Field Crops Research 243 (2019) 107628

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Impact of rice straw biochar and irrigation on maize yield, intercepted radiation and water productivity in a tropical sandy clay loam

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ARTICLE INFO

Keywords:
Ghana
Spectral reflectance
Ratio vegetation index
Semi-deciduous agro-ecological zone
Soil moisture deficit

ABSTRACT

Continuous cultivation of staple crops to feed a growing population in the semi-deciduous agro-ecological zone of eastern Ghana (SDAG) has led to degraded soils and decreased crop yields. Biochar constitutes a potential remedy as it is often reported to improve soil health and increase crop yield of infertile soils. We thus conducted an experiment over two seasons to evaluate the impact of rice straw biochar on yield, radiation interception and water productivity of maize grown in the SDAG. The biochar was incorporated into the soil at rates of 0, 15 and 30 t ha^{-1} under irrigated and non-irrigated conditions. Maize grain yield (GY), accumulated intercepted photosynthetic active radiation (IPAR) and water productivity (WP) were compared among treatments. Regardless of season, the highest GY, IPAR and WP were achieved in plots amended with 30 t ha^{-1} biochar. A biochar rate of 30 t ha^{-1} increased grain yield by 17% and 36% and IPAR by 19% and 25% in 2017 and 2018 seasons, respectively, compared to a no biochar control. For both seasons, maize GY for the 15 t ha^{-1} treatment was statistically similar to that of 0 t ha^{-1} treatment whether irrigated or not. Irrigation increased grain yield by 9% and IPAR by 3% in 2017 and with 30% and 17%, respectively, in the dryer 2018 season. The effects of biochar and irrigation were additive. Water productivity from the 30 t ha^{-1} treatment was significantly higher in the non-irrigated than in the irrigated plots. Overall, in the SDAG, a biochar soil amendment rate of 30 t ha^{-1} might be a viable solution for farmers to increase yield and enhance water productivity of maize. Future studies should focus on the effect of biochar on the soil and crops over a longer time span in order to recommend viable management options to the farmers in SDAG.

1. Introduction

The semi-deciduous agro-ecological zone of eastern Ghana (SDAG) has been identified as a potential food basket for the country due to its favourable climatic conditions to support the production of crops such as maize and cassava (Adjei-Nsiah et al., 2018). However, most soils in the SDAG – as majority of tropical soils - are inherently infertile because of their low soil organic carbon (SOC) content, low water holding capacity and high soil acidity. Soil degrading processes, including erosion, have been accelerated for centuries since the introduction of slash-and-burn agriculture (Breuning-Madsen et al., 2017; Kristensen et al., 2019). It is therefore imperative to adopt soil management practices that can potentially increase SOC, soil water retention (SWR) and pH with long-term positive effects on crop yield.

Biochar is a well-known remedy in such situations, with the potential to improve soil health and increase crop yield. Biochar continues to receive a lot of research attention because of the variety of benefits it offers, such as increased soil water and nutrient retention, improved crop growth and yield and a pathway to sequester carbon to the soil (Blanco-Canqui, 2017; Jeffery et al., 2017; Bornø et al., 2018; Ramlow et al., 2019). Compared to soil, biochar has a high porosity, surface area, pH, and low particle density. Due to these characteristics, biochar

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https://doi.org/10.1016/j.fcr.2019.107628
Received 15 February 2019; Received in revised form 14 September 2019; Accepted 14 September 2019

alters soil's physical and chemical properties with a subsequent effect on crop yield (Gao et al., 2016; Blanco-Canqui, 2017; Jeffery et al., 2017; Xiu et al., 2019).

Research on the effect of biochar on soil properties and its consequent impact on crop yield has shown conflicting results. Crop yield response on fertile temperate soils amended with biochar have shown minor to neutral effects, while significant positive effects have been reported for infertile tropical soils (Jeffery et al., 2017). For example, Jay et al. (2015), reported that wood biochar neither affected growth nor yield of spring barley in the United Kingdom. In contrast, Abiven et al. (2015) and Faloye et al. (2019) reported maize yield increase after application of rice straw and maize cob biochar to a tropical sandy loam soil in Zambia and Nigeria, respectively. Likewise, Kätterer et al. (2019) found *Acacia* wood biochar to increase the yield of maize and soybean in Kenya consistently even 10 years after application, while Ahmed et al. (2018) found that rice straw biochar in sandy soil sustained the transpiration of maize during drought. It therefore seems that the underlying processes whereby biochar alters soil properties and crop yield arise as an interaction of several factors such as soil type, biochar's physical and chemical properties, geographical location, type of feedstock material and aging (Mia et al., 2017). The inconsistent results on biochar's impact on soil properties, crop yield and their duration showcase the complexity of biochar's interaction with the soil medium. Thus, studies are required to clarify the agronomic benefit of biochar as a soil amendment material when introducing biochar in any location. In the SDAG, only one or two studies have investigated biochar's effect on soil properties and crop yield (Monnie, 2016; Eduah et al., 2019). Monnie (2016) found maize cob biochar to increase SWR and maize grain yield, while Eduah et al. (2019) reported increased soil pH and phosphorus (P) availability after application of maize cob biochar. The two studies were, however, conducted in packed soil columns in greenhouses, putting a limitation on extrapolation of the results to field conditions. The present study was thus undertaken to ascertain the effect of biochar on soil properties and maize yield under field conditions in the SDAG.

Most farmers in the SDAG are engaged in rainfed production of staple crops such as maize and cassava. However, climate change is reported to aggravate environmental stress conditions through longer dry spells and increased evapotranspiration resulting in decreased soil moisture available for crop growth (Olesen et al., 2013). Irrigation often relieves such situations by providing insurance against drought and enabling year-round crop production (Rockström et al., 2017). However, irrigation development in Ghana is low with only 0.5% of agricultural land under irrigation (Burney et al., 2013). Even though irrigation and biochar have proven to improve soil health and increase crop yield, there is no research that has investigated how irrigation interacts with biochar-amended soil and compare to the traditional rainfed system in the SDAG.

It is widely known that abiotic stresses such as low soil water and nutrient availability resulting from degraded soils leads to decreased crop yields. Most of the research on the use of biochar to improve the health of degraded soils has concentrated on the examination of crop growth and yield (Paneque et al., 2016). However, it is laborious and expensive to monitor plant growth in the field and to do sampling for yield determination. It therefore becomes important to explore easily measurable plant physiological parameters that can be used to infer plant growth and yield. Spectral reflectance of a crop canopy is a useful non-destructive tool to accurately monitor plant growth and predict the yield (Andersen et al., 1996). Crop yield under optimum soil water and nutrient conditions is closely related to the amount of intercepted radiation (Monteith, 1994). Thus, the yield of crops growing at their full potential may be inferred from the fraction of photosynthetically active radiation (f_{PAR}) that is captured by the crop canopy (Manevski et al., 2017; Zhou et al., 2017) times the incident solar radiation. A strong linear relationship has often been found between yield and accumulated (e.g., seasonal) intercepted photosynthetic active radiation (IPAR) for several crops in different locations (Olesen et al., 2000; Vargas et al., 2002; Oppong Danso et al., 2015). In this study, we examined the impact of rice straw biochar and irrigation on maize yield and IPAR relationship, based on the hypothesis that yield is linearly related to IPAR and that IPAR is influenced by soil conditions- notably soil moisture and nutrient availability (Amir and Sinclair, 1991; Shah et al., 2004). Very few studies, e.g. Zhou et al. (2017), have evaluated the integrated impact of these limiting factors on IPAR and yield and less so on degraded tropical soils. Thus, the objectives of this study were to: *(i)* remotely monitor maize crop growth in terms of f_{PAR} as affected by rice straw biochar amendment under irrigation and non-irrigation conditions in the SDAG as well as establish a relationship between IPAR and grain yield, *(ii)* determine grain yield, IPAR and water productivity of maize crop as affected by rice straw biochar amendment under irrigation and non-irrigated conditions in the SDAG and (*iii*) evaluate the impact of rice straw biochar on SOC, soil pH, SWR and plant available water (PAW).

2. Materials and methods

2.1. Site location and climate

Field experiments were conducted at the University of Ghana's Forest and Horticultural Crops Research Centre (FOHCREC) in Kade. FOHCREC is located on the coordinates 06^0 08′ 37″N, and 00° 54′ 10″ W at an altitude of 180 m above sea level. The Centre lies in the SDAG of eastern Ghana with annual rainfall ranging between 1300–1800 mm (Ofosu-Budu, 2003). The SDAG has a bi-modal rainfall distribution with the main rainy season starting in April and ending in July, while the minor season covers September to October. Close to 80% of the annual rainfall occurs during the main and minor rainy seasons. The rainfall usually peaks in June for the main season and October for the minor season. There is a short dry spell in August and an extended dry period from December to March. Yearly average annual temperature is 28 °C with the maximum temperature recorded in March while the minimum temperature is recorded in August. Temperature variability during the year is less than 5 °C. Recorded annual potential evaporation is about 1400 mm.

2.2. Biochar and soil and characteristics

Biochar for the study was produced from rice straw feedstock by charring in a Lucia stove reactor at temperature range of 500–550 °C for 48 h. After production, the biochar was air dried and sieved to remove all particles > 2 mm before applying it to the soil. The chemical properties of the rice straw biochar used in the experiments are given in

Table 1
Properties of rice straw biochar used in the experiment.

DM	OM	TC	TN	pH	P	K	Ca	Mg	Fe	Cu	ΣPAHs
%					mg kg^{-1}						
91.8	34.9	25.4	1.0	10.3	1420	17700	3020	1330	2030	8	4.13

DM, dry matter; OM, organic matter; TC, total carbon; TN, total nitrogen, PAH, poly-aromatic hydrocarbons (calculated as the mathematical sum of 19 PAHs). Table adopted from Arthur and Ahmed (2017).

Table 2
Texture and other properties of the top soil layer (0–20 cm) before the start of the experiment.

Clay	Silt	Sand	SOC	TN	ρ_b	P	K
		%			g cm^{-3}	mg 100 g^{-1}	
21	11	68	1.33	0.12	1.52	< 0.4	14.8

SOC, soil organic carbon; TN, total nitrogen; ρ_b, dry bulk density.

Table 1.

The soil at the experimental site is a mostly well-drained forest Ochrosol originating from precambium phyllitic rocks. The soil texture is sandy clay loam and the soils in the area are classified as Acrisols in the WRB (2015) classification. Soil physical and chemical measurements were made before the experiments started (Table 2) and after the second season in 2018. Prior to the experiments, we determined soil bulk density, water content at wilting point, texture, SOC and pH by taking intact core soil samples (100 cm^3 volume) and disturbed bulk soil samples from five randomly selected points in the experimental area. The five core samples were oven-dried at 80 °C to constant weight and the bulk density calculated as the ratio of the dry soil to the soil volume. The bulk density for the five locations were then averaged to obtain a single bulk density for the entire experimental area. The wilting point water content was determined from the disturbed bulk samples using a temperature compensated WP4-T dewpoint potentiameter (METER Group Inc., Pullman, WA, USA) as described in Amoakwah et al. (2017b). The wilting point water content (g g^{-1}) was subsequently converted to volumetric water content (cm^3 cm^{-3}) by multiplying by the bulk density. The soil texture was measured following the procedure described in Gee and Or (2002) while pH was determined according to the methodology described in Thomas (1996). For soil total carbon (C) determination, C was oxidised to CO_2 using a FLASH 2000 organic elemental analyzer at a temperature of 1800 °C. The analyzer was coupled to a thermal conductivity detector (Thermo Fisher Scientific, MA, USA). The total C of the soil samples was taken as soil organic carbon as there were no carbonates present in the soil samples.

Soil measurements at the end of the 2018 season were done on only the irrigated plots as we did not expect differences between the irrigated and non-irrigated treatments as far as biochar's effect on soil properties were concerned. On 15th May 2018 (three days after harvest in 2018), undisturbed core samples (100 cm^3) as well as disturbed soil samples were taken from the middle of the irrigated plots to a depth of 0–20 cm (a total of 12 samples: 3 treatments of B_0, B_{15} and B_{30} and four replicates). Both the disturbed and undisturbed samples were taken to the laboratory and the disturbed samples used for the measurements of soil texture, pH, total carbon and permanent wilting point (PWP). The methodology for the analysis is as described above. For the SWR measurements, data was obtained from an accompanying publication by Obour et al. (2019) which gives a detail description of the methodology.

2.3. Experimental design and treatments

Two consecutive field experiments using the same plots were conducted during the years 2017 and 2018. The first experiment covered the period 30th June 2017–11th October 2017, while the second experiment began on 30th January 2018 and ended on 12th May 2018. The experimental design was a randomised split-plot experiment with irrigation levels as the main plots and biochar levels as subplots with four replicates. The main plot size was 10.8 × 5 m, which was then divided into three subplots of size 3.6 × 5 m. We left 2 m buffer strips between both main and sub plots to provide access pathways and more importantly to minimize lateral movement of irrigation water and biochar between plots. A net plot size (2 × 4 m) was demarcated at the centre of each subplot and yield measurement at maturity was taken from net plots to avoid edge effects.

The experimental treatments consisted of irrigated plots (I_i) and non-irrigated plots (I_0) in combination with biochar rates of 0 t DM ha^{-1} (B_0), 15 t DM ha^{-1} (B_{15}) and 30 t DM ha^{-1} (B_{30}). In their seminal work on biochar's effect on crop yield, Jeffery et al. (2017) suggested that biochar in acidic and low organic matter soils will only increase yield if the quantity applied ranges between 10–100 t ha^{-1}. The biochar rates we applied in the present study (15 and 30 t ha^{-1}) fall within this range. Irrigation water was applied through pressure compensated drip emitters (discharge rate of 2 L h^{-1} at 100-kPa pressure) of 16-mm drip laterals (Naandanjain, Jalgaon, India). The drip laterals were connected to a 32 mm polyethylene main line and spaced 50 cm apart. Water for irrigation was pumped from a nearby dam and filtered using a 125 μ diameter (120-mesh) screen filter (Naandanjain, Jalgaon, India). For the I_0 treatments, plots were demarcated with planting and row dimensions similar to the I_i plots. Before biochar incorporation, the soil was thoroughly wetted with about 8 mm of water and subsequently tilled to a depth of 15 cm using a hoe. Because the rice straw biochar contained a high amount of K (17,700 mg kg^{-1}, Table 1), we split the amount of biochar applied into three equal doses to avoid possible salt effects. The first 1/3 of the biochar amount was applied on 10th December 2015, the next 1/3 was applied on 30th June 2016 and the final third application took place on 12th June 2017. Thus, the biochar treatments (B_0), (B_{15}) and (B_{30}) received 0, 5 and 10 t ha^{-1} during each split application, adding up to 0, 15 and 30 t ha^{-1} after the final application. We planted okra *(Abelmoschus esculentum L.)* during the first and second split applications and changed to maize (*Zea mays L.*) after the third application. Even though the B_0 plots received no biochar, they were also similarly tilled as the biochar treated plots during each split application to maintain consistency among treatments. During each split application round, 9 kg (5 t ha^{-1}) and 18 kg (10 t ha^{-1}) of air-dried biochar was manually broad spread on each plot size of 18 m^2. After the biochar had been sprinkled on the surface of the soil, a hand rake was used to spread and evenly mix the biochar throughout the whole plot and into the upper 5 cm of the tilled soil. The 'Obatanpa' maize variety, which was developed by the Crop Research Institute of the Council for Scientific and Industrial Research of Ghana (CSIR-CRI), is the main variety grown by Ghanaian farmers (Poku et al., 2018) and was used as a test crop. The maize was sown on 30th June 2017 and 30th January 2018 for the growing seasons of 2017 and 2018, respectively. The maize was sown by placing 3 seeds in small pits 3 cm deep and covering with soil. One week after germination, thinning was done to obtain two plants per hill. After sowing, all plots (both irrigated and non-irrigated) were supplied with 5 mm of water each day for the first 20 days after which the irrigation treatments were started. Fungicides and insecticides were sprayed in the mornings of every two weeks from 20 days after sowing (DAS) onwards and terminated on 50 DAS. All treatments received the same amount of nitrogen (N), P and potassium (K) fertilizer at rates of 100 kg N ha^{-1}, 60 kg P ha^{-1}, and 60 kg K ha^{-1}. The P and K fertilizer was applied at pre-plant but for N fertilizer, 50% was applied 15 DAS and the remaining 50% applied at 45 DAS (during tasselling). All the fertilizer was banded and buried to a depth of about 5 cm along the crop rows.

2.4. Soil water content, irrigation management, water productivity and agronomic efficiency of applied biochar

The soil water content (SWC) during the two seasons was measured in three replicate plots of each treatment every three to four days using the manual time domain reflectometry (TDR) as described by Plauborg et al. (2005). The TDR instrument (TDR100 from Campbell Scientific, Logan, Utah, USA) was connected to 80 cm length, 6 mm diameter vertically installed stainless steel probes. The SWC data from the TDR were used to calculate the soil water deficit (SWD), defined as soil water content at field capacity minus actual measured soil moisture content.

Field capacity (FC) referred to the soil water content measured two to three days after the soil had been thoroughly wetted by rain followed by natural drainage before sowing. The monitoring of SWC during both seasons started on 21 DAS and stopped on 103 DAS. The PAW was computed as the difference between field capacity water content measured with the TDR and the water content at wilting point determined with the Potentiameter. Finally, soil moisture depletion of maize at which yield decline is not expected (readily available water, RAW) was calculated as 50% of PAW (Allen et al., 1998).

Irrigation water was supplied to the crops of the I_i treatment every three to four days to refill SWD to FC as determined by early morning TDR measurements on the day of irrigation. The length of the drying cycle of the I_0 plots depended on the interval between successive rainfall events. The amount of irrigation water to apply was estimated by using the following equation:

$$I = A \times d \times \left(\frac{1}{AE}\right) \times fw \tag{1}$$

where *I* is amount of irrigation water, *A* is the plot area (m^2); *d* is the irrigation depth (mm) and was equal to measured SWD in the irrigated plots, *AE* is the application efficiency taken as 90% for drip irrigation (Dworak et al., 2007) and *fw* is percentage of the wetted area taken as 40% for drip irrigation (Allen et al., 1998). In this study, water productivity (WP) was defined as maize grain yield per unit volume of seasonal water supply and calculated as:

$$WP = \frac{GY}{TWS} \tag{2}$$

where *WP* is in kg m^{-3}, *GY* is grain yield (kg m^{-2}) and *TWS* is the sum of seasonal rainfall and seasonal irrigation amount (mm). The harvested maize were manually de-husked and air-dried for two weeks. Thereafter, the grains were manually shelled and the grain yield adjusted to 12.5% moisture content.

The agronomic efficiency of the applied biochar (AE_B) was calculated as

$$AE_B = \frac{GY_B - GY_{B0}}{B_{\text{rate}}} \tag{3}$$

where GY_B is the grain yield at biochar rates of 15 or 30 t ha^{-1}, GY_{B0} is the grain yield for the control and B_{rate} is the rate of applied biochar.

2.5. Determination of radiation interception

The canopy spectral reflectance was measured using a handheld, 3-channel radiometer (670 nm, 730 nm and 780 nm) Rapidscan CS-45 (Holland Scientific, Lincoln, Nebraska, USA) in each plot every 7–9 days. The measurements were taken at about 90 cm height above the top of the crop canopy from 12 DAS to 103 DAS. The ratio vegetation index (RVI) was computed as the ratio of near-infrared at 780 nm (ρ_i) to red at 670 nm (ρ_r) reflectance. Daily values of RVI were calculated by linear interpolation between two measurement dates. The function given by Christensen and Goudrian (1993) was used to first approximate RVI from fraction of intercepted photosynthetically active radiation (f_{PAR}; Eqs. (4)–(6)):

$$RVI = \frac{\{\rho_{i,\infty} + (n_i/\rho_{i,\infty})(1 - f_{PAR})\}}{\{\rho_{r,\infty} + (n_r/\rho_{r,\infty})(1 - f_{PAR})^2\}} \times \frac{\{1 + n_r(1 - f_{PAR})^2\}}{\{1 + n_i(1 - f_{PAR})\}} \tag{4}$$

$$n_r = \frac{\rho_{r,\infty} - \rho_{r,s}}{\rho_{r,s} - 1/\rho_{r,\infty}} \tag{5}$$

$$n_i = \frac{\rho_{i,\infty} - \rho_{i,s}}{\rho_{i,s} - 1/\rho_{i,\infty}} \tag{6}$$

where $\rho_{i,\infty}$ is the near-infrared reflectance at maximum *RVI*; $\rho_{r,\infty}$ is the red reflectance at maximum *RVI*; $\rho_{i,s}$ is the near-infrared reflectance from the bare soil where *RVI* was the lowest and $\rho_{r,s}$ is the red reflectance from the bare soil where *RVI* was the lowest. An exponential function was then fitted to tabulated data pairs of f_{PAR} and RVI and the sum of squared differences between the approximated and the exponential model values of f_{PAR} was minimized by iteration using the generalized reduced gradient nonlinear algorithm in Solver tool (Microsoft Excel 2010). The optimized exponential function was finally used to calculate daily f_{PAR} from the interpolated RVI values. This procedure was conducted for each plot. From the computed f_{PAR} values and the measurement of incident global radiation at the local meteorological station, the amount of IPAR (MJ m^{-2}) accumulated from DAS 12 to 103 was calculated as (Hammad et al., 2016; Zhou et al., 2017; Chakwizira et al., 2018):

$$IPAR = \sum_{12}^{103} 0.5 \times Q \times f_{PAR} \tag{7}$$

where *Q* is the daily global radiation (MJ m^{-2}).

2.6. Statistical analysis

To evaluate differences between means of treatment variables (GY, IPAR, WP, soil pH and SOC), linear mixed-effect models were fitted to the data with the *lmer* function in the 'lme4' package for R (R Core Team, 2013). Fixed effects of irrigation, biochar and year, as well as their interactions were analysed considering split-block (replicate) as random effect according to the following model:

$$V_{ijkm} = \mu + I_i + B_j + A_k + I_i \times B_j + I_i \times A_k + B_j \times A_k + P_m + e_{ikmn} \tag{8}$$

where *V* is an observation of the dependent variable, μ is the overall mean, *Ii* is the effect of irrigation ($i = 2$, full irrigation and no irrigation; for pH and SOC $i = 1$, full irrigation only), *Bj* is the effect of biochar application rate ($j = 0$, 15 and 30 t ha^{-1}), *Ak* is the effect of year ($k = 2017$ and 2018; for pH and SOC $k = 2018$ only), *Pm* is the random effect of replicate ($m = 4$) and *e* is the unexplained variation. The parameters of the models were estimated by the restricted maximum likelihood (REML) method. Model residuals were examined for normality and variables were log- or square-root-transformed, if necessary, in order to obtain normally distributed residuals and to stabilise the variance. When *F*-values were significant, Tukey's test at 95% confidence level was used for pair-wise comparison and detection of significant differences between the treatment means of the variables. Linear regression analyses between IPAR and grain yield were done separately for the irrigated and non-irrigated treatments for each experimental year on all the biochar rates.

3. Results

3.1. Climatic conditions

There was similarity between the distribution of rainfall for the two seasons (Fig. 1). In both seasons, rainfall was rather evenly distributed with few long dry spells. The longest dry spell in 2017 occurred during the mid-season growth stage (36 DAS to 56 DAS), whereas that in 2018 occurred during the initial stage of the crop growth (1 DAS to 22 DAS). Total rainfall recorded during the two growing seasons from sowing to harvest were 390 and 364 mm, for 2017 and 2018 season, respectively, whereas total rainfall from the onset of irrigation to the completion of irrigation were 160 and 231 mm, respectively. Total reference evapotranspiration (ET_0) computed with the FAO Penman-Monteith equation (Allen et al., 1998) during the two seasons were 315 and 574 mm, for the 2017 and 2018 season, respectively. The second season was characterised by higher solar radiation compared with the first season with average values of 9 and 16 MJ m^{-2} day^{-1} for the 2017 and 2018 season, respectively.

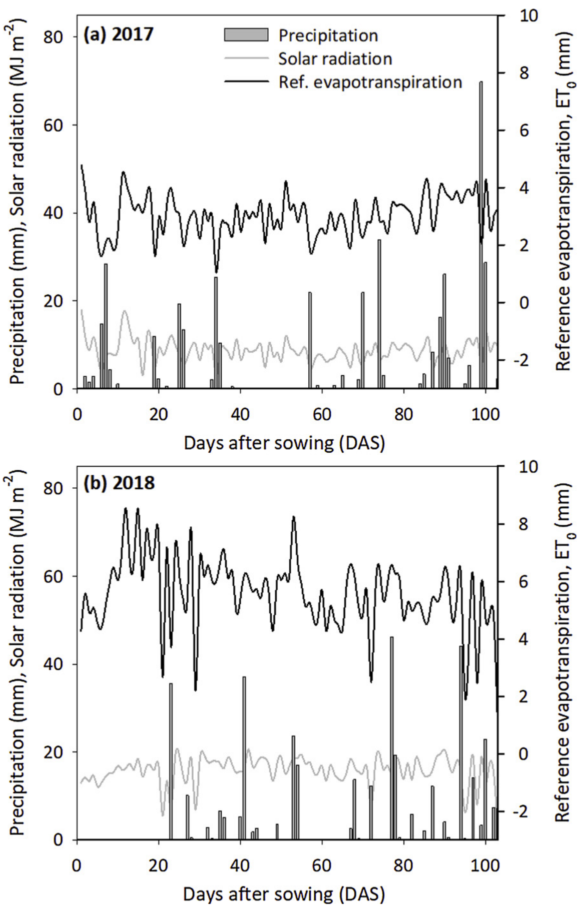

Fig. 1. Meteorological conditions from sowing to harvest for the 2017 and 2018 growing seasons.

3.2. *Soil physical and chemical conditions*

The SWD was generally higher in 2018 than in 2017 (Fig. 2). In the 2017 season, the highest mean deficit for the irrigated and the non-irrigated B_{30} treatments was 15.3 mm and 66.9 mm, respectively, while for the 2018 season the corresponding values were 18.6 mm and 69.7 mm. The I_0B_{30} treatment had three drying cycles in 2017 but their number increased to four during 2018 (Fig. 2a and b). In the 2017 season, the first, second and third drying cycles for the I_0B_{30} treatment lasted for 24, 14, and 18 days reaching 66.9, 28.6 and 26.7 mm SWD, respectively. During these periods, the I_iB_{30} treatment was irrigated six, three, and four times, respectively. Compared to 50% use of PAW, two of the SWD values in 2017 surpassed the limit of 50% use of PAW by 3% and 18%, whereas the rest of the SWD values were below the 50% use of PAW threshold (Fig. 2a). Compared to 2017, only one SWD exceeded 50% use of PAW in 2018 by 23%, although several SWD values were close to the 50% use of PAW than in 2017 (Fig. 2b). During the 2018 season, the drying cycles for the I_0B_{30} treatment ranged between 12 and 26 days. The highest value of 26 days corresponded to SWD of 69.7 mm while the other cycles of 12, 16 and 17 days recorded SWD of 42.6, 25 and 54 mm, respectively. The I_iB_{30} treatment was irrigated six, four, three and another three times during these dry periods, respectively. Opposite to our expectation, the biochar amended plots had lower soil water content as seen from the soil moisture retention curve (Fig. 3a). In fact, the highest biochar amount of 30 t ha^{-1} lowered the soil water content at all the matric potentials (Fig. 3a) whereas the PAW was marginally affected by biochar (Fig. 3b).

Soil pH was affected by biochar and was significantly higher compared to the control treatment (Table 3). Likewise, SOC in the B_{30} treatment was significantly higher by 42% than the B_0 treatment. The

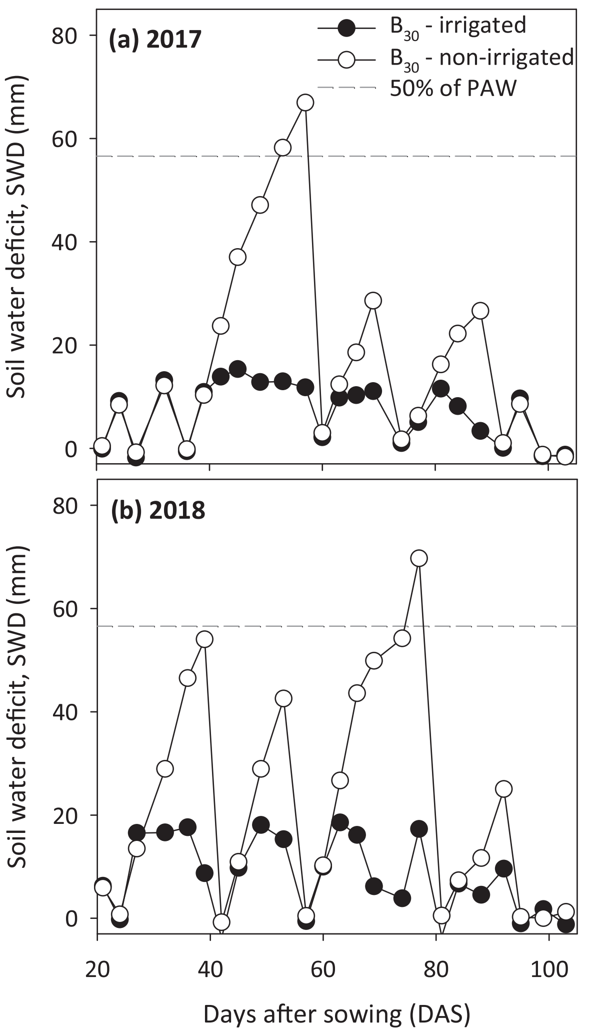

Fig. 2. Soil water deficit for the 30 t ha^{-1} biochar rate (B_{30}) under irrigated and non-irrigated treatments during 2017 and 2018 growing seasons. PAW is plant available water.

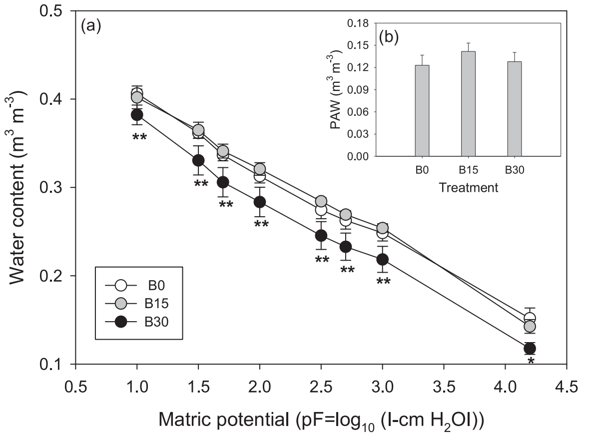

Fig. 3. (a) Soil water content measured in the matric potential range of pF 1.0–4.2 (pF is equivalent to the logarithm of cm water column) for the biochar rates of 0 t ha^{-1} (B_0), 15 t ha^{-1} (B_{15}) and 30 t ha^{-1} (B_{30}) under irrigated treatment in 2018. (b) Plant available water (PAW) for B_0, B_{15} and B_{30} treatments. ** indicates B_{30} is significantly lower ($P \leq 0.05$) than both B_0 and B_{15}, * indicates B_{30} is significantly lower than only B_0. Error bars indicate standard errors of the mean (n = 4). Figure adopted from Obour et al. (2019).

Table 3
pH, soil organic carbon (SOC), and texture (0–20 cm depth) in the different biochar treatments in the irrigated plots in 2018.

	Biochar rate (t ha^{-1})	pH ($CaCl_2$)	pH (H_2O)	SOC (%)	Clay (%)	Silt (%)	Sand (%)
Irrigated	0	4.28a	4.66a	1.04a	23	10	66
	15	4.71b	5.14b	1.12a	22	10	68
	30	4.80b	5.55c	1.48c	19	10	70

Values within the same column without common letters are significantly different at $P \leq 0.05$.

soil texture analysis showed that amended plots had a lower clay fraction compared to the unamended plots. On the other hand, the sand fraction in the amended plots was higher than in the control plot while the silt content remained unchanged between amended plots and control (Table 3).

3.3. Seasonal radiation interception

Fig. 4 shows the dynamics of maize f_{PAR} under different biochar and irrigation regimes. In both seasons, f_{PAR} was responsive to biochar rates and the B_{30} treatment had significant higher values compared to B_{15} and B_0 treatments but only on few of the measurement dates (Fig. 4a–c). Significant differences between the different treatments within DAS were recorded late in the 2017 season on 75 DAS for the irrigated and 69 and 75 DAS for the non-irrigated treatment (Fig. 4a and b). However, during the 2018 season, differences arose quite early at 30 and 40 DAS in the irrigated treatments (Fig. 4c). During the 2017 season, there was no significant difference in f_{PAR} between I_iB_0 and I_iB_{15} and also between I_0B_0 and I_0B_{15} treatments (Fig. 4a and b). During the 2018 season however, f_{PAR} for I_iB_{15} was significantly higher than that for I_iB_0 (Fig. 4c). In both growing seasons, the treatment without biochar (B_0) had significantly the lowest f_{PAR} values, both irrigated and non-irrigated, on five measurement dates. With respect to irrigation levels, there was no significant differences between I_i and I_0 at any date during 2017 but in 2018, significant differences arose early (30 DAS) and persisted until mid-season stage (60 DAS).

Table 4
Maize grain yield and accumulated intercepted photosynthetically active radiation (IPAR) as affected by irrigation and biochar treatments during the study period.

	Biochar rate (t ha^{-1})	Grain yield 2017 (t ha^{-1})	Grain yield 2018 (t ha^{-1})	Mean grain yield (t ha^{-1})
Irrigated	0	4.05 ab	4.43 ab	4.24 ab
	15	4.11 b	5.28 bc	4.69 b
	30	4.64 c	6.28 c	5.46 c
Non-irrigated	0	3.66 d	3.63 a	3.64 a
	15	3.69 ad	3.97 a	3.83 a
	30	4.40 bc	4.71 ab	4.55 b

	Biochar rate (t ha^{-1})	IPAR 2017 (MJ m^{-2})	IPAR 2018 (MJ m^{-2})	Mean IPAR (MJ m^{-2})
Irrigated	0	205 ab	321 abc	263 abc
	15	215 abc	334 bc	274 bcd
	30	246 c	365 c	305 d
Non-irrigated	0	199 a	253 a	226 a
	15	213 abc	271 ab	242 ab
	30	235 bc	350 c	293 cd

Values in columns per year without common letters are significantly different at $P \leq 0.05$.

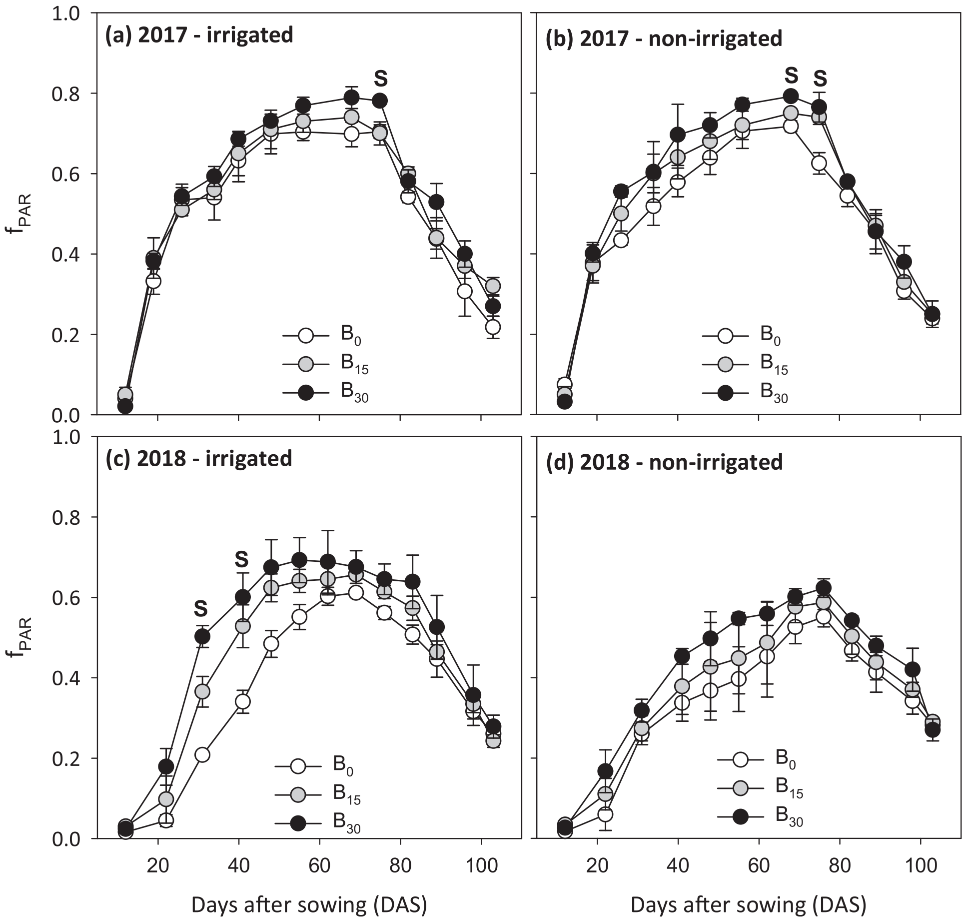

Fig. 4. Evolution of fraction of intercepted photosynthetically active radiation (f_{PAR}) over the growing seasons in 2017 and 2018 as affected by biochar rates 0 t ha^{-1} (B_0), 15 t ha^{-1} (B_{15}) and 30 t ha^{-1} (B_{30}) under irrigated and non-irrigated regimes. Error bars denote standard error of the mean (n = 4). The *S* indicates significant differences ($P \leq 0.05$) between at least two treatments within days after sowing (n = 4).

Table 5

ANOVA showing levels of significance of main effects (irrigation, biochar and year) and interactions on grain yield (GY), accumulated intercepted photosynthetically active radiation (IPAR), water productivity, (WP) soil pH, and soil organic Carbon (SOC). For the F-tests: * denotes $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$. Dash denotes analysis not conducted as pH and SOC were measured only in the irrigated treatment in 2018.

Variation	GY (t ha $^{-1}$)	IPAR (MJ m $^{-2}$)	WP (kg m $^{-3}$)	pH ($CaCl_2$)	pH (H_2O)	SOC (%)
Irrigation	***	**	***	–	–	–
Biochar	***	***	***	*	**	**
Year	***	***	***	–	–	–
Irrigation x biochar	ns	ns	ns	–	–	–
Irrigation x year	**	**	ns	–	–	–
Biochar x year	*	ns	ns	–	–	–
Irrigation x biochar x year	ns	ns	ns	–	–	–

3.4. Treatment effects on crop yield

Biochar increased GY significantly irrespectively of year but was affected by irrigation regime (Tables 4 and 5). Across years, GY for B_{30} under irrigation was significantly higher than all other treatments, whereas GY for B_{30} without irrigation was significantly higher than that of B_{15} and B_0, and the two latter were not significantly different (Table 4). When looking at individual years, no significant difference was found between B_{30} and B_{15} in 2018 even though only B_{30} had significantly higher GY than B_0. When looking at the individual years and treatments, B_{15} was not significantly different from B_0 whether irrigated or not while GY in B_{30} was higher in all cases. Across the two years and particular in 2018, irrigation increased GY significantly in both biochar treatments but not in the control. In 2017 the picture was however different as irrigation increased yield in B_0 and B_{15}, hence giving rise to an interaction between irrigation and year (Table 5). In general, the yield level was slightly higher in 2018 than 2017. Averaged across the two seasons, the non-irrigated treatment with highest biochar rate (I_0B_{30}) recorded GY similar to the irrigated treatment with no biochar (I_iB_0).

Linear regression between grain yield and pH using measurements from individual block replicates in the 2018 season showed grain yield was linearly and significantly ($P \leq 0.05$) related to pH (grain yield = 1.48*pH – 2.24; $R^2 = 0.6$, p-value = 0.003). Also, The GY for both the irrigated and non-irrigated treatments were significantly and linearly related to IPAR in both years except for the non-irrigated treatment in the 2018 season where the relation was not significant (Fig. 5). Overall, IPAR responded to treatments in the same way as GY (Tables 4 and 5) with biochar treatments having higher IPAR values independent of year and irrigation regime. None of the biochar levels had significantly higher IPAR under irrigated conditions than unirrigated in any year (Table 4). Nevertheless, an effect of irrigation and an interaction between irrigation and year was detected, which seemed both to be due to higher response of IPAR to irrigation in 2018 than in 2017, similar to GY. Treatments in the 2018 season intercepted more light i.e. had higher IPAR values compared to the 2017 season.

3.5. Water productivity

Variation in the seasonal amount of applied irrigation water and total water supplied (irrigation plus precipitation) affected WP differently for the two seasons (Table 6 and Fig. 6). Maize WP ranged from 0.69 to 1.0 kg m^{-3} in 2017 and 0.73 to 1.15 kg m^{-3} in 2018. Because the non-irrigated treatments received less water, the highest WP was recorded for the non-irrigated B_{30} treatments in both seasons (Fig. 6). In both years, and for both irrigated and non-irrigated treatments, WP for B_{30} was significantly higher than that of B_0. Averaged for the two seasons, the WP for the B_{30} was significantly higher than both B_{15} and B_0 in the non-irrigated treatment but only higher than B_0 in the irrigated treatment (Fig. 6). The average WP of the same biochar rates for the two seasons showed a significantly higher values in the unirrigated treatments compared to the irrigated treatments. Accordingly, in 2017 the biochar levels under non-irrigated conditions recorded significantly higher WP compared to their counterparts under irrigation in 2017, but not in 2018 that nevertheless showed the same tendency.

3.6. Efficiency of applied biochar

The AE_B values calculated for the two biochar rates of B_{15} and B_{30} were generally higher in the 2018 season compared to the 2017 season (Fig. 7). In fact, the irrigated B_{15} and B_{30} treatments were about fifteen and three times higher, respectively, in the 2018 season compared to the 2017 season whereas for the non-irrigated treatments it was about 9 times for the B_{15} but similar for the B_{30}. The AE_B ranged from 0.2 to 2.6% in 2017 and 2.3 to 6.2% in 2018. The AE_B in the 2017 season for both the irrigated and the non-irrigated B_{30} treatment, was five times higher than that of the B_{15} treatment whereas in the 2018 season the dose-response was comparable for both rates (Fig. 7). Irrigation overall increased the AE_B in both the B_{15} and B_{30} treatments, with a strong response in 2018 but little response in the 2017 season.

4. Discussion

4.1. Radiation interception and yield as affected by biochar and irrigation

Light interception as derived by f_{PAR} is strongly related to green leaf area index and hence to IPAR, thus taking into account the amount of incoming radiation. The present study is probably the first to investigate the impact of biochar amendment and irrigation on maize light interception, making it difficult to compare our results to others. However, studies on many crops have attributed increases in light interception to improved soil moisture and nutrient conditions leading to higher yield (Andersen et al., 1996; Ferreira and Carr, 2002; Oppong Danso et al., 2015; Tabarzad et al., 2016; Gou et al., 2017; Zhou et al., 2017). These observations agree with our results as the regressions showed maize grain yield to be positively and linearly correlated with IPAR, with R^2 of 0.59 and 0.66 for, respectively, irrigated and non-irrigated treatments in 2017 while corresponding R^2 values were 0.55 and 0.31 in 2018 (Fig. 5). The latter rather low R^2 value was likely a result of drought stress causing stomatal closure, which often erodes the relation between growth and green leaf area index found under well-watered conditions (Andersen et al., 1996). When examining the development of f_{PAR} over the season (Fig. 4), the most striking feature was the significant differences, which arose early in 2018 between irrigation levels in synchrony with the first drying cycle starting at around 30 DAS (Fig. 2). Probably early season PAW was still small due to an immature and shallow maize root system (e.g. Chilundo et al., 2017), leading to significant drought impact on leaf area development. At the same time, a clear positive response to biochar amendment was noted only in the irrigated treatments. This pattern indicated that biochar did not influence PAW appreciably, as otherwise a response to biochar would be expected in the non-irrigated treatments. The data on soil water retention are consistent with this showing little difference in PAW between biochar levels. Secondly, the expression of a biochar response in

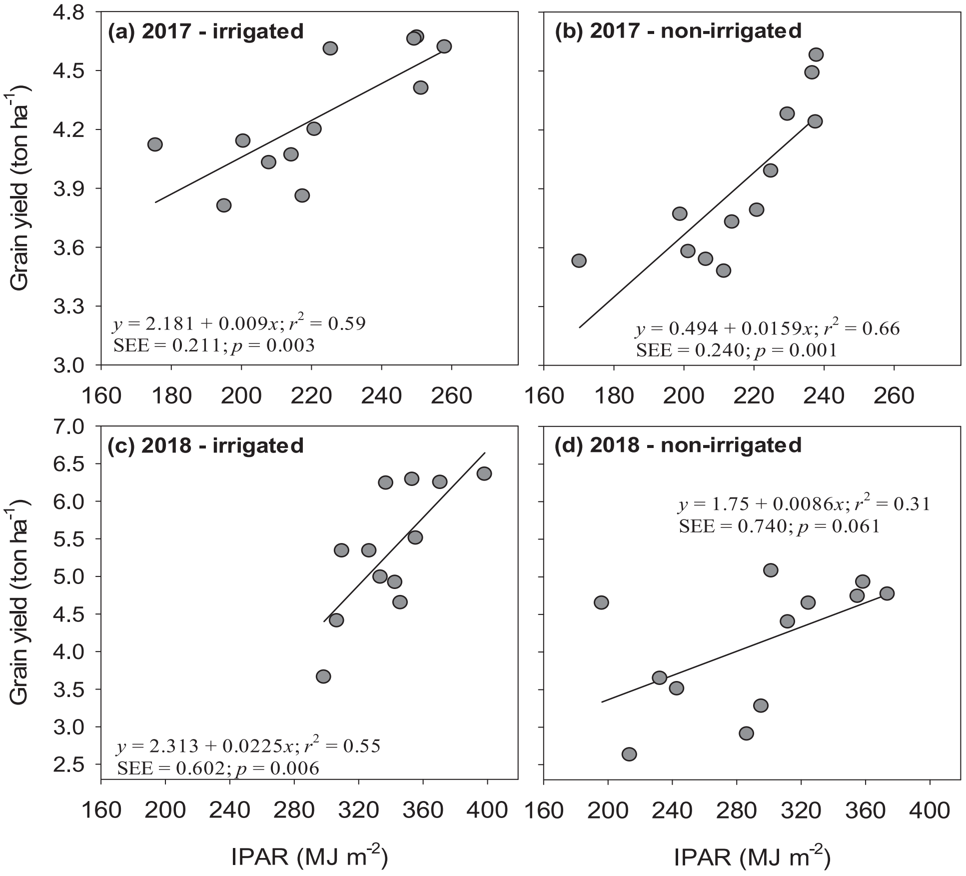

Fig. 5. Linear regressions between accumulated intercepted photosynthetically active radiation (IPAR) and grain yield for the biochar rates of 0 t ha^{-1} (B_0), 15 t ha^{-1} (B_{15}) and 30 t ha^{-1} (B_{30}) under irrigated and non-irrigated regimes for 2017 and 2018 growing seasons. SEE is standard error of the estimate (n = 4).

Table 6
Accumulated rainfall, irrigation water supplied to maize (IWS) and total water supplied to maize (rain + IWS) (TWS) for the different treatments during the growing seasons in 2017 and 2018.

Experimental year	Treatment	Rainfall (mm)	IWS (mm)	TWS (mm)
2017	I_iB_0	390	199.6	589.6
	I_iB_{15}	390	198.9	588.9
	I_iB_{30}	390	198.4	588.4
	I_0B_0	390	44.4	434.4
	I_0B_{15}	390	44.4	434.4
	I_0B_{30}	390	44.4	434.4
2018	I_iB_0	364	242.2	602.2
	I_iB_{15}	364	244.4	608.4
	I_iB_{30}	364	244.5	608.5
	I_0B_0	364	44.4	408.4
	I_0B_{15}	364	44.4	408.4
	I_0B_{30}	364	44.4	408.4

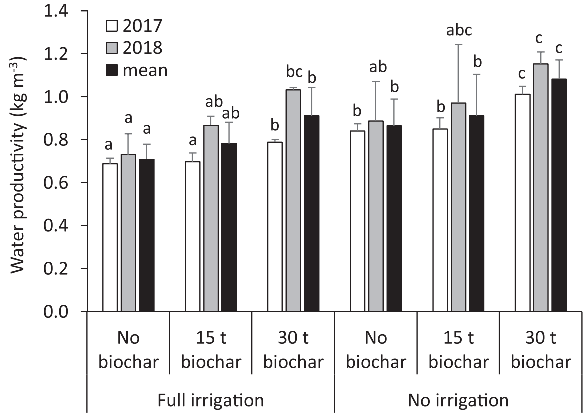

Fig. 6. Water productivity of the maize crop for the biochar rates of 0 t ha^{-1} (B_0), 15 t ha^{-1} (B_{15}) and 30 t ha^{-1} (B_{30}) under irrigated and non-irrigated regimes for both the 2017 and 2018 growing seasons. Bars per year without common letters are significantly different at p ≤ 0.05. Error bars indicate standard error of the mean (n = 4).

irrigated treatments indicated that one or more factors having synergistic effects with water were present in the biochar amended plots. In both seasons and under both irrigated and non-irrigated settings, the seasonal development of f_{PAR} showed the highest values for B_{30} followed by B_{15} and B_0 and this pattern was most pronounced in 2018 (Fig. 4). Collectively, the results indicate that biochar amendment caused better growth conditions in terms of either nutrient availability, soil physical conditions not related to soil water holding capacity or both. The higher crop response of biochar during the second season is consistent with the findings of Hua et al. (2014), whose result pointed to biochar becoming more functional in the second season. They attributed this to increased formations of soil aggregates, especially micro-aggregates, and their stability, and argued that the biochar could be a source of soil nutrients for a very long time span. Kätterer et al. (2019) provided similar interpretation of the persistent positive effects on yield they found over a 10-year period, while Raboin et al. (2016) ascribed the time-limited growth enhancement in their experiments as mainly due to a liming effect of biochar.

4.2. Soil fertility aspects

The yield of maize in the experimental field was moderate even under irrigated conditions, which indicate that soil nutrient availability

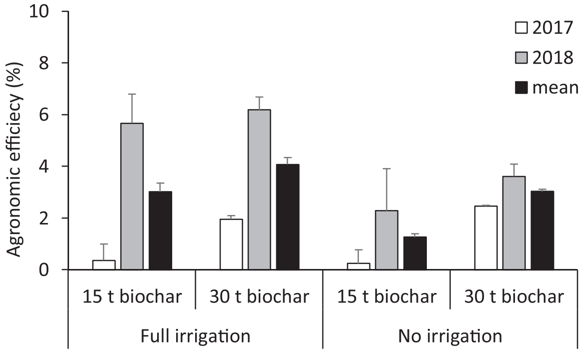

Fig. 7. Agronomic efficiency for biochar (AE_B) rates of 15 t ha^{-1} (B_{15}) and 30 t ha^{-1} (B_{30}) under irrigated and non-irrigated regimes for both the 2017 and 2018 growing seasons. Error bars indicate standard error of the mean (n = 4).

and soil physical properties in addition to water were limiting growth. The results further showed that yield was positively affected by biochar whether the crops were irrigated or not. Irrigation and biochar application had additive effects (Table 5). Such response is usually found when irrigation goes along with increased plant nutrient availability or other plant growth promoting factors e.g. (Perry et al., 2009). The finding of the present study is consistent with this and work of other authors (Gruba and Mulder, 2008; Sohi et al., 2010; Yeboah et al., 2016; Agbna et al., 2017; Cornelissen et al., 2018), who reported increase in maize yield with increasing biochar rate, which they attributed to increase in pH and SOC in biochar treated plots. In accordance with these findings, the addition of the alkaline rice straw biochar in the present study significantly increased pH and SOC in the biochar-treated plots compared to the control. The base pH (H_2O) of 4.66 in the experimental field was very low (Table 3) and the increase in maize grain yield due to biochar amendment was positively correlated with the increase in pH (H_2O). This was likely a reflection of the regularly reported positive effect of decreased soil acidity on nutrient availability and crop yield (Jeffery et al., 2017; Cornelissen et al., 2018). It is well known that e.g. the availability of P is decreased outside an optimum pH range of about 5.7–6.5 (Haynes and Naidu, 1998; Fixen and Bruulsema, 2014). For a range of Ghanaian soils and biochar types, Eduah et al. (2019) concluded that P-desorbability generally increased in the acid soils upon biochar amendment. One of the soils, labelled 'soil A' in the aforementioned study, was actually sampled from our experimental site and as well displayed increased P-desorbability after biochar application. In addition to the increased pH, also increases in SOC in the biochar-treated plots clearly was a result of the addition of high carbon content (25.4%) rice straw biochar (Table 1). The increase of SOC may have promoted root growth through improved soil aggregation (Amoakwah et al., 2017a) which may have been additionally furthered by the increase in pH e.g. Rao et al. (2016) of this low-pH soil.

The hypothesis that SWR and PAW also in the present soil type will increase with biochar amendment was not supported by our results as the soil with the highest biochar rate had significantly reduced SWC within the matric potential range of −10 to −1000 hPa relative to the other biochar rates, while no significant differences were observed in PAW between biochar rates. There is therefore no evidence to link the highest grain yield obtained in the B_{30} treatment to increased SWR and PAW. These results contrast with those often reported for increased SWR and PAW after biochar amendment in sand textured soils (e.g. Mollinedo et al., 2015; Głąb et al., 2016; Obia et al., 2016; Fu et al., 2019). While the results of the present study may appear unusual, it nonetheless agrees with the results of Aller et al. (2017) as well as the findings of Castellini et al. (2015) both of whom reported decreased SWR and PAW after biochar application in fine textured soils. Thus, the conflicting results between our study and the frequently reported SWR and PAW increase after biochar amendment can be explained by different soil types. The soil used in the present study was sandy clay loam with appreciable clay content (Table 2) while those for Mollinedo et al. (2015), Głąb et al. (2016), Obia et al. (2016) and Fu et al. (2019) were sandy textured soils. As explained by Trifunovic et al. (2018), reduction in SWR after biochar amendment in fine textured soils is partly due to increases in the number of soil macropores, which barely hold water under tension and the other part due to the biochar particles blocking micro pores thereby impeding the movement and retention of water in the soil.

4.3. Water productivity and agronomic efficiency of biochar

The combined effect of higher yield as result of biochar amendment and less water being supplied (only rainfall) to the non-irrigated treatments resulted in enhanced WP for the I_0B_{30} treatment. The WP values of the rainfed treatments of the present study were similar to values reported by Asare et al. (2011), who reported an average value of 1.2 kg m^{-3} under similar climatic conditions in Ghana. However, the maize water productivity values were generally low, which may be attributed partly to the general yield level and partly to climatic reasons. Maize can attain WP values of up to about 2.5 kg m^{-3} in this specific region of Ghana (Edreira et al., 2018), but Ghana and indeed large parts of the South Saharan Area often falls appreciably below attainable levels (Edreira et al., 2018). Apart from the yield level, the WP is depending foremost on the evaporative demand of the atmosphere, which is driven by the water vapor pressure deficit (VPD) providing the gradient for the movement of water from soil through plants and to the atmosphere as outlined by Steduto et al. (2007). Therefore, we would have expected WP to be higher in 2017 where there was a lower evapotranspiration (accumulative ET_o of 315 mm) compared to the 2018 season with higher cumulative evaporative demand of 574 mm. However, the yield level was lower in 2017 (Table 4), which apparently counterbalanced the expected VPD effect.

The WP results and the results with respect to agronomic efficiency of biochar application (AE_B) share the common feature that improvement of yield by optimization of any growth factor, not taken into account by the denominator of the indices themselves (Eqs. (2) and (3)), will increase WP and AE_B e.g. (Perry et al., 2009). Thus, WP was increased by biochar amendment of the soil (Fig. 6) and AE_B was enhanced by irrigation. However, unexpectedly, the AE_{30} was higher than AE_{15} in either seasons and whether irrigated or non-irrigated. Especially since agronomic efficiencies for plant nutrient supply usually decline with increasing rates of nutrient applications. Although our data are limited and needs to be confirmed by additional experiments, they indicate that higher yield responses to biochar are best attained at relatively high rates of biochar amendment. The 30 t ha^{-1} that was the maximum rate here may be difficult to supply both from an economic and availability point of view. However, in the SDAG, there are generally plenty of organic residues produced, which may be used for biochar production. As an example, in the palm industry, a large multinational company located in the SDAG, i.e. Ghana Oil Palm Development Company, generates an average 390 ton of oil palm fruit residues per day as a by-product (Richard Nwiah, personal communication). The empty fruit bunch could be used as a low-cost residue to produce biochar, making the application to farmland more economically feasible. Nevertheless, the duration of the biochar effects remains crucial from an economic point of view and needs further and continued long-term investigations.

5. Conclusions

The amendment of biochar to soil is expected to increase crop production and to become a viable management practice. Under the soil and the climatic conditions of the present study, rice straw biochar appreciably increased maize grain yield and intercepted radiation. Furthermore, the application of 30 t ha^{-1} rice straw biochar increased grain yield and intercepted radiation and improved maize water productivity, whether the maize crop was irrigated or not. The yield of non-irrigated maize was reduced by 20% compared to the yield of irrigated maize over the two seasons. Consequently, maize water productivity of non-irrigated treatments was significantly higher compared to the irrigated treatments. Part of the effect was related to enhanced soil pH and organic carbon, but not related to PAW nor SWR. This study showed that in the SDAG of eastern Ghana, biochar application of 30 t ha^{-1} has the potential to become a recommended practice for farmers to increase maize yield and enhance water productivity depending on the price of biochar. The long-term effects of biochar addition to the studied soils should be investigated in future studies.

Declaration of Competing Interest

None.

Acknowledgements

Authors thank Danida, the Ministry of Foreign Affairs of Denmark, for financial support through the project Green Cohesive Agricultural Resource Management of Water, Energy from Biomass, Soil, Organics and Crops (WEBSOC), DFC Project No. 13-01AU.

References

Abiven, S., Hund, A., Martinsen, V., Cornelissen, G., 2015. Biochar amendment increases maize root surface areas and branching: a shovelomics study in Zambia. Plant Soil 395, 45–55.

Adjei-Nsiah, S., Ahiakpa, J., Asamoah-Asante, G., 2018. Productivity of pigeonpea genotypes as influenced by palm bunch ash and NPK fertiliser application and their residual effects on maize yield. Ann. Agric. Sci. 63, 83–89.

Agbna, G.H., Dongli, S., Zhipeng, L., Elshaikh, N.A., Guangcheng, S., Timm, L.C., 2017. Effects of deficit irrigation and biochar addition on the growth, yield, and quality of tomato. Sci. Hortic. 222, 90–101.

Ahmed, F., Arthur, E., Plauborg, F., Razzaghi, F., Kørup, K., Andersen, M.N., 2018. Biochar amendment of fluvio-glacial temperate sandy subsoil: effects on maize water uptake, growth and physiology. J. Agron. Crop. Sci. 204, 123–136.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration-Guidelines for Computing Crop Water Requirements-FAO Irrigation and Drainage Paper 56.

Aller, D., Rathke, S., Laird, D., Cruse, R., Hatfield, J., 2017. Impacts of fresh and aged biochars on plant available water and water use efficiency. Geoderma 307, 114–121.

Amir, J., Sinclair, T., 1991. A model of water limitation on spring wheat growth and yield. Field Crops Res. 28, 59–69.

Amoakwah, E., Frimpong, K.A., Arthur, E., 2017a. Corn cob biochar improves aggregate characteristics of a tropical sandy loam. Soil Sci. Soc. Am. J. 81, 1054–1063.

Amoakwah, E., Frimpong, K.A., Okae-Anti, D., Arthur, E., 2017b. Soil water retention, air flow and pore structure characteristics after corn cob biochar application to a tropical sandy loam. Geoderma 307, 189–197.

Andersen, M.N., Heidmann, T., Plauborg, F., 1996. The effects of drought and nitrogen on light interception, growth and yield of winter oilseed rape. Acta Agric. Scand. Sect. B—Soil Plant Sci. 46, 55–67.

Asare, D.K., Frimpong, J.O., Ayeh, E.O., Amoatey, H.M., 2011. Water use efficiencies of maize cultivars grown under rain-fed conditions. Agric. Sci. 2, 125–130.

Blanco-Canqui, H., 2017. Biochar and soil physical properties. Soil Sci. Soc. Am. 81, 687–711.

Bornø, M.L., Eduah, J.O., Müller-Stöver, D.S., Liu, F., 2018. Effect of different biochars on phosphorus (P) dynamics in the rhizosphere of Zea mays L. (maize). Plant Soil 431, 257–272.

Breuning-Madsen, H., Kristensen, J.Å., Awadzi, T.W., Murray, A.S., 2017. Early cultivation and bioturbation cause high long-term soil erosion rates in tropical forests: OSL based evidence from Ghana. Catena 151, 130–136.

Burney, J.A., Naylor, R.L., Postel, S.L., 2013. The case for distributed irrigation as a development priority in sub-Saharan Africa. Proc. Natl. Acad. Sci. U. S. A. 110, 12513–12517.

Castellini, M., Giglio, L., Niedda, M., Palumbo, A., Ventrella, D., 2015. Impact of biochar addition on the physical and hydraulic properties of a clay soil. Soil Tillage Res. 154, 1–13.

Chakwizira, E., Teixeira, E., Meenken, E., Michel, A., Maley, S., 2018. Radiation use efficiency and biomass partitioning to storage roots in fodder beet crops. Eur. J. Agron. 92, 63–71.

Chilundo, M., Joel, A., Wesström, I., Brito, R., Messing, I., 2017. Response of maize root growth to irrigation and nitrogen management strategies in semi-arid loamy sandy soil. Field Crops Res. 200, 143–162.

Christensen, S., Goudrian, J., 1993. Deriving light interception and biomass from spectral reflectance ratio. Remote Sens. Environ. 43, 87–95.

Cornelissen, G., Nurida, N.L., Hale, S.E., Martinsen, V., Silvani, L., Mulder, J., 2018. Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol. Sci. Total Environ. 634, 561–568.

Dworak, T., Berglund, M., Laaser, C., Strosser, P., Roussard, J., Grandmougin, B., Kossida, M., Kyriazopoulou, I., Kolberg, S., Montesinos Barrios, P., 2007. EU Water Saving Potential (Part 1-Report).

Edreira, J.I.R., Guilpart, N., Sadras, V., Cassman, K.G., van Ittersum, M.K., Schils, R.L., Grassini, P., 2018. Water productivity of rainfed maize and wheat: a local to global perspective. Agric. For. Meteorol. 259, 364–373.

Eduah, J., Nartey, E., Abekoe, M., Breuning-Madsen, H., Andersen, M., 2019. Phosphorus retention and availability in three contrasting soils amended with rice husk and corn cob biochar at varying pyrolysis temperatures. Geoderma 341, 10–17.

Faloye, O., Alatise, M., Ajayi, A., Ewulo, B., 2019. Effects of biochar and inorganic fertiliser applications on growth, yield and water use efficiency of maize under deficit irrigation. Agric. Water Manage. 217, 165–178.

Ferreira, T., Carr, M., 2002. Responses of potatoes (Solanum tuberosum L.) to irrigation and nitrogen in a hot, dry climate: I. Water use. Field Crops Res. 78, 51–64.

Fixen, P.E., Bruulsema, T.W., 2014. Potato management challenges created by phosphorus chemistry and plant roots. Am. J. Potato Res. 91, 121–131.

Fu, Q., Zhao, H., Li, T., Hou, R., Liu, D., Ji, Y., Zhou, Z., Yang, L., 2019. Effects of biochar addition on soil hydraulic properties before and after freezing-thawing. Catena 176, 112–124.

Gao, S., Hoffman-Krull, K., Bidwell, A., DeLuca, T., 2016. Locally produced wood biochar increases nutrient retention and availability in agricultural soils of the San Juan Islands, USA. Agric. Ecosyst. Environ. 233, 43–54.

Gee, G.W., Or, D., 2002. Particle-size analysis. In: Dane, J.H., Topp, C.G. (Eds.), Methods of Soil Analysis: Part 4 Physical Methods. SSSA Book Series. Soil Science Society of America, Madison, WI, pp. 255–293.

Głąb, T., Palmowska, J., Zaleski, T., Gondek, K., 2016. Effect of biochar application on soil hydrological properties and physical quality of sandy soil. Geoderma 281, 11–20.

Gou, F., van Ittersum, M.K., Simon, E., Leffelaar, P.A., van der Putten, P.E., Zhang, L., van der Werf, W., 2017. Intercropping wheat and maize increases total radiation interception and wheat RUE but lowers maize RUE. Eur. J. Agron. 84, 125–139.

Gruba, P., Mulder, J., 2008. Relationship between aluminum in soils and soil water in mineral horizons of a range of acid forest soils. Soil Sci. Soc. Am. J. 72, 1150–1157.

Hammad, H.M., Abbas, F., Ahmad, A., Fahad, S., Laghari, K.Q., Alharby, H., Farhad, W., 2016. The effect of nutrients shortage on plant's efficiency to capture solar radiations under semi-arid environments. Environ. Sci. Pollut. Res. 23, 20497–20505.

Haynes, R.J., Naidu, R., 1998. Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: a review. Nutr. Cycl. Agroecosyst. 51, 123–137.

Hua, L., Lu, Z., Ma, H., Jin, S., 2014. Effect of biochar on carbon dioxide release, organic carbon accumulation, and aggregation of soil. Environ. Prog. Sustain. Energy 33, 941–946.

Jay, C.N., Fitzgerald, J.D., Hipps, N.A., Atkinson, C.J., 2015. Why short-term biochar application has no yield benefits: evidence from three field-grown crops. Soil Use Manage. 31, 241–250.

Jeffery, S., Abalos, D., Prodana, M., Bastos, A.C., Van Groenigen, J.W., Hungate, B.A., Verheijen, F., 2017. Biochar boosts tropical but not temperate crop yields. Environ. Res. Lett. 12, 053001.

Kätterer, T., Roobroeck, D., Andrén, O., Kimutai, G., Karltun, E., Kirchmann, H., Nyberg, G., Vanlauwe, B., de Nowina, K.R., 2019. Biochar addition persistently increased soil fertility and yields in maize-soybean rotations over 10 years in sub-humid regions of Kenya. Field Crops Res. 235, 18–26.

Kristensen, J.A., Boëtius, S.H., Abekoe, M., Awadzi, T.W., Breuning-Madsen, H., 2019. The combined effect of termite bioturbation and water erosion on soil nutrient stocks along a tropical forest catena in Ghana. Catena 178, 307–312.

Manevski, K., Lærke, P.E., Jiao, X., Santhome, S., Jørgensen, U., 2017. Biomass productivityand radiation utilisation of innovative cropping systems for biorefinery. Agric. For. Meteorol. 233, 250–264.

Mia, S., Dijkstra, F.A., Singh, B., 2017. Long-term aging of biochar: a molecular understanding with agricultural and environmental implications. Adv. Agron. 141, 1–51.

Mollinedo, J., Schumacher, T.E., Chintala, R., 2015. Influence of feedstocks and pyrolysis on biochar's capacity to modify soil water retention characteristics. J. Anal. Appl. Pyrolysis 114, 100–108.

Monnie, F., 2016. Effect of biochar on soil physical properties, water use efficiency, and growth of maize in a sandy loam soil. University of Ghana.

Monteith, J.L., 1994. Validity of the correlation between intercepted radiation and biomass. Agric. For. Meteorol. 68, 213–220.

Obia, A., Mulder, J., Martinsen, V., Cornelissen, G., Børresen, T., 2016. In situ effects of biochar on aggregation, water retention and porosity in light-textured tropical soils. Soil Tillage Res. 155, 35–44.

Obour, P.B., Oppong Danso, E., Yakubu, A., Abenney-Mickson, S., Sabi, E.B., Darrah, Y.K., Arthur, E., 2019. Water retention, air exchange and pore structure characteristics after 3 years of rice straw biochar application to an Acrisol. Soil Sci. Soc. Am. J under review.

Ofosu-Budu, K., 2003. Performance of citrus rootstocks in the forest zone of Ghana. Ghana J. Horti. 3, 1–9.

Olesen, J.E., Chirinda, N., Adiku, S.G., 2013. Climate change impacts on crop productivity and possible adaptations in Ghana. Ghana Policy J. 5, 43–61.

Olesen, J.E., Mortensen, J.V., Jørgensen, L.N., Andersen, M.N., 2000. Irrigation strategy, nitrogen application and fungicide control in winter wheat on a sandy soil. I. Yield, yield components and nitrogen uptake. J. Agric. Sci. 134, 1–11.

Oppong Danso, E., Abenney-Mickson, S., Sabi, E., Plauborg, F., Abekoe, M., Kugblenu, Y.O., Jensen, C.R., Andersen, M.N., 2015. Effect of different fertilization and irrigation methods on nitrogen uptake, intercepted radiation and yield of okra (Abelmoschus esculentum L.) grown in the Keta Sand Spit of Southeast Ghana. Agric. Water Manag. 147, 34–42.

Paneque, M., José, M., Franco-Navarro, J.D., Colmenero-Flores, J.M., Knicker, H., 2016.

Effect of biochar amendment on morphology, productivity and water relations of sunflower plants under non-irrigation conditions. Catena 147, 280–287.

Perry, C., Steduto, P., Allen, R.G., Burt, C.M., 2009. Increasing productivity in irrigated agriculture: agronomic constraints and hydrological realities. Agric. Water Manage. 96, 1517–1524.

Plauborg, F., Iversen, B.V., Lærke, P.E., 2005. In situ comparison of three dielectric soil moisture sensors in drip irrigated sandy soils. Vadose Zone J. 4, 1037–1047.

Poku, A.-G., Birner, R., Gupta, S., 2018. Why do maize farmers in Ghana have a limited choice of improved seed varieties? An assessment of the governance challenges in seed supply. Food Secur. 10, 27–46.

R Core Team, 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing. Vienna, Austria. URL https://www.R-project.org/.

Raboin, L.-M., Razafimahafaly, A.H.D., Rabenjarisoa, M.B., Rabary, B., Dusserre, J., Becquer, T., 2016. Improving the fertility of tropical acid soils: liming versus biochar application? A long term comparison in the highlands of Madagascar. Field Crops Res. 199, 99–108.

Ramlow, M., Foster, E., Del Grosso, S., Cotrufo, M., 2019. Broadcast woody biochar provides limited benefits to deficit irrigation maize in Colorado. Agric. Ecosyst. Environ. 269, 71–81.

Rao, I.M., Miles, J.W., Beebe, S.E., Horst, W.J., 2016. Root adaptations to soils with low fertility and aluminium toxicity. Ann. Bot. 118, 593–605.

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M., Steduto, P., 2017. Sustainable intensification of agriculture for human prosperity and global sustainability. Ambio 46, 4–17.

Shah, S., McKenzie, B., Gaunt, R., Marshall, J.W., Frampton, C., 2004. Effect of early blight (Alternaria solani) and different nitrogen inputs on radiation interception, radiation use efficiency, and total dry matter production in potatoes (Solanum tuberosum) grown in Canterbury, New Zealand. J. Crop Horti. Sci. 32, 263–272.

Sohi, S.P., Krull, E., Lopez-Capel, E., Bol, R., 2010. A review of biochar and its use and function in soil. Adv. Agron. 105, 47–82.

Steduto, P., Hsiao, T.C., Fereres, E., 2007. On the conservative behavior of biomass water productivity. Irrig. Sci. 25, 189–207.

Tabarzad, A., Ghaemi, A.A., Zand-Parsa, S., 2016. Extinction coefficients and radiation use efficiency of barley under different irrigation regimes and sowing dates. Agric. Water Manage. 178, 126–136.

Thomas, G.W., 1996. Soil pH and Soil Acidity. Methods of Soil Analysis Part 3—chemical Methods. pp. 475–490.

Trifunovic, B., Gonzales, H.B., Ravi, S., Sharratt, B.S., Mohanty, S.K., 2018. Dynamic effects of biochar concentration and particle size on hydraulic properties of sand. Land Degrad. Dev. 29, 884–893.

Vargas, L., Andersen, M.N., Jensen, C., Jørgensen, U., 2002. Estimation of leaf area index, light interception and biomass accumulation of Miscanthus sinensis 'Goliath' from radiation measurements. Biomass Bioenergy 22, 1–14.

WRB, I.W.G, 2015. World Reference Base for Soil Resources 2014, Update 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106. FAO, Rome.

Xiu, L., Zhang, W., Sun, Y., Wu, D., Meng, J., Chen, W., 2019. Effects of biochar and straw returning on the key cultivation limitations of Albic soil and soybean growth over 2 years. Catena 173, 481–493.

Yeboah, E., Asamoah, G., Kofi, B., Abunyewa, A.A., 2016. Effect of biochar type and rate of application on maize yield indices and water use efficiency on an Ultisol in Ghana. Energy Procedia 93, 14–18.

Zhou, Z., Plauborg, F., Kristensen, K., Andersen, M.N., 2017. Dry matter production, radiation interception and radiation use efficiency of potato in response to temperature and nitrogen application regimes. Agric. For. Meteorol. 232, 595–605.