


# Effect of rice straw biochar and irrigation on growth, dry matter yield and radiation-use efficiency of maize grown on an Acrisol in Ghana

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## Abstract

In order to determine whether the current low productivity associated with rainfed cultivation on degraded soils in Ghana can be improved by biochar amendment and irrigation, field experiments with maize were conducted over two seasons in 2017 and 2018. Rice straw biochar at rates of 0 t/ha ( $B_0$ ), 15 t/ha ( $B_{15}$ ) and 30 t/ha ( $B_{30}$ ) was combined with irrigation regimes of full irrigation ( $I_{100}$ ), deficit irrigation ( $I_{60}$ ) and no irrigation ( $I_0$ ). The  $I_{100}$  treatment was irrigated to field capacity every 3–4 days according to time domain reflectometry measurements while the  $I_{60}$  treatment received 60% of the irrigation amount given to  $I_{100}$  but with the same irrigation frequency. The  $I_0$  treatment was not irrigated. In both seasons, the  $B_{30}$  treatment recorded the highest total dry matter yield (TDMY), intercepted photosynthetically active radiation (IPAR) and radiation-use efficiency (RUE) and these were significantly ( $p \leq .05$ ) higher than  $B_0$  except for RUE in 2017. Irrigation regimes did not significantly affect TDMY, IPAR and RUE in 2017 but compared to  $I_{100}$ ,  $I_0$  significantly reduced TDMY, IPAR and RUE in the relatively dryer 2018 season. Measured ratio vegetation indices differentiated biochar treatments earlier in the 2018 season than during 2017 and increase of leaf chlorophyll content indices with biochar rate in both seasons indicated that biochar amendment improved nitrogen uptake. Our study demonstrated that rice straw biochar is capable of increasing TDMY, IPAR and RUE of maize grown on degraded soils in Ghana. The study further showed that TDMY, IPAR and RUE of deficit irrigated maize for two seasons were similar to the counterpart fully irrigated maize and may be a viable water management option for farmers in Ghana to save irrigation water resources.

## KEYWORDS

intercepted radiation, leaf chlorophyll content, ratio vegetation index, soil water content, weathered tropical soil

## 1 | INTRODUCTION

Most soils in Ghana are degraded due to continuous cultivation without replenishment of nutrients. Restoring the fertility of these degraded soils is a necessity to improve the productivity of farms

in Ghana. One well-known approach to improve the health of degraded soils is biochar amendment. Biochar is a carbon rich substance made by burning biomass at high temperature with limited or no supply of oxygen. The raw materials required to produce biochar are usually low-cost organic residues which are plentiful

in Ghana as rice farmers alone produce around 360,000 tons of rice straw residue annually (Duku, Gu, & Hagan, 2011). Amending the soil with biochar may improve soil physical and chemical properties as well as improve crop performance (Alvarez-Campos et al., 2018; Dong, Ma, Zhu, Li, & Gu, 2013; Jeffery et al., 2017). The underlying processes whereby biochar improve soil and crop performance are complex interactions of several factors such as pyrolysis temperature and the feedstock material (Jeffery, Verheijen, Velde, & Bastos, 2011; Zhao, Cao, Mašek, & Zimmerman, 2013). Consequently, there is wide variation in the response of crops to biochar amended soils (Jeffery et al., 2017; Ramlow, Foster, Grosso, & Cotrufo, 2019).

Biochar amendment in combination with deficit irrigation increases crop yield and improves water-use efficiency (Aller, Rathke, Laird, Cruse, & Hatfield, 2017; Burney & Naylor, 2012; Jeffery et al., 2017). For example, Agegnehu, Bass, Nelson, and Bird (2016) found that willow biochar amendment rate of 10 t/ha increased maize yield by 29% while Faloye, Alatisé, Ajayi, and Ewulo (2017) reported similar findings with increased maize yields of 56, 68 and 76% after amendment with 3, 6 and 10 t/ha rates of corn cob biochar. Likewise, Pandit et al. (2018) reported that forest shrub biochar amendment rates of 15, 25 and 40 t/ha increased maize yield by 50, 43 and 97%, respectively. With regards to deficit irrigation, Ahmed et al. (2018) established that rice straw biochar applied at a concentration of 3% by weight significantly increased maize biomass even under soil drying by sustaining maize transpiration. On the other hand, Agbna et al. (2017) reported no difference in tomato yields for both full irrigation (100% ETc) and deficit irrigation (50% ETc) in plots amended with 25 t/ha wheat straw biochar.

In Ghana, there are very few published field experimental results that show crop performance in biochar amended soils (e.g. Akoto-Danso et al., 2019; Oppong Danso et al., 2019; Steiner et al., 2018). Akoto-Danso et al. (2019) as well as Steiner et al. (2018) reported significant increases in maize and lettuce yield after amendment with 20 t/ha rice husk biochar. However, both studies were carried out under rainfed conditions and no attempt was made to investigate how biochar interacts with soil moisture to affect crop performance. On the other hand, Oppong Danso et al. (2019) investigated the interactive effects of biochar with full irrigation and without irrigation and found the highest maize grain yield in the irrigated treatment amended with 30/ha rice straw biochar. None of the studies investigated biochar's interaction with deficit irrigation to affect crop growth and yield. Thus, field experimental investigations of crop performance in biochar amended soils under deficit irrigation are lacking in Ghana.

Most field experiments have used dry matter yield as marker to determine the impact of biochar and soil moisture on crop performance. Conventionally, a crop's capacity to produce dry matter is highly associated with the quantity of radiation the canopy captures and the conversion of the captured radiation into biomass, the so-called radiation-use efficiency (RUE) (Monteith, 1977). Therefore, for a more dynamic and complete understanding of

crop dry matter production as a function of available resources, it is worthwhile to explore the temporal evolution of radiation interception and RUE as a measure of crop physiological function. However, and as far as we can tell from existing literature, there is no other field experiment in Ghana that has investigated how deficit irrigation and biochar interacts to affect maize crop performance in terms of dry matter yield, intercepted radiation and RUE. The present study was therefore carried out to fill this knowledge gap.

## 2 | MATERIALS AND METHODS

### 2.1 | Site description

The field experiments were carried out at the University of Ghana's Forest and Horticultural Crops Research Centre (06° 08' 37"N, and 00° 54' 10" W), Kade at an altitude of 180 m above sea level. The Research Centre is located within the semi-deciduous agroecological zone of Eastern Ghana. There are two distinct rainy seasons (major and minor seasons) in the study area. The major season starts from April and ends in July while the minor season covers September to October. The yearly rainfall amount ranges between 1,300 and 1,800 mm (Ofosu-Budu, 2003). There is usually a long dry period from December to March. Yearly average annual temperature is 28°C while annual potential evaporation is about 1,400 mm.

### 2.2 | Soil and biochar properties

The soil of the experimental field has a sandy clay loam texture and is classified as an Acrisol in the WRB (2015) classification. The physical and chemical properties of the soil prior to the experiments were as follows: 21% clay, 11% silt, 68% sand, 1.33% organic carbon, 0.12% total nitrogen, bulk density of 1.52 g/cm<sup>3</sup>, pH of 5.5, electrical conductivity of 36 µS/cm, total phosphorus was <0.4 mg 100 g<sup>-1</sup>, potassium content of 14.8 mg 100 g<sup>-1</sup> and magnesium content of 10.3 mg 100 g<sup>-1</sup>. The rice straw biochar used for the study was pyrolysed in a Lucia stove reactor at temperature range of 500°C–550°C. The physical and chemical properties of the rice straw biochar used in the experiments were as follows: 25.5% organic matter, 1.0% total nitrogen, total phosphorus of 142 mg 100 g<sup>-1</sup>, potassium content of 1,770 mg 100 g<sup>-1</sup> and magnesium content of 133 mg 100 g<sup>-1</sup>.

### 2.3 | Experimental layout and treatments

Two field experiments were conducted during the minor rainy season in 2017 (30 June 2017 to 11 October 2017) and large parts of the dry season in 2018 (30 January 2018 to 12 May 2018). These growing periods were chosen outside the major rainy season to

make irrigation relevant. A randomized split-plot factorial design with four replicates with irrigation levels as the main plots and three biochar levels of 0 t/ha ( $B_0$ ), 15 t/ha ( $B_{15}$ ) and 30 t/ha ( $B_{30}$ ) as the sub plots was used in the study. The dimension of the main plot was  $10.8 \times 5$  m, which was then divided into three sub plots with dimensions of  $3.6 \times 5$  m. For the purpose of final harvest, a small plot size of  $2 \times 4$  m was demarcated at the central location of all the subplots. The experimental treatments consisted of three irrigation levels; full irrigation ( $I_{100}$ ), deficit irrigation ( $I_{60}$ ) and no irrigation ( $I_0$ ). During the first 20 days of the growing season, all the irrigation levels ( $I_{100}$ ,  $I_{60}$  and  $I_0$ ) received the same amount of irrigation water of 4 mm per day after which the irrigation treatments were started. For the  $I_{100}$  plots, irrigation was applied every 3–4 days to bring the soil moisture level back to field capacity (FC). For the  $I_{60}$  treatment, the irrigation amount was calculated as 60% of the amount given to the  $I_{100}$  treatment with the same irrigation frequency. The  $I_0$  plots received no irrigation water after the first 20 days. The  $I_{100}$  treatment received irrigation water amounts of 198 and 244 mm during the 2017 and 2018 seasons, respectively, while the  $I_{60}$  received 120 and 147 mm of irrigation water for the 2017 and 2018 seasons, respectively. In order to compare the individual effects of biochar and irrigation, the experimental treatments were separated into two groups: The biochar group was used to assess the performance the rice straw biochar under full, deficit and no irrigation while the irrigation group was used to investigate how the different irrigation regimes performed under the various biochar rates.

The  $I_{100}$  and  $I_{60}$  plots were irrigated using pressure compensated, 16-mm drip laterals (distance between emitters of 0.6 m and discharge rate of 2/Lh at 100 kPa pressure, Naandanjain). The total quantities of biochar applied (30 and 15 t/ha) were divided into three equal amounts and applied yearly for three years (10 December 2015, 30 June 2016 and 12 June 2017) prior to the experiments by spreading and incorporating the biochar into the plough layer (0–15 cm) using a hoe. During the aforementioned dates, biochar was applied prior to planting in an okra-cowpea-maize crop rotation. The biochar levels ( $B_0$ ), ( $B_{15}$ ) and ( $B_{30}$ ) thus received 0, 5 and 10 t/ha during the yearly split application. On 30 June 2017 and 30 January 2018, the "obatanpa" maize variety was planted by using a cutlass to make small pits to a depth of about 3 cm and putting 3 seeds in each pit before covering with soil. At the V4 leaf stage, the seedlings were manually thinned such that only two plants were left per hill which corresponded to a plant density of 66,666 plants/ha. Fungicides and insecticides were sprayed every 2 weeks from 20 days after sowing (DAS) onwards and stopped during tasselling (48 DAS). All treatments were fertilized with the same amount of N, P and K fertilizer. The N fertilizer (calcium nitrate) at a rate of  $100 \text{ kg N ha}^{-1}$  was split into two equal doses, and the first half applied on 15 DAS while the remaining half was applied during tasselling (48 DAS). The rates for P and K were both 60 kg/ha, and these were applied 2 days before sowing using triple super phosphate and muriate of potash, respectively.

## 2.4 | Measurements

### 2.4.1 | Soil water content

The soil water content (SWC) during the experiments was measured in three replicate sub plots of each treatment using the manual time domain reflectometry (TDR) instrument (TDR100 from Campbell Scientific) on probes installed at a lateral distance of 3 cm from the emitter and to a vertical depth of 80 cm. The SWC at FC, defined as soil water content measured 2–3 days after the soil had been thoroughly wetted by rain followed by natural drainage, was determined before sowing. The monitoring of SWC during both seasons started after the establishment stage (21 DAS) and stopped at physiological maturity (103 DAS). The permanent wilting point water content (PWP) was determined from five randomly taken bulk soil samples from the experimental area prior to the experiments using a temperature compensated WP4-T dewpoint potentiometer (METER Group Inc., Pullman) as described in Amoakwah, Frimpong, Okae-Anti, and Arthur (2017).

### 2.4.2 | Ratio vegetative index, intercepted radiation and radiation-use efficiency

The red (670 nm) and near-infrared (780 nm) reflectance from the maize canopy was measured at a height of 90 cm above the canopy using a handheld, radiometer, Rapidscan CS-45 (Holland Scientific). The measurements were taken in each plot every 7–9 days from 12 DAS to physiological maturity (103 DAS). The ratio vegetation index (RVI) was computed as the ratio of near-infrared ( $\rho_r$ ) to red ( $\rho_r$ ) reflectance. Linear interpolation between two consecutive measurement dates for each plot was used to obtain RVI values for each day. The widely used function between RVI and the fraction of intercepted photosynthetically active radiation ( $f_{PAR}$ ) (Christensen & Goudriaan, 1993) was used to calculate  $f_{PAR}$  from the RVI measurements (Equation (1–3)):

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

$$n_r = \frac{\rho_{r,\infty} - \rho_{r,s}}{\rho_{r,s} - 1/\rho_{r,\infty}} \quad (2)$$

$$n_i = \frac{\rho_{i,\infty} - \rho_{i,s}}{\rho_{i,s} - 1/\rho_{i,\infty}} \quad (3)$$

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. These parameter estimates were then used to fit an exponential function between  $f_{PAR}$  and RVI. The  $f_{PAR}$  was varied in steps of 0.1 within the possible sample

space from 0 to 1, corresponding RVI values calculated (Equation 1) followed by least squares fitting of the exponential function to the data using the Solver add-in in Microsoft Excel. The fitted function was then used to calculate the daily  $f_{PAR}$  for each plot from interpolated RVI values. From the computed  $f_{PAR}$  values and the measurement of incident global radiation at the local meteorological station, the amount of accumulated intercepted photosynthetically active radiation (IPAR, MJ/m<sup>2</sup>) that the crop intercepted was calculated as follows:

$$IPAR = \sum_{n=12}^{n=103} 0.5 \times Q \times f_{PAR} \quad (4)$$

where Q is the daily global radiation (MJ/m<sup>2</sup>), and n is the day number after seeding (DAS).

Finally, RUE was calculated at final harvest as follows:

$$RUE = \frac{\text{Total dry matter yield}}{IPAR} \quad (5)$$

where RUE is in g/MJ, and total dry matter yield is in g/m<sup>2</sup>.

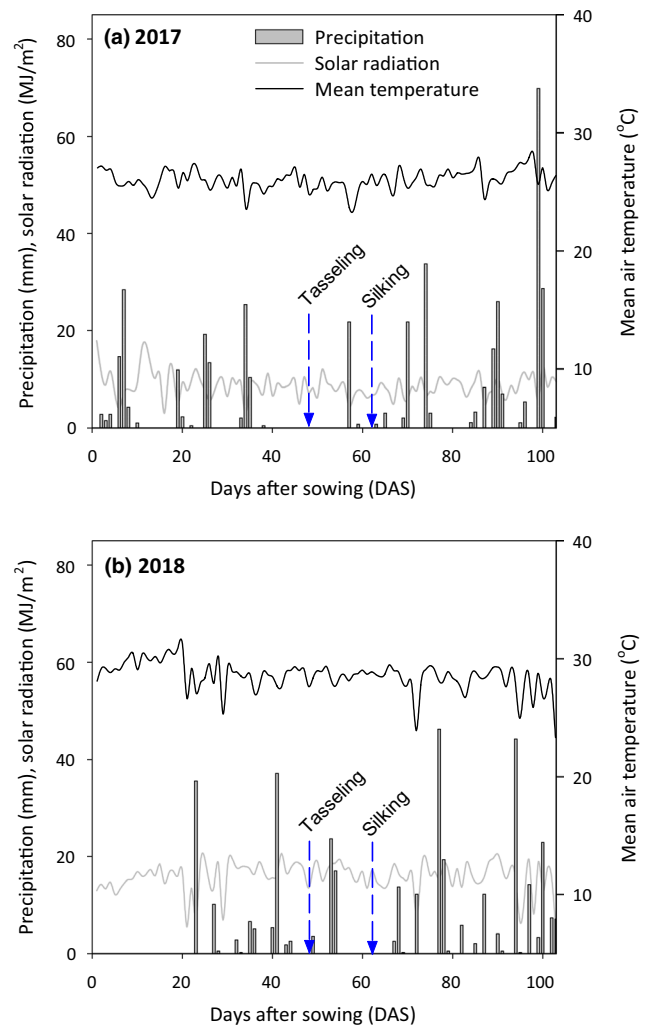
### 2.4.3 | Dry matter sampling, yield and leaf chlorophyll content

Leaf chlorophyll content and dry matter yield were measured at three critical growth stages of V6 leaf stage, tasselling and silking. These stages occurred on 34, 48 and 62 DAS which corresponded to thermal time after sowing (TT, °Cd) of 540, 759, and 973 in the 2017 season and 562, 786 and 1,013 in the 2018 season. The TT was computed daily for both the 2017 and 2018 seasons following the procedures of McMaster and Wilhelm (1997) and Boomsma, Santini, Tollenaar, and Vyn (2009) as follows:

$$TT = \frac{T_{max} + T_{min}}{2} - T_{base} \quad (6)$$

where  $T_{max}$  is the maximum daily air temperature (°C),  $T_{min}$  is the minimum daily air temperature (°C), and  $T_{base}$  is the base temperature taken as 10°C. Any  $T_{max}$  value that exceeded 30°C was reverted to 30°C.

For dry matter yield determination, six plants in each plot were randomly selected, the stem cut 3 cm above ground level to determine the above-ground stover dry matter yield (SDMY). The entire plant dry matter minus the roots was cut into pieces and put through several rounds of weighing and drying at 80°C until the weight remained constant to obtain the SDMY. When the maize reached physiological maturity at DAS 103 which corresponded to TT of 1,623 °Cd in 2017 and 1,617 °Cd in 2018, net plots of 8 m<sup>2</sup> within each gross plot of 18 m<sup>2</sup> were manually harvested from the centre rows. The harvested maize was manually dehusked and the stover separated from the cobs. The cobs and stover were air-dried for 2 weeks after which the grains were manually shelled. The shelled grain together with the stover was put through several rounds of weighing



**FIGURE 1** Daily weather data from sowing to harvest during the growing seasons in 2017 and 2018. Vertical dashed lines indicate tasselling and silking dates [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

and drying at 80°C until the weight remained constant to obtain the total dry matter yield (TDMY). Leaf chlorophyll content (LCC) was estimated using a chlorophyll metre (CCM-200, Opti-Sciences, Inc) in all plots on four leaves per plant and six plants per plot giving a total of 24 readings, which were averaged to obtain one value per plot.

### 2.4.4 | Soil physical and chemical measurements

At the end of the growing season in 2018, both intact core samples (100 cm<sup>3</sup>) and disturbed soil samples were collected from a depth of 0–15 cm in the I<sub>100</sub> plots (a total of 12 samples: 3 treatments and four replicates). We sampled from only the irrigated plots because we expected biochar rather than irrigation to affect soil's physical and chemical properties. The disturbed samples were used to determine soil texture, pH, electrical conductivity (EC) and total carbon while the core samples were used to determine soil water retention (SWR). Thereafter, the plant available water (PAW) defined as water

content the soil held at  $-300$  hPa minus water content the soil held at  $-15,000$  hPa was calculated.

## 2.5 | Statistical analysis

Treatment effects were analysed using analysis of variance (ANOVA), *F* test to determine the statistical significance of irrigation and biochar as well as their interaction effect by employing the GenStat statistical software. Prior to analysis, all the data were checked for normality and homogeneity of variance. The statistical analyses were done individually for each experimental year. Simple linear regression analyses between some selected measurement variables of the full irrigation treatments were done across the biochar levels. Test of significant differences between treatment means was done using the Holm–Sidak post hoc test at 5% probability level.

## 3 | RESULTS

### 3.1 | Weather conditions

Rainfall was evenly distributed during the 2017 and 2018 growing seasons, interspersed by a few dry spells (Figure 1). The highest accumulated rainfall amount of 390 mm was recorded for the 2017 season while the 2018 season had 364 mm total rainfall. The longest period without rainfall for the 2017 season occurred during 39–56 DAS while that for the 2018 occurred very early in the season (from 1 to 21 DAS). The cumulative reference evapotranspiration ( $ET_0$ ) computed with the FAO Penman–Monteith equation (Allen, Pereira, Raes, & Smith, 1998) was 315 and 574 mm for the 2017 and 2018 seasons, respectively. The 2018 season was hotter than the 2017 season with average temperatures of 29°C and 26°C, respectively. The 2018 season also recorded higher solar radiation with an average value of 16 MJ/m<sup>2</sup> day<sup>-1</sup> compared to 9 MJ/m<sup>2</sup> day<sup>-1</sup> for the 2017 season.

### 3.2 | Treatment effects on soil water content, soil physical and chemical properties

There were no large differences in SWC between the  $I_{100}$  and  $I_{60}$  even though the  $I_{60}$  treatment received 40% less irrigation water relative to the  $I_{100}$  treatment (Figure 2). The  $I_0$  treatment showed similar soil water content compared to  $I_{60}$  and  $I_{100}$  during the initial and late season stages but distinctively low values during the tasselling–silking periods (40 to 60 DAS) in 2017 and (40 to 80 DAS) during the 2018 season (Figure 2). The pH and soil organic carbon (SOC) of the  $B_{30}$  treatment recorded significantly ( $p \leq .05$ ) higher values of 5.55 and 1.48 compared to 4.66 and 1.04 for the  $B_0$  treatment. On the other hand, the pH and SOC values of 5.14

and 1.12 for the  $B_{15}$  treatment were statistically similar to the  $B_0$  treatment. Contrary to our expectation, biochar had a decreasing effect on soil water content as the  $B_{30}$  treatment showed a consistent decrease in soil water content at all the matric potentials (Figure 3a). With regards to  $B_{15}$  and  $B_0$ , there was no significant difference between their water contents at all the matric potentials. There was no significant difference in PAW between the biochar rates. (Figure 3b).

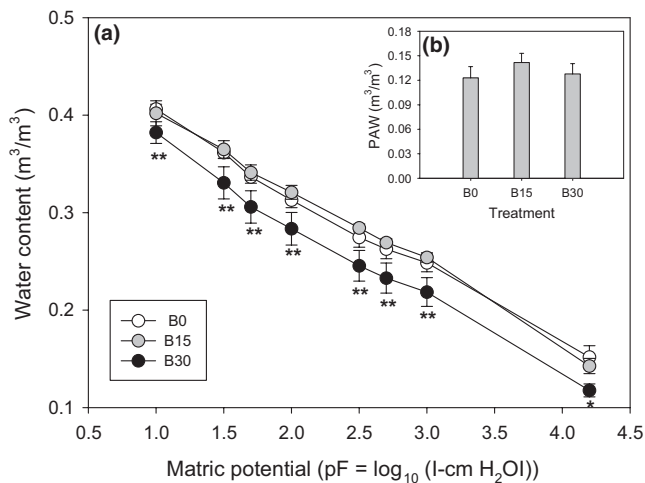
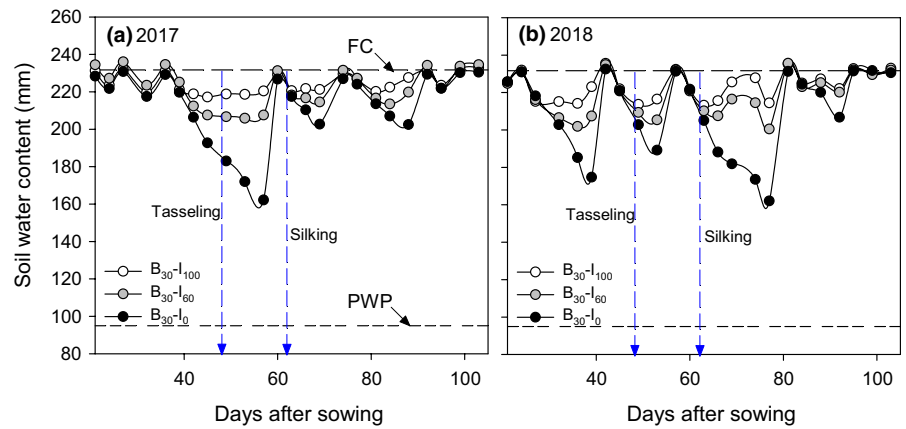
### 3.3 | Biochar and irrigation effects on ratio vegetation index development

Ratio vegetation index during the two seasons progressively increased from 12 DAS onwards, peaked at 68 DAS in 2017 and at 55 DAS in 2018. Hereafter, RVI decreased continuously till the end of the growing season at 103 DAS (Figure 4). The  $B_{30}$  treatment recorded significantly higher RVI value, compared to  $B_{15}$  and  $B_0$  during both seasons but only for  $I_{100}$  and  $I_{60}$  and on only one measurement date in 2017 and four measurement dates in 2018 (Figure 4a, g and h). The biochar's effect on RVI was revealed late in the 2017 season on 75 DAS but quite early during the 2018 season on 26, 34, 48 and 56 DAS. There was no significant effect of irrigation in both seasons ( $p \leq .05$ ) from 12 to 103 DAS (Figure 4)d–f and j–l).

### 3.4 | Biochar and irrigation effects on total dry matter yield, intercepted radiation, radiation-use efficiency and leaf chlorophyll content

There was no interactive effect between biochar and irrigation on TDMY, IPAR, RUE and LCC (Tables 1 and 2). The  $B_{30}$  significantly increased the TDMY in both years (Table 1). In the 2017 season, the TDMY of  $B_{30}$  was significantly higher than that of  $B_0$ , but not  $B_{15}$  and there was no significant difference between  $B_{15}$  and  $B_0$ . In the 2018 season, however,  $B_{30}$  was significantly higher than both  $B_0$  and  $B_{15}$  while  $B_{15}$  was also significantly higher than  $B_0$ . Irrigation did not influence the TDMY significantly in the 2017 season (Tables 1 and 2). However, in the dryer 2018 season,  $I_0$  was significantly lower than both  $I_{60}$  and  $I_{100}$  while  $I_{60}$  was also significantly lower than  $I_{100}$ . The IPAR trend was similar to that of TDMY data with  $B_{30}$  significantly higher than  $B_0$  in both seasons while there was no irrigation effect in 2017 but  $I_0$  had significantly lower IPAR than  $I_{100}$  in the 2018 season. Neither biochar rate nor irrigation regime significantly affected RUE in the 2017 season (Tables 1 and 2). In the 2018 season, however, there was a significant increase in RUE at biochar level  $B_{30}$  compared to  $B_0$  and at  $I_{100}$  compared to  $I_0$ . For the LCC, there were significant differences between all treatments for both seasons with the only exception being  $I_{60}$  in 2017, which was statistically similar to  $I_{100}$ . Linear regression analysis between LCC and both TDMY and IPAR showed that the LCC correlated well with both TDMY and IPAR. (Table 3).

**FIGURE 2** Soil water content to a depth of 80 cm for the different irrigation regimes under the 30 t/ha ( $B_{30}$ ) treatment. FC and PWP denote water contents at field capacity and permanent wilting point, respectively. Vertical dashed lines indicate tasselling and silking dates [Colour figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 3** (a) Water content at given matric potential (pF 1.0–4.2) under no biochar ( $B_0$ ), 15 t/ha biochar ( $B_{15}$ ) and 30 t/ha biochar ( $B_{30}$ ). (b) Plant available water (PAW) for the  $B_0$ ,  $B_{15}$  and  $B_{30}$  treatments. \*\* indicates  $B_{30}$  is significantly lower ( $p \leq .05$ ) 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 ( $n = 4$ ). Source: Obour et al. (2019)

### 3.5 | Biochar and irrigation effects on dry matter accumulation

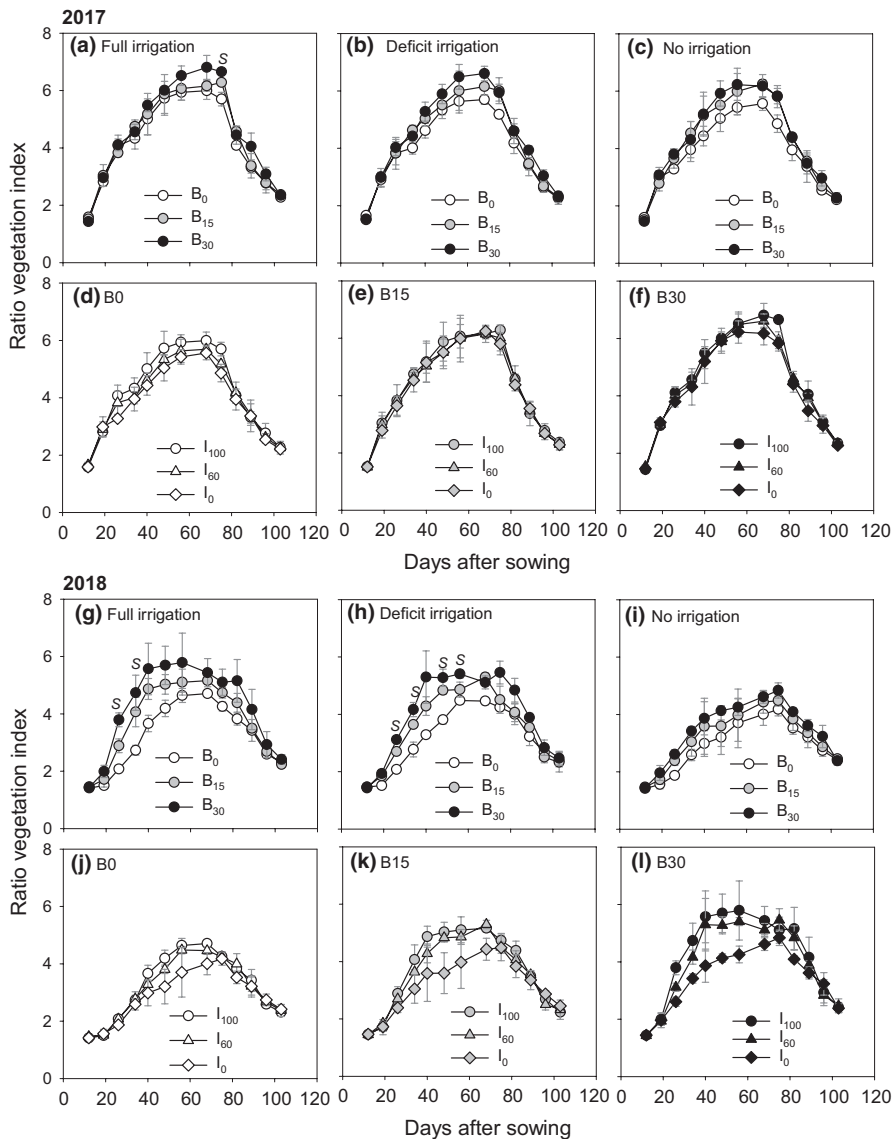
Stover dry matter accumulation increased progressively from 34 (V6 stage), 48 (tasselling stage) and 62 (silking stage) DAS (Figure 5). In both seasons, the lowest and highest SDMY was observed in the  $B_0$  and  $B_{30}$ , respectively (biochar group), and  $I_0$  and  $I_{100}$  (irrigation group) treatments (Figure 5). In the 2017 season, and for all the treatments, more than half of the TDMY was realized at the silking stage (Table 1 and Figure 5). In the 2018 season, however, less than half of the TDMY was produced up to the silking stage. In both years, and for all treatments, the STMY accumulation up to the tasselling and silking stages was not significantly ( $p < .05$ ) affected by irrigation (Figure 5). The exceptions were  $B_0$  in 2017 where  $I_{100}$  was significantly higher than  $I_0$  during both tasselling and silking and  $B_{30}$  in 2018 where  $I_{100}$  was significantly

higher than  $I_0$  but only during the V6 stage. The  $I_{60}$  treatment did not significantly reduce SDMY compared to  $I_{100}$  during both seasons and for all the phenological stages. With regards to biochar treatments,  $B_{15}$  did not significantly increase SDMY compared to  $B_0$  in both years and for all the phenological stages. On the other hand, the impact of the highest biochar rate was felt later in the season (silking stage) where  $B_{30}$  was significantly higher than  $B_0$  in both years except under  $I_0$  in 2018.

## 4 | DISCUSSION

### 4.1 | Crop growth, dry matter yield, IPAR and RUE as affected by biochar

Plant growth has been improved when biochar is used as a soil conditioner (Hossain, Strezov, Chan, & Nelson, 2010; Liu et al., 2014). These observations concur with our results as the maize growth measured using RVI as proxy was highest in  $B_{30}$  and  $B_{15}$  compared to  $B_0$  (Figure 4). In fact,  $B_{30}$  consistently maintained RVI at the highest level compared to  $B_{15}$  and  $B_0$  (Figure 4)a–c and g–i) throughout the season resulting in significant higher seasonal light interception (IPAR, Table 1). The TDMY results from our study also reveal higher values for the biochar treated plots during both seasons (Table 1). Nevertheless, there was no complete agreement between patterns of RVI (Figure 4) and SDMY (Figure 5), as the earlier differentiation between RVI of biochar treatments in 2018 was not reflected in significant differences in SDMY. However, SDMY differences are hard to establish based on sampling of a few plants while RVI constitute an integrated measure of the whole plot. Studies on many crops have observed an enhanced radiation interception to be directly related to improved uptake of soil N when soil moisture was not limiting (Andersen, Heidmann, & Plauborg, 1996; Oppong Danso et al., 2015; Zhou, Plauborg, Thomsen, & Andersen, 2017). Although we did not determine crop N uptake in the present study, the LCC is usually taken as a surrogate measure of the N content of crops due to the linear relation between the two (Afonso, Arrobas, Ferreira, & Rodrigues, 2018; Muchecheti, Madakadze, & Soundy, 2016). In line with this, the LCC in our study was significantly and linearly related to both



**FIGURE 4** Evolution of ratio vegetation index (RVI) with days after sowing (DAS) separated into 2 groups: Group 1 (the first upper 3 plots in both years (a–c in 2017 and g–i in 2018)) compares  $B_{30}$ ,  $B_{15}$  and  $B_0$  under full irrigation deficit irrigation and no irrigation. Group 2 (the lower 3 plots in both years (d–f in 2017 and j–l in 2018)) compares  $I_{100}$ ,  $I_{60}$  and  $I_0$  under no biochar, 15 t/ha biochar and 30 t/ha biochar. Error bars indicate standard error of the mean ( $n = 4$ ). Means with an S indicate significant differences ( $p \leq .05$ ) at least between two treatments within a given day after sowing

TDMY and IPAR in both years with  $R^2$  of 0.7 and 0.8 in 2017 and 0.5 and 0.8 in 2018 (Table 3). This concurs with frequently reported positive effects of increased crop N uptake on dry matter yield and IPAR (Andersen et al., 1996; Shah, McKenzie, Gaunt, Marshall, & Frampton, 2004) and may also explain the increase of RUE by biochar amendment (Kuzuyakov & Gavrichkova, 2010; Wohlfahrt, Piloni, Hörtnagl, & Hammerle, 2010). The RUE only increased significantly in 2018. It therefore suggests that the increase in TDMY was mainly caused by the increase in IPAR. The range of RUE observed in this study (3.2–4.6/MJ) is close to the theoretical RUE values proposed for  $C_4$  crops (4.0–5.5 g/MJ) by Loomis and Amthor (1999).

With regards to soil moisture dynamics, we did not find any evidence to suggest that the increases in TDMY and IPAR in the biochar treated plots were related to SWR and PAW as the  $B_{30}$  treatment significantly reduced SWC at all the matric potentials as shown in Figure 3a. Also, there were only marginal increases in PAW when comparing both  $B_{15}$  and  $B_{30}$  to  $B_0$  (Figure 3b). Even though we did not expect these results, similar results have been reported by Trifunovic, Gonzales, Ravi, Sharratt, and Mohanty (2018), who

established that biochar particle size of <2 mm as used in the present study can inhibit water transport in the soil by clogging pore spaces and consequently reduce SWR. Also, Graber et al. (2010) reported pepper yield increase in a biochar amended soil without a detectable change in PAW. Atkinson (2018) reported that the link between yield increase and PAW in biochar experiments usually occurs in structurally poor sandy soils rather than soils with appreciable clay content like our experimental soil.

For acidic and highly weathered tropical soils with similar characteristics as our experimental soil, crop performance when the soil is amended with biochar is often linked with increases in SOC and pH (Cornelissen et al., 2018; Crane-Droesch, Abiven, Jeffery, & Torn, 2013). Results from our study confirm this assertion as  $B_{30}$  significantly increased SOC and pH relative to  $B_0$ . The moderate carbon content of the rice straw biochar used in our study (25.1%) explains why there was only a marginal increase in SOC for the  $B_{15}$  treatment but significant increase for the  $B_{30}$  treatment. It therefore seems that biochar amendment is likely to improve soil fertility at higher application rates as found for the 30 t/ha treatment

**TABLE 1** Total dry matter yield, accumulated intercepted photosynthetically active radiation (IPAR), radiation-use efficiency (RUE) and leaf chlorophyll content (LCC) content as affected by the different biochar and irrigation treatments

Irrigation	2017 biochar rate (t/ha)				2018 biochar rate (t/ha)			
	0	15	30	Mean	0	15	30	Mean
Total dry matter yield (t/ha)								
I <sub>100</sub>	9.31	9.82	11.74	10.29a	10.91	13.22	17.77	13.97c
I <sub>60</sub>	8.97	9.52	11.22	9.90a	8.47	11.42	15.38	11.76b
I <sub>0</sub>	7.44	9.29	9.71	8.81a	7.02	8.94	11.59	9.18a
Mean	8.57a	9.54ab	10.89b		8.80a	11.19b	14.92c	
IPAR (MJ/m <sup>2</sup> )								
I <sub>100</sub>	205.4	215.4	245.7	222.2a	321.1	333.6	364.8	339.9b
I <sub>60</sub>	204.4	214.2	246.1	221.5a	261.2	325.3	362.5	316.3ab
I <sub>0</sub>	199.1	212.9	235.4	215.8a	252.6	270.6	349.8	291.0a
Mean	203.0a	214.1a	242.4b		278.3a	309.8b	359.0c	
RUE (g/MJ)								
I <sub>100</sub>	4.52	4.55	4.80	4.63a	3.40	3.94	4.88	4.07b
I <sub>60</sub>	4.40	4.49	4.56	4.48a	3.28	3.52	4.24	3.68ab
I <sub>0</sub>	3.73	4.32	4.12	4.06a	2.93	3.37	3.34	3.21a
Mean	4.22a	4.46a	4.49a		3.20a	3.61ab	4.15b	
LCC at tasselling								
I <sub>100</sub>	33.8	40.3	47.2	40.4b	49.2	52.0	56.3	52.5c
I <sub>60</sub>	32.3	39.1	45.2	38.8b	42.9	44.9	50.3	46.0b
I <sub>0</sub>	24.5	29.0	35.0	29.5a	36.2	41.7	44.8	40.9a
Mean	30.2a	36.1b	42.5c		42.7a	46.2b	50.4c	

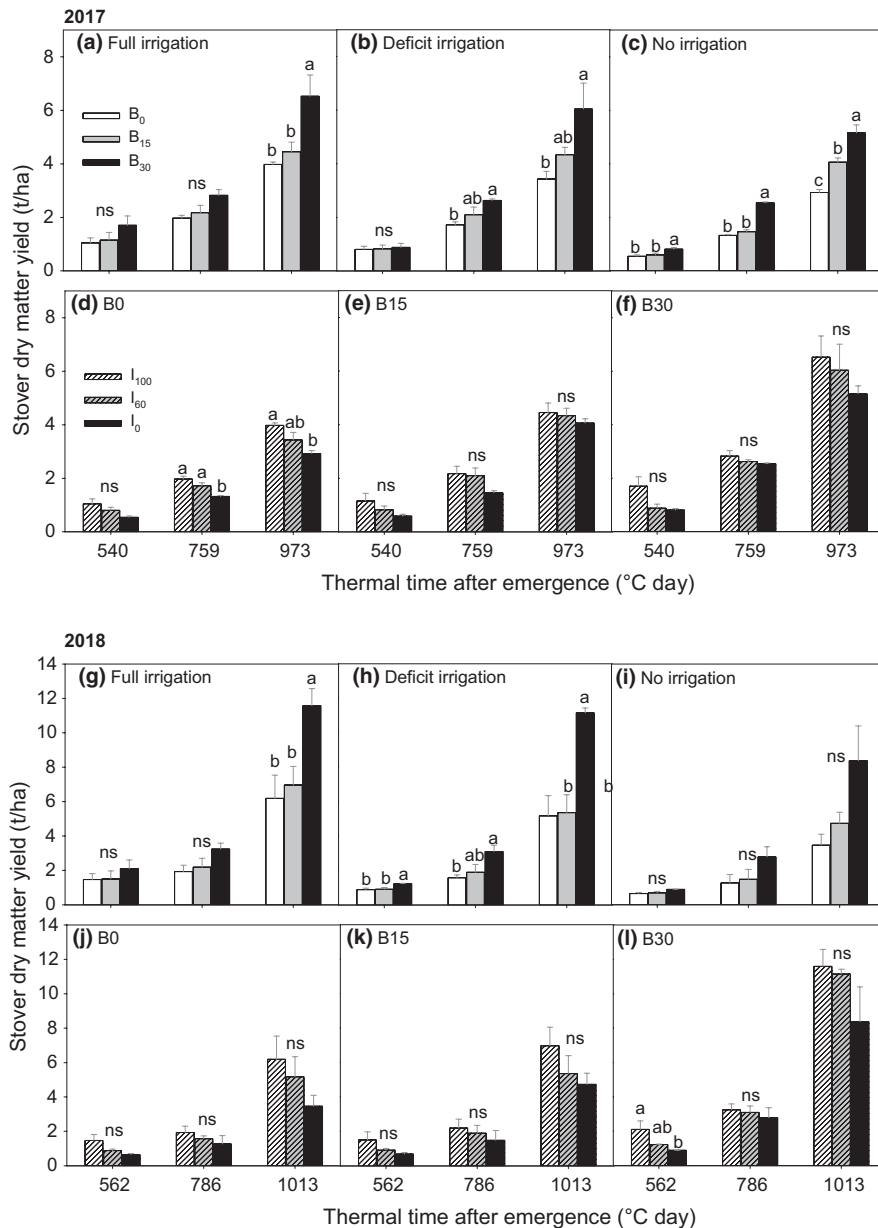
Note: Values within the same column or row in the same experimental year without common letters are significantly different at  $p \leq .05$ .

**TABLE 2** Analysis of variance showing significant levels of sole and interaction effects of irrigation and biochar on measured crop variables of total dry matter yield (TDMY), accumulated intercepted photosynthetically active radiation (IPAR), radiation-use efficiency (RUE) and Leaf chlorophyll content (LCC). For the *F* tests: \* denotes  $p < .05$ , \*\* $p < .01$  and \*\*\* $p < .001$

Year	Variation	TDMY (t/ha)	IPAR (MJ/m <sup>2</sup> )	RUE (g/Mj)	LCC
2017	Irrigation	ns	ns	ns	***
	Biochar	**	***	ns	***
	Irrigation × bio-char	ns	ns	ns	ns
2018	Irrigation	***	**	*	***
	Biochar	***	***	**	***
	Irrigation × bio-char	ns	ns	ns	ns

**TABLE 3** Simple linear regressions for some selected measurement parameters for the full irrigation treatments across biochar levels of B<sub>0</sub>, B<sub>15</sub> and B<sub>30</sub>. The analysis for the pH against both dry matter yield and intercepted radiation was done for only the 2018 growing season

Regression variables	Regression equations	R <sup>2</sup>	p value
2017			
TDMY against LCC	TDMY = 0.29 × LCC - 5.49	0.69	<0.001
IPAR against LCC	IPAR = 5.19 × LCC - 59.57	0.82	<0.001
2018			
TDMY against LCC	TDMY = 0.38 × LCC - 7.84	0.55	<0.01
IPAR against LCC	IPAR = 3.95 × LCC + 113.97	0.82	<0.001
TDMY against pH	TDMY = 6.32 × pH - 18.37	0.73	<0.001
IPAR against pH	IPAR = 44.64 × pH + 111.47	0.51	<0.01



**FIGURE 5** Change in maize stover dry matter yield with thermal time after emergence separated into 2 groups: Group 1 (the first upper 3 plots in both years (a–c in 2017 and g–i in 2018)) compares no biochar (B<sub>0</sub>), 15 t/ha biochar (B<sub>15</sub>) and 30 t/ha biochar (B<sub>30</sub>) under full irrigation (I<sub>100</sub>), deficit irrigation (I<sub>60</sub>) and no irrigation (I<sub>0</sub>). Group 2 (the lower 3 plots in both years (d–f in 2017 and j–l in 2018)) compares I<sub>100</sub>, I<sub>60</sub>, I<sub>0</sub> under B<sub>0</sub>, B<sub>15</sub> and B<sub>30</sub>. Error bars indicate standard error of the mean ( $n = 4$ ). Bars with different letters are significantly ( $p \leq .05$ ) different while *ns* indicates no significant differences between the treatments. In each sub-figure, the group of bars from left to right indicate V6, tasselling and silking stages, respectively

in the present study. The high pH of the of the rice straw biochar (10.3) coupled with the low pH of the experimental soil (5.5) resulted in increased soil pH, which likely enhanced the availability of nutrients for the maize plants and eventually increased the dry matter yield. Haynes and Naidu (1998) established that the conducive environment for P to be available for crops is within a pH range of about 5.6–6.5. Eduah, Nartey, Abekoe, Breuning-Madsen, and Andersen (2019) corroborated this finding by investigating the P desorbability for acidic and neutral Ghanaian soils amended with rice straw biochar and associated enhanced P desorbability to the priming effect of biochar. The soil in our experimental area was one of the acid soils investigated in the aforementioned work (Soil A, (Eduah et al., 2019)). We can thus infer that P availability in the B<sub>30</sub> treatment, which had pH within the recommended range of 5.6–6.5, may have been better and consequently increased the TDMY and IPAR. Overall, the results align with our hypothesis and

add to other studies where dry matter yield was enhanced due to the use of biochar (Agbna et al., 2017; Yeboah, Asamoah, Kofi, & Abunyewa, 2016), which in our case seemed related to effects on crop nutrient uptake.

#### 4.2 | Dry matter yield, IPAR and RUE as affected by irrigation

In 2018, regardless of biochar rate, water application significantly increased the dry matter yield and IPAR (Table 1 and Figure 5) and the trends were the same in 2017 although with no significant differences between treatments. This agrees with Payero, Tarkalson, Irmak, Davison, and Petersen (2008) that water consumed by crops is closely related to dry matter yield. The 2018 season was characterized by high evaporative demand (accumulative ET<sub>0</sub> of 574 mm)

and higher temperatures (average air temperature of 29°C) while the 2017 season had relatively low evaporative demand (accumulative  $ET_o$  of 315 mm) and lower temperatures (average air temperature of 26°C). The high temperatures and  $ET_o$  in 2018 compared to 2017 led to longer dry spells in the growing season in 2018 (Figure 1) and consequently decreased the soil moisture available for the maize plants (Figure 2). In addition, the 2017 season recorded higher accumulated rainfall amount (390 mm) than the 2018 season (364 mm). However, there was no significant difference between  $I_{100}$  and  $I_{60}$  for TDMY in the 2017 season but there was a tendency of lower yield in  $I_{60}$  for both seasons. Soliman (2006) reported similar findings, which highlight the possible irrigation water saving by deficit irrigation. The RUE values of our study were generally higher in 2017 compared to 2018. There may be two plausible explanations for this. Firstly, the 2017 season received lower average daily global radiation (9 MJ/m<sup>2</sup> day<sup>-1</sup>) vis-à-vis the 2018 season (16 MJ/m<sup>2</sup> day<sup>-1</sup>). Several authors have reported that lower solar radiation could increase photosynthesis rate, as measured per amount of photons absorbed, leading to a corresponding increase in RUE (Bange, Hammer, & Rickert, 1997; Sinclair, Shiraiwa, & Hammer, 1992; Van Roekel & Purcell, 2014). In a potato field experiment, Manrique, Kinry, Hodges, and Axness (1991) showed an increase in potato RUE by about 0.15 g/MJ when average daily global radiation decreased by 1 MJ/m<sup>2</sup> day<sup>-1</sup>. Similarly, Van Roekel and Purcell (2014) found an increase in RUE of 0.04 g/MJ in soybean when global radiation decreased by 1 MJ/m<sup>2</sup> day<sup>-1</sup>. Secondly, there were more and longer dry spells during the dryer 2018 season compared to the wetter 2017 season (Figures 1 and 2). Consequently, the RUE values in the dryer 2018 season were significantly reduced by soil moisture stress when comparing  $I_0$  to  $I_{100}$  but the difference was not significant in the wetter 2017 season. Averaged across years, RUE was reduced by 20 and 12% by  $I_0$  and  $I_{60}$ , respectively. This finding is similar with the work of Earl and Davis (2003), who reported a reduction in maize RUE of 13% under light water stress and 24% under acute water stress, which leads to partial closure of stomata and reduced photosynthesis. We could thus conclude that the low RUE values in 2018 compared to 2017 in the present study was due to the differences in the mean incident solar radiation and soil moisture stress for the two seasons.

## 5 | CONCLUSIONS

Most farmers in Ghana are engaged in the rainfed cultivation of staples on highly weathered and infertile soils with very low yields. Biochar is widely used to improve soil fertility while irrigation is well known to stabilize and increase yields when replacing rainfed cropping systems. For biochar and irrigation to be suitable productivity enhancing technologies, increase in crop production must be guaranteed. Results from our study show that irrespective of whether maize was grown under full irrigation, deficit irrigation or no irrigation, the application of 30 t/ha rice straw biochar significantly increased TDMY, IPAR and RUE of maize. Also, yield, IPAR and RUE of the maize crop were similar whether fully or deficit irrigated. We

can thus conclude that biochar amendment together with deficit irrigation may be a viable management option for farmers in Ghana to increase maize yield and at the same time save irrigation water resources.

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## REFERENCES

- Afonso, S., Arrobas, M., Ferreira, I. Q., & Rodrigues, M. Â. (2018). Assessing the potential use of two portable chlorophyll meters in diagnosing the nutritional status of plants. *Journal of Plant Nutrition*, 41, 261–271.
- 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. *Scientia Horticulturae*, 222, 90–101. <https://doi.org/10.1016/j.scienta.2017.05.004>
- Agegehu, G., Bass, A. M., Nelson, P. N., & Bird, M. I. (2016). Benefits of biochar, compost and biochar-compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. *Science of the Total Environment*, 543, 295–306. <https://doi.org/10.1016/j.scitoenv.2015.11.054>
- 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. *Journal of Agronomy and Crop Science*, 204, 123–136. <https://doi.org/10.1111/jac.12252>
- Akoto-Danso, E. K., Manka'abusi, D., Steiner, C., Werner, S., Häring, V., Nyarko, G., ... Buerkert, A. (2019). Agronomic effects of biochar and wastewater irrigation in urban crop production of Tamale, northern Ghana. *Nutrient Cycling in Agroecosystems*, 115(2), 231–247. <https://doi.org/10.1007/s10705-018-9926-6>
- 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*. 300, D05109.
- 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. <https://doi.org/10.1016/j.geoderma.2017.08.007>
- Alvarez-Campos, O., Lang, T. A., Bhadha, J. H., McCray, J. M., Glaz, B., & Daroub, S. H. (2018). Biochar and mill ash improve yields of sugarcane on a sand soil in Florida. *Agriculture, Ecosystems & Environment*, 253, 122–130. <https://doi.org/10.1016/j.agee.2017.11.006>
- Amoakwah, E., Frimpong, K. A., Okae-Anti, D., & Arthur, E. (2017). Soil water retention, air flow and pore structure characteristics after corn cob biochar application to a tropical sandy loam. *Geoderma*, 307, 189–197. <https://doi.org/10.1016/j.geoderma.2017.08.025>
- Andersen, M. N., Heidmann, T., & Plauborg, F.-J.-A.-A.-S.-B.-P.-S.-S. (1996). The effects of drought and nitrogen on light interception, growth and yield of winter oilseed rape. *Acta Agriculturae Scandinavica B-Plant Soil Sciences*, 46, 55–67. <https://doi.org/10.1080/09064719609410947>
- Atkinson, C. (2018). How good is the evidence that soil-applied biochar improves water-holding capacity? *Soil Use and Management*, 34, 177–186. <https://doi.org/10.1111/sum.12413>

- Bange, M., Hammer, G., & Rickert, K. (1997). Effect of radiation environment on radiation use efficiency and growth of sunflower. *Crop Science*, 37, 1208–1214. <https://doi.org/10.2135/cropsci1997.0011183X003700040030x>
- Boomsma, C. R., Santini, J. B., Tollenaar, M., & Vyn, T. J. (2009). Maize morphophysiological responses to intense crowding and low nitrogen availability: An analysis and review. *Agronomy Journal*, 101, 1426–1452. <https://doi.org/10.2134/agronj2009.0082>
- Burney, J. A., & Naylor, R. L. (2012). Smallholder irrigation as a poverty alleviation tool in sub-Saharan Africa. *World Development*, 40, 110–123. <https://doi.org/10.1016/j.worlddev.2011.05.007>
- Christensen, S., & Goudriaan, J. (1993). Deriving light interception and biomass from spectral reflectance ratio. *Remote Sensing of Environment*, 43, 87–95. [https://doi.org/10.1016/0034-4257\(93\)90066-7](https://doi.org/10.1016/0034-4257(93)90066-7)
- 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. *Science of the Total Environment*, 634, 561–568. <https://doi.org/10.1016/j.scitotenv.2018.03.380>
- Crane-Droesch, A., Abiven, S., Jeffery, S., & Torn, M. S. (2013). Heterogeneous global crop yield response to biochar: A meta-regression analysis. *Environmental Research Letters*, 8, 044049. <https://doi.org/10.1088/1748-9326/8/4/044049>
- Dong, X., Ma, L. Q., Zhu, Y., Li, Y., & Gu, B. (2013). Mechanistic investigation of mercury sorption by Brazilian pepper biochars of different pyrolytic temperatures based on X-ray photoelectron spectroscopy and flow calorimetry. *Environmental Science & Technology*, 47, 12156–12164. <https://doi.org/10.1021/es4017816>
- Duku, M. H., Gu, S., & Hagan, E. B. (2011). Biochar production potential in Ghana—a review. *Renewable and Sustainable Energy Reviews*, 15, 3539–3551. <https://doi.org/10.1016/j.rser.2011.05.010>
- Earl, H. J., & Davis, R. F. (2003). Effect of drought stress on leaf and whole canopy radiation use efficiency and yield of maize. *Agronomy Journal*, 95, 688–696. <https://doi.org/10.2134/agronj2003.6880>
- 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. <https://doi.org/10.1016/j.geoderma.2019.01.016>
- Faloye, O., Alatise, M., Ajayi, A., & Ewulo, B. (2017). Synergistic effects of biochar and inorganic fertiliser on maize (zea mays) yield in an alfisol under drip irrigation. *Soil and Tillage Research*, 174, 214–220. <https://doi.org/10.1016/j.still.2017.07.013>
- Graber, E. R., Harel, Y. M., Kolton, M., Cytryn, E., Silber, A., David, D. R., ... Elad, Y. (2010). Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. *Plant and Soil*, 337, 481–496. <https://doi.org/10.1007/s11104-010-0544-6>
- Haynes, R. J., & Naidu, R. J. E. I. (1998). Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: A review. *Nutrient Cycling in Agroecosystems*, 51, 123–137.
- Hossain, M. K., Strezov, V., Chan, K. Y., & Nelson, P. F. (2010). Agronomic properties of wastewater sludge biochar and bioavailability of metals in production of cherry tomato (*Lycopersicon esculentum*). *Chemosphere*, 78, 1167–1171. <https://doi.org/10.1016/j.chemosphere.2010.01.009>
- 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. *Environmental Research Letters*, 12, 053001. <https://doi.org/10.1088/1748-9326/aa67bd>
- Jeffery, S., Verheijen, F. G., van der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems & Environment*, 144, 175–187. <https://doi.org/10.1016/j.agee.2011.08.015>
- Kuzyakov, Y., & Gavrichkova, O. (2010). Time lag between photosynthesis and carbon dioxide efflux from soil: A review of mechanisms and controls. *Global Change Biology*, 16, 3386–3406.
- Liu, Z., Chen, X., Jing, Y., Li, Q., Zhang, J., & Huang, Q. (2014). Effects of biochar amendment on rapeseed and sweet potato yields and water stable aggregate in upland red soil. *Catena*, 123, 45–51. <https://doi.org/10.1016/j.catena.2014.07.005>
- Loomis, R. S., & Amthor, J. S. (1999). Yield potential, plant assimilatory capacity, and metabolic efficiencies. *Crop Science*, 39(6), 1584. <https://doi.org/10.2135/cropsci1999.3961584x>
- Manrique, L., Kinry, J., Hodges, T., & Axness, D. (1991). Dry matter production and radiation interception of potato. *Crop Science*, 31, 1044–1049. <https://doi.org/10.2135/cropsci1991.0011183X003100040040x>
- McMaster, G. S., & Wilhelm, W. (1997). Growing degree-days: One equation, two interpretations. *Agricultural and Forest Meteorology*, 87, 291–300. [https://doi.org/10.1016/S0168-1923\(97\)00027-0](https://doi.org/10.1016/S0168-1923(97)00027-0)
- Monteith, J. L. (1977). Climate and the efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London B, Biological Sciences*, 281, 277–294.
- Muchechechi, F., Madakadze, C., & Soundy, P. (2016). Leaf chlorophyll readings as an indicator of nitrogen status and yield of spinach (*Spinacia oleracea* L.) grown in soils amended with *Lucaena leucocephala* prunings. *Journal of Plant Nutrition*, 39, 539–561.
- Obour, P. B., Danso, E. O., Yakubu, A., Abenney-Mickson, S., Sabi, E. B., Darrah, Y. K., & Arthur, E. (2019). Water Retention, Air Exchange and Pore Structure Characteristics after Three Years of Rice Straw Biochar Application to an Acrisol. *Soil Science Society of America Journal*. <https://doi.org/10.2136/sssaj2019.07.0230>
- Ofori-Budu, K. (2003). Performance of citrus rootstocks in the forest zone of Ghana. *Ghana Journal of Horticulture*, 3, 1–9.
- Oppong Danso, E., Abenney-Mickson, S., Sabi, E., Plauborg, F., Abekoe, M., Kugblenu, Y. O., ... 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. *Agricultural Water Management*, 147, 34–42. <https://doi.org/10.1016/j.agwat.2014.07.029>
- Oppong Danso, E., Yakubu, A., Darrah, Y. O. K., Arthur, E., Manevski, K., Sabi, E. B., ... Andersen, M. N. (2019). Impact of rice straw biochar and irrigation on maize yield, intercepted radiation and water productivity in a tropical sandy clay loam. *Field Crops Research*, 243, 107628. <https://doi.org/10.1016/j.fcr.2019.107628>
- Pandit, N. R., Mulder, J., Hale, S. E., Zimmerman, A. R., Pandit, B. H., & Cornelissen, G. (2018). Multi-year double cropping biochar field trials in Nepal: Finding the optimal biochar dose through agronomic trials and cost-benefit analysis. *Science of the Total Environment*, 637, 1333–1341. <https://doi.org/10.1016/j.scitotenv.2018.05.107>
- Payero, J. O., Tarkalson, D. D., Irmak, S., Davison, D., & Petersen, J. L. (2008). Effect of irrigation amounts applied with subsurface drip irrigation on corn evapotranspiration, yield, water use efficiency, and dry matter production in a semi-arid climate. *Agricultural Water Management*, 95, 895–908. <https://doi.org/10.1016/j.agwat.2008.02.015>
- Ramlow, M., Foster, E., Del Grosso, S., & Cotrufo, M. (2019). Broadcast woody biochar provides limited benefits to deficit irrigation maize in Colorado. *Agriculture, Ecosystems & Environment*, 269, 71–81. <https://doi.org/10.1016/j.agee.2018.09.017>
- 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. *Journal of Crop Horticulture Science*, 32, 263–272.
- Sinclair, T. R., Shiraiwa, T., & Hammer, G. L. J. C. S. (1992). Variation in crop radiation-use efficiency with increased diffuse radiation. *Crop Science*, 32, 1281–1284. <https://doi.org/10.2135/cropsci1992.0011183X003200050043x>

- Soliman, S. (2006). Effect of irrigation at different available soil moisture levels, N and K fertilization on maize yield and its attributes. *Journal of Agricultural Science Mansoura University*, 31, 7525–7540.
- Steiner, C., Bellwood-Howard, I., Häring, V., Tonkudor, K., Addai, F., Atiah, K., ... Buerkert, A. (2018). Participatory trials of on-farm biochar production and use in Tamale, Ghana. *Agronomy for Sustainable Development*, 38, 12. <https://doi.org/10.1007/s13593-017-0486-y>
- 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 Degradation & Development*, 29, 884–893. <https://doi.org/10.1002/ldr.2906>
- Van Roekel, R. J., & Purcell, L. C. (2014). Soybean biomass and nitrogen accumulation rates and radiation use efficiency in a maximum yield environment. *Crop Science*, 54, 1189–1196. <https://doi.org/10.2135/cropsci2013.08.0546>
- Wohlfahrt, G., Piloni, S., Hörtnagl, L., & Hammerle, A. J. B. (2010). Estimating carbon dioxide fluxes from temperate mountain grasslands using broad-band vegetation indices. *Biogeosciences*, 7, 683. <https://doi.org/10.5194/bg-7-683-2010>
- 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.
- 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. <https://doi.org/10.1016/j.egypro.2016.07.143>
- Zhao, L., Cao, X., Mašek, O., & Zimmerman, A. (2013). Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. *Journal of Hazardous Materials*, 256, 1–9. <https://doi.org/10.1016/j.jhazmat.2013.04.015>
- Zhou, Z., Plauborg, F., Thomsen, A. G., & Andersen, M. N. (2017). A RVI/LAI-reference curve to detect N stress and guide N fertigation using combined information from spectral reflectance and leaf area measurements in potato. *European Journal of Agronomy*, 87, 1–7. <https://doi.org/10.1016/j.eja.2017.04.002>

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