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Maize production under combined Conservation Agriculture and Integrated Soil Fertility Management in the sub-humid and semi-arid regions of Kenya

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ABSTRACT

Crop production in Sub-Saharan Africa (SSA) is constrained by rainfall variability and declining soil fertility. This has over time led to a decrease in crop yield, among them also maize. This decrease is also experienced in the sub-humid and semi-arid locations of Kenya. Among the commonly used soil and water management practices in SSA are Conservation Agriculture (CA) and integrated soil fertility management (ISFM). Crop response to these management practices is influenced by the existence of soil fertility gradients which are common among smallholder farmers. This paper presents results from a study done in the sub-humid and semi-arid location of Kenya, focusing on the effects of CA- and/or ISFM-based practices on maize yield. Trials were set out on farms within the two locations using a one farm one replicate randomized design. In each farm, 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) were laid down on fields representing high and low fertility soils. The trials started in the long rains of 2017 (LR2017) running for four seasons i.e., LR2017, short rains 2017 (SR2017), long rains 2018 (LR2018) and short rains 2018 (SR2018). Soil water content (SWC) and nitrogen use efficiency (NUE) were also monitored and evaluated. In either high or low fertility fields, maize grain yield was significantly different between the control and both NTR, CTM and NTRM with no significant differences between NTR, CTM and NTRM. Maize grain yield increase compared to the control was highest under ISFM in the low fertility fields in both locations and all seasons. For example, during the last season, SR2018, NTR, CTM and NTRM significantly increased maize grain yield by 136 %, 297 %, and 208 %, respectively, compared to the control, in the low fertility fields of sub-humid Kibugu. In the semi-arid Machang'a, the increase by NTR, CTM and NTRM, respectively, in the low fertility fields was 146 %, 379 % and 183 % for SR2018. This was linked to the tendency of ISFM to improve crop yield in the short run. For both locations, SWC and NUE were highest under NTR. In the sub-humid Kibugu, during SR2018, at the grain filling stage, 78 days after sowing, SWC under NTR, CTM and NTRM was higher by 16 %, 9 % and 20 %, respectively, compared to the control. Also at 78 days after sowing, in the semi-arid Machang'a, SWC was 18 %, 7 % and 15 % significantly higher under NTR, CTM and NTRM, respectively, compared to the control. The higher SWC observed under NTR and NTRM was related to no tillage with residue retention while under CTM it was related to improved soil organic matter through manure addition. NUE, on the other hand, was 26 % and 23 % in Kibugu and Machang'a, respectively, and lowest under the combined practice (NTRM), i.e., 19 % and 15 % in Kibugu and Machang'a, respectively. The high NUE under CA was attributed to the placement of urea in the planting holes while maintaining residue on the soil surface. The low NUE under NTRM was linked to fertilizer N immobilization. Lastly, from the biomass yield, our study showed that monocrop maize under NTR requires a kick-starting by an ISFM-based practice in the low fertility fields of the semi-arid region.

1. Introduction

Agriculture will continue to be the backbone of the economy in Sub-Saharan Africa (SSA) where more than 95 % of the farmed land is rain-fed and under a smallholder farming system (Mupangwa et al., 2012). Agricultural production and hence food security in this area is

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constrained by a high spatial and temporal variability of rainfall, drought, dry spells (Rockström et al., 2010) and a degrading natural resource base (Vanlauwe et al., 2014a). In most cases, crop yields are also limited by poor agronomic practices during seasons with good rainfall distribution (Mupangwa et al., 2012). SSA's population is expected to increase 2.5-fold, tripling cereals, the main diet component, demand in this area (Van Ittersum et al., 2016; OECD/FAO, 2019). In addition, the Montpellier Panel report (2015) reports that hunger and child malnutrition in SSA will increase by as much as 20 % by 2050 as a result of climate change. The biggest question, therefore, is whether SSA can meet the expected cereal increase in a more sustainable way without extensification and its related consequences of biodiversity loss and greenhouse gas emissions (Van Ittersum et al., 2016). This raises the need to investigate main means of improving the production of the three major cereals (maize, wheat and rice) in this area. As rain-fed agriculture will continue to be the main means to cereal production in SSA (Cooper et al., 2008), investing in the improvement of cereal management systems is a key obligation (Cairns et al., 2013).

Maize (*Zea mays L.*) is an important crop for food security in Kenya with 90 % of the population consuming it as a staple food (Ochieng et al., 2017). Production of maize in the country is mostly in the hands of smallholder farmers who depend on agriculture for income and have limited resources to invest in practices. Current levels of maize grain productivity are as low as 1.0 ton ha^{-1} while attainable potentials amount to 6–8 ton ha^{-1} (Kiboi et al., 2019). This yield gap is primarily caused by widespread soil fertility degradation in croplands arising from the removal of nutrients by crop production without satisfactory replenishment and generally poor management (Tittonell et al., 2008; Mucheru-Muna et al., 2010). Erratic rainfall and increased frequency of drought, lack of soil water conservation practices, and low adoption of improved germplasm further contribute to low maize yield levels (Mucheru-Muna et al., 2014; Ngetich et al., 2014). This situation is expected to worsen over the next decade as the population in Kenya is rapidly growing. In addition, changes in rainfall patterns will aggravate (Rowell et al., 2015). Scaling practices improving plant nutrition and soil water retention is of key importance to break this vicious circle. However, so far, adoption of the practices has not been successful with smallholder farmers in the country.

Conservation Agriculture (CA) and Integrated Soil Fertility Management (ISFM) have been disseminated to intensify crop production (Sommer et al., 2018). Implementing CA is defined by minimum soil tillage, permanent covering of soil surfaces and crop diversification (FAO, 2002; Wall et al., 2013). In African settings, it has been found that CA is challenged by weed management and low biomass production (Giller et al., 2009). To the above-mentioned effects, there has been suggestions to include a fourth principle in CA, such as weed management (Farooq et al., 2011) and appropriate use of mineral fertilizers (Vanlauwe et al., 2014a). However, Thierfelder et al. (2018) state that the good agronomic practices such as weed management and use of mineral fertilizers should be adopted while implementing CA. As such, they should not be defined as principles of CA (Sommer et al., 2014). ISFM practices, in turn, include the use of improved germplasm, inorganic fertilizers, organic inputs, and other adaptations, maximizing agronomic use efficiency of the applied nutrients and improving crop productivity (Vanlauwe et al., 2010). Generally, it has been found that ISFM improves crop productivity in the short term, while CA does so in the medium or long-term (Mupangwa et al., 2012). Thierfelder et al. (2018) has stated that appropriate nutrient management to enable increased productivity and biomass and also improved stress-tolerant varieties to overcome biotic and abiotic stresses as complementary practices while implementing CA. This implies that the main difference between CA and ISFM is tillage and crop residues which provides long-term sustainability in CA based systems. Nevertheless, the comparative advantages of CA, ISFM or their combination have not been tested elaborately in farming systems of Kenya, although they are of major importance towards identifying pathways that enable nutrient uptake. Pittelkow et al. (2015) highlighted the need for increased no-till research in tropical environments before they can be promoted for use by smallholder farmers. For this reason, we defined our CA practice by two principles, no tillage and the use of residue as soil cover. It is hypothesized that ISFM can kick-start CA-based practices as it allows to produce straw to achieve 30 % soil cover (Vanlauwe et al., 2014a).

Smallholder farming systems are characterized by a large variation in soil properties and rainfall conditions, which may influence the effects of CA and/or ISFM-based practices on maize yields. Differences in physical, chemical and biological conditions of soils exist at regional as well as at field scale (Tittonell et al., 2005). Weather patterns also vary in time and space. To ensure that the practices result in gains for farmers, it is key to understand where and when the practices are most effective. This requires assessing crop responses across gradients in agro-ecological conditions. Sustainability of practices is intricately connected with nitrogen use efficiency (NUE), as it represents a key aspect of crop nutrition and environmental protection. It is, however, known to depend on climate, soil texture, nutrient and water cycling, quality and placement of used organic inputs, as well as on soil biota (Grahmann, 2014). Desirable plant productivity requires a good balance between the supply of nutrients and good soil moisture conditions. It is, therefore, important to understand the effects of management practices, not only on soil fertility but also on soil water retention. Application of organic inputs under tillage-based practices improves soil moisture retention, aided by improved soil organic matter (Kiboi et al., 2019). On the other hand, under CA-based practices, soil moisture is enhanced by SOC build-up, resulting from no tillage as well as from reduced evaporation aided by soil surface cover.

In this study, we evaluated grain yields of maize crop without and with CA and/or ISFM-based practices on smallholder farm fields on two contrasting sites and four growing seasons. Gradients in soil fertility at local scale were distinguished by the productivity of control trials. The specific objectives of this paper were to evaluate: i) differences in mean yield responses to CA-based practice (NTR), ISFM-based practice (CTM) and their combination (NTRM) in two study locations, four seasons and two soil fertility levels, ii) differences in nitrogen use efficiency (NUE) of maize production under NTR, CTM and NTRM, and iii) trends in soil water content (SWC) under the different studied practices. The findings of this study will enable the authors to give concrete recommendations concerning CA-based and ISFM based practices to maize producing farmers.

2. Material and methods

2.1. Study areas and experimental design

The experiment was conducted at two locations with contrasting soil and climate types across the Embu county in Kenya; i.e., Kibugu (0°26′S and 37°26′E) dominated by Nitisol and sub-humid rainfall, and Machang'a (0°46′S and 37°39′E) characterized by Cambisol and semi-arid weather.

Rainfed trials with maize (*Zea mays L.*) as the test crop were 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). The study was designed to run for such a period so as to enable provision of short-term effects of the management practices on crop productivity to farmers. It is important to note that farmers from Kenya and SSA in general own less than 2 ha of land and some even hire land for subsistence farming (Tittonell et al., 2007). As we also observed during our study period, farmers are also faced with land subdivision issues. For these reasons, farmers are still interested in short term benefits from management practices thereby making such short-term studies relevant to them. During the study period, two farmers in Machang'a dropped out of the trials due to land subdivision reasons, leaving a total of 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.

Farmers in Machang'a identified high fertility fields as sections where they always planted maize while low fertility fields were identified as sections where they planted either cowpeas *(Vigna unguiculata)* or millet (*Panicum miliaceum)*. In Kibugu, farmers differentiated high and low fertility fields mainly by maize grain yield production history. After this differentiation, the actual maize grain production from our control treatment was used to reclassify the farms using data from the first season of grain production in each location. In Kibugu, the first trial season (LR2017) grain production was used for the reclassification, while in Machang'a, the second trial season (SR2017) grain production was used since there was no grain production in LR2017. Control fields with a production of below 1 ton ha^{-1} were classified as low fertility fields. As majority of farmers in the study area practiced maize-monocropping, the trials tried to mimic their practice. In addition to this observation, Pittelkow et al. (2015) has 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 NTR and NTRM management systems on maize-monocropping. Studies have also shown that farmers from Africa tend to adopt one or two principles of CA as an entry point to full adoption (Corbeels et al., 2014). In support of this, Thierfelder and Wall (2009) stated that "the principle of minimum soil disturbance is more adopted by farmers, the retention of crop residues as mulch and the introduction of crop rotations and associations is more complex". Stepwise adoption of CA has also been reported, with farmers first implementing reduced tillage followed by the introduction of 30 % residue retention (Lahmar, 2010). For the purpose of this study, we define our management practices as follows; 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). Table 1 shows a summary of the management practices as implemented. In each field, the four treatments were laid down following a one farm one replicate randomized design. Per location, plots measured 10 by 5 m in two farms (mother farms) and 5 m by 3.5 m in eight farms (satellite farms). In the mother farms, SWC was monitored during the trial period and NUE was determined. 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.

At the start of the experiment, seedbeds for plots under tillage (control and CTM) were prepared by hand, hoeing up to 15 cm, while plots under no tillage (NTR and NTRM) were sprayed with a non-selective herbicide (Wipeout, Juanco SPS limited). This herbicide contains glyphosate as an active ingredient and was applied at an application rate of 1.0 L ha^{-1} to clear all weeds. Following the recommendations of the Kenya Agricultural Research Institute (KARI) for the two locations, hybrid maize varieties, H513 and DH04, produced by the Kenya Seed Company were sown in Kibugu and Machang'a, respectively. The maturity period of the used maize varieties is 145 and 105 days on average for H513 and DH04, respectively. Because of the difference in agro-ecology, the spacing recommended by the Kenyan Ministry of Agriculture differed for both sites. Maize was planted at 0.75 by 0.25 m in sub-humid Kibugu and at 0.90 by 0.30 m in semi-arid Machang'a (Mucheru-Muna et al., 2010), resembling a plant density of 53,333 and 37,037 plants ha^{-1}, respectively. Plots under NTR, CTM and NTRM were fertilized with 80 kg N ha^{-1} (urea) using split application (40 kg N ha^{-1} at planting and top-dressed at the same rate 6 weeks after planting) 30 kg P ha^{-1} (triple superphosphate) and 40 kg K ha^{-1} (muriate of potash) every growing season. Fertilizer was used under the improved treatments firstly because use of fertilizer is part of the ISFM principles and secondly, to enable a fair comparison between the improved treatments. Fully decomposed cow manure containing 2.1 % N was applied at 2 t ha^{-1} on plots under CTM and NTRM. Two weeks after germination, 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. Two weeks were allowed for germination to take place before application of soil cover. Plots under the control 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. Weeding was performed two times per season using a hand hoe for plots under tillage and a selective herbicide (Tingatinga, Geneva agrochemical limited). Tingatinga contains atrazine as an active ingredient and was applied at an application rate of 1.5 L ha^{-1} for plots under no tillage. Army worms were controlled by preventive and curative spraying two to three times per season using Volium (Targo pesticides, Syngenta) which contains Chlorantraniliprole and Abamectin as the active ingredients at an application rate of 0.5 L ha^{-1}. During planting, manure was first applied on a furrow. A sisal twine marked with the appropriate maize spacing was then placed above the furrow to mark planting holes. Fertilizer was applied on each planting hole and covered with soil. Maize seeds were then placed and lightly covered with soil.

Maize grain yield was determined when 75 % of plants in a trial had dried up, sampling a net plot of 28 m^2 and 6.75 m^2 for mother farms and satellite farms, respectively. Total fresh weight was measured in the field and subsamples were taken to the laboratory for oven drying, i.e., six maize cobs of different sizes. The subsamples were dried in an oven at 65 °C for 48 h. Grain productivity was calculated by multiplying the total fresh weight of cobs in a net plot with the proportion of oven dry kernels obtained from the subsampled cobs to the total fresh weight of the subsampled cobs.

2.2. Rainfall data

Rainfall during the trial period was recorded daily from weather stations (ATMOS 41, Meter Group, Germany) installed at one farm per location at a distance of about 5 km to the farthest farm. Daily rainfall data outside the trial period (past 20 years) was retrieved from 0.05 × 0.05 degree raster data of the Climate Hazards Group Infrared Precipitation (CHIRPS) (Funk et al., 2014). Cumulative rainfall was computed starting from 14 days before planting, covering a total growing period of 5 and 4 months for long rains and short rains,

Table 1
Management practices implemented at Kibugu and Machang'a.

Management	Tillage system	Inorganic fertilizer	Organic inputs	Soil cover
C	Conventional	0	0	0
NTR	No tillage H	$N_{80}P_{30}K_{40}$	0	Maize stover (30 %)
CTM	Conventional	$N_{80}P_{30}K_{40}$	Manure (2 t ha^{-1})	0
NTRM	No tillage H	$N_{80}P_{30}K_{40}$	Manure (2 t ha^{-1})	Maize stover (30 %)

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, No tillage H is no tillage with the use of herbicide, $N_{80}P_{30}K_{40}$ is 80 kg N ha^{-1}, 30 kg P ha^{-1} and 40 kg K ha^{-1}, respectively.

respectively. The software package Rainbow (Raes et al., 2006) was used to analyze rainfall data for the recurrence period and probability of exceedance (Eqs. 1 and 2).

$$Pe = \frac{r}{n}100 \tag{1}$$

$$T = \frac{100}{Pe\%} \tag{2}$$

where Pe is a probability of exceedance, r is rank number, n is the number of observations and T is event return period.

2.3. Soil sampling and chemical analysis

Soils were sampled (0–15 cm) 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 established over the four growing seasons. At the end of the trials in season four, sampling was done using a similar sampling procedure. Composite soil samples were collected at $0-15$ cm since this is the depth where most of the maize roots get concentrated. In addition, undisturbed soil samples were collected from 0 to 15 cm and 15–30 cm using Kopecky rings of 5 cm inner diameter and 5.1 cm height with a volume of 100 cm^3 for soil water retention curve analysis. The soil samples were air-dried, 2 mm sieved and analysed for selected physico-chemical soil properties. Total N, SOC and $\delta^{15}N$ 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 (Gee and Bauder, 1986; Smith and Mullins, 1991).

2.4. Nitrogen use efficiency (NUE) experiment

The NUE experiment was carried out on the high fertility fields. A subplot of 3.73 m^2 and 5.4 m^2, was marked in Kibugu and Machang'a, respectively, enough for representing 20 maize plants. All inputs were added at the same rate and according to the procedure stated in Section 2.2. For this experiment, the conventional urea was replaced by ^{15}N labelled urea, i.e., 4.56 and 4.54 % in Kibugu and Machang'a, respectively, and applied in liquid form. At physiological maturity, maize was harvested from a subplot of 1.1 m^2 and 1.6 m^2 in Kibugu and Machang'a, respectively. The harvesting procedure was similar to that described in Section 2.2. In the laboratory, the samples were air-dried, weighed and milled (SM 100 Retsch, Germany) for total N and ^{15}N analysis (see 2.6). After harvesting, soil samples were taken from 0 to 15 cm and $15-30$ cm depth using a 2.0 cm diameter soil auger to measure the recovery of urea-derived N across the soil profile. At each depth, samples were collected along the planting line in five replicates and mixed thoroughly to make one composite sample. The samples were then air-dried, sieved and used for total N and ^{15}N analysis. NUE calculations were performed using calculation and principles presented by (Bosshard et al., 2009). The fraction of applied urea-N recovered in the soil was calculated using Eq. (3) (Vanlauwe et al., 2001).

$$\text{soil recovery}=\frac{\text{soil total N (kg ha}^{-1}) \times \text{Ndfu}-\text{soil}}{\text{rate of N application (kg N ha}^{-1})} \tag{3}$$

^{15}N enrichment of the respective soil layers from the control treatment was used as background to calculate the atom % ^{15}N excess values for the soil samples of the other treatments.

2.5. Soil water content (SWC)

On the mother farms (i.e., two per location), two access tubes were diagonally installed in each plot, 2.6 m from the edge and at 6 m from each other for soil-water content (SWC) measurements. SWC was measured fortnightly over 0–40 cm (where maize roots are concentrated) in each plot in 10 cm depth increments using a Diviner2000™ Version 1.5 190 capacitance sensor (Sentek Sensor Technologies, Stepney, Australia). Two access tubes installed near the plots were used for calibration. To that end, soil samples were taken in intact 100 cm^3 cores with a dedicated auger near the tubes and at the depth at which Diviner2000™ readings were taken. SWC was then measured gravimetrically by oven-drying at 105 °C for 24 h and volumetric SWC was obtained by accounting for bulk density, determined concurrently on the same cores.

Soil water retention curve analyses were made at different matric potentials as stipulated by Cornelis et al. (2005). For lower matric potentials -10 hPa, -30 hPa, -50 hPa, 70 hPa and -100 hPa, the sand box apparatus (Eijkelkamp Agrisearch Equipment, the Netherlands) was used. Measurements at lower potentials of -340 hPa, -1020 hPa and $-15,300$ hPa were done using pressure chambers (Soilmoisture Equipment, Santa Barbara, CA, USA). The collected data enabled the construction of the soil water retention curves (SWRC) using the function of Van Genuchten (1980) with $m = 1-1/n$. Soil dry BD was determined at -100 hPa matric pressure during the retention curve analysis.

Soil water content at which the maize crop experienced stress was determined at -500 and $-10,000$ hPa for the vegetative and grain filling stage, respectively (Taylor and Ashcroft, 1972). To these effects, the van Genuchten equation was fitted using the RECT programme to obtain all required parameters; θ_S, θ_r, α and n (Eq. (4)).

$$\theta = \theta_r + (\theta_s - \theta_r)\left[\frac{1}{1+(\alpha[h])^n}\right]^m \tag{4}$$

where θ is the volumetric soil water content ($m^3\,m^{-3}$) at a given matric potential, h (hPa), θ_S is the volumetric soil water content at saturation ($m^3\,m^{-3}$), θ_r is the residual volumetric soil water content ($m^3\,m^{-3}$) at which soil water movement virtually ceases and α (hPa^{-1}) as well as the dimensionless n and m are curve fitting parameters with $m = 1-1/n$.

2.6. 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 maize grain yield in each location per growing season 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 random intercepts of all mixed models were based on individual farm fields. The residual normal distribution and homoscedasticity of all models were ascertained by plotting residuals against quantiles and fitted values. Per location, maize grain and biomass yield were compared between treatments and soil fertility levels based on their main and interactive effects. 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. Pairwise comparisons of means was made by least-squares with confidence intervals and standard errors of difference using the 'lsmeans' package. Responsiveness to the different management practices was calculated as the difference between yields obtained from the improved treatments (NTR, CTM or NTRM) and from the control. These data were analysed through ordinary linear regression. Per location, treatment effect on SWC and NUE was evaluated through analyses of variances (ANOVA) at a probability level of $P \le 0.05$. Prior to this, the data were tested for normality. Where

Table 2
Type of season analysis in Kibugu and Machang'a for long rain (LR) and short rain (SR) periods in 2017 and 2018; mean 20-year rainfall (with standard deviation in parentheses), study year, seasonal rainfall, event return period (T), and probability of exceedance (Pe).

Location	Study year	Season	Mean 20-year rainfall (mm)*	Season rainfall (mm)	T (Years)	Pe (%)	Season type
Kibugu	2017	LR	521 (201)	488	2	50	Normal
	2018	SR	354 (106)	468	7	14	Wet
		LR	521 (201)	1053	250	0.4	Extremely wet
		SR	354 (106)	402	3	33	Normal
Machang'a	2017	LR	333 (122)	184	1	100	Extremely dry
	2018	SR	302 (98)	335	3	33	Normal
		LR	333(122)	665	250	0.4	Extremely wet
		SR	302 (98)	335	3	33	Normal

* 20 years rainfall data obtained from ftp://ftp.chg.ucsb.edu/pub/org/chg/products/CHIRPS-2.0/africa_daily/tifs/p05.

significance was detected, means were compared using Tukey test.

3. Results

3.1. Rainfall conditions and soil properties

Kibugu and Machang'a experienced different weather conditions during the study period (Table 2 and Fig. 1). A season is considered wet when the probability of exceedance (Pe) is equal to or below 20 %, which defines a rainfall event with above normal precipitation. A dry season has a Pe equal to or above 80 %, denoting a rainfall event below normal precipitation (Zinyengere et al., 2011). The probability of exceedance defines the probability that the actual rainfall received during a particular season is equal to or higher than the estimated seasonal rainfall mean. An event return period (T) defines the interval within which a similar rainfall event can reoccur (recurrence period). Compared to the 20 years average, Kibugu experienced normal and wet seasons during the study period, while Machang'a experienced a wide range of seasons from dry, normal to wet. In both locations, LR2018 was extremely wet with a probability of exceedance of 0.4 %. "We considered Pe below 1 % or above 95 % as extremes". Observed cumulative rainfall, planting, flowering and harvesting dates during each growing season are shown in Fig. 1.

The mean values of initial soil properties at the start of the experiment in both locations are presented in Table 3. On average, soils from Kibugu had a significantly lower pH ($p < 0.0001$), a significantly higher SOC ($p < 0.0001$), significantly higher total nitrogen (TN) ($p < 0.0001$), significantly higher total phosphorus (TP) ($p < 0.0001$) and a significantly lower bulk density (BD) ($p < 0.0001$) compared to the soils from Machang'a.

3.2. Maize grain and biomass production

Maize grain yield at both locations and for all seasons is shown in Fig. 2. In Kibugu, maize grain yield under NTR, CTM and NTRM was not significantly different ($p > 0.05$ for pairwise comparison) in the

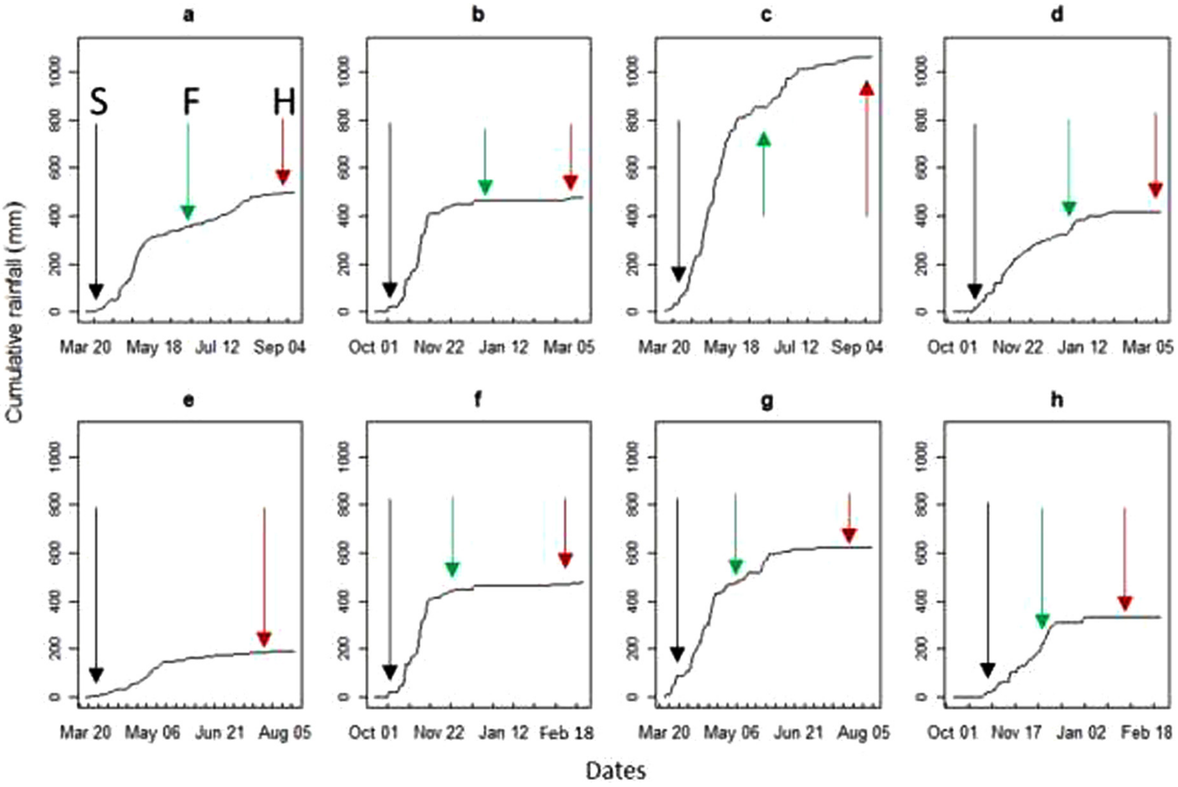

Fig. 1. Cumulative rainfall, and sowing (S) (black arrow), flowering (F) (green arrow) and harvesting (H) (brown arrow) dates during LR2017 (a, e), SR2017 (b, f), LR2018 (c, g) and SR2018 (d, h) in Kibugu (top panels) and Machang'a (bottom panels), respectively. Brown arrow in box e shows biomass harvesting time, there was no maize grain harvest. LR and SR are long rains and short rains, respectively.

Table 3
Mean values of basic soil properties with standard deviations in parentheses at the start of the trial period for the locations Kibugu and Machang'a and for the high and low soil fertility levels (SF); pH-(H_2O), soil pH-water (1:5); soil organic carbon (SOC); total nitrogen (TN), Resin-P, available P; exchangeable K (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)	5.0 (0.2)	$p < 0.001$	6.9 (0.6)	6.8 (0.5)	ns
SOC (g kg^{-1})*	19.2 (4.3)	14.8 (9.3)	0.03	6.2 (3.8)	4.6 (0.4)	ns
TN (g kg^{-1})*	2.2 (1.2)	1.7 (0.8)	ns	0.7 (0.4)	0.5 (0.1)	ns
TP (g kg^{-1})*	1.3 (0.2)	0.9 (0.3)	$p < 0.001$	0.1 (0.0)	0.1 (0.0)	ns
Resin-P (mg kg^{-1})	16.5 (21.4)	4.1 (4.9)	0.02	7.5 (9.6)	1.5 (2.4)	ns
Exch. K (mg kg^{-1})	0.4 (0.2)	0.4 (0.3)	ns	0.7 (0.4)	0.4 (0.1)	ns
BD (Mg m^{-3})*	0.9 (0.0)	0.9 (0.0)	ns	1.5 (0.0)	1.5 (0.0)	ns
Clay (g kg^{-1})	747	811		134	112	
Silt (g kg^{-1})	158	135		125	152	
Sand (g kg^{-1})	88	54		747	737	

Soil properties marked with * were significantly different ($p < 0.05$) between Kibugu and Machang'a. Per location significance difference between high soil fertility (SF) and low SF fields are shown by p values.

high fertility fields in all seasons. Significant differences existed only between NTR, CTM, NTRM and the control ($p < 0.05$). Similar results were observed in the low fertility fields, except during the wet SR2017 when grain yield for NTR, CTM and NTRM was not significantly different from the control. In Machang'a, there was no maize grain yield during the extremely dry LR2017. During the other three seasons, similar to Kibugu, grain yield under NTR, CTM and NTRM was not significantly different in the high or low fertility fields.

In Kibugu, during the normal LR2017 season, grain yield production under the improved treatments ranged from 5.9 ton ha^{-1} to 6.7 ton ha^{-1} and from 1.6 ton ha^{-1} to 2.8 ton ha^{-1} for the high and low fertility fields, respectively. These values were higher by 69 %, 65 % and 49 % under CTM, NTRM and NTR, respectively, compared to the non-fertilized control in the high fertility fields. In the low fertility fields, the values were higher by 264 %, 143 % and 114 % under CTM, NTRM and NTR, respectively compared to the control. In the wet SR2017, compared with the normal LR2017, maize grain yields decreased in all fields. Productivity was between 1.6 ton ha^{-1} and 2.0 ton ha^{-1} (NTRM > CTM > NTR) and between 0.1 ton ha^{-1} and 0.1 ton ha^{-1} (CTM > NTR > NTRM) for the high and low fertility

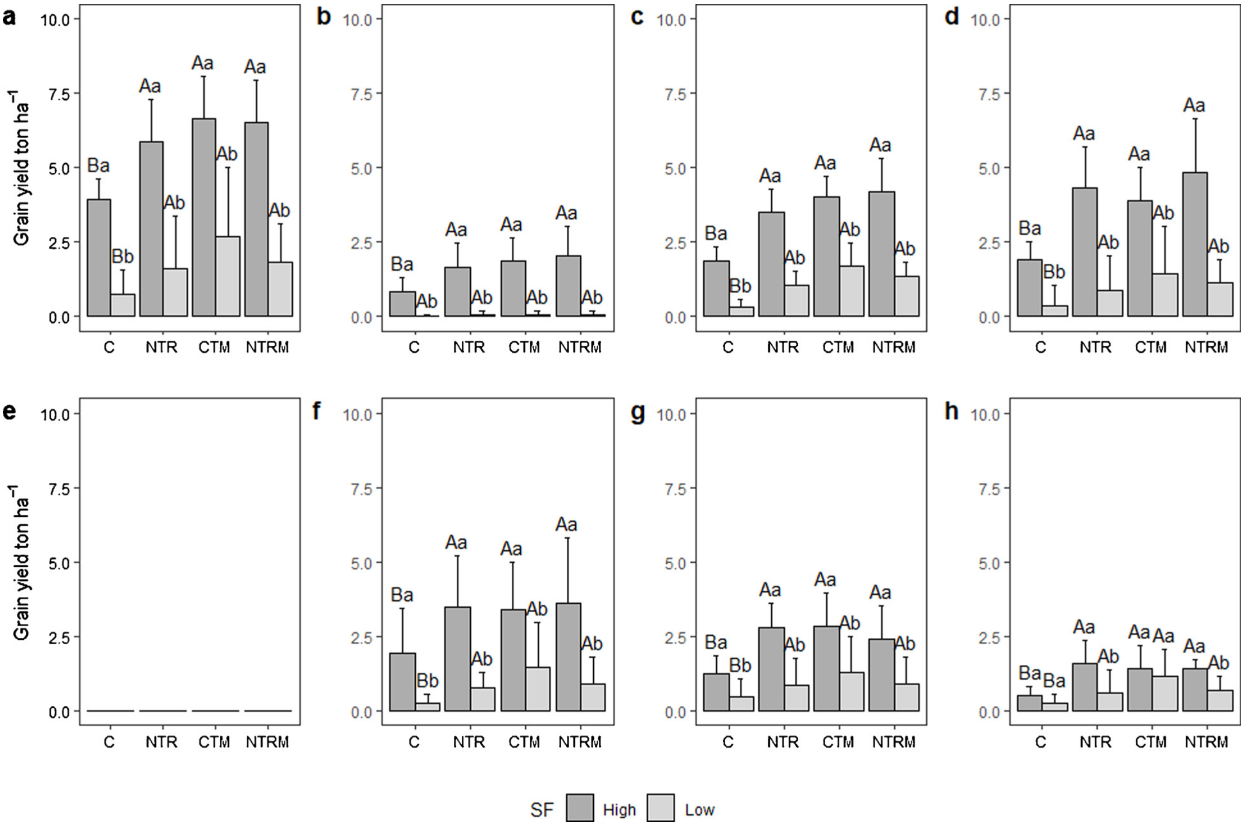

Fig. 2. Maize grain yield productivity under control (C), no tillage with residue retention (NTR), conventional tillage with use of manure (CTM) and no tillage with residue retention and use of manure (NTRM) during LR2017 (a, e), SR2017 (b, f), LR2018 (c, g) and SR2018 (d, h) in Kibugu (top panels) and Machang'a (bottom panels), respectively, for high and low fertility (SF) fields. In each location, per season, bar graphs indicated with the same capital letters are not significantly different ($p < 0.05$) between the treatments under the same fertility level, while bars indicated with the same small letters are not significantly different between high and low fertility fields under each treatment. Empty box e shows zero maize grain harvest. LR and SR are long rains and short rains, respectively.

fields, respectively. During the extremely wet LR2018, the high fertility fields yielded in the range of 3.5 ton ha^{-1} to 4.3 ton ha^{-1} (NTRM > CTM > NTR) while the low fertility fields produced between 1.0 ton ha^{-1} and 1.7 ton ha^{-1} (CTM > NTR > NTRM). During the normal SR2018, production ranged from 3.9 ton ha^{-1} to 4.9 ton ha^{-1} (NTRM > NTR > CTM) and from 0.9 ton ha^{-1} to 1.5 ton ha^{-1} (CTM > NTRM > NTR) for the high and low fertility fields, respectively. The values were higher than the non-fertilized control by 156 %, 128 % and 106 % under NTRM, NTR and CTM, respectively, for the higher fertility fields. For the low fertility fields, grain production values were higher by 297 %, 208 % and 166 % under CTM, NTRM and NTR, respectively, compared to the non-fertilized control.

In Machang’a, normal SR2017 maize productivity from the improved treatments ranged from 3.4 ton ha^{-1} to 3.6 ton ha^{-1} and from 0.8 ton ha^{-1} to 1.5 ton ha^{-1} for the high and low fertility fields, respectively. Compared to the non-fertilized control, the values were higher by 85 %, 80 % and 75 % under NTRM, NTR and CTM, respectively, for the high fertility fields. In the low fertility fields, compared to the non-fertilized control, the values were higher by 444 %, 240 % and 188 % under CTM, NTRM and NTR, respectively. During the wet LR2018, productivity under the improved treatments ranged from 2.4 ton ha^{-1} to 2.9 ton ha^{-1} and from 0.9 ton ha^{-1} to 1.3 ton ha^{-1} for the high and low fertility fields, respectively. In the high fertility fields, production was in the order CTM > NTR > NTRM while in the low fertility fields it was CTM > NTRM > NTR. Production in the high fertility fields ranged from 1.4 ton ha^{-1} to 1.6 ton ha^{-1} during the normal SR2018. The values were higher than the non-fertilized control by 203 %, 175 % and 171 % under NTR, NTRM and CTM, respectively. In the low fertility fields, production ranged from 0.6 ton ha^{-1} to 1.2 ton ha^{-1}. Compared to the non-fertilized control, these values were higher by 379 %, 183 % and 146 % under CTM, NTRM and NTR, respectively.

Grain yield under C, NTR, CTM and NTRM was significantly different between high and low fertility fields in all four seasons (LR2017, SR2017, LR2018 and SR2018) in Kibugu (Fig. 2). In Machang’a, during the normal SR2017 and the extremely wet LR2018, grain production under C, NTR, CTM and NTRM was significantly different between the high and low fertility fields. During the normal SR2018, grain production under C and ISFM was not significantly different between the high and low fertility fields. Also during this season, significant differences in grain yield existed between the high and low fertility fields under the NTR and NTRM treatments.

Biomass production in Kibugu under C, NTR, CTM and NTRM (Fig. 3) was significantly different between the high and low fertility fields in all four seasons (LR2017, SR2017, LR2018 and SR2018). Differences in biomass production between the high and low fertility fields in Machang’a varied seasonally. In this region, during the extremely dry LR2017 and extremely wet LR2018, no differences in biomass production were observed between the high and low fertility fields under the C, NTR, CTM and NTRM treatments. During the normal SR2017, biomass production under C, NTR, CTM and NTRM was significantly different between the high and low fertility fields. During the normal SR2018, a significant difference in biomass production between the high and low fertility fields was observed only under NTR treatment. The high fertility fields in Kibugu produced at least 3 ton ha^{-1} biomass (needed to achieve 30 % soil cover in CA) under NTR and CTM in all four seasons, while under NTRM, it was not achieved during the wet SR2017. In the low fertility fields, this production was achieved during the normal LR2017 and SR2018 under NTR, CTM and NTRM. In Machang’a, 3 ton ha^{-1} biomass production was obtained under NTR, CTM and NTRM during the normal SR2017 and SR2018 in the high fertility fields. In the low fertility fields, this was only obtained under NTRM during the normal SR2017 and under CTM during the normal SR2018.

3.3. NTRM yield response

In Kibugu, grain yield response under the combined practice, NTRM, demonstrated non-significant negative relationship (shown by p values) with yield response under NTR over the four growing seasons (Fig. 4a). Similarly, yield response from NTRM showed non-significant negative relationship with yield response under CTM in Kibugu (Fig. 4b). Yield response from the two practices, NTRM, as compared to the separate practices were generally positive on high fertility fields and negative on low fertility fields.

In Machang’a, yield response under the combined practice, NTRM exhibited a significant (LR2018 and SR2018) and non-significant (SR2017) negative relationship with yield responses under NTR (Fig. 5a). Yield response under NTRM showed a significant (SR2017 and SR2018) and a non-significant (LR2018) negative relationship with yield response under CTM (Fig. 5b). Overall few high fertility fields showed a positive yield response under NTRM in Machang’a with majority of fields demonstrating a negative response. In general, from the two locations, as yield response under NTR or CTM increased, yield response from the combined practice, NTRM decreased.

3.4. Nitrogen use efficiency (NUE)

Observed urea NUE (maize grain and above ground biomass) and soil N recovery (0 − 30 cm) are presented in Table 4. In Kibugu, maize grain NUE was significantly higher under NTR ($p = 0.03$) compared to CTM and NTRM. No significant differences were observed between treatments for biomass NUE ($p = 0.97$) or soil N recovery ($p = 0.85$). In Machang’a, no significant differences were observed in grain ($p = 0.59$) and biomass ($p = 0.82$) NUE, and in soil N recovery ($p = 0.50$) between treatments. Generally, maize grain NUE was highest under NTR for both locations, i.e., 26 and 23 % in Kibugu and Machang’a, respectively, and lowest under the combined practice (NTRM), i.e., 19 % and 15 % in Kibugu and Machang’a, respectively. CTM resulted in 20 % and 21 % grain NUE in Kibugu and Machang’a, respectively. Soil N recovery in the 0 − 30 cm soil profile was non-significantly higher under NTRM (14 %) and non-significantly lower under ISFM (12 %) in Kibugu, while in Machang’a, it was non significantly higher under CTM (7 %) and non-significantly lower under NTRM (5 %).

3.5. Soil water content

Soil water content (SWC) expressed in mm of water and indicating the amount of water stored in the top 40 cm of the soil profile for seasons SR2017 and SR2018 in the two locations is shown in Figs. 6 and 7. Measurements taken during LR2017 and LR2018 were not consistent because of mechanical problems with the Diviner 2000. At both locations, SWC in the soil profile responded to the seasonal rainfall pattern. Generally, SWC was higher in Kibugu compared to Machang’a with a declining trend during the grain filling stage at both locations. SWC was significantly higher in NTR and NTRM, with the control showing the lowest SWC. During grain filling stage, we observed a consistently high SWC under CA-based practices. For example, in the wet SR2017, at day 67 after sowing, SWC under NTR, CTM and NTRM was not significantly higher by 20 %, 9% and 16 %, respectively, compared to the control in Kibugu. Eighty-eight days after sowing, SWC was significantly higher under NTR by 17 % compared to the control. No significant differences in SWC existed between the control and CTM or NTRM. In Machang’a, during the normal SR2017, SWC under NTR, CTM and NTRM was 19 %, 11 % and 18 % higher, respectively, compared to the control, at day 53 after sowing. During SR2017, the maize crop in Kibugu did not become water-stressed during the vegetative stage (blue horizontal line) while during the grain filling stage (red horizontal line), the maize crop under the control was water-stressed at day 88 after sowing. In Machang’a, the maize crop was not water-stressed during the two stages.

In the normal SR2018 (Fig. 7), SWC in Kibugu was significantly

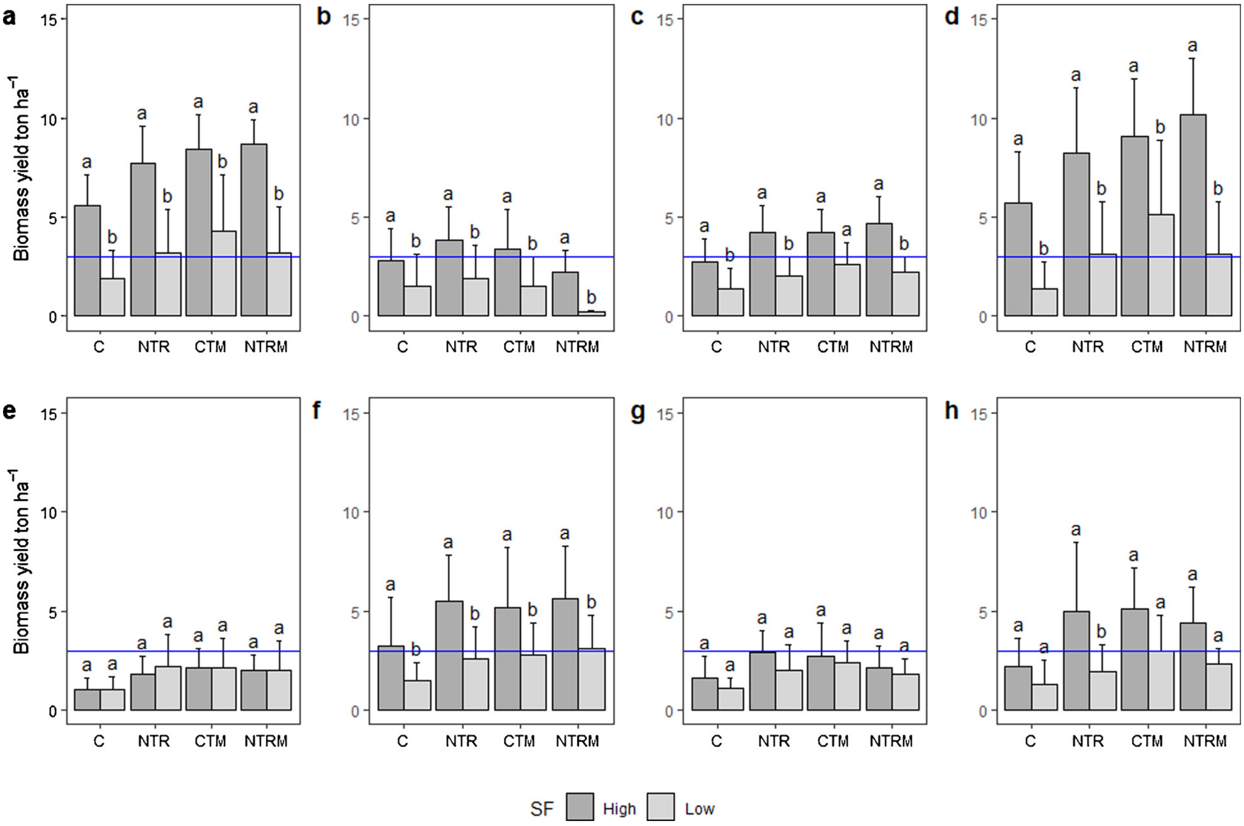

Fig. 3. Biomass yield productivity under control (C), no tillage with residue retention (NTR), conventional tillage with use of manure (CTM) and no tillage with residue retention and use of manure (NTRM) during LR2017 (a, e), SR2017 (b, f), LR2018 (c, g) and SR2018 (d, h) in Kibugu (top panels) and Machang'a (bottom panels), respectively, for the high and low fertility fields. In each location per season, bar graphs indicated with similar letters are not significantly different ($p = 0.05$) between high and low fertility fields. The blue horizontal line shows a biomass production of 3 ton ha^{-1}, needed to achieve 30 % soil cover in CA. LR and SR are long rains and short rains, respectively.

higher under NTR, CTM and NTRM by 12 %, 9 % and 21 %, respectively, compared to the control at day 57 after sowing. At day 78 after sowing, SWC under NTR, CTM and NTRM was higher by 16 %, 9 % and 20 %, respectively, compared to the control. In Machang'a, NTR, CTM and NTRM showed 29 %, 17 % and 28 % significantly higher SWC, respectively, compared to the control at day 57 after sowing. At day 78 after sowing, SWC was 18 %, 7 % and 15 % significantly higher under NTR, CTM and NTRM, respectively, compared to the control. Generally, SWC in $0-40$ cm was higher under CA-based practices than under ISFM. In Kibugu, during SR2018, the maize crop under the control was water- stressed during both vegetative and grain filling stages. In Machang'a, no water stress occurred during the vegetative or grain filling stages.

4. Discussion

4.1. Grain yield productivity

In both locations, there was no significant difference in productivity between the improved treatments (NTR, CTM and NTRM) in either the high or the low fertility fields. However, these significant differences occurred between the high and low fertility fields under NTR, CTM and NTRM. The effects of the treatments on soil chemical properties (data shown in the supplementary file) were also not significantly different between the improved treatments which could explain the above observations. In addition, drought stress during the monitored days seemed limited. The low yields during the extremely wet LR2018 could be attributed to nutrient leaching beyond the root zone. As reported by Laird et al. (2010), leaching reduces soil fertility and consequently crop yields. Even though there were no significant differences in productivity between the treatments, trends can be perceived when considering the mean values, which are anyway an important outcome of the experiments (Webster, 2007) and allow to provide farmers with recommendations.

CTM showed the highest grain yield in all low fertility fields and during some seasons also in the high fertility fields. This is possible because ISFM based practices has been known to relieve soil fertility limitations in a short period of time (Vanlauwe et al., 2014b). This process is aided by the use of organic inputs enhancing the efficiency of inorganic fertilizers to improve the soil fertility and nutrient availability to crops (Habte et al., 2018). In addition, the decomposition of inputs is known to be enhanced under tillage systems, leading to a faster supply of nutrients (Dikgwatlhe et al., 2014). Even though NUE was not the highest under CTM to confirm the observed high grain increase under this treatment, several authors have reported high yields under ISFM-based practices. Kiboi et al. (2019) reported a significantly higher maize grain yield with the use of crop residues, inorganic fertilizers with organic inputs as compared to crop residues and inorganic fertilizers during SR2017 in Chuka, Kenya. In Zambia, cassava productivity was improved through the integrated use of NPK and manure (Biratu et al., 2018). In Pakistan, the use of 25 % poultry manure and 75 % single superphosphate resulted in the highest maize grain (7.8 ton ha^{-1}) compared to the control (4.8 ton ha^{-1}) as reported by Ali et al. (2019). In China, pig manure with NPK resulted in a significantly higher maize grain yield (6.8 ton ha^{-1}) compared to only NPK or manure with 6.0 ton ha^{-1} of grain yield under each management (Wang et al., 2018). The low NUE observed under CTM could be due to N fertilizer immobilization in the presence of low-quality manure. Under this treatment, the SWC was also high compared to the control which could have created a better environment for microbial activity (Stark and

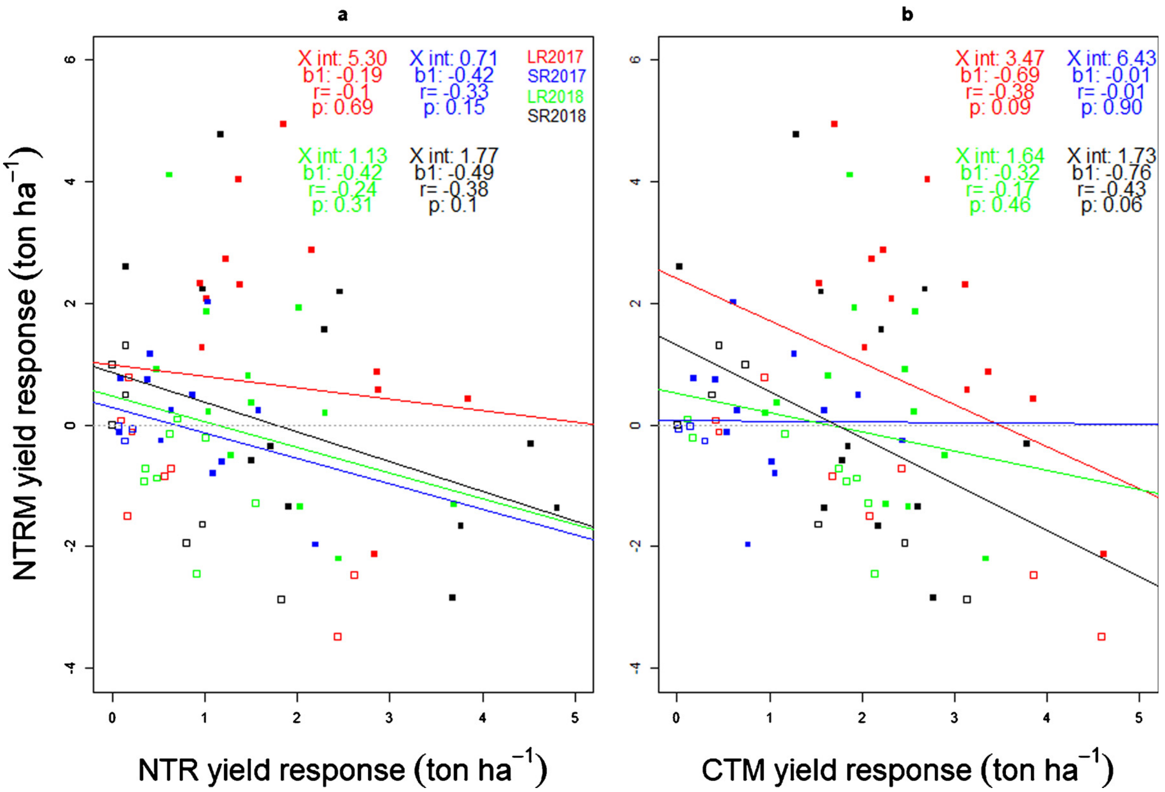

Fig. 4. Yield response under the combined practice, no tillage with residue retention and use of manure (NTRM) as a function of yield response under (a) no tillage with residue retention (NTR) and (b) conventional tillage with use of manure (CTM) over the four growing seasons in Kibugu. Zero on the Y-axis represents the additive effect above and below which we have a positive and negative yield response under NTRM, respectively. Closed and open symbols present yield response from the high and low fertility fields. The red, blue, green and black line are the regression lines during LR2017, SR2017, LR2018 and SR2018, respectively. X int is the intercept on the X-axis, b1 is the slope, r is the goodness of fit and p is the significance of regressions. LR and SR are long rains and short rains, respectively. Response is the difference in yield between the improved treatment and the control.

Firestone, 1995). The observed high SWC could be explained by the effect of organic inputs, enhancing the soil organic carbon. In the central highlands of Kenya, Kiboi et al. (2019) reported a high SWC under organic matter treatment.

Consequently, in the low fertility fields, the observed lower grain yield compared to CTM, was mostly obtained under the CA-based practices NTR and NTRM, which could be attributed to the time dependency of CA in improving crop yields (Thierfelder et al., 2015; Corbeels et al., 2014). There have been contrasting results from different regions and cropping situations concerning the effects of CA-based practices on crop yield. Our study reports positive yield under no-tillage with residue retention. This is in line with Thierfelder et al. (2013) who reported that no-tillage with residue retention improves yields as compared to yields from conventional tillage. This yield increase was linked to prevention of soil crusting by residue retention under no-tillage. Earlier studies have also shown that CA-based practices perform better in seasons with rainfall below the long-term season average (Kuhn et al., 2016; Munodawafa and Zhou, 2008; Mupangwa et al., 2012; Patil et al., 2016; Pradhan et al., 2016). For example, the grain yield under NTR in the low fertility fields of the semi-arid Machang’a region was lowest in the wet LR2018, which is in line with earlier studies. The observed higher grain under NTR in Machang’a during the normal SR2018 season could be attributed to the soil fertility build-up within the four seasons. The high fertility fields had non significantly higher SOC, Resin-P and exchangeable K. Benefits under CA-based practices have been reported to accrue with time due to gradual improvement in soil properties (Madarász et al., 2016; Micheni et al., 2016; Sithole et al., 2016; Thierfelder et al., 2015; Corbeels et al., 2014; Thierfelder and Wall, 2012). Even though our study was done only for four seasons, in the last season, SR2018, in the high fertility fields, NTR resulted in a higher grain yield in both the sub-humid Kibugu and the semi-arid Machang’a as compared to CTM.

Management practices were expected to relieve soil fertility constraints in the low fertility fields, thereby eradicating productivity differences between high and low fertility fields. For example, in the western province of Kenya, Vanlauwe et al. (2006) found no significant differences in maize grain yield between fields of different soil fertility status when using NPK fertilizers. In their study, grain production from the control reflected the decrease in soil fertility status. However, we observed significant differences in grain yield and biomass production between the high and low fertility fields, with grain yields mostly lower in the treated low fertility fields in comparison with the non-treated high fertility control. This contradicting results could first be explained by the different soil fertility gradients. Vanlauwe et al. (2006) defined the soil fertility gradients by distances from the homestead. In our study, differences in soil fertility gradients were defined by past management and later reclassification based on production from the control. Secondly, there is a possibility that soils from our low fertility fields were probably limited by other factors than the major nutrient limitation we tackled through NPK and organic matter inputs. For example, in Zimbabwe, crop response to N and P fertilizers was limited by deficiencies of Zn, Ca, Mg and K (Zingore et al., 2008).

4.2. *Kick-starting CA-based practice with ISFM*

Under maize mono-cropping systems, production of over 3 ton ha^{-1} biomass under NTR and CTM in the high fertility fields in Kibugu could suggest that kick-starting NTR with CTM is not needed in these fields. In the low fertility fields, in normal seasons, kick-starting is not necessary either. However, in the wet season and in the low fertility fields, it

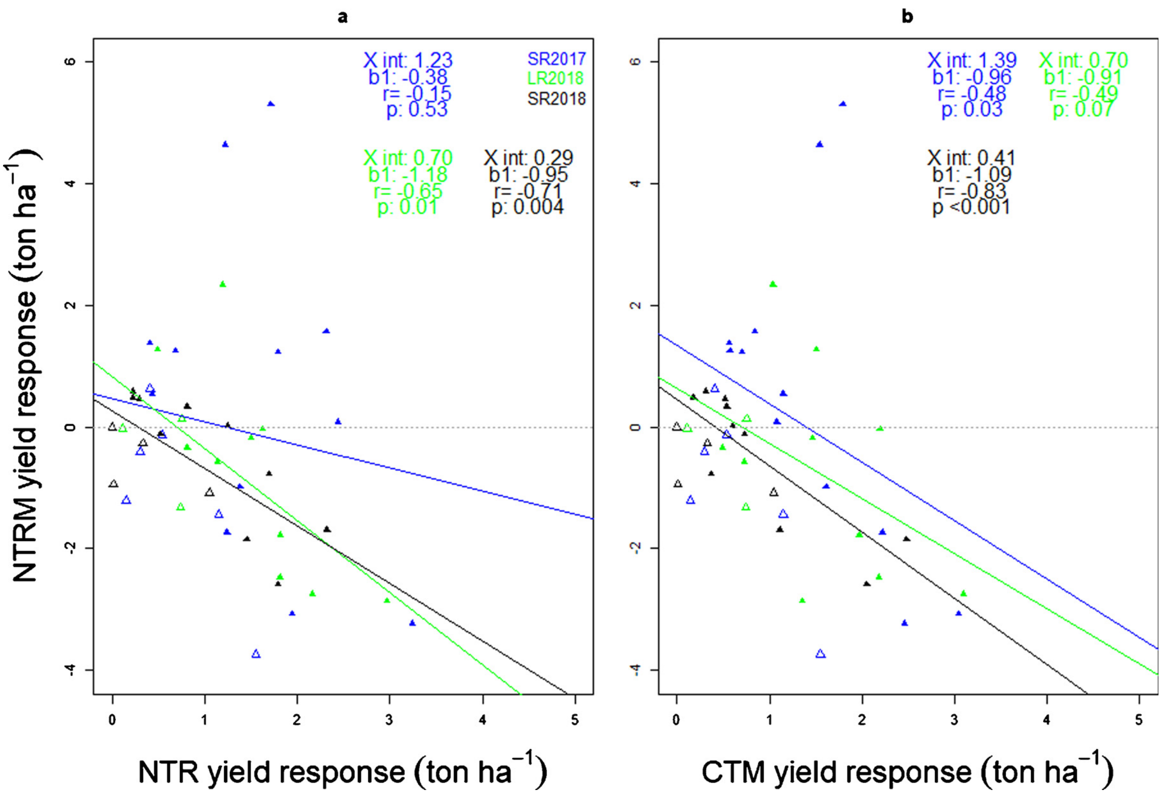

Fig. 5. Yield response under the combined practice, no tillage with residue retention and use of manure (NTRM) as a function of yield responses under (a) no tillage with residue retention (NTR) and (b) conventional tillage with use of manure (CTM) over the four growing seasons in Machang'a. Zero on the Y-axis represents the additive effect above and below which we have a positive and negative yield response under NTRM, respectively. Closed and open symbols present yield response from the high and low fertility fields. The blue, green and black line are the regression lines during SR2017, LR2018 and SR2018, respectively. X int is the intercept on the X-axis, b1 is the slope, r is the goodness of fit and p is the significance of regressions. LR and SR are long rains and short rains, respectively. Response is the difference in yield between the improved treatment and the control.

Table 4

Effects of different management practices: no tillage with residue retention (NTR), conventional tillage with use of manure (CTM), no tillage with residue retention and use of manure (NTRM) on nitrogen use efficiency (NUE) split up in grain and above-ground biomass and soil nitrogen recovery at 0-30 cm depth for the locations Kibugu (sub-humid) and Machang'a (semi-arid); values are means with standard deviation in parentheses.

Location	Management practice	Grain NUE (%)	Above-ground biomass NUE (%)	Soil N Recovery (%)
Kibugu	NTR	26.3(1.9)	18.4(11.1)	12.9(3.7)
	CTM	20.2(1.9)	18.3(3.3)	11.9(4.1)
	NTRM	18.6(5.5)	17.3(4.6)	13.8(5.7)
p value		0.03	ns	ns
Machang'a	NTR	22.8(11.1)	14.3(11.3)	6.7(2.1)
	CTM	20.5(9.3)	9.8(6.8)	6.9(1.4)
p value	NTRM	15.5(9.4)	11.8(12.1)	5.4(2.1)
		ns	ns	ns

For each property, significance difference between management practices per location is shown by P values.

might be difficult to implement NTR, for biomass production under CTM is also not enough to attain a 30 % cover. Nevertheless, the effects of NTR in a wet season were minimal, insinuating no need for kick-starting NTR with CTM in the sub-humid regions.

In Machang'a, the production of over 3 ton ha^{-1} biomass under NTR and CTM in the normal seasons in the high fertility fields could suggest that kick-starting of NTR by CTM is not necessary when rainfall is normal. However, in the low fertility fields, such a kick-starting in normal seasons is necessary. In wet and extremely dry seasons in the semi-arid regions, NTR might be challenged by a lack of soil cover, both in the high or low fertility fields. But again, studies have shown that NTR does not increase crop yields during wet and extremely dry seasons (Munodawafa and Zhou, 2008; Mupangwa et al., 2012). Therefore, the proposed kick-starting could be necessary for low fertility fields in the semi-arid regions in normal seasons. This might also hold for (not extremely) dry seasons, but it was not demonstrated in this study since such weather conditions did not occur during our four seasons study period.

It is important to note that the discussion in this paper with regard to kick-starting of NTR by CTM assumes that farmers won't need biomass for other functions, for example for livestock feeding. Researchers have documented trade-offs that exist between the use of residues as mulch under CA-based systems for livestock feeding in mixed farming systems (Giller et al., 2009; Jaleta et al., 2013; Valbuena et al., 2012). This has not been considered here. It is also important to note that the discussed kick-starting of NTR by CTM is only applicable under maize mono-cropping. The introduction of CA's third principle, i.e., crop rotations, might significantly change the situation. Legumes grown in association or in rotation with maize have the ability to improve soil structure and fertility (Thierfelder et al., 2012; Giller, 2001). This will in term increase biomass production under CA-based practice even in the low fertility fields and thus enable the production of 3 ton ha^{-1} biomass.

4.3. Yield response under NTRM

Even though major differences in grain yield between NTR and CTM were not anticipated, an additive effect on grain yield from the combined practice, NTRM was expected. In contrast, yield response under the combined practice, NTRM in relation to the separate practices, NTR

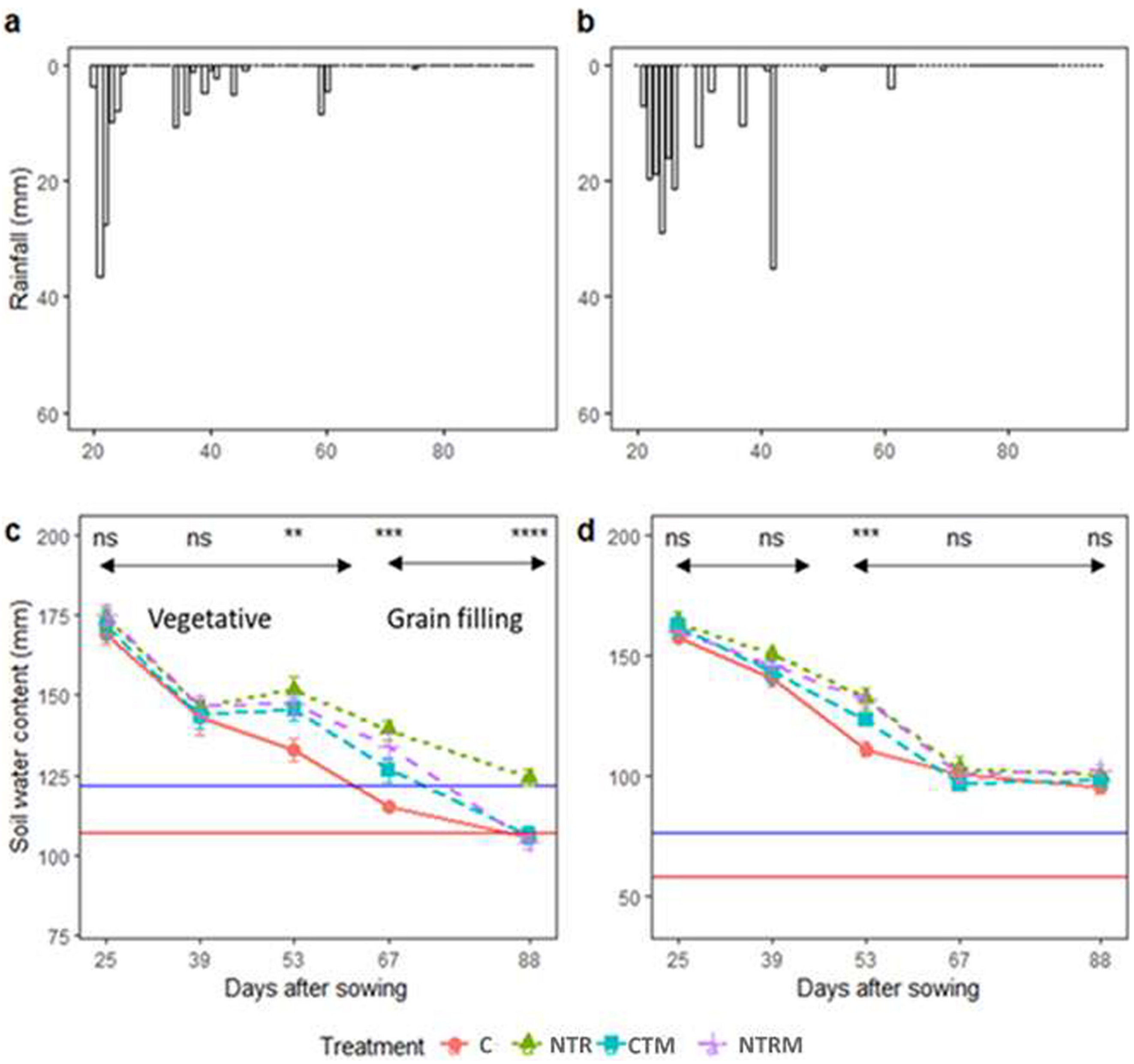

Fig. 6. Daily rainfall (a, b) and soil water content over 0-40 cm depth for different practices, control (C), no tillage with residue retention (NTR), conventional tillage with use of manure (CTM) and no tillage with residue retention and use of manure (NTRM) during the SR2017 season for sub-humid Kibugu (left panels) and semi-arid Machang'a (right panels). Blue and red horizontal lines indicate soil water content at which the maize crop becomes water-stressed, for vegetative and grain filling stages, respectively. Significance levels of diff ;erences in soil water content during the growing season are indicated; ****, $p < 0.0001$; ***, $p < 0.001$; **, $p < 0.01$;*, $p < 0.05$.

and CTM, showed a negative relationship in both locations. The negative trends occurred because NTRM showed lower grain response on fields where the response under the separate practices, NTR or CTM, was high.

In support of the negative yield response trends is NUE data which was lowest under NTRM. Generally, under this treatment, soil microbial N immobilization could have increased, aided by crop residues and the observed high water content. This increase coupled with the presence of low-quality cow manure could have resulted in higher fertilizer N immobilization. Addition of organic fertilizer has been reported to significantly enhance microbial immobilization of applied fertilizer N (Choi et al., 2001). Jensen et al. (1999) also indicated that the availability of inorganic fertilizer N is greatly influenced by the presence of organic fertilizer. In this case, the immobilized N is temporary locked up during the current season and becomes available to the plants in the subsequent seasons. In contrast, incubation experiments have shown that the use of mineral fertilizers in combination with cow manure reduces N fertilizer immobilization in SSA soils (Nyamangara et al., 2009). This could raise a need for further investigation into the combined practice, NTRM, in terms of N immobilization to unfold the overlying causes of the observed negative effects. Nevertheless, yield response under NTRM were higher in the sub-humid Kibugu compared to the semi-arid Machang'a. This could indicate that the combined practice, NTRM, could better perform in the sub-humid than in the semi-arid zone. In addition, NTRM showed the highest grain yield increase relative to the control in the high fertility fields of the sub-humid zone in three out of four seasons, confirming the observed better response.

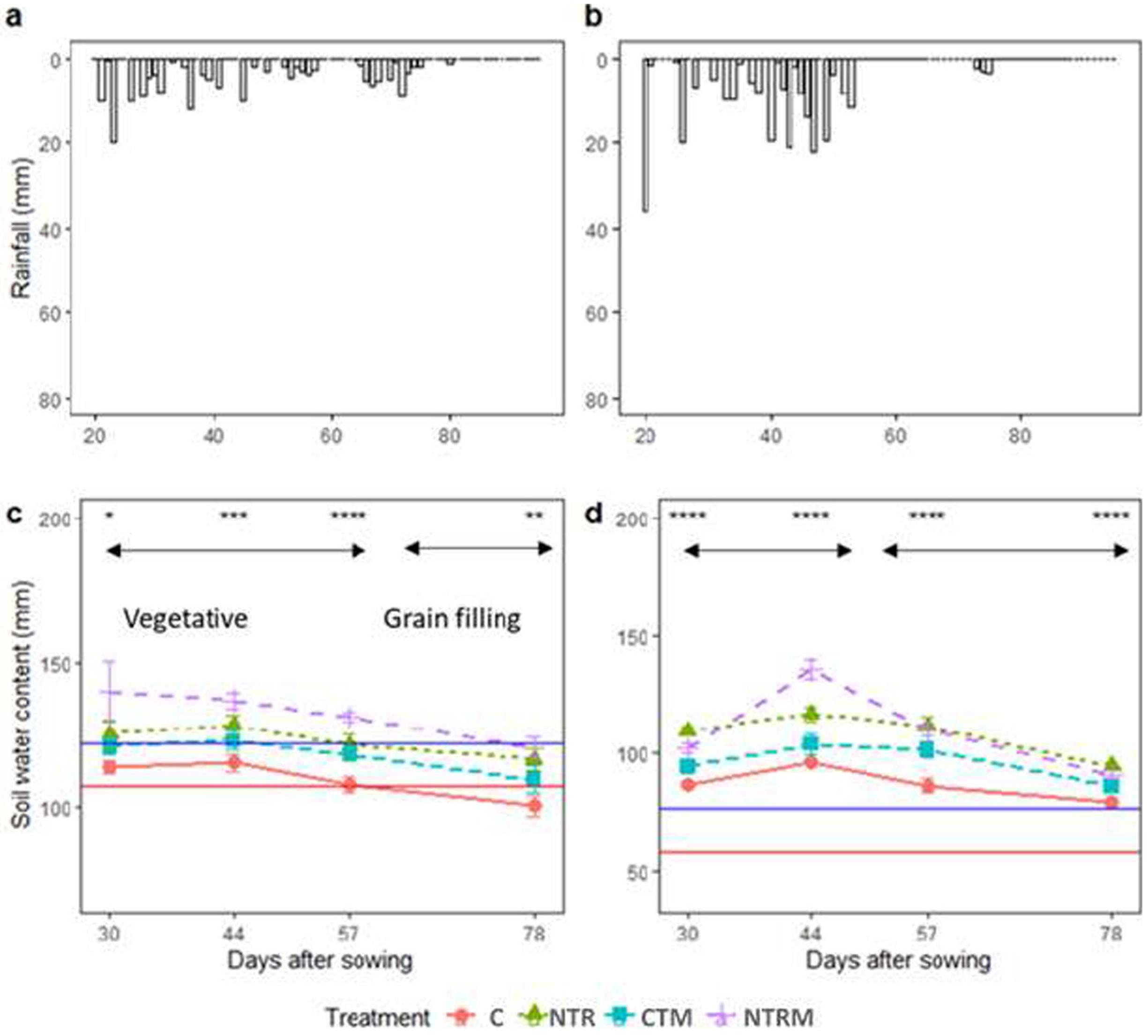

Fig. 7. Daily rainfall (a, b) and soil water content over 0-40 cm depth for different practices, control (C), no tillage with residue retention (NTR), conventional tillage with use of manure (CTM) and no tillage with residue retention and use of manure (NTRM) during the SR2018 season for sub-humid Kibugu (left panels) and semi-arid Machang'a (right panels). Blue and red horizontal lines indicate soil water content at which the maize crop becomes water-stressed, for vegetative and grain filling stages, respectively. Significance levels of diff ;erences in soil water content during the growing season are indicated; ****, $p < 0.0001$; ***, $p < 0.001$; **, $p < 0.01$;*, $p < 0.05$.

4.4. Soil water content and nitrogen use efficiency

The highest SWC and NUE were obtained under NTR, while it showed the lowest grain yield increase. The high SWC could be attributed to the effect of no tillage with the use of mulch. CA- based practices have been reported to improve soil water retention (Zhang et al., 2018; Thierfelder and Wall, 2009; Mupangwa et al., 2007). Other authors have also reported a high SWC under CA which does not necessarily translate in high yields. For example, in the sub-humid region of Zimbabwe, Mupangwa et al. (2017) reported a high soil water retention while using maize residue as mulch. Nevertheless, the increased SWC under CA did not result in an increased maize grain yield. Similar results were reported by Agbede (2010), who found significantly higher SWC under no tillage compared to conventional tillage. In their study, a higher sweet potato tuber yield was found under conventional tillage compared to no tillage. The application of fertilizer-N and residue under NTR could have increased microbial activity and in the absence of manure, mineralization could have increased leading to the observed higher NUE. In China, Liu et al. (2010) reported an increased microbial biomass under CA. In Malawi, a higher earthworm abundance was reported in continuous maize under no tillage compared to conventional tillage (TerAvest et al., 2015). Other studies have also reported an increased soil microbial community under no-tillage with residue application (Govaerts et al., 2007). A higher N derived from urea was reported under treatments receiving only mineral fertilizer as compared to treatments receiving combined organic and inorganic fertilizer (Choi et al., 2001).

Compared to the sub-humid Kibugu, maize was expected to be water-stressed in the semi-arid Machang'a. Surprisingly, we observed a higher tendency of maize to become water-stressed in sub-humid Kibugu (during wet SR2017 and normal SR2018) compared to the semi-arid Machang'a (for both normal SR2017 and SR2018). There have been indications that periods of water stress can occur even in regions characterized by high annual precipitation (Rimski-Korsakov et al., 2009) as we saw in the sub-humid Kibugu. Moreover, this tendency of water stress was more prominent during the normal SR2018 season, suggesting that even under normal rainfall conditions, maize in sub-humid regions can become water-stressed. This observation could also be attributed to texture differences between the two locations. Due to their high clay content, the forces retaining water by capillarity and adsorption are much higher (Jury and Horton, 2004) in the Nitisols of Kibugu as compared to sandy Cambisols soils of Machang'a. Besides, this water stress occurred mainly under the control treatment, which also had the lowest soil water content. Low water content could be linked to low SOC in the no input control.

In the semi-arid Machang'a, lack of water stress during the grain filling stage is in line with Mati (2000). Using crop growth models, he predicted no maize crop water stress at the grain filling stage during the short rains in the semi-arid regions of Kenya. We, however, cannot confidently conclude that maize was not water-stressed because we could not monitor soil water content for the entire growing season or evaluate crop properties indicating water stress. Nevertheless, the two locations had normal and wet seasons which could explain the lack of maize water stress during the monitored days.

5. Conclusions

Relative to the farmer practice, the control, NTR, CTM and NTRM substantially had higher maize crop yield in both sub-humid and semi-arid agro-ecological zones and in both the high and low soil fertility fields. Higher grain yields were observed under CTM in the low fertility fields. On the other hand, the combined practice, NTRM, mostly resulted in higher grains in the high fertility fields of the sub-humid. Yield response data under NTRM in relation to the separate practices, NTR or CTM showed a negative relationship. In the sub-humid, these responses were positive in the high fertility fields. These observations make it advisable for farmers from the semi-arid region to implement either NTR or CTM separately. For high fertility fields in the sub-humid zone, in addition to implementing the practices separately, it could be interesting to try the combined treatment, NTRM. In the low fertility fields of both regions, CTM could be a better option due to its ability to improve grain yields in such fields. In addition, these results are important to farmers who are interested in short-term yield returns from management practices. However, a cost-benefit study would be necessary to ascertain the profitability of these practices.

The discussion about the kick-starting of NTR is applicable only under maize mono-cropping because benefits of including legumes under CA were not included in our study. In addition, our study did not take into consideration all biomass uses. Nevertheless, from the perspective of using biomass for soil cover only and under maize mono-cropping, NTR might need such a kick-starting in the low fertility fields of the semi-arid region. Emerging from our study is also the potential of CA-based practices to enhance soil moisture content during short rains in both regions. It could be recommendable to study the effects of both management practices on soil moisture during the long rain periods in the two regions.

Declaration of interests

None.

CRediT authorship contribution statement

Eunice A. Mutuku: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Dries Roobroeck:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Bernard Vanlauwe:** Conceptualization, Methodology, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Pascal Boeckx:** Conceptualization, Methodology, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Wim M. Cornelis:** Conceptualization, Methodology, Writing - review & editing, Visualization, Supervision, Project administration, Funding acquisition.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fcr.2020.107833.

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