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Conservation tillage and biochar improve soil water content and moderate soil temperature in a tropical Acrisol

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ABSTRACT

Projected climate change in Sub-Saharan Africa involves increased drought and elevated soil temperature. Conservation farming (CF), including minimum tillage, crop rotation and crop residue retention, is proposed as a climate smart soil management option to adapt to climate change through enhanced climate resilience. Here, we determine the effect on soil moisture and temperature of CF planting basins in a Zambian Acrisol. Construction of CF planting basins (40 cm x 15 cm, while 20 cm deep), using hand-hoes, is a commonly used minimum tillage practice among small holders in southern Africa, effectively requiring tillage of only 10 % of a field. The study included basins under regular CF and under CF with 4 t ha^{-1} pigeon pea biochar (CF + BC). Effects are compared with those in an adjacent soil under conventional tillage, where the entire land surface is ploughed. Soil moisture and temperature sensors were installed in the root zone, 10–12 cm deep, for continuous monitoring during two growing seasons. Soil moisture decreased in the order CF + BC > CF > conventional farming. Due to rainwater harvesting in the basins, maximum soil water retention under CF + BC and CF was greater than under conventional farming (+59 % to +107 % and +15 % to +65 %, respectively). Soil drying after free drainage until permanent wilting point lasted longer under CF + BC (18.4–22.3 days) than under both CF and conventional farming (13.3–18.4 days and 14.9–17.8 days, respectively). *In situ* soil maximum temperature and diurnal temperature range in the growing season increased in the order CF + BC < CF < conventional farming due to decreases in soil moisture. However, additional laboratory tests, with soil-BC mixtures at field capacity, revealed that BC addition to soil, which caused a decrease in bulk density, also resulted in a significant decline in soil thermal conductivity ($p < 0.001$). Thus, we hypothesize that BC-enhanced soil moisture in basins helped to reduce soil temperature and its fluctuations, due to both increased heat capacity and decreased thermal conductivity. This study shows that CF in combination with BC in an Acrisol, through enhancing plant-available water and moderating soil temperature, is important for crop productivity and has potential as an element of climate smart agriculture.

1. Introduction

In recent years, water availability in rain-fed tropical agriculture systems has become more problematic largely due to increasingly erratic rainfall (Feng et al., 2013; Thornton et al., 2014). The unreliable rainfall patterns and associated drought episodes will be ever more challenging in the future due to climate change (Thornton et al., 2014). This calls for climate-smart solutions that can increase resilience, contribute to mitigation and adaptation to climate change, while increasing productivity and income (Thierfelder et al., 2017). Combining conservation farming (CF) and biochar (BC) application to soil is an approach that may offer a climate-smart solution including a reduction of the effect of drought on agricultural production (Cornelissen et al., 2013; Martinsen et al., 2014).

Conservation farming involves zero or reduced tillage, residue retention on the soil surface and crop rotation, which in combination are meant to maintain or improve soil quality with the ultimate aim of increasing crop productivity (Farooq and Siddique, 2015). With this, CF is expected to alleviate negative impacts of ploughing the entire land surface in conventional farming, which causes e.g. reduced organic

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carbon content, elevated soil erosion and physical degradation of soil. In Zambia where this study was conducted, CF practices among smallholder farmers mainly consist of minimum tillage where only planting basins (~40 cm length * 15 cm width * 20 cm depth) are dug, which occupy about 10 % of the land surface as opposed to ploughing the entire land surface in conventional farming (Cornelissen et al., 2013). The planting basins allow optimization of resource use such as fertilizer addition in the basins.

Digging planting basins at 10 % of the land surface means only specific spots of the land surface have been loosened, which may promote improved infiltration of water and this may allow harvesting of rainwater by funneling it to the direction of crop roots. The harvested water may be stored in the root zone hence increased soil water retention. *In-situ* water harvesting towards crop roots has been considered a key attribute of CF, further aided by residue retention (Cornelis et al., 2013). In long-term experiments of ≥10 years, CF has been reported to increase water infiltration in a range of soil types by 7–780 mm hr^{-1} (20–300%) as compared to ploughing of the entire land surface in conventional farming (He et al., 2009; Thierfelder and Wall, 2009). The increase in infiltration resulted in increased soil moisture content under CF as e.g. reported by Thierfelder and Wall (2009). Soil moisture content was greater under CF than under conventional farming at 0–60 cm depth by up to 10 % and 18 % in Zimbabwean Luvisol and Zambian Lixisol, respectively (Thierfelder and Wall, 2009). Likewise, in a clay loam Cambisol in China, soil moisture content at field capacity was 16 % greater under CF than under conventional farming at 15–30 cm depth (He et al., 2009). The observed rainwater harvesting and increase in water storage in the root zone under CF can increase productivity as reported for Ethiopia, Kenya, Tanzania and Zambia (Rockström et al., 2009; Thierfelder and Wall, 2009).

Inclusion of BC amendment in CF practices can further enhance soil water retention, given BC's high porosity of 55–85% v/v (Brewer et al., 2014; Suliman et al., 2017) and positive effect on soil aggregation (Jien and Wang, 2013; Obia et al., 2016). Several studies have reported that BC increases soil water retention as reviewed by Mukherjee and Lal (2013). The effect of BC on soil water retention is determined by factors such as soil and BC type and doses (Mukherjee and Lal, 2013) as well as residence time of BC in soil (Madari et al., 2017). To date most studies reporting BC effects on soil moisture have been conducted in the laboratory or greenhouse or are based on soil-BC samples from field experiments. On-site season-long high resolution field measurements are largely lacking for both regular CF and for BC-soil mixtures under CF. Such data could improve our understanding of soil water dynamics under CF with and without BC in comparison to conventional farming.

Soil temperature regime is a soil property that can be affected by the proportion of water- and air-filled soil pores due to their opposite effects on soil thermal properties; thermal conductivity and heat capacity. Water has an increasing effect on both soil thermal conductivity and soil heat capacity and the opposite is true for air. An increase in soil thermal conductivity increases temperature whereas an increase in soil heat capacity reduces temperature.

Conservation farming and BC application to soil and the combination thereof can increase soil moisture contents (Cornelissen et al., 2013; Martinsen et al., 2014), which is attributable to increase in the proportion of water-filled pores (alteration in pore size distribution) (Obia et al., 2016, 2018). Such increase in soil moisture content has been found to increase soil thermal conductivity and soil heat capacity (Al-Kayssi et al., 1990). Al-Kayssi et al. (1990) also found a reduction in soil temperature showing that the effect of greater soil heat capacity in reducing temperature overshadowed the opposite effect of greater thermal conductivity. CF and the associated crop residue cover have been reported to reduce near surface soil temperature (Cook et al., 2006; Johnson and Lowery, 1985), due to increased soil moisture and shading by soil cover. Zhang et al. (2013) reported that BC reduced soil diurnal temperature fluctuations by moderating high and low temperature extremes in the North China Plain. The reduced temperature fluctuation was explained by reduced soil thermal conductivity and increased reflectance of near-ultraviolet and blue-light wavelengths and decreased reflectance in infrared wavelength range. Liu et al. (2018) also reported a reduction in soil thermal conductivity due to BC application.

The decrease in soil temperature and fluctuations can be treated as a positive effect in tropical environment given the often high soil temperature in these areas. Soil temperature is an important factor in agriculture, because it affects microbial activity (Guntiñas et al., 2012; Karhu et al., 2010; Reth et al., 2005; Zhou et al., 2014), nutrient dynamics, especially nitrogen (Guntiñas et al., 2012; McGarry et al., 1987; Reddell et al., 1985), as well as root activity and seed germination (Hopper et al., 1979; Wilcox and Pfeiffer, 1990).

Given the reported greater moisture content in soil under CF compared to conventional farming and in soil under CF amended with BC, the following hypotheses were tested. 1) CF planting basins increase total soil moisture content in the root zone through *in-situ* rainwater harvesting during the entire growing season compared to conventional farming. 2) BC addition further increases water-holding capacity of the soil in CF planting basins, where most of the roots occur, as recently shown by Abiven et al. (2015). 3) CF planting basins and BC reduce diurnal temperature fluctuations compared to conventional farming due to greater soil moisture contents and hence greater soil heat capacity. Testing of these hypotheses was carried out by monitoring conventional farming and CF plots with and without BC amendment in a block experiment in Zambia. Probes that measure both moisture and temperature were installed in the CF planting basins or, in the case of conventional farming, in the root zone of the growing crop in order to continuously measure moisture contents and temperature throughout the growing season. The observations were related to data for rainfall, solar radiation and air temperature obtained from a weather station adjacent to the experimental field. In addition, in order to understand the mechanism controlling the effect of BC on soil temperature, the thermal conductivity of soil/BC mixtures was studied in the laboratory. This is the first *in situ* study to carry out a continuous assessment of the combined effect of CF and BC on soil moisture and temperature in comparison with conventional tillage.

2. Materials and methods

2.1. Biochar

Biochar was produced from feedstock composed of 93 % dry pigeon pea (*Cajanus cajan*) stems in a flame curtain kiln made by digging a conical pit in the ground with a diameter of about 2.5 m and a depth of 1.5 m (Cornelissen et al., 2016). Pigeon pea was chosen as feedstock because it produces large amounts of biomass and may eliminate the shortage of biomass for BC production for large scale implementation of BC technology. During pyrolysis, the feedstock was added in a stepwise manner to maintain the flame at the surface of the kiln, as full pyrolysis continues beneath, with the measured peak pyrolysis temperature of 575 ^{0}C. It took about two hours to fill the pit, after which the BC was quenched by sprinkling water before covering it with soil. The BC was then harvested the next day and its characteristics are presented in Table 1. This flame curtain method has been found to consistently produce high quality char at a narrow maximum temperature range as demonstrated by Schmidt and Taylor (2014); Cornelissen et al. (2016) and Pandit et al. (2017). The method suits the local context of rural African conditions for implementation of BC technology, as high-tech methods may not be practical.

2.2. Field experiment

The experiment was established in Mkushi, Zambia (S13°45′27.0″ E29°03′54.6″) on 31st October 2015 following a completely randomized block design with four blocks (Fig. S1). Treatments each covering

Table 1
Properties (± std) of the soil and biochar used in the experiment[a].

Soil/biochar property	Soil from CF basins	Biochar
Total C (%)	0.7 ± 0.1	55.5 ± 8.0
Total N (%)	0.05	0.7 ± 0.1
Total H (%)	–	1.1 ± 0.2
CEC ($cmol_c$ Kg^{-1})	3.8 ± 0.6	38.9 ± 2.2
pH $CaCl_2$	6.3 ± 0.1	9.2 ± 0.1
Bulk density (g cm^{-3})	1.36 ± 0.04	0.25
Sand	69.3 ± 1.9	–
Silt	21.5 ± 2.3	–
Clay	9.2 ± 0.5	–

[a] Soil data was obtained at the onset of the experiment but the site had been under conservation farming (basins) for seven years.

a plot of 4 m * 6 m were randomized within each block. The treatments considered in this study were three farming practices consisting of CF with 4 t ha^{-1} pigeon pea BC ("CF + BC"), regular CF with minimum tillage, residue retention and crop rotation, without BC ("CF") and conventional farming consisting of overall digging to mimic ploughing with crop rotation but no residue retention ("conventional farming"). Crop residues added in the CF and CF + BC treatments were placed between maize rows.

The CF practice, as advocated for small holders in Zambia, involves minimum tillage using planting basins (~40 cm length * 15 cm width * 20 cm depth), where about 10 % of the land surface is tilled compared to conventional farming, where 100 % of the land surface is ploughed (Cornelissen et al., 2013; Obia et al., 2016). The planting basins were dug once without re-opening the following seasons. In CF + BC, crushed BC was concentrated and mixed within the basins at 2.0 % w/w corresponding to 4 t ha^{-1} overall application rate. The soil-BC mixture in the basins (added in the first year only (October 2015) and placed at 5–20 cm depth) was then covered with 5 cm soil. Within the CF and CF + BC plots, there were four fixed rows each with six fixed planting basins, which were used for planting each year (viz. the position of a basin was not changed from one year to the next). Overall digging of the plots under conventional farming was done each year before planting in November. Plots under conventional farming also had four rows each with six planting stations that were always opened during planting. Planting stations are planting positions for maize in a row in a conventionally tilled field. The within and between row spacing of planting basins or stations was 80 cm x 90 cm. Planting basins (CF and CF + BC) and planting stations (conventional farming) were planted with three maize seeds each in the first season (2015/2016) and ten to twelve soybeans seeds per basin/station in the second season (2016/2017). Maize and soybean were planted on 20th November 2015 and 29th November 2016, respectively. Before planting of maize, 200 Kg ha^{-1} basal NPK fertilizer at a ratio of 10:20:10 was applied in the planting basins and stations, followed by a top dressing of 200 Kg ha^{-1} urea before tasseling stage in the first season. There was no fertilization in the case of soybeans (season 2). In CF and CF + BC, soybean was planted without re-opening the basins by scratching the surface, dropping seeds and covering with soil. The growing season in Zambia normally extends from the end of November until the end of May in the following year. Before this experiment, the site was under regular CF for seven years but with yearly opening of basins (Martinsen et al., 2019).

An onsite weather station was established to measure weather variables. The weather instruments installed were ECRN–100 High Resolution Rain Gauge, VP–4 Sensor (Temp/RH/Barometer), DS–2 Sonic Anemometer and Pyranometer (Decagon Devices, Pullman, WA, US) for measurement of rainfall, air temperature/relative humidity/air pressure, wind speed, wind direction and total solar radiation, respectively. The measurement of weather variables were registered every 15 min by Em50 Digital Data Logger, 5–Channel (Decagon Devices, Pullman, WA, US).

2.3. Field measurement of soil moisture and temperature

Soil moisture and temperature were measured using a single device that measure both soil moisture and temperature (5 T M Soil Moisture and Temp Sensor; Decagon Devices, Pullman, WA, US). Moisture content measurement with this device is based on the time domain reflectometry (TDR) method. Sensors were installed at 10–12 cm below the soil surface at an angle of about 20 – 30° above the horizontal axis under the maize and soybeans plants on 25th February 2016 and 27th October 2016, respectively, as illustrated in Fig. S2. The 10–12 cm depth corresponds to the middle of the rooting depth where 95 % of maize roots was found in Mkushi according to Abiven et al. (2015). For soybeans, the sensors were installed before planting. Four sensors were installed per plot (total of 48 sensors) with each sensor under the plants in one of the four middle planting basins/stations (Fig. S2). The four sensors were therefore pseudo-replicates within each plot. Each treatment had four real replicates represented by four plots, one in each block. Thus, in total there were 16 replicate measurements per treatment. The data from the sensors were logged every two hours using Em50 Digital Data Logger. The data was collected from 26th February to 2nd May 2016 (second half of the season) in the first growing season and from 28th October 2016 to 21st April 2017 (full season) in the second growing season.

2.4. Handling of field data

The soil moisture data for the four sensors per plot and the four blocks were averaged to obtain the overall moisture dynamics during the season. The average moisture content was plotted against time to show the moisture dynamics under CF + BC, CF and conventional farming for both seasons. Three and four heavy rainfall events on different dates during the first and second season, respectively, were selected to assess the maximum soil moisture contents under field conditions. The selected rainfall events are those that resulted in a large peak in soil moisture contents. The moisture contents after free drainage achieved 24 h after maximum soil moisture, which may be termed field capacity, were assessed for the three and four selected rainfall events during the first and second seasons, respectively. We further assessed the soil drying after free drainage (starting after 24 h of free drainage) following three occasions (29th March 2016, 30th November 2016 and 11th March 2017) that marked the start of extended periods of 6–10 days without rain during the growing seasons. Overall, we assessed soil moisture pattern over the entire season, maximum soil moisture after heavy rainfall, field capacity (following 24 h of free drainage), and the number of days for the soil to dry until permanent wilting point (PWP) estimated by linear extrapolation. The PWP of the soil (5.5 % v/v), as determined in an earlier study at the same site, was not affected by BC content (Obia et al., 2016). Linear extrapolation was expected to provide a good indication of the number of days for drying until PWP although soil drying is commonly non-linear with a decrease in drying rate as soil moisture content drops. However, the R^2 values for linear and exponential decrease in moisture content were similar e.g. for CF + BC at 0.25 and 0.23, respectively. Thus, linear extrapolation was assumed to provide a good measure for assessing the drying behavior of our soils.

To assess the impact of treatments on temperature changes in the soil, diurnal temperature fluctuation was calculated by subtracting minimum temperature from maximum temperature. Minimum temperature in the soil was always observed between 6 a.m. and 8 a.m. in the morning, while maximum temperature occurred between 2 pm and 4 pm. Corresponding soil moisture contents at 8 a.m. and 4 pm were also extracted from the dataset in order to assess the impact of soil moisture on soil temperature changes. There was a general minor decrease in soil moisture content between 8 a.m. and 4 pm except on rainy days. Therefore, the average moisture content between 8 a.m. and 4 pm was used to assess the impact of soil moisture on diurnal soil

Table 2

Drying pattern of Mkushi soil, starting after 24 h of free drainage following maximum soil moisture content, under conventional and conservation farming with and without BC for three selected drying cycles. *MC* is soil moisture content. The regression coefficient for CF + BC is tested if different from zero, while CF and conventional plots are compared to CF + BC.

Farming practice	Drying equation (t = time hrs.)	Sig.1 Intercept	Sig.2 Slope	Days to PWP[a]	Drying rate (mm day^{-1})[b]
First drying event (132 h, 29 March 2016)					
CF + BC	$MC = 26.59(0.50) - 0.045(0.002)t$	***	***	19.2	2.2
CF	$MC = 20.96(0.20) - 0.035(0.003)t$	***	***	18.4	1.7
Conventional	$MC = 20.42(0.20) - 0.035(0.003)t$	***	***	17.8	1.7
Second drying event (216 h, 30 November 2016)					
CF + BC	$MC = 25.85(0.44) - 0.038(0.001)t$	***	***	22.3	1.8
CF	$MC = 17.18(0.17) - 0.028(0.001)t$	***	***	17.4	1.3
Conventional	$MC = 14.82(0.17) - 0.026(0.001)t$	***	***	14.9	1.2
Third drying event (202 h, 11 March 2017)					
CF + BC	$MC = 27.99(0.75) - 0.051(0.001)t$	***	***	18.4	2.4
CF	$MC = 18.59(0.21) - 0.041(0.002)t$	***	***	13.3	2.0
Conventional	$MC = 19.17(0.20) - 0.036(0.002)t$	***	***	15.8	1.7

CF + BC is the reference to which CF and conventional are compared. Sig.1 and Sig.2 are levels of significance for intercept and slope, respectively: '***' $p < 0.001$. Numbers in brackets are SEs.

[a] The number of days for soil to dry until permanent wilting point of 5.5 % v/v *MC*, assuming no rainfall.

[b] Drying rate for 20 cm plough layer / basin depth. The random effects (standard deviation) of blocks and block*SensorsPerPlot was 0.01 and 0.01, 0.00 and 0.02, and 0.01 and 0.02 for the first, second and third drying cycle, respectively.

temperature fluctuations. Daily total solar radiation was also included as a predictive parameter for changes in soil temperature (daily minimum, maximum and diurnal temperature fluctuation). Overall, variations in daily minimum, maximum temperature and diurnal temperature fluctuations were assessed as a function of farming practices including BC addition, soil moisture and daily total solar radiation.

2.5. Thermal conductivity measurement in the laboratory

Soil and pigeon pea BC were the same as used in the field experiment in Mkushi. The air-dry soil with moisture content of 1 % v/v and BC with moisture content of 3 % v/v were both prepared by crushing and passing through a 3.15 mm sieve. Crushing and sieving was done to allow easy mixing of the two materials. The soil was then mixed with BC at a rate of 5 %, 10 %, 20 %, 30 %, 40 % and 50 % on a volume-by-volume basis. Soil without BC as well as pure BC were also included in the measurement. Soil, BC, and soil-BC mixtures were filled into tubes of 16 cm length and 4.4 cm diameter. The length of the tube was decided based on the length of the measurement probe of 15 cm and the diameter was based on recommendations described in the method, where 2 cm is the minimum recommended diameter (TP02 probe, Hukseflux Thermal Sensors, Delft, The Netherlands). The procedure for filling the tubes was operationally defined. To ensure equal compaction of amended soil during filling of tubes, the weights of the tubes filled with either pure BC or pure soil were recorded after mild compaction. The weights of soil and BC in the tubes were 356.06 g and 45.13 g, respectively. The amounts of BC and soil in the mixtures filling each tube was derived from Eq. 1.

$$BC + Soil\,for\,each\,tube = (a*45.13) + ((1-a)*356.06) \quad (1)$$

Where a is the volumetric fraction of BC. The soil and BC were then thoroughly mixed in a plastic bag before filling the tube followed by tapping until all the mixture just filled the tube. Two sets of thermal conductivity measurements were carried out; one for air-dry soil/mixtures and the other at field capacity (40–60% v/v soil moisture for various doses of BC). The field capacity was obtained by saturating the sample tubes overnight followed by free drainage for 24 h. The volumetric moisture contents after free drainage were determined for all the tubes by oven-drying sub-samples at 110 ^{0}C. There were six replicates for each BC dose.

Thermal conductivity of the soil, BC and mixtures was measured using a TP02 probe, a non-steady state probe connected to a CR1000 data logger (Campbell Scientific, Logan, Utah US). Measurements were controlled by a computer with PC 208 W 3.2 software, connected to the data logger.

The TP02 probe has two thermocouple junctions, where one of the tips serves as "cold" junction and the other, at 1/3 of the total length, as "hot" junction. The signal is the difference between the hot and cold joints. Heating of the probe was started digitally and the temperature rise of the cold joint (ΔT) in Kelvin (K) at time t in seconds depends on the heating power (Q) in Watts (W) and the thermal conductivity (λ) in W m^{-1} K^{-1} of the soil mixtures according to Eq. 2. The total heating time was 100 s.

$$\Delta T = \left(\frac{Q}{4\pi\lambda}\right).\ (ln\,t + B) \quad (2)$$

Where, B is a constant. The thermal conductivity was derived as the inverse of the slope of the plotted 4πΔT/Q versus natural log of time in Eq. 3.

$$\frac{4\pi\Delta T}{Q} = \frac{1}{\lambda}.\ (ln\,t + B) \quad (3)$$

2.6. Statistical analysis

The data was analyzed using R software (R Core Team, 2016). The maximum soil moisture content after heavy rainfall, the field capacity (i.e. moisture contents after free drainage achieved 24 h after maximum soil moisture) and the soil drying rate were first fitted using linear mixed effect models of the lme4 library. Maximum soil moisture and field capacity (Fig. 3) were fitted as a function of farming practice (categorical fixed effect factors at three levels) while drying (Table 2) was fitted as a function of farming practice and time (continuous fixed effect factor) in hours. Variation between blocks and between sensors per plot (SensorsPerPlot) were modelled by means of random effects. The random effect factors (block and block*SensorsPerPlot) were significant only for soil drying rates. Therefore, the random factors were excluded from the analysis of maximum soil moisture and field capacity, and instead they were analyzed using a simple linear model – one-way ANOVA for each rainfall event.

The daily minimum and maximum temperature and diurnal temperature fluctuation were analyzed as a function of the fixed factors, farming practice (categorical), soil moisture (continuous variable) and daily total solar radiation (continuous variable) using linear mixed effects models. Only two-way interactions of farming practice with moisture and farming practice with solar radiation were included in the models. The random factors (block and block*SensorsPerPlot) were significant for all the temperature parameters showing that mean temperature parameter for a block deviated significantly from the grand mean of the site and for a plot deviated significantly from that of a random block. This means that blocking and repeated measurements within the plot was important and allowed detection of effects of treatments. Differences between mean values for total biomass yields, temperature parameters as well as for soil moisture were tested using independent sample *t*-test by comparing each of conventional farming and CF with CF + BC at 5 % level of significance.

The laboratory data on thermal conductivity of the soil under various doses of BC were analyzed by analysis of covariance that combines analysis of variance (ANOVA) and regression (linear in this case). The independent variables were the soil water classes of air dry and field capacity as a categorical variable and BC dose and bulk density as continuous variables. All graphs were plotted using SigmaPlot 10 (Systat Software, Point Richmond, CA, USA).

3. Results

3.1. Soil moisture dynamics

Soil moisture content increased sharply and reached a maximum during rainfall or shortly thereafter in both growing seasons (Figs. 1 and 2). The maximum soil moisture content, which is the highest amount of soil water following rainfall varied depending on antecedent soil moisture content, rainfall intensity, amounts and duration. The sharp increase in soil moisture content with time (wetting rate) in response to rainfall was similar under CF + BC, CF and conventional farming (Figs. 1 and 2 and S5). Peaks in soil moisture content following rainfall were greatest in the CF + BC, followed by CF and least in conventional farming plots. The differences were attributed to rainwater harvesting in the basins under CF + BC and CF, and the lack of it in conventionally tilled plots. Towards the end of the first season (2015/2016), CF did not harvest significantly more water compared to conventionally farmed plots ($p > 0.05$). In the initial months of the second season of the experiment (2016/2017), rainwater harvesting of the CF + BC and CF treatments, as shown by the maximum moisture content, was significantly greater than that of the conventional farming ($p < 0.05$; Fig. 3A). The maximum moisture content in the conventional farming plots increased towards the end of the season compared to early season.

After 24 h free drainage, the soil moisture retained in CF + BC was significantly greater than that in CF and conventional farming for all selected rainfall events during the two growing seasons ($p < 0.05$; Fig. 3B). The moisture contents in CF plots were slightly, but not significantly ($p > 0.05$) greater than those in the conventional farming plots for the two growing seasons.

In the second growing season, free drainage, 24 h after the selected rainfall episodes, decreased in the order CF + BC > CF > conventional farming plot as seen from the drop in moisture content with mean ± SE of 12.1 ± 1.2 vol% > 7.9 ± 0.5 vol% > 1.7 ± 0.3 vol%, respectively, (difference between Fig. 3A and B). This was different for the last part of the growing season, as the antecedent soil moisture content in conventional farming plots gradually approached that of the soil under CF, while the growing season was progressing (Fig. 1). In the last part of the growing season, the volume of water lost from the plough layer (20 cm depth) within 24 h after an event is largely due to drainage and was similar for all three treatments (CF + BC ≈ conventional farming ≈ CF; Fig. 3, first season).

The TDR-based measurement of soil moisture content such as in this study may be affected by the effect of BC on the di-electric constant of the soil. Only BCs with pyrolysis temperature of > 600 °C have been reported to affect dielectric constant of soil (Kameyama et al., 2014). Therefore, the soil moisture content reported here was likely not affected by BC as pyrolysis temperature was < 600 °C.

3.2. Soil drying after free drainage

After free drainage of water, soil drying was controlled by evapotranspiration. In Table 2, the intercept of the drying equation (soil moisture at time zero) is the moisture content after free drainage (also shown in Fig. 3B), while the slope is the drying rate expressed as decrease in soil moisture content per hour. The moisture content after free drainage and the drying rate were significantly greater for CF + BC compared to those for CF and conventional farming for all the three selected rainfall events ($p < 0.001$, Table 2). The drying rate in the basins were in the range of 0.026 – 0.051 vol% hr^{-1} that translates to a range of 1.25–2.45 mm day^{-1} calculated by multiplying fractional water content by 24 h and by 200 mm basin depth. The CF + BC treatment took the longest estimated time to dry until PWP, viz. 18.4–22.3 days, due to high initial moisture content (intercept). For CF, the moisture content after free drainage was significantly smaller than for CF + BC ($p < 0.001$) but greater than for conventional farming for the first two drying cycles and similar in the third drying cycle. The drying rate for CF was significantly smaller than that for CF + BC but similar to that for conventional farming. For CF, this resulted in a shorter estimated drying period to PWP of 13.3–18.4 days. Conventional farming had the smallest moisture content after free drainage, except after the third rain event when this was similar to CF, resulting in a drying period of 14.9–17.8 days. Overall, the drying period until PWP estimated using linear extrapolation was in the order CF + BC > CF ≈ conventional farming. It was not possible to distinguish between actual water loss in the field (depending on the actual plant growth) and soil potential to store plant available water, as the former parameter was not measured.

3.3. Soil and air temperature dynamics

In the growing season, the soil temperature varied between 17–37 ^{0}C (Figs. 1C and 2 C), but it was higher just prior to the growing season (before onset of rains) at 23–42 ^{0}C (Fig. 2C). The air temperature followed a similar pattern of 12–34 ^{0}C during growing season (Figs. 1C and 2 C) and 13–37 ^{0}C before the start of the season (Fig. 2). There was less variation in soil minimum temperature than in soil maximum temperature as shown by smaller amplitudes between days (Figs. 1C and 2 C). Solar radiation, being the source of energy that warms air and soil, followed a similar pattern as maximum soil and air temperatures.

3.4. Effect of farming practice and soil moisture on soil temperature

The linear equations in Tables 3 and 4 show the magnitude of the effects of farming practices, soil moisture and solar radiation on daily minimum, maximum and diurnal soil temperature. The daily soil temperature rose from a minimum in the morning reaching a maximum between 2 and 4 pm. The effect of solar radiation on maximum soil temperature under the three farming practices was very significant ($p < 0.001$). This effect was similar under CF + BC and CF ($p > 0.05$) and much greater under conventional farming plots ($p < 0.001$) (Table 3) in the first year (measurements in the second half of the season only). Therefore, each unit of daily total solar radiation resulted in greater increase in maximum temperature under conventional farming (by 2.2 and 3.5 ^{0}C in the first and second season, respectively) compared to CF practice (by 1.7 and 3.1 ^{0}C in the first and second growing season, respectively). Maximum soil temperature was more sensitive for soil moisture under conventional farming than under CF or CF + BC practice: it decreased by 0.06 – 0.09 ^{0}C for every 1 % increase in moisture content under CF + BC and CF, and significantly more

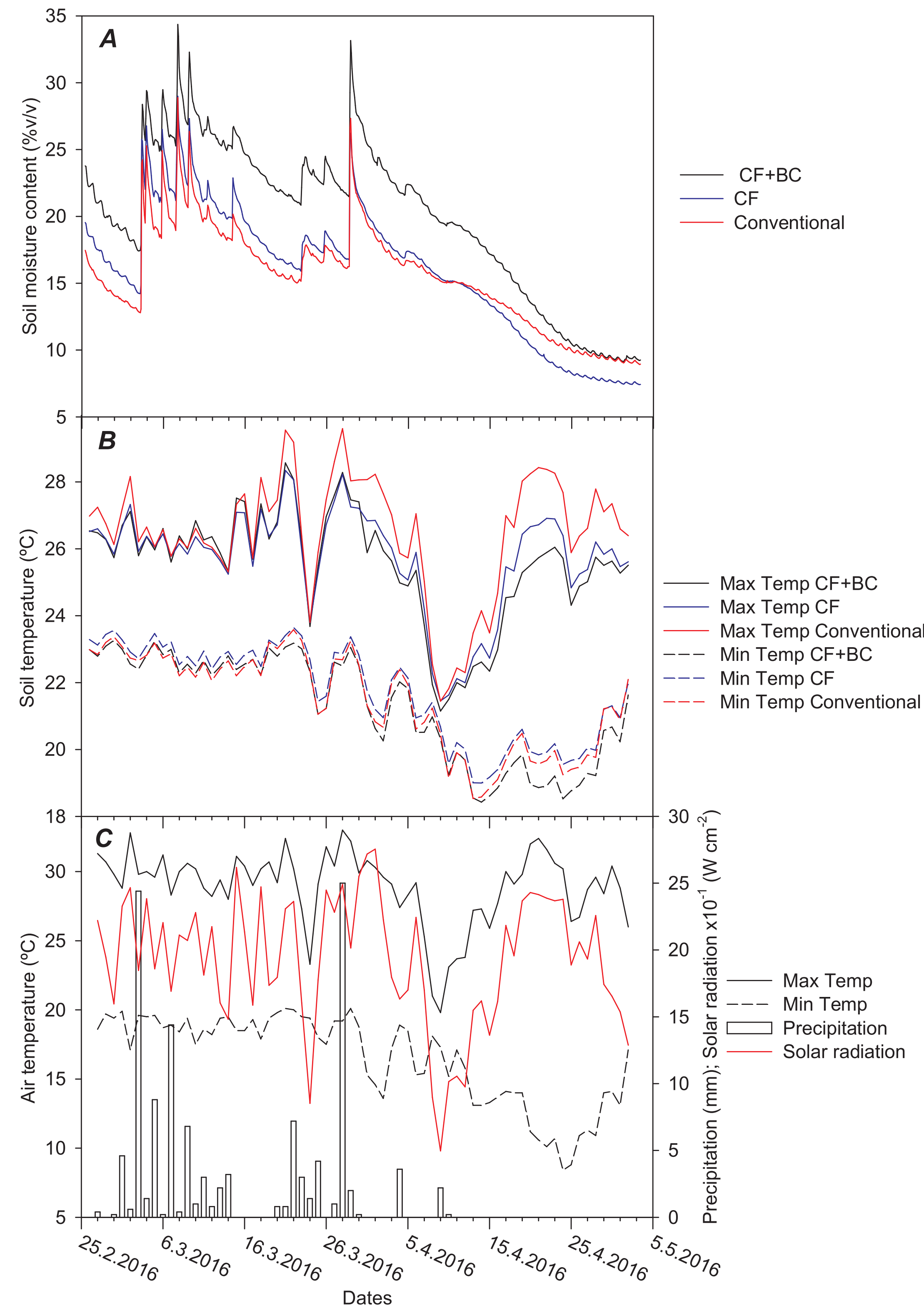

Fig. 1. Soil moisture (A) and temperature (B) changes under conventional and conservation farming planting basins with (4 t ha^{-1}) and without BC and the daily weather pattern (C) during 2015/2016 growing season in Mkushi, Zambia. Soil moisture/temperature sensors were installed at 10–12 cm depth and measurements were conducted in second half of the season. Maize was planted on 20th November 2015.

strongly under conventional farming (by 0.18 – 0.38 ^{0}C), in both growing seasons (Tables 3 and 4). The lowest daily soil minimum temperature increased in the order of CF + BC < CF < conventional farming though not significant in all cases for both the first (21.9 < 22.5 ≈ 22.6 ^{0}C) and second (21.28 ≈ 21.55 < 22.14 ^{0}C) growing season (Tables 3 and 4). The minimum temperature depended on the daily total solar radiation of the previous day and soil moisture ($p < 0.001$). The minimum temperature increased with increasing solar radiation but decreased with increasing soil moisture content.

Diurnal soil temperature generally followed similar pattern as

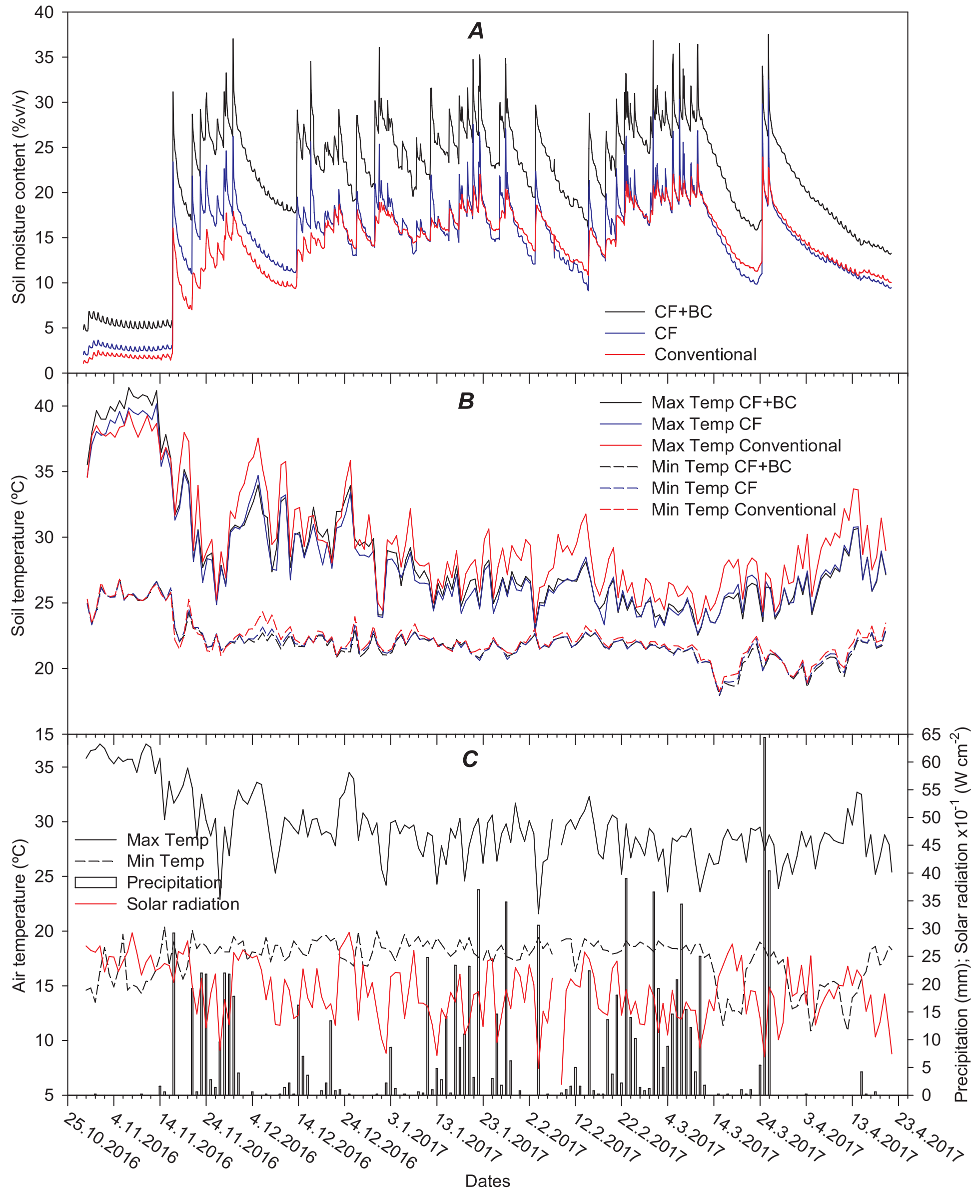

Fig. 2. Soil moisture (A) and temperature (B) changes under conventional and conservation farming planting basins with (4 t ha^{-1}) and without BC and the daily weather pattern (C) during 2016/2017 growing season in Mkushi, Zambia. Rainfall data from 16th December 2016 to 7th February 2017 was obtained from a nearby weather station ~1 km away due to faulty onsite rain gauge. Soil moisture/temperature sensors were installed at 10–12 cm depth. Soybeans was planted on 29th November 2016.

maximum temperature, being more moderate for CF and CF + BC practices than for the conventional farming. The magnitude of the effect of solar radiation and moisture content across the farming practices were also similar to that of maximum temperature. Soil cover associated with CF practice was placed between rows of basins only and did not affect temperature changes here, as there was no cover on the basins where temperature probes were installed.

3.5. Soil/biochar thermal conductivity; laboratory results

The soil thermal conductivity was significantly different ($p < 0.001$) between the two soil moisture states of air-dry (0.25 ± 0.02 W $m^{-1}K^{-1}$) and field capacity (2.27 ± 0.03 W $m^{-1}K^{-1}$; Fig. 4). The thermal conductivity of the bulk BC was lower than that of the soil, at 0.05 ± 0.001 and 0.42 ± 0.02 W $m^{-1}K^{-1}$ in air-dry state (3 % moisture) and at field capacity (57 % moisture), respectively.

Biochar significantly ($p < 0.001$) lowered the thermal conductivity of the soil. In the air-dry soil, BC reduced the thermal conductivity linearly by 0.0021 ± 0.0005 W $m^{-1}K^{-1}$ per percent BC added ($p < 0.001$) (Fig. 4A). At field capacity, the thermal conductivity, being one order of magnitude greater than in air-dry soil, also decreased linearly (0.019 ± 0.001 W $m^{-1}K^{-1}$ % BC^{-1} ($p < 0.001$) (Fig. 4A). Biochar reduced bulk density linearly and consequently thermal conductivity decreased with decreasing bulk density ($p < 0.001$) by 0.163 ± 0.040 and 1.451 ± 0.057 W $m^{-1}K^{-1}$ in air-dry soil and at field capacity, respectively (Fig. 4B).

The addition of BC significantly ($p < 0.001$) increased the measured water content of the soil. The moisture content of air-dry soil was 0.8 vol% and it increased by 0.02 % per percent BC added. The moisture content at field capacity on the other hand was 36.6 vol% and increased by 0.16 % per percent BC added (Fig. S3).

3.6. Effect of farming practices on crop yields

In the first growing season, total biomass of maize was greater in CF

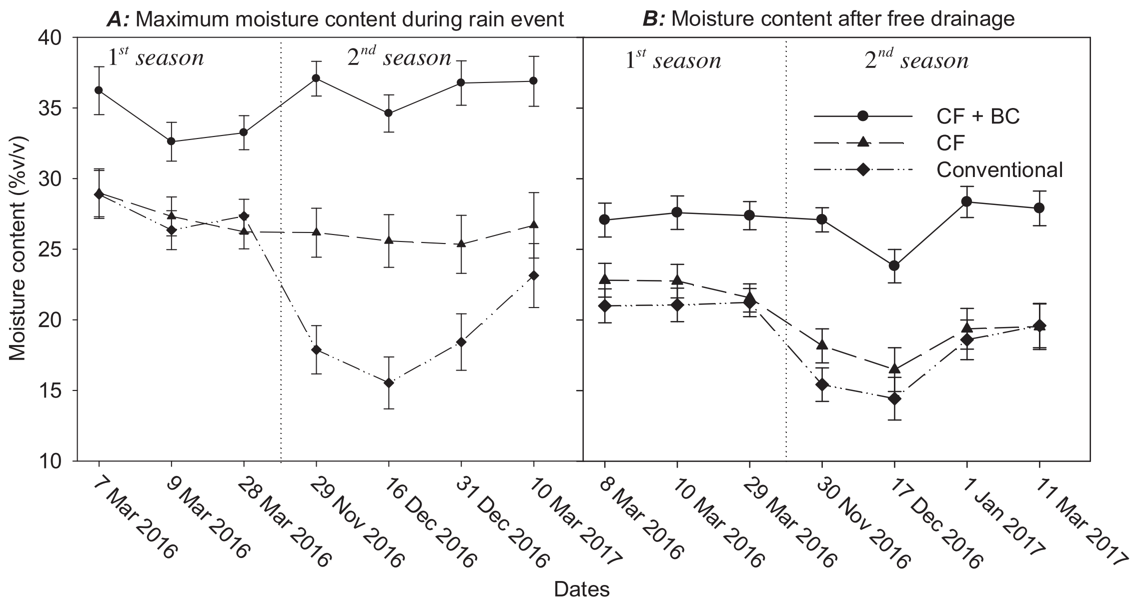

Fig. 3. Mean maximum moisture content of conservation farming planting basins with (4 t ha^{-1}) and without BC in comparison to conventional farming during a rainfall event (A) and mean water holding capacity, 24 h later after free drainage (B) in a sandy loam Acrisol in Zambia. Seven different rainfall events on different dates were selected: Three in March 2016 (first season) and four in November 2016 – March 2017 (second season). The error bars represent standard errors and differences between means was tested at $p < 0.05$.

and CF + BC treatments compared to conventional farming treatment (Table 5, $p < 0.1$). After a rotation with soybean in the second growing season, the pattern was the same, where biomass of soybeans was in the order CF + BC ≈ CF > conventional farming, although the yield difference was equally significant only at $p < 0.1$.

4. Discussion

4.1. Soil moisture dynamics

Increasing soil organic matter and enhancing water retention are agricultural practices that improve resilience against drought. They are considered climate smart as they combine climate change adaptation and mitigation (Farooq and Siddique, 2015; Thierfelder et al., 2017).

Table 3

Effect of farming practices, soil moisture and solar radiation on soil temperature between 26th. February to 31st. March 2016 (first growing season), Mkushi Zambia. The regression coefficients for CF + BC are tested whether they are different from zero while CF and conventional farming are compared to CF + BC.

Predictors	Farming practice	Temp (°C) prediction equation	Sig.1 Intercept	Sig.2 Slope
Minimum soil temperature (Min T) occurring at 8.00 h daily				
Solar radiation (W cm^{-2})[a]	CF + BC	*Min T* = 21.95(0.18) + 0.38(0.06)*x*	***	***
	CF	*Min T* = 22.45(0.24) + 0.41(0.08)*x*	*	
	Conventional	*Min T* = 22.57(0.23) + 0.58(0.08)*x*	**	*
Moisture content (% v/v)	CF + BC	*Min T* = 21.95(0.18) − 0.01(0.01)*x*	***	
	CF	*Min T* = 22.45(0.24) − 0.02(0.01)*x*	*	
	Conventional	*Min T* = 22.57(0.23) − 0.06(0.01)*x*	**	***
Maximum soil temperature (Max T) occurring at ~14.00 h daily				
Solar radiation (W cm^{-2})[b]	CF + BC	*Max T* = 24.56(0.32) + 1.66(0.09)*x*	***	***
	CF	*Max T* = 24.75(0.42) + 1.65(0.13)*x*		
	Conventional	*Max T* = 25.76(0.41) + 2.21(0.13)*x*	**	***
Moisture content (% v/v)	CF + BC	*Max T* = 24.56(0.32) − 0.06(0.01)*x*	***	***
	CF	*Max T* = 24.75(0.42) − 0.09(0.01)*x*		
	Conventional	*Max T* = 25.76(0.41) − 0.18(0.02)*x*	**	***
Diurnal temperature range (Max T – Min T)				
Solar radiation (W cm^{-2})[b]	CF + BC	*Rise T* = 1.21(0.31) + 2.02(0.09)*x*	***	***
	CF	*Rise T* = 0.80(0.38) + 2.00(0.12)*x*		
	Conventional	*Rise T* = 1.90(0.37) + 1.48(0.12)*x*		***
Moisture content (% v/v)	CF + BC	*Rise T* = 1.21(0.31) − 0.06(0.01)*x*	***	***
	CF	*Rise T* = 0.80(0.38) − 0.07(0.01)*x*		
	Conventional	*Rise T* = 1.90(0.37) − 0.15(0.01)*x*		***

CF + BC is the reference where CF and conventional is compared to. Sig.1 and Sig.2 are significance codes for intercept and slope, respectively: 0 '***' 0.001 '**' 0.01 '*' 0.05. Numbers in brackets are SEs. The random effects of blocks and block*SensorsPerPlot (standard deviation) was 0.09 and 0.12, 0.07 and 0.30, and 0.22 and 0.36 for minimum, maximum and temperature range, respectively.

[a] Total solar radiation of a given day was used as a predictor of the minimum temperature of the following day.

[b] Maximum temperature and temperature range was predicted from total solar radiation of the same day.

Table 4
Effect of farming practices, soil moisture and solar radiation on soil temperature between 20th. November 2016 to 31st. March 2017 (second growing season), Mkushi Zambia. The regression coefficients for CF basins + BC are tested whether they are different from zero while CF basins and conventional farming are compared to CF basins + BC.

Predictors	Farming practice	Temp (°C) prediction equation	Sig.1 Intercept	Sig.2 Slope
Minimum soil temperature (Min T) occurring at 6.00 h daily				
Solar radiation (W cm^{-2})[a]	CF basins + BC	$Min\ T = 21.28(0.14) + 0.34(0.03)x$	***	***
	CF basins	$Min\ T = 21.55(0.15) + 0.34(0.03)x$		
	Conventional	$Min\ T = 22.14(0.15) + 0.34(0.03)x$	***	
Moisture content (% v/v)	CF basins + BC	$Min\ T = 21.28(0.14) - 0.01(0.01)x$	***	
	CF basins	$Min\ T = 21.55(0.15) - 0.01(0.02)x$		**
	Conventional	$Min\ T = 22.14(0.15) - 0.05(0.02)x$	***	***
Maximum soil temperature (Max T) occurring at ~14.00 h daily				
Solar radiation (W cm^{-2})[b]	CF basins + BC	$Max\ T = 24.07(0.51) + 3.19(0.12)x$	***	***
	CF basins	$Max\ T = 22.77(0.53) + 3.11(0.16)x$	*	
	Conventional	$Max\ T = 28.28(0.53) + 3.46(0.16)x$	***	
Moisture content (% v/v)	CF basins + BC	$Max\ T = 24.07(0.51) - 0.09(0.01)x$	***	***
	CF basins	$Max\ T = 22.77(0.53) - 0.09(0.02)x$	*	
	Conventional	$Max\ T = 28.28(0.53) - 0.38(0.02)x$	***	***
Diurnal temperature range (Max T – Min T)				
Solar radiation (W cm^{-2})[b]	CF basins + BC	$Rise\ T = 1.98(0.45) + 3.41(0.10)x$	***	***
	CF basins	$Rise\ T = 0.10(0.45) + 3.38(0.14)x$	***	
	Conventional	$Rise\ T = 4.44(0.44) + 3.93(0.14)x$	***	***
Moisture content (% v/v)	CF basins + BC	$Rise\ T = 1.98(0.45) - 0.09(0.01)x$	***	***
	CF basins	$Rise\ T = 0.10(0.45) - 0.06(0.02)x$	***	*
	Conventional	$Rise\ T = 4.44(0.44) - 0.31(0.02)x$	***	***

CF basins + BC is the reference where CF basins and conventional is compared to. Sig.1 and Sig.2 are significance codes for intercept and slope, respectively: 0 '***' 0.001 '**' 0.01 '*' 0.05. Numbers in brackets are SEs. The random effects (standard deviation) of blocks and block*SensorsPerPlot was 0.00 and 0.14, 0.38 and 0.59, and 0.38 and 0.52 for minimum, maximum and temperature range, respectively.

[a] Total solar radiation of a given day was used as a predictor of the minimum temperature of the following day.

[b] Maximum temperature and temperature range was predicted from total solar radiation of the same day.

Results from this study fit well within this concept of climate smart agriculture. We observed greater soil moisture content and biomass yields in the CF plots compared to conventional farming (Figs. 1 and 2, and Table 5). The greater soil moisture contents in CF plots can be attributed to the funneling of water into the planting basins from the surrounding area (Cornelis et al., 2013). Application of BC further enhanced the moisture content in CF basins due to its positive effect on soil water retention (Obia et al., 2016). The BC increased the maximum moisture content relative to CF and conventional farming by 22–25% in the first year. In the second year, the measured maximum moisture content for CF + BC and CF plots exceeded that of conventional farming by 59–107% and 15–65%, respectively (Fig. 3A). The greater moisture content in the CF plots with or without BC in comparison to conventionally tilled soils during the initial stage of the growing season is particularly important for crop establishment. After free drainage, moisture content followed a similar pattern as maximum moisture content. The actual infiltration rates deduced from wetting rates (Fig. S5) were similar between CF + BC, CF and conventionally farmed plots, also shown by sharp rise in soil moisture during or shortly after rainfall (Figs. 1 and 2). There was more water in the basins due to rainwater harvesting, where rainwater from in-between plant rows was believed to be funneled towards the basins with loosened soil, hence greater

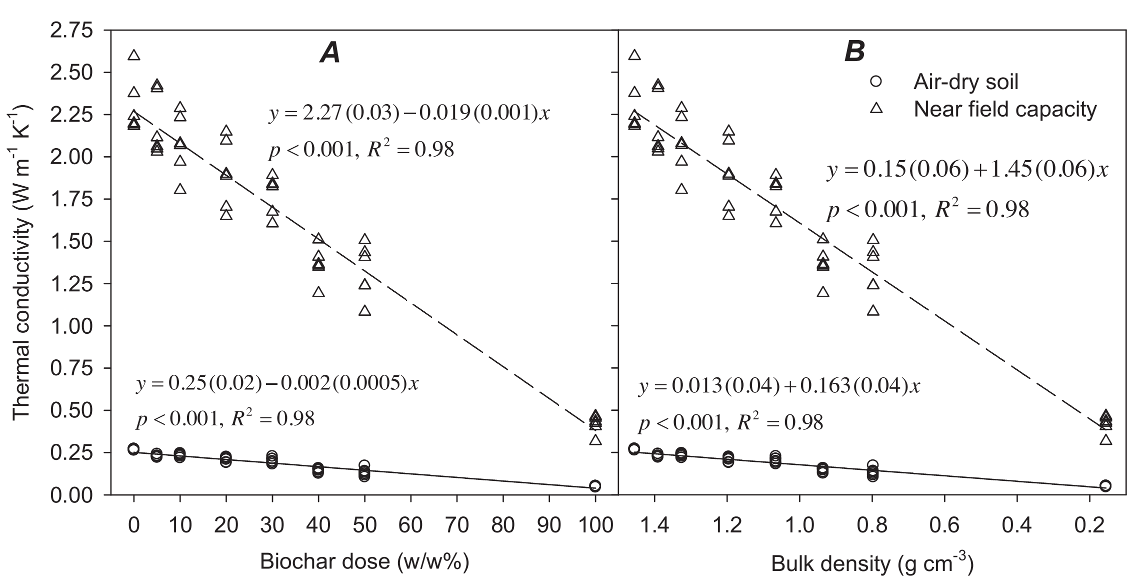

Fig. 4. Thermal conductivity of Mkushi soil mixed with pigeon pea BC as a function of BC dose (A) and bulk density (B).

Table 5
Total biomass yield of maize and soybean at harvest in the first (2016) and second (2017) season, respectively (mean dry weight in t ha^{-1} ± std).

Treatment	Maize biomass yield, 2016	Soybeans biomass yield, 2017
Conventional farming	9.40 ± 1.55	3.59 ± 0.95
CF	11.32 ± 1.06	4.82 ± 0.76
CF + BC	11.19 ± 1.41	4.90 ± 0.86

infiltration. The measured soil water content was greater under CF and CF + BC immediately after each rainfall event (Figs. 1 and 2) compared to conventional practice hence the importance of funneling. Water infiltration in the conventional plots is expected to be spatially homogeneous.

Rapid drainage during heavy rainfall events occurred preventing or minimizing chances of extended periods of soil water saturation. The moisture content under all treatments at any one day was less than 40 % during the two seasons (Figs. 1 and 2). This was less than the water saturation (total porosity) of 53 % for the same soil reported in Obia et al. (2016), which may be associated with generally greater water flow rate (Fig. 5S) compared to rainfall intensity. Overall, there was therefore good soil internal drainage in CF planting basins likely due to increased macro-porosity (Obia et al., 2016), despite the funneling of rainwater into the planting basins. The good internal drainage in CF basins reported here is contrary to observations by Esser (2017) for different soil types (e.g. texture, organic matter) in Zambia where drainage in CF basins was reported to be poor in an artificial rainfall experiment where ponding and run off was observed.

The high water holding capacity, which is the amount of water the soil can hold against free drainage, in CF + BC treatment attributed to increased soil water retention by BC (Obia et al., 2016), enhanced drought resilience. The increased water retention in CF + BC ensured greater antecedent soil moisture before each rainfall event. In case of a dry spell after a heavy rainfall event, soils under CF + BC could remain moist above PWP between 8 days (early in the season) and 2–4 days (late in the season) longer than under conventional farming. The difference in soil drying rates under CF + BC treatment between early and late season could be due to greater transpiration demand of the crop late season, as has been demonstrated for maize and wheat in the North China Plain (Liu et al., 2002). Changes in weather variables such as relative humidity and wind speed cannot explain the observed increase in drying rate as the season progressed, because relative humidity and wind speed increased and decreased, respectively, later in the season (Fig. S4). The CF practice showed slightly slower drying rates than conventional farming (1.6–3.5 days longer).

In the first month of the second growing season, conventionally farmed plots had smaller maximum moisture content than CF, following rainfall events (Fig. 3). However, maximum soil moisture content of the conventional plot increased as the season progressed, reducing the difference with CF plots (Fig. 3). The CF basins were rapidly recharged within the first month after the dry season due to rainwater harvesting. Conventional farming plots, on the other hand needed more rainwater to recharge the entire more homogeneous plot.

4.2. Soil temperature dynamics

Before the start of the rainy season, soil temperature decreased in the order of CF + BC > CF > conventional farming plots, but flipped around after the onset of rains (Fig. 2B). Before the rainy season, soil moisture was very low at ≤5 % and therefore the effect of soil moisture on soil temperature (Al-Kayssi et al., 1990) was small. In CF + BC, despite lower thermal conductivity due to BC addition (Fig. 4), it may have gradually warmed up during the long dry season. During the rainy season, CF + BC and CF had reduced soil temperature due to greater heat capacity introduced by more water compared to conventional farming (Figs. 1B and 2 B).

Soil temperature at the study site was high and in excess of 40 ^{0}C in some cases especially early in the season (Fig. 2B). Such high soil temperature may restrict seed germination. For example, soybean has been reported to have optimal germination temperature of 30–35 ^{0}C (Hopper et al., 1979). Additionally, nutrient uptake and root (root hairs present in the entire rooting depth) growth may be affected at a soil temperature > 20–25 ^{0}C, as shown for tomato with limited chance of full recovery at soil temperature > 40 ^{0}C (Giri et al., 2017). High soil temperature above 28 ^{0}C has also been shown to reduce wheat growth (Monje et al., 2007). Thus, high maximum temperature (> 30 °C) early in the season, e.g. in conventional plot, may have affected crop growth (Fig. 2). The minimum temperatures irrespective of the farming practice was within the optimal range for crops such as tomato and wheat (Giri et al., 2017; Monje et al., 2007). Therefore, a farming practice, such as CF and CF + BC, that reduces maximum temperature and temperature fluctuations (Figs. 1B and 2 B) may be of particular relevance in tropical agriculture.

4.3. Effect of soil moisture dynamics on soil temperature

There was decrease in soil temperature in CF and CF + BC treatments where there was increase in soil moisture content compared to conventionally farmed plots (Tables 3 and 4). The effect of soil moisture on soil temperature can be attributed to its increasing effect on soil heat capacity and thermal conductivity (Al-Kayssi et al., 1990). Greater heat capacity reduces temperature while greater thermal conductivity increases temperature. The observed decrease in soil temperature in the field implies that the greater heat capacity of soil due to more soil moisture was more important than increase in thermal conductivity (Fig. 4A, intercept; 0 % BC).

Despite increase in moisture contents due to BC, thermal conductivity decreased with increasing BC dose (Fig. 4A, slope). Biochar affected both soil moisture and air contents (Obia et al., 2016), where the effect of increased soil moisture was counteracted by greater increase in air content (decrease in bulk density/increase in porosity) resulting in a decrease in thermal conductivity (Fig. 4). The relatively coarse BC with size of up to 3.15 mm in the laboratory experiment may have greatly contributed to macropores and air-filled pores rather than to water-filled pores at field capacity. The observed decrease in thermal conductivity due to BC addition is similar to observation by Liu et al. (2018).

In the wetter soil under CF + BC, reduced thermal conductivity at field capacity due to greater increase in air content as a result of BC porosity and improved soil aggregation (Obia et al., 2016), coupled with larger heat capacity of water, resulted in an overall lower maximum temperature. There was therefore lower increase in temperature per unit solar energy in CF + BC (Tables 3 and 4). Conventional farming had greater bulk density of 1.42 vs 1.36 g cm^{-3} for CF (Table 1), which increases contact points between soil particles and facilitates faster heat transfer (Abu-Hamdeh, 2003; Becker et al., 1992), in addition to lower volume of water resulting in lower heat capacity. The net effect was the greater increase in temperature per unit solar energy in conventional farming plots (Tables 3 and 4). We therefore hypothesize that BC affects soil thermal properties in two ways: first by increasing soil moisture content (Figs. 1–3) and secondly by reducing bulk density (Fig. 4) and associated increase in air-filled pore space. Decrease in soil bulk density and increase in soil porosity by BC in coarse-textured soils have been reported in several studies (Abel et al., 2013; Cornelissen et al., 2013; Liu et al., 2017; Obia et al., 2016) and was attributed to both weight dilution and increased soil aggregation effects of BC. Heat capacity of soil has also been reported to decrease with decrease in soil bulk density (Abu-Hamdeh, 2003; Liu et al., 2018). This may be related to the lower heat capacity of air, of which the content increases in soil with decreased bulk density. Overall, the soil water content and bulk density/porosity explains the wide daily soil temperature fluctuation in conventional farming and lower fluctuation in CF plots observed in the field in Zambia. Soil residue cover may be excluded as the main explanation for the observation since the residue was placed in between the rows and not under the plants where the sensors were installed. Likewise, canopy may not explain difference in temperature since the differences were also clear before canopy establishment (Fig. 2B before planting of soybean on $29^{th.}$ Nov. 2016). Reduced soil temperature as observed in CF may reduce soil moisture evaporation and improve rainwater productivity.

5. Conclusions

Planting basins under conservation tillage promoted rainwater harvesting from areas surrounding the basins causing an increase in soil moisture content compared to conventional farming in an Acrisol in Zambia. In the presence of BC, the planting basins retained more of the harvested water early in the season and maintained a higher antecedent moisture content before each of the subsequent rainfall events. The moisture content of the soil decreased therefore in the order CF + BC > CF > conventional farming. The planting basins with or without BC had greater free drainage than that of conventional farming plots. The increased soil moisture content in basins, enhanced by BC, also helped in regulating soil temperature, particularly reducing the maximum temperature and temperature fluctuations. The reduction in soil temperature fluctuations, due to BC addition to the soil, was enhanced by increased porosity, in part air-filled. The combined increase in heat capacity and decrease in bulk density/increase in porosity (air-filled) outweighed the increase in thermal conductivity in presence of more moisture in regulating soil temperature. Biochar is therefore an important amendment that can enhance soil quality under conservation farming for improved soil productivity with a likely wider applicability beyond the specific soil presented in this study. With improved soil water and temperature in case of drought, conservation farming in combination with BC, may be considered as climate smart.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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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.still.2019.104521.

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