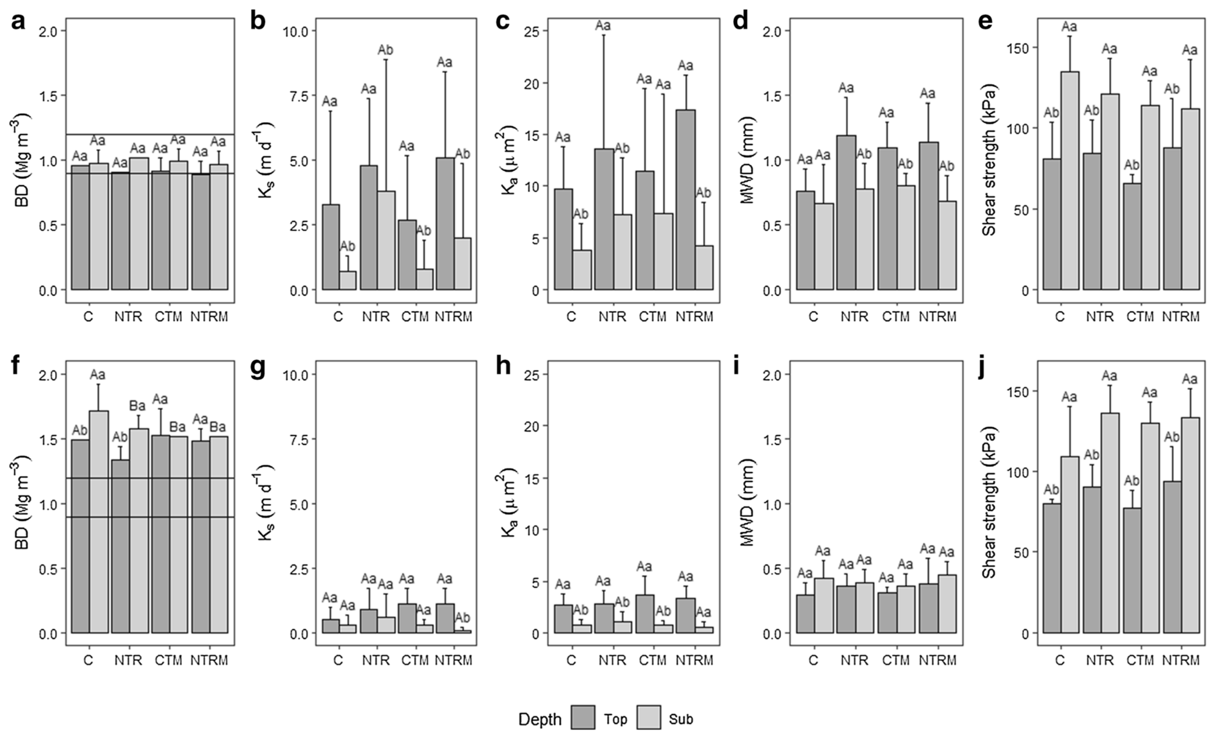


**Fig. 1** Soil physical properties under control (C), no tillage with residue retention (NTR), conventional tillage with use of manure (CTM) and no tillage with residue retention and use of manure (NTRM) for Kibugu (a-e) and Machang'a (f-j) in the top and sub soil after four seasons. In each location, bar graphs indicated with the same capital letters are not significantly different ($p < 0.05$) between the treatments in the same depth, while bars indicated with the same small letters are not significantly different between top and sub soil under each treatment. BD is bulk density, $K_s$ is saturated hydraulic conductivity, $K_a$ is air permeability and MWD is mean weight diameter. Black horizontal lines indicate lower and upper BD thresholds below and above which soils have insufficient water retention and reduced soil aeration, respectively

reported that soil physical properties have strong spatial dependence. Though differences were not significant, some trends in treatment effect on $K_s$, $K_a$, MWD and shear strength can be perceived in Kibugu, but not always in Machang'a. In Kibugu, higher mean values for $K_s$, $K_a$, MWD and shear stress were obtained under NTR and NTRM as compared to CTM over the top soil with no clear trend in the sub soil.

BD values in Kibugu ranged between 0.89 and 1.02 Mg m$^{-3}$ while in Machang'a they ranged from 1.34 to 1.72 Mg m$^{-3}$. Overall, in the top soil, the order for $K_s$, $K_a$ and MWD was NTRM > NTR > CTM, while in the sub soil, it was NTR > NTRM > CTM. In the top soil, MWD was in the order NTR > NTRM > CTM in Kibugu and NTRM > NTR > CTM in Machang'a. Even though there was no trend in MWD in the sub soil of the two locations, highest MWD was recorded under NTR in Kibugu and NTRM in Machang'a. In Kibugu, between and within planting rows soil properties were not significantly different in most of the treatments (Fig. 2). In all treatments, BD was lower in the within row position compared to between row position. Consequently, hydraulic conductivity was lower within rows compared to between rows with the values being significantly different under NTR. In Machang'a on the other side, all the soil properties with an exception of BD under NTRM, were not significantly different between row positions. Under NTRM, BD was significantly lower within rows compared to between rows.

## Treatment effects on physical soil quality indicators

The improved management practices had no significant effect on physical soil quality indicators in either the top or the sub soil in both the sub-humid Kibugu

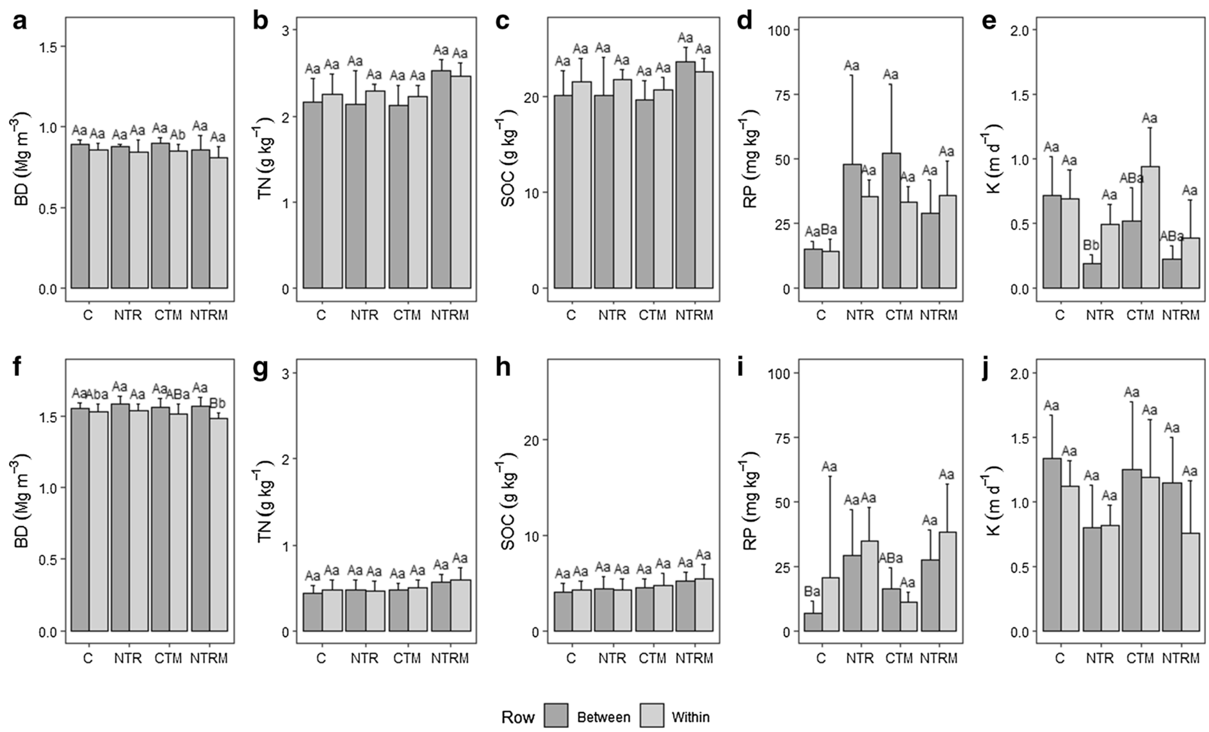


**Fig. 2** Soil properties under control (C), no tillage with residue retention (NTR), conventional tillage with use of manure (CTM) and no tillage with residue retention and use of manure (NTRM) for Kibugu (**a**–**e**) and Machang'a (**f**–**j**) between and within rows after six seasons. In each location, bar graphs indicated with the same capital letters are not significantly different ($p < 0.05$) between the treatments in the same row position, while bars indicated with the same small letters are not significantly different between row positions (within and between row) under each treatment. BD is bulk density, TN is total Nitrogen, SOC is soil organic carbon, RP is resin phosphorus and K is hydraulic conductivity

and the semi-arid Machang'a after four seasons since their introduction (Figs. 3, 4). In Kibugu, macro-porosity, matrix-porosity and air capacity showed significant differences between the top and sub soil under CTM and NTRM. Values were higher in the top, sub and top soil for macro-porosity, matrix-porosity and air capacity, respectively. In Machang'a, field capacity, permanent wilting point, air capacity and relative water capacity were significantly different under CTM and NTRM. Their values were higher in the sub, sub, top and sub for field capacity, permanent wilting point, air capacity and relative water capacity, respectively. Macro-porosity and matrix-porosity showed significant differences between the top and sub soil only under CTM. Higher values were recorded in the top and sub soil for Macro-porosity and matrix-porosity, respectively.

While there was no significant treatment effect on physical soil quality indicators, comparing the obtained values to set critical thresholds is important in order to establish any limitations to optimal soil functioning. MacPOR values were in the range of 0.15 to 0.24 m m$^{-3}$ and 0.10 to 0.18 m m$^{-3}$ for Kibugu and Machang'a, respectively (Fig. 4). PAWC values in Kibugu ranged between 0.05 to 0.09 m$^3$ m$^{-3}$ while in Machang'a, they ranged between 0.05 to 0.06 m$^3$ m$^{-3}$. AC values ranged between 0.20 to 0.30 and 0.16 to 0.27 m$^3$ m$^{-3}$ for Kibugu and Machang'a, respectively. In Kibugu, RWC values ranged between 0.51 and 0.64 while in Machang'a, the values were between 0.35 and 0.57.

## Nutrient agronomic use efficiency and economic analysis

N, P and K-AUE were not significantly different between treatments in the high or low fertility levels in Kibugu (Fig. 5). Under NTR and NTRM for both locations, the low fertility fields had significantly lower AUE's compared to the high fertility fields

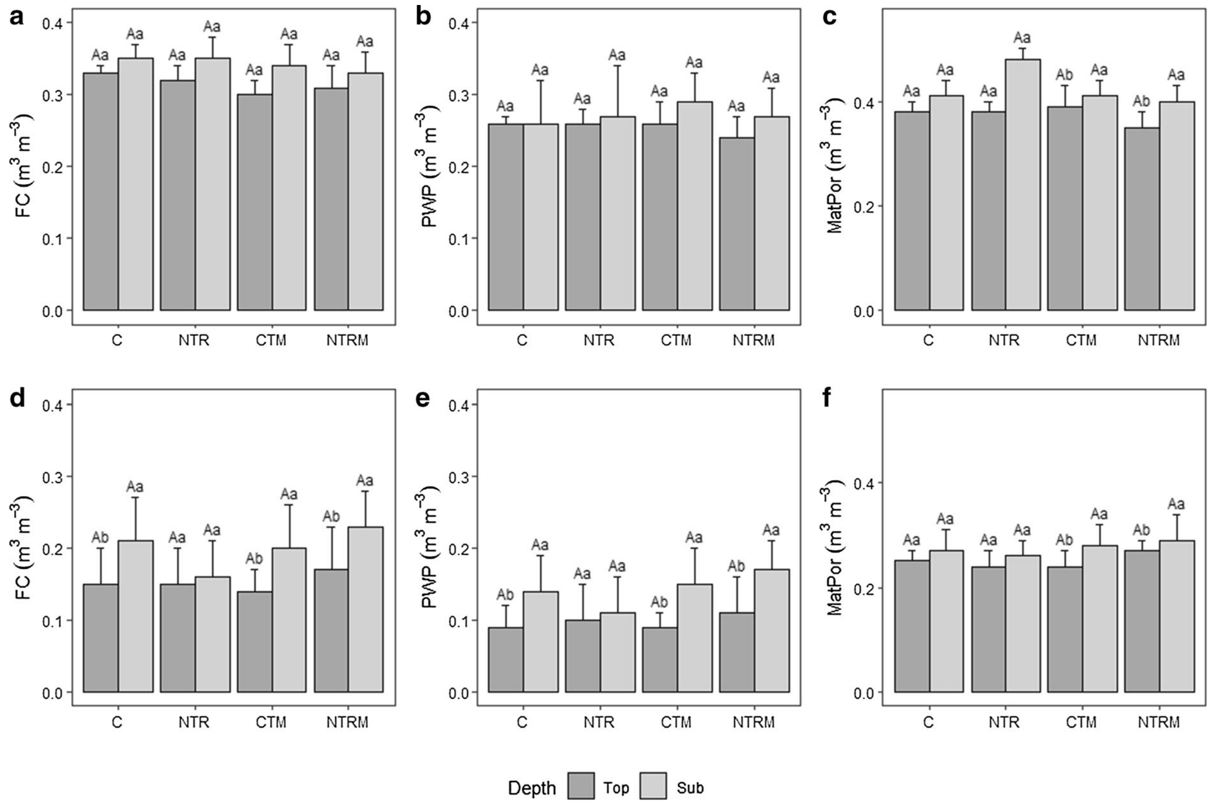


**Fig. 3** Physical soil quality indicators under control (C), no tillage with residue retention (NTR), conventional tillage with use of manure (CTM) and no tillage with residue retention and use of manure (NTRM) for Kibugu (**a**–**c**) and Machang'a (**d**–**f**) in the top and sub soil after four seasons. In each location, bar graphs indicated with the same capital letters are not significantly different ($p < 0.05$) between the treatments in the same depth, while bars indicated with the same small letters are not significantly different between top and sub soil under each treatment. FC is field capacity, PWP is permanent wilting point and MatPor is matrix-porosity

while AUE values under CTM were not significantly different between the high and low fertility fields. In the high fertility fields of Kibugu nitrogen AUE (N-AUE) values ranged between 28 and 21 kg grain (kg N)$^{-1}$ while in the low fertility fields, they ranged from 14 to 7 kg grain (kg N)$^{-1}$. Phosphorus AUE (P-AUE) ranged between 76and 57 kg grain (kg P)$^{-1}$ in the high fertility fields while values in the low fertility fields were in the range of 38–18 kg grain (kg P)$^{-1}$. In the high fertility fields, potassium AUE (K-AUE) values were 58–43 kg grain (kg K)$^{-1}$ while in the low fertility fields, the values ranged between 29 and 13 kg grain (kg K)$^{-1}$.

There were no significant difference in nutrient AUE between treatments in the high or low fertility fields in Machang'a (Fig. 5). In this location, N-AUE values ranged between 18 and 15 kg grain (kg N)$^{-1}$ in the higher fertility fields while they ranged from 13 to 5 kg grain (kg N)$^{-1}$ in the low fertility fields. P-AUE values in the high fertility fields were in the range of 47 to 41 kg grain (kg P)$^{-1}$ while in the low fertility fields, the values ranged between 34 and 15 kg grain (kg P)$^{-1}$. Lastly, K-AUE values in the range of 35 to 30 kg grain (kg K)$^{-1}$ were observed for the high fertility fields with low fertility field they ranged between 26 and 11 kg grain (kg K)$^{-1}$. In general, the order of N, P and K-AUE for the high fertility fields was NTRM > CTM > NTR and CTM > NTRM > NTR for the low fertility fields of Kibugu. In Machang'a, the order was NTR > CTM > NTRM for the high fertility fields and CTM > NTRM > NTR for the low fertility fields.

In both locations, cost were in the order NTRM > CTM > NTR > C (Table 4). In the high fertility fields, the order of gross profit was NTRM > CTM > NTR > C and NTR > CTM > NTRM > C, for

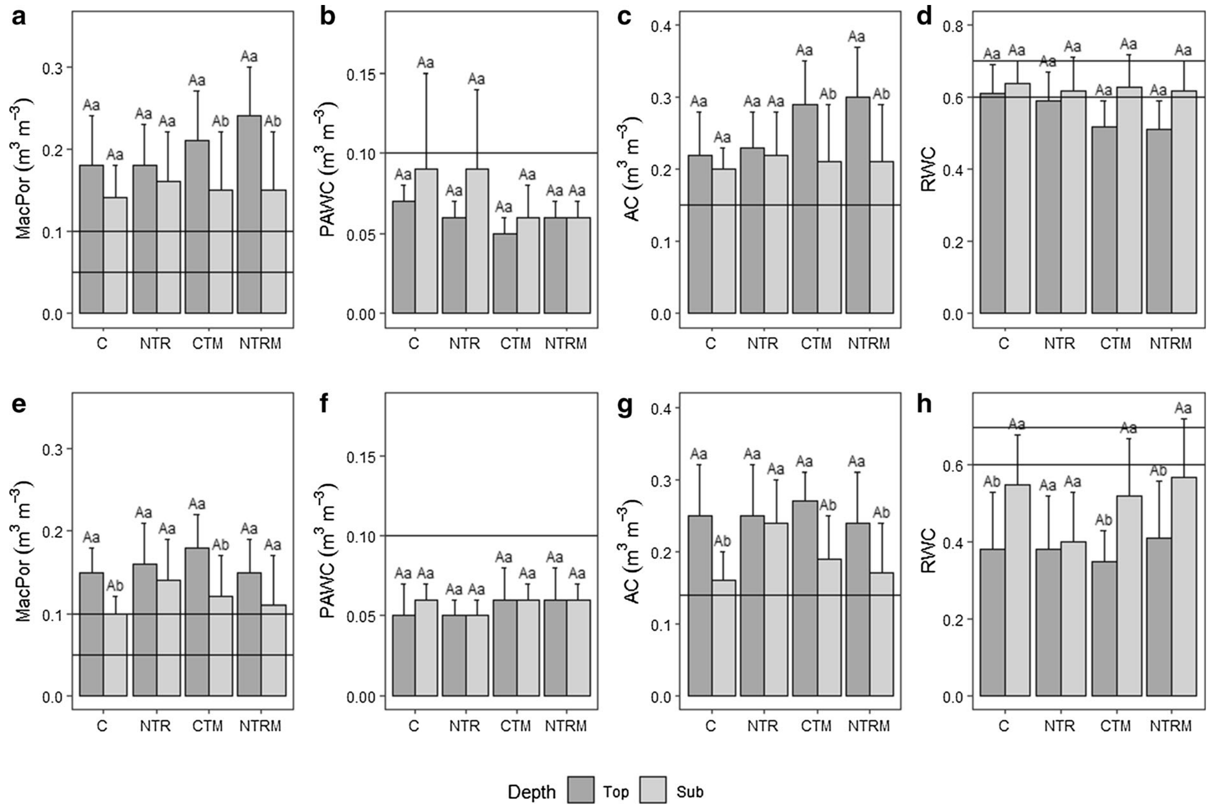


**Fig. 4** Physical soil quality indicators under control (C), no tillage with residue retention (NTR), conventional tillage with use of manure (CTM) and no tillage with residue retention and use of manure (NTRM) for Kibugu (**a**–**d**) and Machang'a (**e**–**h**) in the top and sub soil after four seasons. In each location, bar graphs indicated with the same capital letters are not significantly different ($p < 0.05$) between the treatments in the same depth, while bars indicated with the same small letters are not significantly different between top and sub soil under each treatment. MacPor is macro-porosity, PAWC is plant available water content, AC is air capacity and RWC is relative water capacity. Black horizontal lines indicate thresholds below and above which soils are physically restricted

Kibugu and Machang'a, respectively. The low fertility fields in both location resulted to a gross loss, with CTM showing a lower gross loss compared to NTR and NTRM. The gross loss was in the order CTM < C < NTR < NTRM and C < CTM < NTR < NTRM, for Kibugu and Machang'a, respectively.

## Discussion

### No tillage improves SOC

Even though there were no significant differences in measured soil chemical properties between the improved treatments and given the duration of the study, trends can be perceived when considering the mean values, which are anyway an important outcome of experiments (Webster 2007). In addition, the use of a 'one-farm-one-replicate' design resulted to high standard deviations thereby masking significant differences between treatments at $p < 0.05$. The observed higher levels of SOC under both NT practices compared to CT could be explained by the combined effects of no tillage and residue retention. No tillage is known to protect SOC from rapid oxidation and thus enhance build-up of SOC over time (Cooper et al. 2016). Gwenzi et al. (2009) also found higher SOC in the 0–0.15 m soil layer under minimum and no tillage compared to conventional tillage in Zimbabwe, with differences being significant. In South Africa, no tillage resulted in insignificantly higher SOC (27.1 g kg$^{-1}$ compared to conventional tillage (26.6 g kg$^{-1}$) after 13 years since its introduction (Sithole et al. 2019). CA-based

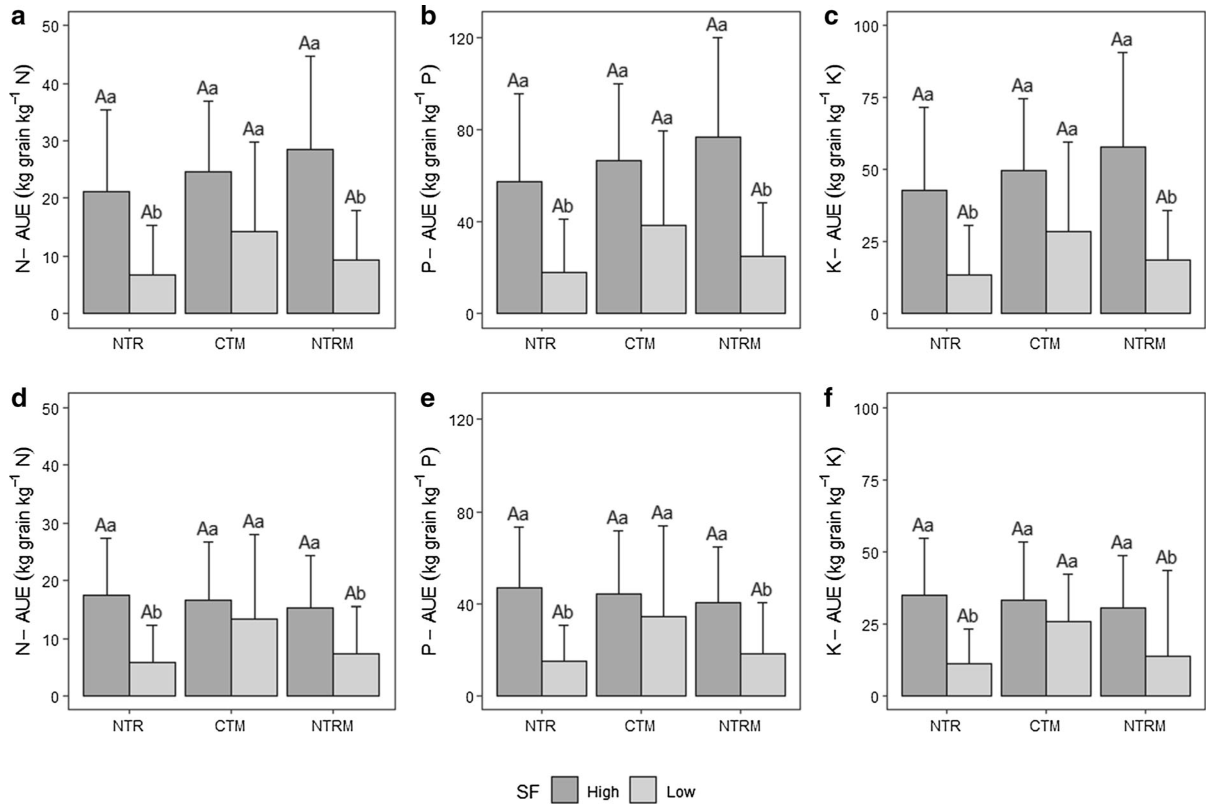


**Fig. 5** Nutrient Agronomic Use Efficiency (AE) under no tillage with residue retention (NTR), conventional tillage with use of manure (CTM) and no tillage with residue retention and use of manure (NTRM) for Kibugu (**a–c**) and Machang'a (**d–f**) in the top and sub soil after four seasons. In each location, bar graphs indicated with the same capital letters are not significantly different ($p < 0.05$) between the treatments in the same fertility level, while bars indicated with the same small letters are not significantly different between high and low soil fertility under each treatment. N is nitrogen, P is phosphorus and K is potassium

**Table 4** Total cost, revenue and gross profit averaged for the four seasons under control (C), no tillage with residue retention (NTR), conventional tillage with use of manure (CTM) and no tillage with residue retention and use of manure (NTRM)

| Location | Treatment | Cost (US\$ ha$^{-1}$) | Revenue (US\$ ha$^{-1}$) High fertility | Gross profit (US\$ ha$^{-1}$) | Revenue (US\$ ha$^{-1}$) Low fertility | Gross profit (US\$ ha$^{-1}$) |
|---|---|---|---|---|---|---|
| Kibugu | C | 195 | 446 | 251 | 72 | − 123 |
| | NTR | 362 | 768 | 406 | 178 | − 184 |
| | CTM | 400 | 822 | 422 | 300 | − 100 |
| | NTRM | 408 | 882 | 474 | 218 | − 190 |
| Machang'a | C | 175 | 258 | 85 | 62 | − 113 |
| | NTR | 338 | 536 | 199 | 152 | − 186 |
| | CTM | 386 | 522 | 137 | 270 | − 116 |
| | NTRM | 404 | 510 | 107 | 174 | − 230 |

C is control, NTR is no tillage with residue retention, CTM is conventional tillage with use of manure, NTRM is no tillage with residue retention and use of manure. US$ is united states dollar and ha is hectare practices have been shown to enhance SOC (Derpsch et al. 2010). Under the farmer practice, C, the semi-arid Machang'a had a relative higher SOC loss compared to the sub-humid Kibugu on the high fertility fields. This is mainly an effect of its lower clay content in the soil. According to Feller and Beare (1997), the amount of soil organic matter loss is higher on coarse textured than fine textured soils mostly due to lack of physical protection of organic matter in sandy soils. Higher SOC gain under NTRM treatment is explained, by the effects of no tillage and manure. SOC carbon is enhanced by addition of manure while no tillage ensures less loss of SOC by oxidation. In Kibugu, soils under the control and top layer under CTM had SOC values below the lower critical value of 23% proposed by Greenland (1981) below which tillage-induced loss of structure may occur in fine-textured soils. In Machang'a, all soils were below the lower critical value. However, care should be taken while interpreting SOC limits in Machang'a for the used SOC limits refer to fine textured soils. In Kibugu, the below the critical level SOC could be related to SOC loss through oxidation occurring under soil tillage while in Machang'a the low levels are related to inherent low SOC nature of Cambisols.

### The use of physical soil quality indicators

MacPor values for our soil were all within the critical values (MacPor $\geq$ 0.05–0.10 $m^3$ $m^{-3}$) indicating that soils are in good physical condition and their potential to quickly drain excess water and allow good root development (Drewry et al., 2001). This could be confirmed by the fact that within the four seasons of our study, there was no water logging related problems observed. All the soils were also above the upper critical threshold of 0.10 $m^3$ $m^{-3}$ which could indicate excess water drainage and could be a possible cause of meteorological drought. For all the treatments in both locations, PAWC values were below 0.10 $m^3$ $m^{-3}$ indicating poor water availability for crop uptake (Reynolds et al. 2009). While PAWC could be improved through an increase in SOC we did not find a significant correlation between SOC and PAWC. An increase in organic carbon in soil has been reported to have a small effect on soil water content (Minasny & Mcbratney, 2018). In this meta-analysis, a 1% mass increase in soil SOC on average increased available water capacity by 1.16%, volumetrically. These could mean that an increase in PAWC cannot be related to one single parameter due to other processes that affect it. In Machang'a, all soils had RWC values below the given optimal range of 0.6 $\leq$ RWC $\leq$ 0.7 (Reynolds et al. 2007). The below optimal values are an indicator that these soils cannot achieve maximum microbial activity due to soil water limitation and consequently low nutrient uptake which explains the observed low AUE.

### Where to invest

Given that fertilizer was applied at the same rate in the high and low fertility fields, the low N-AUE in the low fertility fields could suggest that these soils are either biologically, physically or chemically (in respect to micro-nutrients) limited, which restrains responses to the applied fertilizer. These soils have been referred to as 'poor, less-responsive soils' by Vanlauwe et al. (2010). It is important to eliminate the existing restriction in these low fertility fields before farmers can successfully apply nutrients. Soils in Kibugu had higher nutrient agronomic efficiency compared to soils from Machang'a which could be attributed to inherent soil fertility conditions in the two regions. The observed average N-AUE are in line with values reported elsewhere. For example, N-AUE values of 30.6 kg grain (kg N)$^{-1}$ for fertilizer application rate of 90 kg ha$^{-1}$ were reported in USA under irrigated maize (Johnson and Raun 2003). In Pakistan, maize N-AUE of 28, 23 and 19 kg grain (kg N)$^{-1}$ were reported for fertilizer application rates of 60, 120 and 180 kg ha$^{-1}$ (Amanullah and Alkas 2009). From our observations, CTM enhances nutrient use efficiency in low fertility fields of both locations which is related to the combined use of organic and inorganic inputs as it has been reported earlier that ISFM principles can substantially improve AUE (Vanlauwe et al. 2011). Based on the cost benefit analysis of four seasons in 2017 and 2018, higher economic returns were obtained under NTRM and NTR for the high fertility fields of Kibugu and Machang'a, respectively. The low nutrient AUE in the low fertility fields of both locations was reflected by economic losses in the same fields. Therefore, investing on the low fertility fields at our input rates is not advisable for farmers in both locations.

## Conclusion

Improved SOC under no tillage indicates the possibility of CA to help solving one of the pressing soil fertility issues in SSA: build SOC which improves soil physical and chemical properties crucial for water management and nutrient availability. With the obtained lower nutrient AUE and economic losses from the low fertility fields, further investigation could therefore be needed to ascertain which other soil physico-chemical parameters need to be enhanced to increase AUE. In addition, an in-depth study is required to determine at which input rates could the low fertility fields result to economic gain.

**Acknowledgements** The authors acknowledge Ghent University special fund (BOF) and International Institute of Tropical agriculture (IITA), Nairobi, for providing financial support to conduct the trials. We are grateful to farmers from Kibugu and Machang'a for willingly providing the trial fields.

**Funding** This work was supported by Ghent University special fund (BOF_01W02816), International Institute of Tropical agriculture (IITA), Nairobi, Kenya (CGIAR Excellence in Agronomy Platform) and VLIR UOS-Global Minds Fund (BE2017GMUUG0A103), Ghent, Belgium.

### Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

## References

Amanullah, Alkas LK (2009) Partial factor productivity, agronomic efficiency, and economic analyses of maize in wheat-maize cropping system in Pakistan. No. 46747. Southern Agricultural Economics Association Annual Meetings, Atlanta, Georgia, 2009, 26 pp.

Bates D, Mächler M, Bolker BM, Walker SC (2015) Fitting linear mixed-effects models using lme4. J Stat Softw 67:1. https://doi.org/10.18637/jss.v067.i01

Chianu JN, Chianu JN, Chianu N (2012) Mineral fertilizers in the farming systems of sub-Saharan Africa. A review the factors contributing to declining soil fertility in Africa. Agron Sustain Dev 32:545–566. https://doi.org/10.1007/s13593-011-0050-0

Chivenge P, Vanlauwe B, Gentile R, Six J (2011) Comparison of organic versus mineral resource effects on short-term aggregate carbon and nitrogen dynamics in a sandy soil versus a fine textured soil. Agr Ecosyst Environ 140:361–371. https://doi.org/10.1016/j.agee.2010.12.004

Cooper J, Baranski M, Stewart G, Nobel-de Lange M, Bàrberi P, Fließbach A, Mäder P (2016) Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: a meta-analysis. Agron Sustain Dev 36:1. https://doi.org/10.1007/s13593-016-0354-1

Curtis PG, Slay CM, Harris NL, Tyukavina A, Hansen MC (2018) Classifying drivers of global forest loss. Science 361:1108–1111. https://doi.org/10.1126/science.aau3445

Derpsch R, Friedrich T, Kassam A, Hongwen L (2010) Current status of adoption of no-till farming in the world and some of its main benefits. Int J Agric Biol Eng 3:1–25. https://doi.org/10.3965/j.issn.1934-6344.2010.01.001-025

Drewry JJ, Cameron KC, Buchan GD (2001) Effect of simulated dairy cow treading on soil physical properties and ryegrass pasture yield. N Z J Agric Res 44:181–190. https://doi.org/10.1080/00288233.2001.9513476

FAO (Food and Agriculture Organization of the United Nations) (2002) Conservation agriculture: case studies in Latin America and Africa. FAO Soils Bulletin 78 FAO, Rome.

FAO (2009) Global agriculture towards 2050. FAO, Rome

Feller C, Beare MH (1997) Physical control of soil organic matter dynamics in the tropics. Geoderma 79:69–116. https://doi.org/10.1016/S0016-7061(97)00039-6

Gerland P, Raftery AE, Ševčíková H, Li N, Gu D, Spoorenberg T, Alkema L, Fosdick BK, Chunn J, Lalic N, Bay G, Buettner T, Gerhard K, Heilig GK, Wilmoth J (2014) World population stabilization unlikely this century. Science 346:234–237. https://doi.org/10.1126/science.1257469

Greenland DJ (1981) Soil management and soil degradation. J Soil Sci 32:301–322

Grover BL (1955) Simplified air permeameters for soil in place. Soil Sci Soc Am Proc 19:414–418

Gwenzi W, Gotosa J, Chakanetsa S, Mutema Z (2009) Effects of tillage systems on soil organic carbon dynamics, structural stability and crop yields in irrigated wheat (*Triticum aestivum* L.)-cotton (*Gossypium hirsutum* L.) rotation in semi-arid Zimbabwe. Nutr Cycl Agroecosyst 83:211–221. https://doi.org/10.1007/s10705-008-9211-1

Huggins DR, Reganold JP (2008) No-till: the quiet revolution. Sci Am 299:70–77. https://doi.org/10.1038/scientificamerican0708-70

Jarvis NJ (2007) A review of non-equilibrium water flow and solute transport in soil macropores: principles, controlling factors and consequences for water quality. Eur J Soil Sci 58:523–546. https://doi.org/10.1111/j.1365-2389.2007.00915.x

Johansen C, Haque ME, Bell RW, Thierfelder C, Esdaile RJ (2012) Conservation agriculture for small holder rainfed farming: opportunities and constraints of new mechanized seeding systems. Field Crops Res 132:18–32. https://doi.org/10.1016/j.fcr.2011.11.026

Johnson GV, Raun WR (2003) Nitrogen response index as a guide to fertilizer management. J Plant Nutr 26:249–262. https://doi.org/10.1081/PLN-120017134

Kapkiyai JJ, Karanja NK, Qureshi JN, Smithson PC, Woomer PL (1999) Soil organic matter and nutrient dynamics in a Kenyan nitisol under long-term fertilizer and organic input management. Soil Biol Biochem 31:1773–1782

Kifuko MN, Othieno CO, Okalebo JR, Kimenye LN, Ndung'u KW, Kipkoech AK (2007) Effect of combining organic residues with Minjingu phosphate rock on sorption and availability of phosphorus and maize production in acid soils of western Kenya. Exp Agric 43:51–66

Kuznetsova A, Brockhoff PB, Christensen RHB (2017) lmerTest Package: tests in linear mixed effects models. J Stat Softw 82:13. https://doi.org/10.1863/jss.v082.i13
Le Bissonnais YL (1996) Aggregate stability and assessment of soil crustability and erodibility: I. Theory and methodology. Eur J Soil Sci 47:425–437. https://doi.org/10.1111/j.1365-2389.1996.tb01843.x
Minasny B, McBratney AB (2018) Limited effect of organic matter on soil available water capacity. Eur J Soil Sci 69(1):39–47. https://doi.org/10.1111/ejss.12475
Mugendi DN, Nair PKR, Mugwe JN, O'Neill MK, Woomer PL (1999) Alley cropping of maize with calliandra and leucaena in the subhumid highlands of Kenya: Part 1. Soil-fertility changes and maize yield. Agrofor Syst 46:39–50. https://doi.org/10.1023/A:1006288301044
Mutuku EA, Roobroeck D, Vanlauwe B, Boeckx P, Cornelis WM (2020) Maize production under combined Conservation Agriculture and Integrated Soil Fertility Management in the sub-humid and semi-arid regions of Kenya. Field Crops Res 254:107833. https://doi.org/10.1016/j.fcr.2020.107833
Pittelkow CM, Linquist BA, Lundy ME, Liang X, van Groenigen KJ, Lee J, van Gestel N, Six J, Venterea RT, van Kessel C (2015) When does no-till yield more? A global meta-analysis. Field Crops Res 183:156–168. https://doi.org/10.1016/j.fcr.2015.07.020
R Development Core Team (2016) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria
Reynolds WD, Bowman BT, Drury CF, Tan CS, Lu X (2002) Indicators of good soil physical quality: Density and storage parameters. Geoderma 110:131–146. https://doi.org/10.1016/S0016-7061(02)00228-8
Reynolds WD, Drury CF, Yang XM, Fox CA, Tan CS, Zhang TQ (2007) Land management effects on the near-surface physical quality of a clay loam soil. Soil Tillage Res 96:316–330
Reynolds WD, Drury CF, Tan CS, Fox CA, Yang XM (2009) Use of indicators and pore volume-function characteristics to quantify soil physical quality. Geoderma 152:252–263. https://doi.org/10.1016/j.geoderma.2009.06.009
Reynolds WD, Drury CF, Yang XM, Tan CS (2008) Optimal soil physical quality inferred through structural regression and parameter interactions. Geoderma 146:466–474. https://doi.org/10.1016/j.geoderma.2008.06.017
Richard G, Le J (2004) Estimation of runoff critical shear stress for soil erosion from soil shear strength. CATENA 57:233–249. https://doi.org/10.1016/j.catena.2003.11.007
Schjønning P, Elmholt S, Christensen BT (2004) Soil quality management—concepts and terms. In: Schjønning P, Elmholt S, Christensen BT (eds) Managing soil quality: challenges in modern agriculture
Sithole NJ, Magwaza LS, Mafongoya PL (2016) Conservation agriculture and its impact on soil quality and maize yield: a South African perspective. Soil Tillage Res 162:55–67. https://doi.org/10.1016/j.still.2016.04.014
Sithole NJ, Magwaza LS, Thibaud GR (2019) Long-term impact of no-till conservation agriculture and N-fertilizer on soil aggregate stability, infiltration and distribution of C in different size fractions. Soil Tillage Res 190:147–156. https://doi.org/10.1016/j.still.2019.03.004
Smith KA, Mullins CE (1991) Soil analysis. Physical methods. Marcel Dekker, New York, p 620
Sommer R, Paul BK, Mukalama J, Kihara J (2018) 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. https://doi.org/10.1016/J.AGEE.2017.11.004
Tittonell P, Giller KE (2013) When yield gaps are poverty traps: the paradigm of ecological intensification in African smallholder agriculture. Field Crops Res 143:76–90. https://doi.org/10.1016/j.fcr.2012.10.007
Tittonell P, Vanlauwe B, Leffelaar PA, Rowe EC, Giller KE (2005) Exploring diversity in soil fertility management of smallholder farms in western Kenya: I. Heterogeneity at region and farm scale. Agric Ecosyst Environ 110:149–165. https://doi.org/10.1016/j.agee.2005.04.001
Van Ittersum MK, Van Bussel LGJ, Wolf J, Grassini P, Van Wart J, Guilpart N, Cassman KG (2016) Can sub-Saharan Africa feed itself? Proc Natl Acad Sci USA 113:14964–14969. https://doi.org/10.1073/pnas.1610359113
van Vliet N, Mertz O, Heinimann A, Langanke T, Pascual U, Schmook B, Adams C, Schmidt-Vogt D, Messerli P, Leisz S, Castella J, Jørgensen L, Birch-Thomsen T, Hett C, Bech-Bruun T, Ickowitz A, Chi VuK, Yasuyuki K, Fox J, Padoch C, Dressler W, Ziegler AD (2012) Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: a global assessment. Glob Environ Change 22:418–429. https://doi.org/10.1016/j.gloenvcha.2011.10.009
Vanlauwe B, Tittonell P, Mukalama J (2006) Within-farm soil fertility gradients affect response of maize to fertiliser application in western Kenya. Nutr Cycl Agroecosyst 76:171–182. https://doi.org/10.1007/s10705-005-8314-1
Vanlauwe B, Kihara J, Chivenge P, Pypers P, Coe R, Six J (2011) Agronomic use efficiency of N fertilizer in maize-based systems in Sub-Saharan Africa within the context of integrated soil fertility management. Plant Soil 339:35–50. https://doi.org/10.1007/s11104-010-0462-7
Vanlauwe B, Wendt J, Giller KE, 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 Crops Res 155:10–13. https://doi.org/10.1016/j.fcr.2013.10.002
Wall PC, Thierfelder C, Ngwira A, Govaerts B, Nyagumbo I, Baudron F (2013) Conservation agriculture in Eastern and Southern Africa. In: Jat RA, Graziano-de-Silva J (eds) Conservation agriculture: global prospects and challenges. CABI, Cambridge. https://doi.org/10.1079/9781780642598.0263
Webster R (2007) Analysis of variance, inference, multiple comparisons and sampling effects in soil research. Eur J Soil Sci 58:74–82. https://doi.org/10.1111/j.1365-2389.2006.00801.x
World reference base for soil resources (2006) A framework for international classification, correlation and communication. Rome, p 103

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.