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Biochar addition persistently increased soil fertility and yields in maize-soybean rotations over 10 years in sub-humid regions of Kenya

Thomas Kätterer[a,*], Dries Roobroeck[b], Olof Andrén[c], Geoffrey Kimutai[b], Erik Karltun[d], Holger Kirchmann[d], Gert Nyberg[e], Bernard Vanlauwe[b], Kristina Röing de Nowina[f]

[a] Swedish University of Agricultural Sciences (SLU), Department of Ecology, P.O. Box 7044, 750 07 Uppsala, Sweden
[b] International Institute of Tropical Agriculture (IITA), Nairobi, Kenya
[c] Oandren, Björklundavägen 3, 756 46 Uppsala, Sweden
[d] Swedish University of Agricultural Sciences (SLU), Department of Soil and Environment, Uppsala, Sweden
[e] Swedish University of Agricultural Sciences (SLU), Department of Forest Ecology and Management, Umeå, Sweden
[f] Center for International Forestry Research (CIFOR), Nairobi, Kenya

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ABSTRACT

Application of biochar has been shown to increase soil fertility and enable soil carbon sequestration, indicating potential for agricultural and environmental benefits from using locally produced biochar on African smallholder farms. However, previous studies have been rather short-term and little is known about the longer-term effects of biochar application on crop yields. Biochar contains ash, but the potential liming effect and nutrient release from ash may be short-lasting. To investigate long-term effects, we set up a series of field trials replicated at three sites in Kenya in 2006. The trials are still on-going and are possibly the longest biochar trials in sub-Saharan Africa. Here, we report effects on crop yield and soil properties over 10 years after applying biochar, produced mainly from *Acacia* spp., at a rate of 50 + 50 Mg ha^{-1} during the first two seasons. Maize (*Zea mays*) and soybean (*Glycine max*) were grown in rotation, with or without inorganic fertiliser, and crop yield was monitored. For comparison of soil properties, additional plots were kept in bare fallow. Biochar addition slightly increased soil porosity, pH, plant-available phosphorus and soil water-holding capacity. Crop yield responded positively to biochar at all sites and yield responses were similar with and without mineral fertiliser, i.e., the effects of biochar and mineral fertiliser were additive. The seasonal yield increase due to biochar application was in average around 1.2 Mg ha^{-1} for maize and 0.4 Mg for soybean, independently of fertilisation, over seasons and sites. Application of mineral fertiliser to maize increased maize yield by 1.6 Mg ha^{-1} and the subsequent, unfertilized soybean yield by 0.6 Mg ha^{-1}, illustrating a carry-over effect. Most importantly, the effect on maize and soybean yield of adding biochar to soil persisted over the whole 10-year period. Analysis of the carbon (C) balance in topsoil indicated that about 40% of biochar C was apparently lost through mineralization, erosion or vertical translocation. Moreover, changes in soil carbon/nitrogen ratios indicated that biochar application increased nitrogen mineralization from native soil organic matter.

1. Introduction

Smallholder farming systems in sub-humid regions of Kenya are primarily based on cereal and legume production, and are of large importance for the food security in the region. However, yields of maize and soybean in these agro-ecosystems are far below potentially attainable levels, due to multiple interacting factors. These include nutrient limitations in the soil as a result of insufficient replenishment by inorganic and organic fertilisers and the highly weathered state of soils (Tittonell et al., 2008; Keino et al., 2015). In addition, yields of cereals and legumes on smallholder farms in Kenya are strongly dependent on the amount and pattern of rainfall (Fosu-Mensah et al., 2012; Adamgbe and Ujoh, 2013). Research on soil fertility, crop nutrition and socio-economics in African agro-ecosystems over the past 30 years has repeatedly shown that there is a need for concerted investments in organic inputs, inorganic fertilisers, improved germplasm and agronomic practices, in order to achieve sustainable increases in crop productivity (Vanlauwe et al., 2014). The rates of organic inputs such as manure or crop residues applied to croplands are typically insufficient, due to low crop productivity and livestock density, alternative use of biomass for

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[*] Corresponding author.
E-mail address: Thomas.Katterer@slu.se (T. Kätterer).

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energy and construction, and labour shortage (Berazneva et al., 2017). Besides being scarce, organic resources decompose rapidly in tropical climates, which make it difficult to build up soil fertility (Andrén et al., 2007).

Biochar is the carbonised end-product obtained following pyrolysis of biomass from wood, straw or other crop residues and waste. Compared to incineration the pyrolysis process is much more energy efficient and can substantially reduce total fuel consumption (Woolf et al., 2010; Njenga et al., 2016). At the same time, biochar can be a very useful organic amendment for cropland, as it can improve soil chemical, physical and/or biological properties. Previous studies on the effects of biochar inputs to soils have demonstrated increases in pH, nutrient availability, cation exchange capacity, water-holding capacity, soil structure and soil microbial diversity, combined with decreases in nutrient leaching, emissions of nitrous oxide and soil tensile strength (Scholz et al., 2014; Cernansky, 2015). Effects on crop yield have been reported to vary from mildly negative to highly positive, depending on climate, soil, crop and type of biochar (Jeffery et al., 2011; Liu et al., 2013). A recent meta-analysis by Jeffery et al. (2017) showed that biochar added to soils in tropical agro-ecosystems increased crop yield by on average 25%, whereas responses of crops in temperate regions were small or even negative. Biochar addition to soils also allows carbon from the atmosphere to be sequestered, because a large proportion of biochar decomposes very slowly and carbon remain in the soil for longer than carbon derived from manure, compost, sludge or raw residues (Kimetu and Lehmann, 2010). Biomass gasification combined with the use of biochar as a soil amendment could potentially contribute to improved productivity of smallholder farmers if the beneficial effects of biochar addition on crop productivity and soil carbon content are sufficiently large and long-lasting (Liu et al., 2013).

Only a few field experiments have addressed the effects of biochar addition on cereal and legume production in sub-humid agro-ecosystems of sub-Saharan Africa. A two-year study in western Kenya found that application of biochar to maize crops receiving inorganic fertiliser substantially increased grain yield in fields that had been cultivated for 40 years or more (Kimetu et al., 2008). Long-term experiments at the same sites showed that within three to four years, the yield of fertilised maize in biochar-amended plots declined to that of plots which received only fertiliser (Güereña et al., 2015). Biochar inputs to soils have been demonstrated to increase soybean growth, owing to effects on nutrient availability and shifts in growth-promoting bacterial communities (Egamberdieva et al., 2016). Responses in the productivity of maize-soybean rotations to biochar addition in smallholder farming and retention of carbon (C) and nitrogen (N) in soils have not been studied over the long term. Such information is of key importance for determining the effectiveness and viability of biochar addition for agricultural intensification, which remains unresolved (Ahmed et al., 2016; Baveye et al., 2018). In 2006 we established a series of field experiments replicated at three sites in Kenya with the objective to investigate the long-term effect of biochar application on crop productivity and soil properties. The experiments are carried out on small-holder farms but are managed by researchers. These experiments are still ongoing and, to our knowledge, are the longest-running biochar field trials in sub-Saharan Africa.

In this paper, we report findings from the first 10 years of these trials, which are assessing the effect of biochar addition on maize and soybean rotations in smallholder farmers' fields at three sites in two sub-humid regions of Kenya. Specific objectives were to analyse the effects of biochar input on: i) the yield of maize and soybean without and with inorganic fertiliser, ii) yield reliability, i.e. random variation among seasons, and iii) soil C and N stocks, extractable phosphorus (P) and potassium (K) content, acidity, water-holding capacity and bulk density. Plots without any plant cover (bare fallow) were also included in the experiment, to determine the effect of biochar addition on soil properties in the absence of other litter inputs.

Table 1

Location of the Kibugu, Nyabeda and Siaya experimental sites, soil pH and soil texture (mean ± stdev) measured at the start of the experiments in November 2006.

	Kibugu	Nyabeda	Siaya
County	Embu	Siaya	Siaya
Latitude	0° 30' S	0° 07' 51" N	0° 08' 01" N
Longitude	37° 30'E	34° 24' 11" E	34° 24' 18" E
Altitude (m)	1480	1333	1347
pH(H_2O)	5.01	5.96	5.25
SOC (%; n = 9)	2.01 ± 0.17	1.66 ± 0.12	1.56 ± 0.16
Sand (%; n = 3)	21.7 ± 2.3	23.0 ± 4.2	22.4 ± 2.0
Clay (%; n = 3)	43.5 ± 1.1	60.1 ± 5.3	60.1 ± 2.0

2. Material and methods

2.1. Field sites, trial design and treatments

In November 2006, trials were set up on four cropland fields in two sub-humid agro-ecosystems in Kenya. There were two sites (Siaya, Nyabeda) in Siaya County in the Lake Victoria basin and two (Kibugu, Embu) in Embu County, located on the foothills of Mount Kenya. However, one of the trials in Embu County (Embu) was terminated after a few years due to a land dispute and was therefore omitted from the present analysis. The geographical position and major soil characteristics (measured at the start of the experiment) of the remaining three field sites are listed in Table 1. All these sites have a bimodal annual precipitation pattern, with long rains (LR) and short rains (SR), during which maize and soybean, respectively, were grown (for full cropping sequence with dates of sowing and harvest, see Table A.1 in Supplementary material). Before the start of the experiment, the fields were cropped with rotations of maize or finger millet and common beans. According to the farmers, mineral fertiliser had never been applied, while farmyard manure had been applied frequently. All trials were located on fields with a flat or gently sloping topography.

At each field site, a complete randomized block experiment was established with three replications and three main treatments; bare fallow (Fal), unfertilised crop (UC) and fertilised crop (FC) and with the biochar (BC) addition as a split-plot treatment in all plots. Plots with main treatments measured 8 m by 12 m and were surrounded by a buffer strip of 0.75 m or 1.0 m. Surface runoff and erosion from the plots were observed during heavy rain events during the first seasons, Therefore, metal sheet frames (20 cm high) were inserted about 5 cm into the soil around the plots. The trials were managed by the research team, in collaboration with the land owners. The soil was prepared for planting by manual hoeing, in accordance with local practice. Management decisions related to general farming practices (e.g. weeding, bird-scaring) were taken by the farmers, but weeding was done at least two times per season. The bare fallow treatments were kept vegetation-free by cutting and pulling shoots at least two to three times per season. The crops were planted in late September or early October 2006 (Table A.1 in Supplementary material). The crop rotation thereafter consisted of maize (*Zea mays*) grown during the long rains, followed by soybeans (*Glycine max*) grown during the short rains.

Maize of a commonly used hybrid variety (H513, Kenya Seed Company) that is drought-tolerant was sown at an inter-row spacing of 0.75 m and an intra-row spacing of 0.25 m. Soybean seed of an early maturing variety (SB19), sourced from cooperative seed multipliers, was sown at an inter-row spacing of 0.50 m and an intra-row spacing of 0.05 m. Thinning and gap filling was carried out in the first two weeks after planting, bringing the density in maize stands to 5.7 plants m^{-2} and in soybean stands to 40 plants m^{-2}. Inorganic fertiliser was applied following common local practice in small-holder farms with an addition to maize corresponding to a rate of 50–60 kg N ha^{-1}, and with no fertilizer addition to the soybean. The fertiliser applied to maize was the commonly used ‘Mavuno’ with NPK 10:26:10 and enriched with boron (B), calcium (Ca), copper (Cu), magnesium (Mg), molybdenum (Mo), sulphur (S) and zinc (Zn) (MEA Ltd, Kenya). The fertiliser was applied manually along the planting lines, one half at planting and the second half six weeks later. The UC and FC plots were weeded two or three times per season, and insect and fungal pests were controlled by spraying all trials every season.

2.2. Biochar application and properties

The biochar used at the three sites was sourced from an artisanal charcoal maker and was produced mainly from *Acacia* spp. wood, through pyrolysis in brick kilns. Before being applied to soils in the trials, the biochar was crushed to pieces smaller than 1 cm. The application rate was 100 Mg dry weight ha^{-1}, which was divided between two equal doses applied at the start of growing seasons SR2006 and LR2007. The biochar was spread by hand and then incorporated to around 20 cm depth using hoes. A composite sample of four subsamples was taken from the batches of biochar applied in the first two seasons of the experiment. These samples were dissolved in lithium metaborate and sulphuric acid and analysed for total content of ash, oxides and metals using ICP-SFMS (ALS Scandinavia AB, Sweden) (Table A.2 in Supplementary material). In addition, a sample was taken from the biochar applied in each of the nine subplots that received biochar at every field site for detecting potential fractionation when splitting the biochar between sites and experimental plots. These individual samples were analysed for pH in distilled water (ratio 1:2.5 w/v) and total C,N and S content through dry combustion (LECO Corp., USA). Bicarbonate extractable P (Olsen) was determined calorimetrically. Total and/or exchangeable K, Ca, Mg and Na were determined by dissolution in sulphuric acid or extraction with ammonium acetate. Extractable Ca and Mg were analysed with atomic absorption spectrophotometry and Na and K were analysed with flame photometry (Table A3 in Supplementary material). Based on these chemical analyses (Tables A2, A3 in Supplementary material), application of 100 Mg biochar ha^{-1} supplied a total of 0.73 Mg N, 0.034 Mg P, 0.58 Mg K and 0.75 Mg S ha^{-1}. The amount of micronutrients supplied was 11.4 kg Zn, 1.3 kg Cu and 0.33 kg Mo ha^{-1}.

2.3. Yield measurements

When maize and soybean crops started senescing after reaching physiological maturity, 4.5 m^2 at the centre of each subplot was harvested. All maize cobs and soybean pods of these samples were separated from stover and haulms, and the total fresh weight of each fraction was determined in the field. Representative subsamples of five maize cobs and corresponding stover, or 30 soybean pods and 10 haulms, were taken, after which grains were separated from cores or shells and their fresh weight was measured. Yield of maize/soybean grain per hectare was calculated by multiplying the total fresh weight of cobs/pods by the proportion of dry kernels/ beans per unit fresh weight, based on analysis of subsamples. After harvest, all aboveground crop residues were removed from the field trials.

2.4. Soil sampling and analyses

Soil samples were taken to 20 cm depth in all 18 individual plots at each site at the start of growing seasons SR2006, LR2007, SR2007, LR2015 and SR2015. Composite samples for analysis consisted of 10 auger samples per subplot. All soil samples were air-dried for 14 days and passed through a 2 mm sieve. Samples collected before the start of the experiment in SR2006 were analysed for texture, pH and total C (Table 1). Soil pH was also measured in all samples taken at the start of the five growing seasons, after being archived as air-dried samples for 2–11 years. All samples from LR2007 were analysed for extractable P and K (Olsen method). During season LR2007, soil bulk density was determined for all individual plots. During season LR2011, bulk density and water-holding capacity were measured in bare fallow plots, without and with biochar amendment, at the three sites. All samples taken at start of season SR2015 were analysed for total C and N concentrations, after about two years of storage of air-dried samples.

Fractions of sand, silt and clay in soil were determined through sedimentation and pipetting (Gee and Bauder, 1986). The soil at all sites was clay, with a clay content of 44% at Kibugu and 60% at the two sites in Siaya County (Table 1). Soil carbon content was slightly higher in Kibugu (2.0%) than in Nyabeda (1.7%) and Siaya (1.6%). For pH analysis, soil samples were mixed with distilled water at a mass ratio of 1:2.5 and measured using a glass-membrane electrode; values ranged from 5.0 to 5.9. Total C and total N content in soil were measured through dry combustion, as described for the biochar samples. Extractable P and K were determined using 10 g of soil in 20 ml bicarbonate solution, and analysed with ICP-OES (Perkin Elmer, USA). For estimating dry soil bulk density, samples were taken at 7.5–12.5 cm depth at two locations within each plot at all sites, using standard steel cylinders with a volume of 95.4 cm^3. The samples were dried at 105 °C and the mass/volume ratio was calculated. Soil water-holding capacity was determined by applying excess water several times during one day to 0.8 kg of soil placed in a pot with free drainage and weighing the pots on the following day and after drying at 105 °C to constant weight.

2.5. Amount and distribution of rainfall

Daily rainfall data for each field site and growing season were retrieved from 0.05 × 0.05° rasters of the Climate Hazards Group Infrared Precipitation with Station data (Funk et al., 2014). Cumulative rainfall (Rfl) was computed starting from 14 days before planting up to crop harvest. The same rainfall data were used for Siaya and Nyabeda, because these sites are located only around 1 km from one another. Rainfall irregularity (Rir) was calculated for each growing season as the residual variation in cumulative daily precipitation from zero-intercept linear regressions representing a normal rainfall distribution (Table A4 in Supplementary material).

2.6. Soil carbon and nitrogen stocks and balances

Soil C and N stocks were calculated using bulk density values and C and N concentrations measured in samples taken at the beginning of SR2015. Soil bulk density in all individual plots was only determined in SR2007, but was assumed to be the same in SR2015.

The bulk density of soils was considerably altered by biochar addition and therefore the depth to which a certain mass of soil was distributed was calculated to enable meaningful comparisons between treatments (Ellert and Bettany, 1995). Equivalent soil depth was calculated considering both the non-organic mass added with biochar and the equivalent soil mass in each treatment pair without and with biochar (Kätterer et al., 2011). Thus, the mineral soil mass to 0.2 m depth was calculated for each site and treatment as:

$$M_{sm} = depth \bullet BD \bullet (1 - SOM) \tag{1}$$

where M_{sm} = soil mineral mass [Mg m^{-2}], BD = soil bulk density [Mg m^{-3}] and SOM = soil organic matter mass fraction [-], which was calculated from the SOC analysis with the assumption that it contained 58% carbon. This mineral soil mass was further reduced by the mass of oxides added in biochar (0.0045 Mg m^{-2}) according to analyses presented in Table A2 in Supplementary material. The treatment with the lowest soil mineral mass in each treatment pair, which was always was the treatment with biochar, was taken as reference mass (M_{sm_ref}) in order to calculate the equivalent depth ($depth_{equ}$) to which M_{sm_ref} was distributed in the heavier pair receiving no biochar:

$$depth_{equ} = \frac{M_{sm\_ref}}{M_{sm}} \bullet depth \tag{2}$$

Carbon stocks to equivalent depth were then calculated for each treatment and site. The same approach was used for calculating N stocks. Differences in C and N stocks between subplots without and with biochar for each main treatment were used to estimate the apparent C and N recovery from the applied biochar.

2.7. Data analysis

Statistical analyses and graphical design were carried out using R software (version 3.3.2), and SAS software (version 9.4; SAS Institute, USA). Differences in mean grain yield of the two crops were tested for the main effects of study site, fertilizer input and biochar amendment and their interactions by linear mixed-effect modelling in the 'lme4' package of R. One random effect term had intercepts for split-plot biochar addition in each block replication, and a second term had random intercepts for growing seasons that were separately estimated for all input treatments. The residual normal distribution and homoscedasticity were ascertained by plotting residuals of the model against theoretical quantiles and fitted values. Pairwise comparisons between all levels of main effects were made on the basis of least-squares with confidence intervals and standard errors of difference. Mean responses of measured maize and soybean grain yields to biochar input for UC and FC treatments were calculated for all growing seasons at each study site, and ordinary linear regression lines were fitted to test changes of effects during the long-term experiment. The temporal variation in grain yield for each input treatment, an indicator for the influence of weather conditions and agricultural management on crop production, was derived from the standard deviation of random intercepts for growing seasons. Coefficients for temporal variation for each treatment were further calculated as the proportion of the mean yield estimated from the model. Treatment effects on grain yield and soil properties in the study sites were also tested for specific growing season, using an ordinary linear model with fertilizer as main effect, biochar addition as split-plot factor and block as random variable.

3. Results

3.1. Crop productivity under different input practices

The mean and distribution of measured grain yields of maize and soybean over all growing seasons are shown for each study site in Fig. 1. Overall average increases in crop productivity were only significant between the UC and FC + BC treatments, owing to high variation between growing seasons (Fig. 2). Individual main effects of site, biochar and fertilization on grain yields were however found to be significant for grain yields of both crops (Table A.5 in Supplementary material). Interactions between the effects of fertilizer and biochar addition on the productivity of both crops were highly insignificant (Table A.5 in Supplementary material), which indicates that responses of crops to addition of biochar and fertilizer were additive. Thus yield increases in FC + BC over UC were similar to the sum of responses for UC + FC and UC + BC over UC. Yield responses to biochar addition across sites and fertilizer treatments were 1.17 and 0.43 Mg ha^{-1} for maize and soybean, respectively, in average over growing seasons (Table 2). These yield increases were significant in 8 out of 10 growing seasons for maize and 5 out of 8 seasons for soybean. The significant interaction between site and fertilization was due to significant lower yield increases caused by fertilization in Kibugu (0.92 Mg ha^{-1} for maize and 0.26 Mg ha^{-1} for soybean) compared with those at the other two sites, in average 1.95 and 0.78 Mg ha^{-1}, respectively (Table A6 in Supplementary material). Yield levels were also generally lower at Kibugu compared with the other two sites (Fig. 1).

Mean responses of maize and soybean grain yield to biochar input for UC and FC treatments did not show significant linear trends over time in none the study sites (Fig. 3). This suggests that the effect of biochar on crop production, without and with co-application of fertilizers to maize phases, largely remained constant of the 10-year study period.

3.2. Yield reliability under different treatments

The variation in yields of maize and soybean crops, grown with or without fertiliser and/or biochar inputs, among growing seasons in Fig. 2 is illustrating the effects of weather conditions on attainable yields at each study site. Although variation in local weather conditions would be an obvious driver for yield variation between seasons, we found no straightforward relationship between yields and precipitation among seasons. Accumulated precipitation during the growing seasons explained between 2 and 37% of the variation in maize and soybean yields among seasons according to linear regression analysis, but the slopes of regression lines were not significant.

Standard deviations of random effects in maize grain productivity between growing seasons, derived from mixed modelling, were smaller for UC + BC than UC but larger for FC and FC + BC than UC (Table 3). The proportions of temporal variation in maize yields as compared to the mean, on the other hand, indicated to be reduced when biochar was applied, without and with input of fertilizer, and thus crop productivity was more reliable under fluctuating weather conditions. The standard deviation of random effects in soybean grain yields between growing seasons, in turn, was smaller for UC than UC + BC, UC + FC and FC + BC than UC. Proportions of temporal variation in soybean yields also indicated to be decreased when biochar was applied, without and with input of fertilizer to maize phases, and thus productivity of the legume was more reliable under fluctuating weather conditions. Effects of biochar amendment on yield reliability were greater for soybean than for maize, whilst relative increases in mean grain productivity were similar or larger for soybean than for maize.

3.3. Effects of biochar and/or fertiliser inputs on soil properties

The addition of biochar lead to pronounced increases of the soil pH at the Kibugu and Siaya sites characterized by more acidic soil conditions (Table A.7 in Supplementary material). The effect of biochar on pH was significant in Kibugu at three out of the five sampled growing seasons and in one season in Siaya. On average over the five seasons, the pH increased by 0.3 and 0.1 units in Kibugu ($p < 0.0001$) and Siaya ($p = 0.051$), respectively, in the three treatment pairs receiving biochar compared with those without biochar. This indicates that the effect tended to persistent over time at these two study sites. In the Nyabeda site, characterized by less acidic soil conditions, the application of BC lead to minor and insignificant changes in soil pH over the sampled growing seasons.

Addition of biochar significantly increased extractable P levels in soils at all study sites, as measured during the second growing season (Table 4). Fertiliser application significantly increased P availability at the Siaya and Nyabeda sites, where P levels were originally lowest, but not at the Kibugu site, where extractable P levels in the soil are inherently higher. The increase in available P was not long-term, as the P analysis in 2015 revealed no differences between treatments (Table A.8 in Supplementary material). Surprisingly, available K decreased significantly after biochar addition at one site (Siaya), but was not significantly affected by biochar at the other two sites.

For individual sites, biochar addition significantly decreased soil bulk density, measured in 2007 at all sites, by 8% in Kibugu, 10% in Siaya and 13% in Nyabeda (Table 4). Bulk density remained significantly lower ($p = 0.0041$) in treatment Fal + BC compared with bare fallow (Fal) even after around five years after biochar application when it was measured again in 2011 (Table 5), which shows that this effect persisted at least during five years after biochar application. Water-holding capacity, determined in 2011, was also significantly higher ($p = 0.029$) in Fal + BC than in bare fallow (Table 5). Although WHC was only measured in the fallow treatments, it is reasonable to

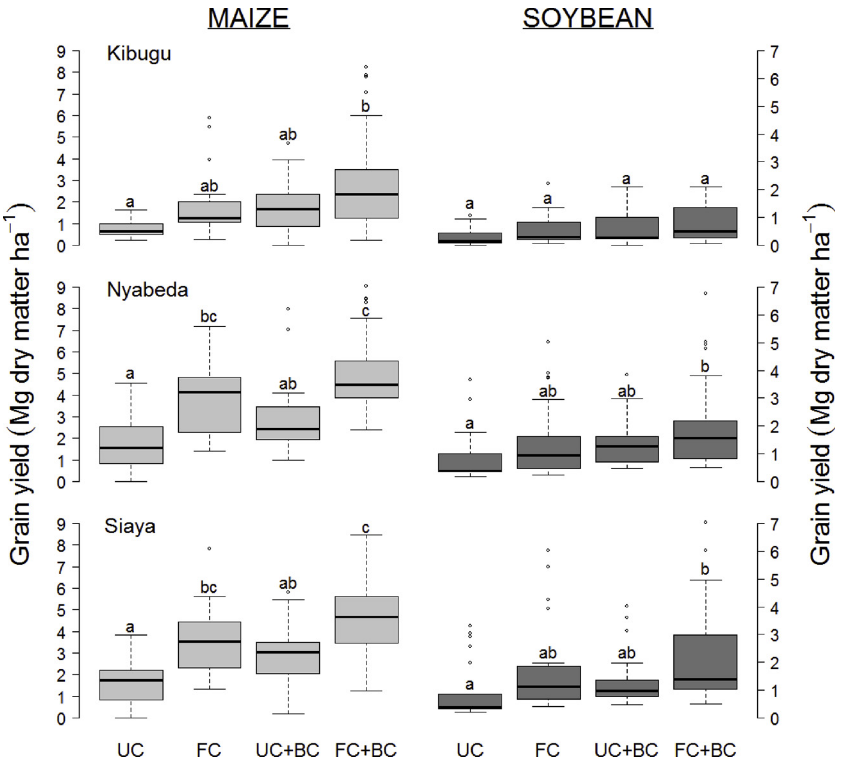

Fig. 1. Dry matter grain yield of (left) maize and (right) soybean, averaged over all seasons from 2006 to 2016, in the four cropped treatments at the Kibugu, Nyabeda and Siaya sites. The line in the middle are the medians, boxes are interquartile ranges, whiskers are 95% confidence intervals and bullets are outliers, n = 8 in Kibugu; n = 10 at the other sites for maize, n = 8 for soybean. UC = unamended control, FC = fertilised control, BC = biochar addition. Different lower case characters indicate significant difference between treatments per crop and site.

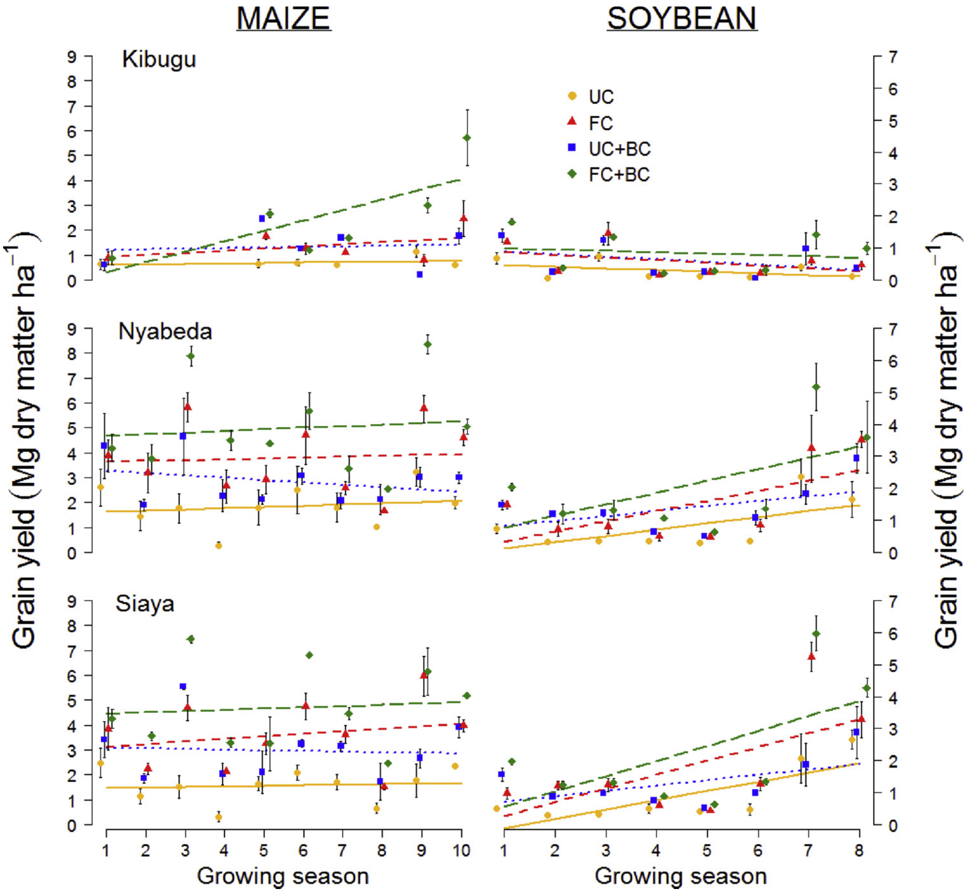

Fig. 2. Grain yield of (left) maize and (right) soybean in the four treatments across growing seasons at the Kibugu, Nyabeda and Siaya sites. UC = unamended control, FC = fertilised control, BC = biochar addition.

Table 2
Maize and soybean grain yield increases due to biochar addition (means and standard error per season and overall average values across seasons; Mg ha^{-1}) across sites and fertilizer treatments per growing season. Increases were significant ($p < 0,05$; Tukey-Kramer test) in 8 out of 10 seasons for maize and 5 out of 8 seasons for soybean.

Season	Yield increase	SE	p-value
Maize			
SR2006	0.55	0.29	0.074
LR2007	0.77	0.30	0.12
LR2008	2.93	0.54	< 0.0001
LR2009	1.68	0.32	< 0.0001
LR2010	0.82	0.31	0.015
LR2011	0.89	0.30	0.0068
LR2012	0.83	0.20	0.0003
LR2014	1.00	0.30	0.032
LR2015	0.79	0.35	0.038
LR2016	1.44	0.28	< 0.0001
Average	1.17		
Soybean			
SR2007	0.78	0.09	< 0.0001
SR2008	0.37	0.056	< 0.0001
SR2009	0.42	0.13	0.061
SR2010	0.26	0.046	< 0.0001
SR2011	0.14	0.027	0.0064
SR2013	0.32	0.077	0.0006
SR2014	0.56	0.31	0.092
SR2015	0.56	0.28	0.14
Average	0.43		

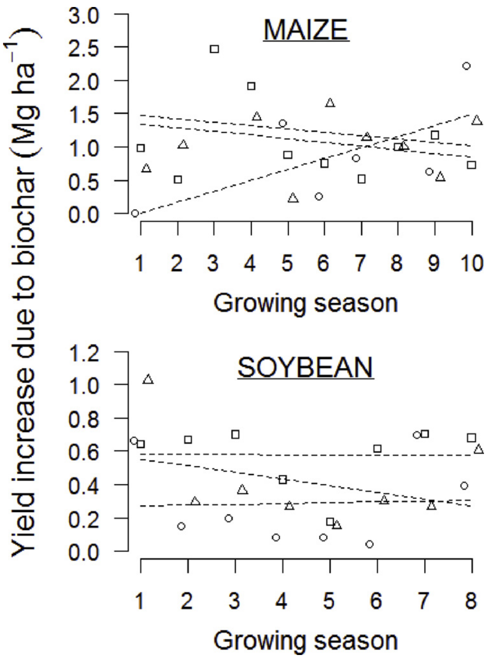

Fig. 3. Mean responses of maize and soybean grain yield to biochar input for UC and FC treatments for all growing seasons at each study site. Circles represent the Kibugu study site, squares the Nyabeda site and triangles the Siaya site. None of the slopes of the regression lines were significant indicating that the effect of biochar persisted over time.

assume that the significant effect of biochar on WHC was also present in the other treatments due to high correlation between WHC and bulk density values which responded in a similar way to biochar application in all treatments in 2007. In absolute terms, the mean difference in water-holding capacity between biochar-treated and non-treated soil was 0.025 g water g^{-1} soil. This is equivalent to a difference in water storage of 4.5–5.2 mm in the topsoil to 20 cm depth when also considering the expansion of the soil volume due to changes in bulk density.

Application of 100 Mg biochar led to effective addition of 28.1 Mg C ha^{-1} and 0.73 Mg N ha^{-1} (Table A.3 in Supplementary material). Organic soil C and N concentrations and stocks generally increased in the order Bare fallow < Control < Fertilization, but differences between these treatments were not significant. Nevertheless, biochar addition significantly increased both soil C and N concentrations (Table 6). Mass balance calculations based on comparison of the treatment pairs with or without biochar revealed that, on average over treatments and sites, 60% of the C and 44% of the N added with biochar was still present in the upper 20 cm of the soil after around nine years (Table 6). Recovery rates varied greatly between treatments (32–96% for C, 27–61% for N) and were generally higher at Kibugu than at the other sites.

4. Discussion

4.1. Sustainable intensification of crop productivity

The application of *Acacia* biochar at the beginning of the 10-year experiment had significant positive effects on mean crop yield at all sites for treatments with and without fertiliser input. There are many examples of biochar-amended soils showing improved fertility over hundreds of years (Lehmann et al., 2006). Our multi-site trial, which is probably the longest-running controlled biochar field study in sub-Saharan Africa, clearly showed that biochar consistently enhanced crop yield at least for one decade. The persistent increases in maize and soybean yield following input of biochar at the different sites are a very important indicator of the economic viability of scaling up the method (Liu et al., 2013).

Several reasons for increases in crop yield following biochar addition have been reported in the literature. These include liming effects, increased water-holding capacity, structural soil improvement, increased surface area for nutrient adsorption and others (Partey et al., 2014; Scholz et al., 2014; Blanco-Canqui, 2017). The prolonged increase in soil pH and high ash content of the biochar added to soils in our trial suggest that a liming effect is one possible factor for the positive yield responses observed here. The increased water-holding capacity and decreased bulk density of soils amended with biochar are likely to have affected root architecture and improved water supply during droughts. We found that the mean water storage in the top 20 cm of soil was increased by about 5 mm after biochar application, which may have contributed to the higher yield. Other field studies have shown that the effect of biochar on water supply may become more pronounced over time with ageing of the biochar (Paetsch et al., 2018). Crops in biochar treatments in our trial were visibly less affected by dry periods, i.e. less curling and senescence of leaves, but no actual measurements were made.

The delivery of nutrients from biochar and ash may have also been a

Table 3
Random variation of maize and soybean yield between growing seasons for each treatment across the study sites estimated from mixed effect model.

Crop	Maize				Soybean			
Treatment	UC	UC + BC	FC	FC + BC	UC	UC + BC	FC	FC + BC
Standard deviation (Mg ha^{-1})	0.75	0.63	0.89	1.05	0.14	0.47	0.52	0.78
Coefficient of variation (%)	57.3	21.5	37.2	25.5	46.0	34.5	47.3	32.5

Table 4
Soil properties for all treatments (Fal = bare fallow, UC = unamended control, FC = fertilised control, BC = biochar addition) and sites (Kibugu, Nyabeda, Siaya) measured in July 2007 (during short-rain growing season, LR2007). Values are mean with standard deviation (Stdev). The overall effect of biochar application across treatments and sites (least squares means and p-values) is also presented.

Site	Treatment	Bulk density [g cm^{-3}]		P (Olsen) [μg g^{-1}]		K (Olsen) [mg g^{-1}]	
		Mean	Stdev	Mean	Stdev	Mean	Stdev
Kibugu	Fal	0.79	0.07	19.69	2.79	0.85	0.30
	Fal + BC	0.73	0.01	28.18	9.15	1.17	0.41
	UC	0.77	0.03	16.99	1.56	0.59	0.54
	UC + BC	0.73	0.06	20.33	6.17	1.06	0.27
	FC	0.80	0.02	28.13	6.38	0.85	0.37
	FC + BC	0.72	0.08	33.40	8.82	1.03	0.81
Nyabeda	Fal	0.98	0.05	2.44	1.10	0.60	0.22
	Fal + BC	1.00	0.17	2.55	0.80	0.31	0.20
	UC	1.11	0.08	1.60	0.50	0.41	0.20
	UC + BC	0.95	0.20	2.93	0.54	0.22	0.09
	FC	1.11	0.08	2.66	0.60	0.56	0.26
	FC + BC	0.92	0.10	5.71	1.32	0.43	0.15
Siaya	Fal	1.06	0.03	2.23	0.81	0.28	0.23
	Fal + BC	0.94	0.04	3.60	0.50	0.24	0.09
	UC	1.13	0.05	2.41	0.90	0.43	0.28
	UC + BC	0.98	0.10	3.87	0.20	0.38	0.24
	FC	1.08	0.04	7.07	0.97	0.52	0.05
	FC + BC	0.93	0.16	9.68	2.18	0.51	0.14
Across sites and treatments							
	Without BC	0.98		9.25		0.57	
	With BC	0.88		12.2		0.59	
	p-value	0.0081		< 0.0001		0.75	

Table 5
Soil bulk density and water-holding capacity measured in bare fallow (Fal) and bare fallow + biochar (Fal + BC) treatments at the Kibugu, Nyabeda and Siaya sites in 2011. The effect of biochar addition on bulk density (p = 0.0041) and water-holding capacity (p = 0.029) was according to a Tukey-test across sites.

Site	Fal		Fal + BC	
	Mean	Stdev.	Mean	Stdev.
	Bulk density [g cm-3]			
Kibugu	0.89	0.05	0.82	0.01
Nyabeda	1.07	0.04	1.02	0.03
Siaya	1.01	0.01	0.96	0.04
Across sites	0.99		0.93	
	Water-holding capacity [g g-1]			
Kibugu	0.424	0.020	0.453	0.020
Nyabeda	0.319	0.018	0.340	0.018
Siaya	0.330	0.008	0.354	0.008
Across sites	0.358		0.382	

driver for crop yields. Assuming that the 56% of biochar N (0.4 Mg N ha^{-1}) which was not recovered at the end of the experiment had been available to plants, this would have corresponded to fertilisation with around 45 kg N ha^{-1} year^{-1}. However, the equivalent amount of fertiliser needed to obtain observed yield increases of maize and soybean was on average 72 kg N ha^{-1} year^{-1}. This indicates that the N released from biochar could only explain a portion of the N recovered in crop yields, and the majority of the additional N taken up in BC treatments must have come from other sources. One possible explanation is increased biological N fixation by soybean, which may also have affected yields of maize due to more residual root N. In fact, biochar application greatly increased soil concentrations of Mo, an essential element for N fixation. Typically, Mo concentrations are below 1 kg ha^{-1} in acid soils (Kabata-Pendias, 2000), and through biochar around 0.3 kg Mo was added in our trial. An alternative explanation could be increased mineralisation of soil organic matter, as discussed further below. Further studies are needed to evaluate the mechanisms that govern the availability of nutrients from biochar other than N, as they may become a yield-limiting factor over time.

4.2. Contributions to strengthening yield reliability

The findings to date from this long-term trial demonstrate that amendment of soils with biochar increases the yield reliability of maize and soybean across the study sites, in both treatments with and without fertilisation. The lower coefficient of variation in crop yield between seasons in treatments receiving biochar can be attributed to the significant positive effect on the water-holding capacity of soils (Table 5) which provided about 5 mm more water to the crop during every major wetting/drying cycle. Positive effects of biochar on water supply to crops are also supported by the lower bulk density in those treatments, which may have been caused by the formation of microaggregates resulting from organo-mineral interactions (Weng et al., 2017). The high porosity of biochar added to soils in this trial may also have improved soil aggregation (Liu et al., 2017). The results also show that the application of biochar during the first year and repeated fertiliser addition to maize led to substantially greater yields even under adverse rainfall conditions. This indicates that smallholder farming systems may become more resilient to climate change when adding biochar.

4.3. Sequestration of carbon and nitrogen in soils

The plots with biochar were easily recognisable from a distance due to a shift in soil colour towards a greyish hue compared with control plots. This was true for the whole soil matrix in the upper soil layer. The change in soil colour after biochar addition will be the subject of forthcoming studies.

The apparent loss of C from biochar estimated from C balances in this study (about 40% averaged of sites and treatments) is similar to that found in some other studies, i.e., 40% loss after 5 years in a Chinese study (Dong et al., 2017) or about 35% loss after 2 years in field studies in Western Africa (Häring et al., 2017), but higher than in a range of Spanish biochar experiments (11–27% loss; de la Rosa et al., 2018). Inputs of C by crops can be expected to have increased when biochar was applied, due to higher biomass production (Bolinder et al., 2007).

Table 6

Total soil organic carbon (SOC) and nitrogen (SON) concentrations measured in soil samples taken at the beginning of the short-rain growing season SR2015 in the six treatments (Fal = bare fallow, UC = unamended control, FC = fertilised control, BC = biochar addition) at the Kibugu, Nyabeda and Siaya sites, corresponding carbon (C) and nitrogen (N) stocks to equivalent soil depth ($\mathrm{Depth_{eq}}$) and apparent C and N recovery (rec.) from biochar (BC) calculated for treatment pairs with or without biochar addition. SOC concentrations across treatments with biochar were significantly higher (Tukey-Kramer test) compared with treatments receiving no biochar at all sites.

Site	Treatment	C [%]	Stdev.	N [%]	Stdev.	$\mathrm{Depth_{eq}}$ [cm]	SOC [Mg $\mathrm{ha^{-1}}$]	SON [Mg $\mathrm{ha^{-1}}$]	C rec. [%]	N rec. [%]
Kibugu	Fal	2.32	0.07	0.24	0.006	17.3	31.7	3.33		
	Fal + BC	4.03	0.87	0.26	0.017	20.0	58.8	3.78	96	61
	UC	2.39	0.17	0.25	0.015	17.9	33.0	3.44		
	UC + BC	3.60	0.58	0.26	0.021	20.0	52.5	3.80	70	49
	FC	2.37	0.04	0.25	0.007	16.9	32.1	3.42		
	FC + BC	3.88	0.22	0.27	0.009	20.0	55.9	3.91	85	66
Nyabeda	Fal	1.76	0.12	0.13	0.004	19.7	34.0	2.46		
	Fal + BC	2.50	0.33	0.14	0.004	20.0	50.1	2.76	57	41
	UC	1.86	0.30	0.13	0.006	16.5	34.0	2.41		
	UC + BC	2.66	0.56	0.14	0.013	20.0	50.5	2.74	59	45
	FC	2.02	0.26	0.14	0.009	16.0	36.0	2.56		
	FC + BC	2.45	0.13	0.15	0.003	20.0	45.1	2.76	32	28
Siaya	Fal	1.56	0.16	0.13	0.009	17.1	28.4	2.35		
	Fal + BC	2.10	0.16	0.14	0.005	20.0	39.5	2.56	40	28
	UC	1.65	0.40	0.13	0.009	16.7	31.1	2.39		
	UC + BC	2.39	0.63	0.14	0.004	20.0	46.8	2.69	56	41
	FC	2.02	0.12	0.14	0.005	16.6	36.2	2.47		
	FC + BC	2.57	0.36	0.15	0.004	20.0	47.8	2.73	41	36

Although crop residues were removed at harvest in our trial, the input of C from roots and rhizodeposits, which have been shown to be retained longer in soil than above-ground plant tissues (Kätterer et al., 2011), were likely higher in the biochar treatments. Part of the soil organic C stock increase in the biochar treatments probably originated from root-derived inputs, as supported by the stepwise increase in soil organic C along with crop yields from the fallow (Fal), unamended control (UC) to fertilised control (FC) treatments at the two sites in western Kenya (Table 6). This implies that using the mass balance approach leads to overestimation of soil retention of C and N from biochar. Thus, biochar may have decomposed to a larger extent when considering crop residue turnover.

Several processes may have contributed to the relatively high loss of C and N following biochar addition to soil. It was evident to the eye judgement that erosion, and preferential lateral movement of biochar due to low mass per volume, played an important role, particularly in the first year of the experiment before barriers were put up around plots. Vertical migration of biochar due to solute transport and bioturbation along the soil profile may also have contributed to the losses, but is unlikely to explain the large decline in soil C and N stocks within 10 years. Decomposition of charred biomass in soils and/or increased mineralisation of soil organic matter due to biochar addition (i.e. the priming effect) may have also contributed to the apparent loss of biochar from the topsoil. Incubation studies have shown that biochar is not totally inert (e.g. Carlsson et al., 2012). A recent meta-analysis of short-term stable isotope incubation and field studies indicated that about 3% of the C in biochar becomes bioavailable on a decennial time scale (Wang et al., 2016), suggesting very low decomposition rates of biochar. However, long-term studies on the residence time of pyrogenic organic C in a range of soils have found that loss rates are greater than estimated in short-term studies (Lutfalla et al., 2017). On the other hand, addition of biochar has been reported to lead to positive or negative priming effects on decomposition of soil organic matter, with degraded and low fertility soils tending to predominantly exhibit increased rates of decay (Wang et al., 2016). The low apparent recovery of N from biochar according to the mass balance analysis may imply substitution of N-rich soil organic matter with N-poor biochar. Such a mechanism would support the hypothesis that biochar addition leads to priming and N-mining of soil organic matter. This statement remains speculative, but will be followed up with natural isotope abundance tracing in our trial in Kenya.

5. Conclusions and outlook

The longevity of the increases in crop yield and soil C after one-time application of biochar observed in this experiment indicates that this practice provides great opportunities for intensifying agricultural production and mitigating greenhouse gas emissions in the farming systems studied. Significant positive responses to biochar addition in terms of maize and soybean yield were obtained under both fertilised and unfertilised conditions at all three sites studied, confirming the applicability of biochar treatment under varying conditions. The results obtained to date from our trial suggest that biochar can make valuable contributions to integrated soil fertility management and climate-smart agriculture.

Although many factors like pests, weeds and timing of field operations may have had an influence on yield, the trial allowed us to identify various ways in which biochar could have affected yields. First, supply of N to crops increased by around 45 kg N $\mathrm{ha^{-1}\ yr^{-1}}$ following biochar addition. Second, analysis of soil physical properties revealed higher water-holding capacity, by 0.025 g water $\mathrm{g^{-1}}$ soil equivalent to around 5 mm additional water storage, through biochar addition. Third, the large amount of Mo added with biochar could have improved N fixation by soybean, resulting in a greater N supply to maize through nitrogen-rich soybean residues.

Analysis of the C balance in topsoil indicated that about 40% of biochar C was apparently lost through mineralization, erosion or vertical translocation and changes in C/N ratios indicated that biochar application may have increased nitrogen mineralization from native soil organic matter. More comprehensive investigations are needed to identify the mechanisms behind the observed increases in crop productivity after biochar application. Forthcoming studies will include detailed analyses of how physical, chemical and biological processes are affected by biochar and we hope that it will be possible to maintain our unique set of trials for longer-term in-depth analyses.

The question arises as to whether the cost of applying biochar can be recovered by the yield increases. This obviously depends on access to market, grain prices, availability of feedstock (here acacia wood) for producing biochar, the magnitude of yield increases and, particularly, the longevity of yield increases. Sustainability of feedstock and biochar production is also a critical issue that must be considered before scaling up this technology. The sustained increases in yield seen in this study indicate that biochar application to cropland becomes increasingly beneficial with time. While the amount of biochar used in our trials was high (100 Mg dry weight ha^{-1}), preliminary results from other ongoing trials in Kenya show that even 1 Mg biochar ha^{-1} has significant effects on grain yield of maize.

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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.2019.02.015.

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