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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, Alatise, 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^3, pH of 5.5, electrical conductivity of 36 µS/cm, total phosphorus was <0.4 mg 100 g^{-1}, potassium content of 14.8 mg 100 g^{-1} and magnesium content of 10.3 mg 100 g^{-1}. 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^{-1}, potassium content of 1,770 mg 100 g^{-1} and magnesium content of 133 mg 100 g^{-1}.

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 × 5 m, which was then divided into three sub plots with dimensions of 3.6 × 5 m. For the purpose of final harvest, a small plot size of 2 × 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 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 potentiameter (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 (ρ_i) to red (ρ_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)):

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

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

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

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^2) that the crop intercepted was calculated as follows:

$$\mathrm{IPAR} = \sum_{n=12}^{n=103} 0.5 \times Q \times f_{\mathrm{PAR}} \tag{4}$$

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

Finally, RUE was calculated at final harvest as follows:

$$\mathrm{RUE} = \frac{\text{Total dry matter yield}}{\mathrm{IPAR}} \tag{5}$$

where *RUE* is in g/MJ, and *total dry matter yield* is in g/m^2.

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:

$$\mathrm{TT} = \frac{T_{\max} + T_{\min}}{2} - T_{\mathrm{base}} \tag{6}$$

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^2 within each gross plot of 18 m^2 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 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.

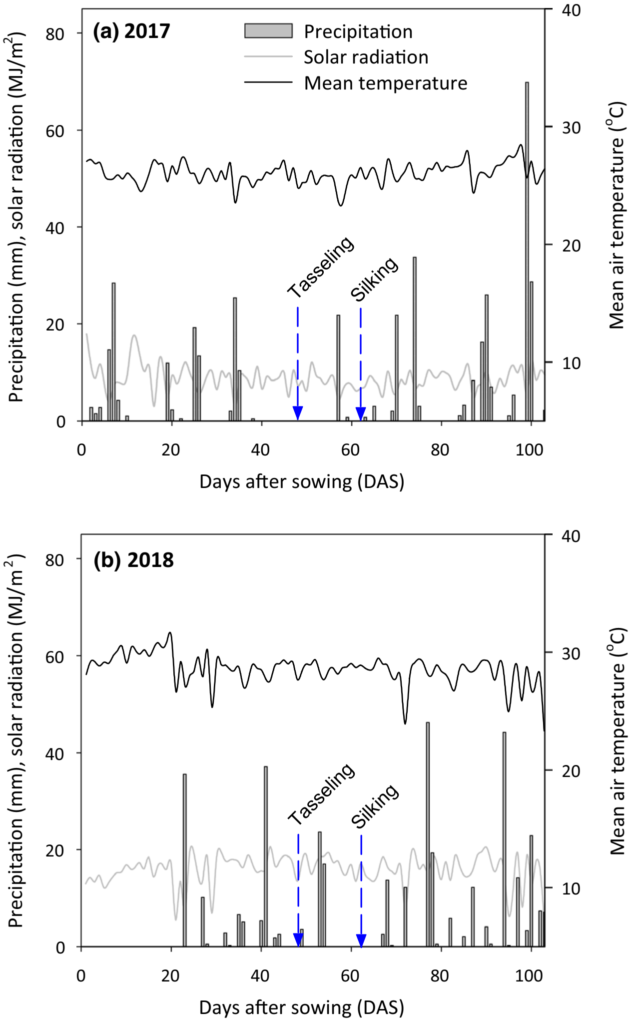

FIGURE 1 Daily weather data from sowing to harvest during the growing seasons in 2017 and 2018. Vertical dashed lines indicate tasselling and silking dates [Colour figure can be viewed at wileyonlinelibrary.com]

2.4.4 | Soil physical and chemical measurements

At the end of the growing season in 2018, both intact core samples (100 cm^3) and disturbed soil samples were collected from a depth of 0–15 cm in the I_{100} 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 $MJ/m^2 day^{-1}$ compared to 9 $MJ/m^2 day^{-1}$ 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 ($p \le .05$) 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 ($p \le .05$) 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).

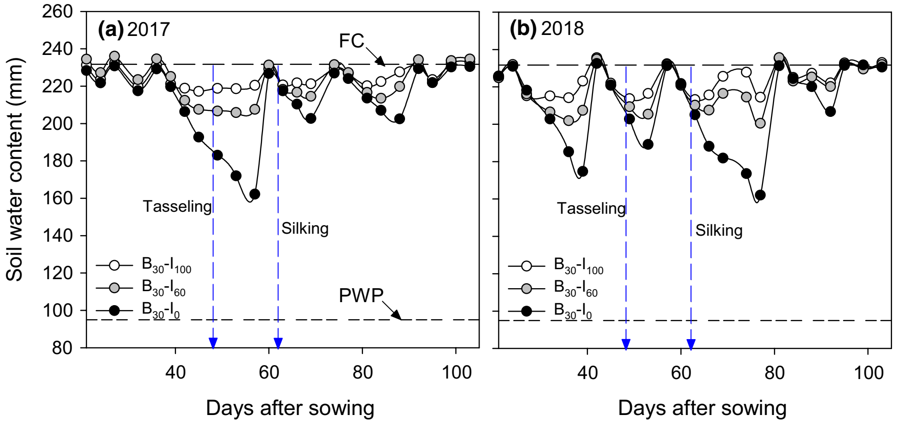

FIGURE 2 Soil water content to a depth of 80 cm for the different irrigation regimes under the 30 t/ha (B_{30}) treatment. FC and PWP denote water contents at field capacity and permanent wilting point, respectively. Vertical dashed lines indicate tasselling and silking dates [Colour figure can be viewed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

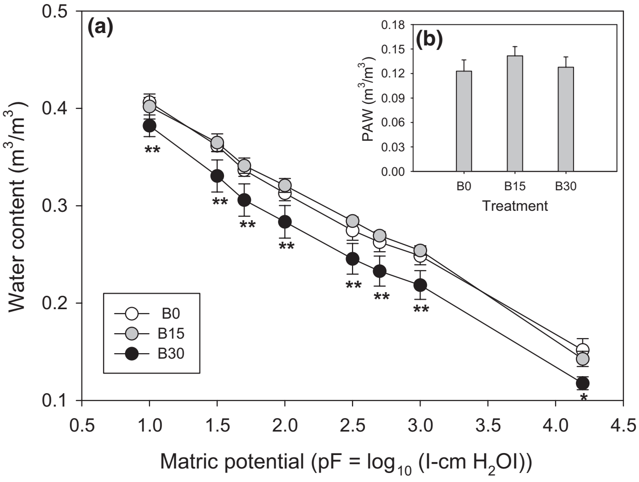

FIGURE 3 (a) Water content at given matric potential (pF 1.0–4.2) under no biochar (B_0), 15 t/ha biochar (B_{15}) and 30 t/ha biochar (B_{30}). (b) Plant available water (PAW) for the B_0, B_{15} and B_{30} treatments. ** indicates B_{30} is significantly lower ($p \le .05$) than both B_0 and B_{15}, * 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

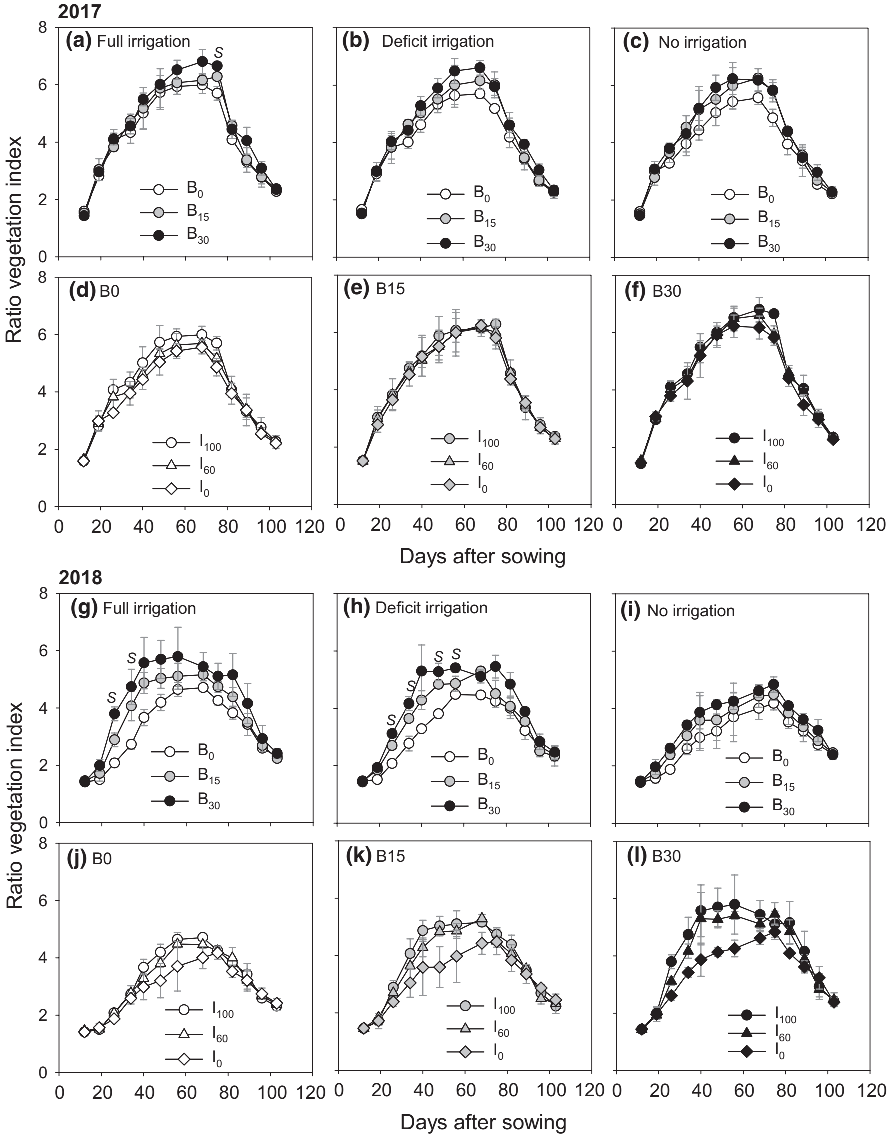

FIGURE 4 Evolution of ratio vegetation index (RVI) with days after sowing (DAS) separated into 2 groups: Group 1 (the first upper 3 plots in both years (a–c in 2017 and g–i in 2018)) compares B_{30}, B_{15} and B_{30} under full irrigation deficit irrigation and no irrigation. Group 2 (the lower 3 plots 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 ($p \le .05$) 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 (Kuzyakov & Gavrichkova, 2010; Wohlfahrt, Pilloni, 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

	2017 biochar rate (t/ha)				2018 biochar rate (t/ha)			
Irrigation	0	15	30	Mean	0	15	30	Mean
Total dry matter yield (t/ha)								
I_{100}	9.31	9.82	11.74	10.29a	10.91	13.22	17.77	13.97c
I_{60}	8.97	9.52	11.22	9.90a	8.47	11.42	15.38	11.76b
I_0	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^2)								
I_{100}	205.4	215.4	245.7	222.2a	321.1	333.6	364.8	339.9b
I_{60}	204.4	214.2	246.1	221.5a	261.2	325.3	362.5	316.3ab
I_0	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_{100}	4.52	4.55	4.80	4.63a	3.40	3.94	4.88	4.07b
I_{60}	4.40	4.49	4.56	4.48a	3.28	3.52	4.24	3.68ab
I_0	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_{100}	33.8	40.3	47.2	40.4b	49.2	52.0	56.3	52.5c
I_{60}	32.3	39.1	45.2	38.8b	42.9	44.9	50.3	46.0b
I_0	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 $p \le .05$.

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^2)	RUE (g/Mj)	LCC
2017	Irrigation	ns	ns	ns	***
	Biochar	**	***	ns	***
	Irrigation × biochar	ns	ns	ns	ns
2018	Irrigation	***	**	*	***
	Biochar	***	***	**	***
	Irrigation × biochar	ns	ns	ns	ns

TABLE 3 Simple linear regressions for some selected measurement parameters for the full irrigation treatments across biochar levels of B_0, B_{15} and B_{30}. 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^2	*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

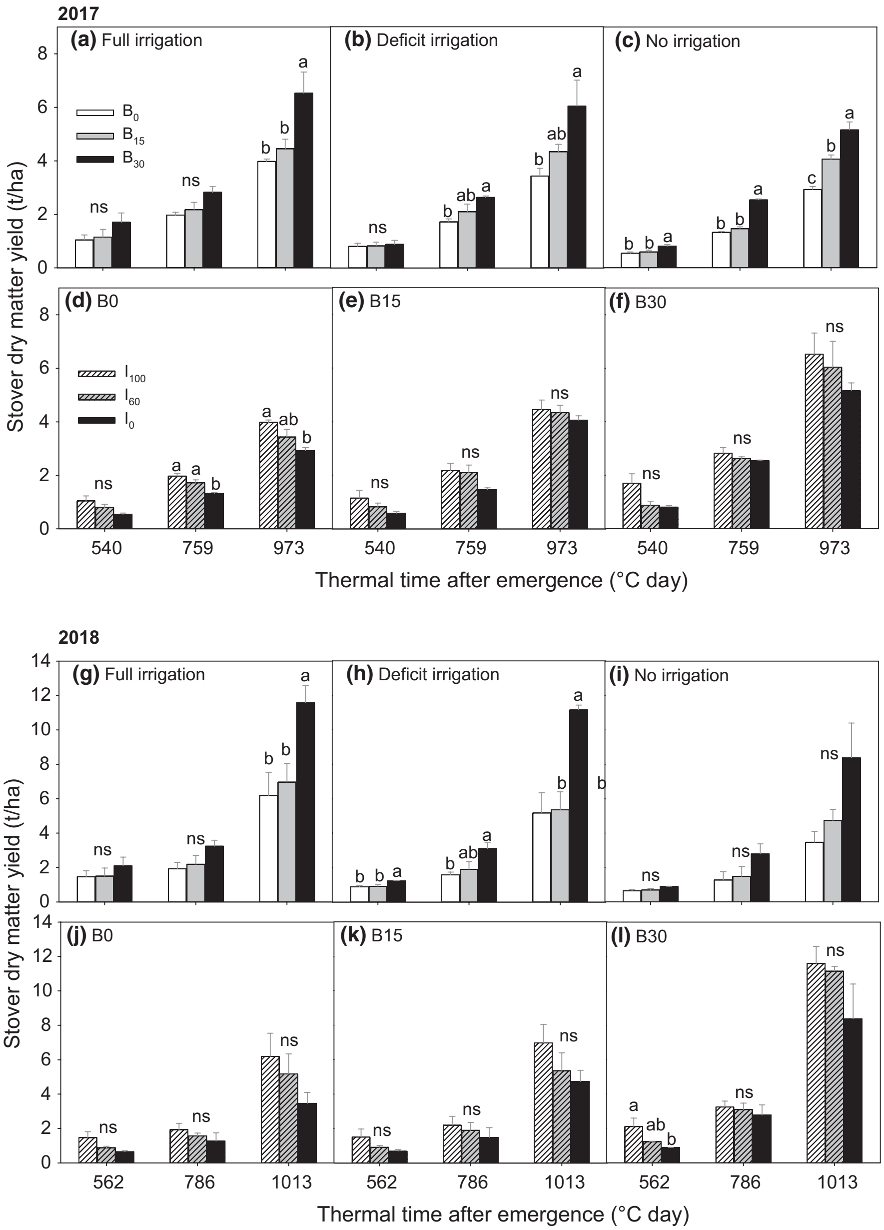

FIGURE 5 Change in maize stover dry matter yield with thermal time after emergence separated into 2 groups: Group 1 (the first upper 3 plots in both years (a–c in 2017 and g–i in 2018)) compares no biochar (B_0), 15/tha biochar (B_{15}) and 30 t/ha biochar (B_{30}) under full irrigation (I_{100}), deficit irrigation (I_{60}) and no irrigation (I_0). Group 2 (the lower 3 plots in both years (d–f in 2017 and j–l in 2018)) compares I_{100}, I_{60}, I_0 under B_0, B_{15} and B_{30}. Error bars indicate standard error of the mean (*n* = 4). Bars with different letters are significantly ($p \le .05$) 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_{30} 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_o 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^2 day^{-1}) vis-à-vis the 2018 season (16 MJ/m^2 day^{-1}). 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^2 day^{-1}. 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^2 day^{-1}. 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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