Mode of Biochar Application to Vertisols Influences Water Balance Components and Water Use Efficiency of Maize (*Zea mays* L.)

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Abstract

Vertisols belong to a group of soils with high fertility but poor physical properties of swelling when wet and shrinking and cracking when dry. The swelling inhibits infiltration, resulting in flooding, limiting the production of upland crops. Biochar (BC) application has been shown to reduce the shrink-swell behaviour of Vertisols. However, the mode of biochar application to these soils may affect the effectiveness of the amendment. This study investigated the water relations and maize (*Zea mays* L.) growth under two BC application modes: (i) biochar applied into cracks that develop with drying, ***C***, and (ii) biochar that was surface broadcast and incorporated into the topsoil, ***FM***. A control treatment did not receive any BC amendment. Maize was grown on the BC-amended Vertisols using the two modes of application in a greenhouse under two seasonal water regimes of 610 and 450 mm. The results showed that the proportion of total water application lost to runoff was 37%, 49% and 53% for ***C, FM*** and control treatments, respectively. Both maize yield and Water Use Efficiency (***WUE***), for the ***C*** treatments were significantly ($p < 0.05$) higher than those for ***FM*** treatments. The maize yield under the ***C*** treatments was 19% over the control. Similarly, the ***WUE*** for the ***C*** treatments was 28% above the control treatment. It is concluded that the application of biochar into cracks is a more effective way of improving the water relations and upland crop productivity and ***WUE*** in Vertisols than the traditional surface incorporation.

Keywords: Biochar application mode; drainage; crack; runoff; Vertisol; water use efficiency

Introduction

Vertisols constitute a group of clayey soils with high fertility but very poor physical properties. In Ghana, Vertisols cover about 1,830 km^2 total area, with 1,630 km^2 (90%) situated within the coastal savanna (Asiedu et al., 2001). Several works have shown that these soils have cation exchange capacity (CEC) often exceeding 29.00 cmol$_c$kg^{-1} (Coulombe et al., 1996; Asiedu et al., 2001; MacCarthy et al., 2020). Their pH is often in the range of 6.2 to 7.9, which is suitable for the growth of most crops. Despite the high fertility, the major physical limitation relates to the clay mineralogy, whereby the parent material (2:1 montmorillonitic) results in soils that also swell upon wetting (40-50% swelling) becoming very sticky, and clog farm implements during farm operations (Coulombe et al., 1996; Yangyuoru et al., 2012). Upon swelling, the large soil pores close and prevent any further infiltration, leading to frequent ponding and flooding conditions. On the other hand, when dry, the Vertisols shrink, harden and develop deep cracks (Brierley et al., 2011; Zong et al., 2014). In general, whether wet or dry, cultivation is handicap. These unique shrink-swell characteristics limit their agricultural uses (Thakur et al., 2016), especially with regard to upland crop production. In Ghana, the traditional agricultural use of the Vertisols has largely been limited to large-scale irrigated rice production during the wet season and for livestock grazing during the dry seasons (Ahmad and Mermut, 1996; Asiedu et al., 2001). However, the increasing population on land has forced small-scale farmers to bring portions of the Vertisols under cultivation by establishing small vegetable fields on raised beds (Qureshi et al., 2008; Scherr and Hazell, 1994).

The major task in bringing Vertisols into large-scale upland crop production is how to minimize the shrink-swell characteristics. Indeed, several works (Ahmad and Mermut, 1996; Zong et al., 2014) have observed that the elimination of the shrink-swell physical constraints is key to the productive use of Vertisols in sustainable upland agriculture. This will require that there is permanence and continuity of soil pores that can admit water into the soils without closing, thereby reducing the ponding or flooding conditions. Though the natural cracking of the Vertisols provides a means of enhancing water entry (Elias et al., 2001), the rapid closure of the pores upon swelling makes the infiltration process a non-permanent feature.

In this regard, the effect of applied fresh organic resources, though has been shown to improve soil physical properties (Lim et al., 2016), will only be short-lived once the material decomposes. On the contrary, amending with biochar (pyrolysed organic resource) would be more effective, given that the biochar carbon is stable, recalcitrant, and the material being a fluffy bulking agent will increase the overall porosity of the Vertisol. Several studies have shown that biochar application improved the physical properties such as the hydraulic conductivity and infiltration of Vertisols (Jones et al., 2010; Masulili et al., 2010; Hardie et al., 2013; Herath et al., 2013;). Limited unpublished preliminary studies by Adiku et al. (2015) have also demonstrated that biochar application significantly reduced the cracking intensity of Vertisol. Even with the selection of biochar as a suitable amendment, a further issue of application mode remains unresolved. Hence, the research questions of this study are: (i) what mode of biochar application to Vertisols would effectively enhance the physical properties and water entry? and (ii) what quantity of biochar application would be optimum for physical property enhancement to alleviate the practical challenges of flooding?

Biochar is often broadcast applied and incorporated into the top 5 to 10 cm of the soil, thus limiting its effectiveness to the topsoil. Though the infiltration into the topsoil may improve, water intake into the deeper layers would still be handicapped. Furthermore, the quantity of biochar material and the necessary technology required for application and incorporation pose practical challenges to the small-scale tropical farmer. Recommended biochar rates for soil fertility and physical property enhancement are often more than 20 ton ha^{-1} (Major et al., 2012; Hardie et al., 2014; Zong et al., 2014). For instance, 20 ton biochar ha^{-1} broadcast-applied and incorporated into a clayey soil did not significantly improve soil conditions (Major et al., 2012), but the effect was highly significant at 60 ton ha^{-1} (Zong et al., 2014). Therefore, the quest for an alternative mode of biochar application that will require lower application rates but still enhance soil conditions remains and requires further understanding of biochar-soil macropore interactions in Vertisols. It is the hypothesis of this study that the direct application of biochar into the natural cracks, instead of the traditional surface broadcast and incorporation, will keep the cracks open for infiltration, reduce flooding and lead to an overall improvement of Vertisol productivity. To date, the question on the approriate mode of biochar application for optimized improvement of water relations in Vertisols has received limited attention.

In this study, a new mode of application is proposed, whereby the biochar is directly incorporated into the natural cracks that develop upon drying and shrinking, instead of surface broadcast. In other words, given that the biochar has high macroporosity, rapid water intake into the biochar-filled cracks will be expected. Besides, the presence of the bulky, fluffy non-swelling biochar would resist the closure of the soil pores, keeping them open, resulting in quasi-permanent zones of weakness in the soil into which applied water would preferentially flow and enhance infiltration. This innovation is referred to as the "in-crack biochar fill" technology. To date, we have not witnessed any studies using this innovation on the Vertisols. It is the purpose of this study to carry out a proof of concept of the "in-crack biochar fill" technology under greenhouse conditions, using maize as the test crop.

Materials and Methods

Soils, sampling, and biochar preparation

The soils for the study were sampled from the University of Ghana, Soil and Irrigation Research Centre (SIREC) Kpong. The soils are classified as, Calcic Vertisols (FAO/UNESCO, 1990) and locally known as Akuse series or Tropical Black Clay (Adu, 1985; Amatekpor and Dowuona, 1995). These soils are deep and contain montmorillonitic clay (30-55%), giving rise to poor internal drainage resulting in intermittent ponding during high rainfall in depressions and flat areas. The Akuse series is characterized by shrink-swell properties, with deep cracks in the absence of rains. The vegetation is grassland with sparse shrubs.

Topsoil (0-15 cm) sampled at SIREC were brought to the laboratory of the Department of Soil Science, University of Ghana, Accra, and passed through a 2 mm sieve for the studies. Portions of the air-dried sieved soils were used for laboratory analysis. The particle size distribution followed the modified Day's Bouyoucous hydrometer method (Day, 1965). The bulk density (ρb) was determined using undisturbed soil cores. The pH was determined in water (H_2O) using a soil: water ratio of 1:1 (w/v). The organic carbon (OC) was determined by the wet combustion method of Walkley and Black (1934). The CEC was determined using a 1 M ammonium acetate extract, buffered at pH 7.0 (NH_4OAc, pH 7.0). Biochar was prepared by charring of rice husks using a locally made kiln at a temperature of 350 °C at SIREC. The rice husks were obtained from the waste product of rice cultivated at the centre. Approximately 40 tons of these waste products are burned off each year at the Centre (MacCarthy et al., 2020). The pH of the rice husk biochar (RHB) was determined using a Pancitronic MV 88 pH glass electrometer at 1:10 ratio of the RHB to water. The organic carbon content and cation exchange capacity were determined as described for the soil. The bulk density (ρb) was determined by carefully packing the RHB into a measuring cylinder to a determined volume by intermittently tapping on the laboratory bench to ensure sufficient packing. The quantity of the repacked RHB was then transferred into moisture can and oven-dried for 48 hours at 105 °C and the dried mass determined.

Greenhouse experimental procedure

Cylindrical buckets of height 22.0 cm and internal diameter 21.5 cm (Area=363.2 cm^2) were filled with the sampled disturbed Vertisols to a height of 16.0 cm to bulk density of 1.39 Mg m^{-3}. Drainage holes were drilled at the bottom of the buckets to allow free water drainage, which was collected using catch plastic lids. Also, holes were drilled near the top of the buckets for runoff collection. Artificial cracks were constructed at the centre of the buckets reaching down to the bottom and filled with biochar. The crack areas were 3 and 6 % of the total soil surface area. The choice of the crack areas was based on the earlier work by Elias et al. (2001) who observed crack volumes between 70 and 230 m^3ha^{-1} in some natural Vertisol landscapes in Gezira, Sudan, corresponding to 3.1 and 5.3 % per hectare. Biochar was applied at three (3) rates, namely 0, 7.7, and 18.0 t ha^{-1} to the soils using different application modes (Table 1). The ***NB*** stands for No Biochar (control). For the "in-crack biochar fill" treatments, the crack was directly filled with the biochar. This treatment was labeled "***C***". In other treatments, the biochar was surface-applied and fully mixed within the top 4 cm. The designations I1 and I2 correspond to two (2) seasonal watering regimes.

Maize (*Zea mays* L.) variety, *Obatanpa*, was selected as a test crop and was grown under 2 seasonal irrigation regimes. The irrigation amounts and intervals were selected to reflect the typical rainfall patterns as described by MacCarthy et al. (2018) at SIREC during the major season (I1), and the minor season (I2). All the treatments were replicated six (6) times resulting in 60 experimental units arranged in a Completely Randomized Design (CRD). Four seeds were sown per bucket and thinned to two at 2 Weeks After Planting (WAP). A basal fertilizer (NPK 15-15-15) was applied at a rate of 1.45 g pot^{-1} (60 kg. ha^{-1}) at 2 WAP and later top-dressed with ammonium sulphate [$(NH_4)_2SO_2$] at 0.51 g pot^{-1} (30 kg. ha^{-1}) in 2 split applications at 5 and 7 WAP. Weeds on the soil surfaces were uprooted by hand. Before sowing, the soils were pre-saturated and allowed to drain to Field Capacity (FC).

All plants received adequate watering for the first three weeks before the imposition of the irrigation treatments I1 (610 mm) and I2 (452 mm) as shown in Table 3. The buckets with the plants were weighed before and after each irrigation event. At each irrigation event, data on runoff and drainage were collected. A typical greenhouse maize growth in response to ***FM*** and **C** treatments is shown in Figure 1. At the end of the study, the cumulative seasonal evapotranspiration (ET) was determined from the water balance equation given as:

$$\pm\Delta W = I - ET - R - D \qquad [1]$$

where, ΔW is the change in soil water storage, I is irrigation amount, ET is the evapotranspiration, R is runoff and D is drainage. All the terms were expressed in mm. Plant parameters recorded during the experiment include the Leaf Area per plant (LA) determined from length (l) and width (w) of the maize leaves x 0.75 (Montgomery 1911;

TABLE 1
Treatment descriptions

Treatment description	Application mod	Crack area (%)	Biochar rate (t ha^{-1})
NB I1 & I2	No biochar	0	0
FM 3 I1 & I2	Fully mixed	0	7.7
FM 6 I1 & I2	Fully mixed	0	18.2
C 3 I1 & I2	In-crack filled biochar	3	7.7
C 6 I1 & I2	In-crack filled biochar	6	18.2

NB = no biochar; ***FM*** = full mixed biochar application; ***C*** = in-crack biochar fill application; I1 = irrigation level 1; I2= irrigation level 2

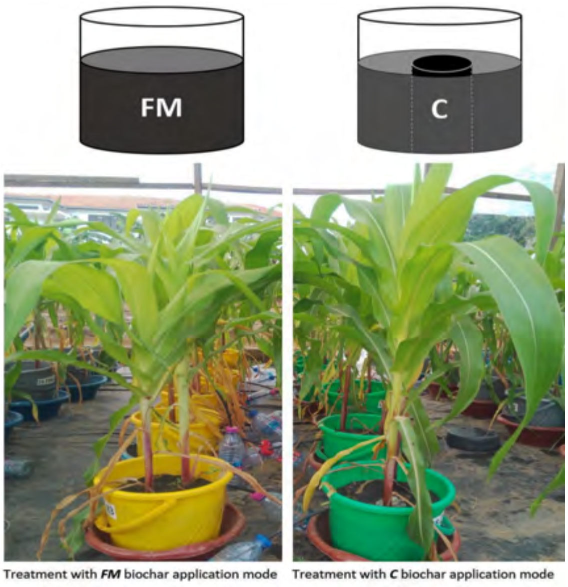

Figure 1 A typical greenhouse maize growth in response to ***FM*** and ***C*** treatments

Pearce et al. 1975), total dry weight, and grain weight at maturity. At 14 WAP, when the plants reached maturity, they were harvested for dry weight and yield determination.

The above-ground biomass was chopped and oven-dried at 70 degrees for 48 hours, and then weighed. The roots of the harvested plants were washed and also oven-dried and weighed. Maize grains were sun-dried to constant weight. The Water Use Efficiency (WUE) was determined as:

$$WUE = \frac{Grain\ mass\ (kg/pot)}{Cummulative\ ET(mm)} \quad [2]$$

Statistical analysis

Microsoft Excel (version 2016) was used for data entry, and graphical representation of data was with GraphPad Prism 8.0.2 (263 version). Experimental data were analyzed with the Analysis of Variance (ANOVA) technique using GenStat statistical software (12th edition, 2009). Duncan Multiple Range Test was used for means separation, compared at 5% level of significance.

Results

Soil and biochar characterization

The physical and chemical characteristics of the Vertisols used are presented in Table 2. The particle size analysis showed that the soil used had 47.5% clay which is typical of Vertisols with a bulk density of 1.39 Mg m^{-3}. The soil pH can be described as neutral and would not inhibit plant growth (Mandal et al., 2019). The organic content of the Vertisols used was 9.43 g kg^{-1}. The Cation Exchange Capacity (CEC) of 37.29 $cmol_c kg^{-1}$ could be considered to be fairly high. The rice husk biochar (RHB) had a bulk density of 0.21 Mg m^{-3}, pH (H_2O) was 6.8, organic carbon was relatively high at about 53% (Table 2). The CEC of the rice husk biochar used was approximately 20 $cmol_c kg^{-1}$ giving it an enhanced capacity to hold or fix some nutrients.

Seasonal water balance

The cumulative water applied under the two irrigation treatments were 610 mm (I1) and 452 mm (I2), respectively (Tables 3). Water balance components varied with treatment. For drainage, the ***C*** (in-crack biochar fill) treatments recorded significantly ($p < 0.001$) higher drainage than the remaining treatments. The order was ***C***6 I1 > ***C***3 I1 > ***FM***6 I1 > ***FM***3 I1 > ***NB*** I1. About 50% of the applied irrigation was lost as drainage in the ***C*** treatments compared to about 35% in the remaining treatments. Contrary to the drainage trend, ***NB*** runoff was highest and was significantly

TABLE 2

Some physical and chemical characteristics of the Vertisols and biochar used

Parameter	Value
Physical analysis	
Bulk density (Mg m^{-3})	1.39
Sand (%)	46.80
Silt (%)	5.70
Clay (%)	47.50
Chemical analysis	
pH (H_2O)	6.73
Organic Carbon (%)	0.94
CEC (cmolc kg^{-1})	37.29
Biochar	
Bulk Density (Mg m^{-3})	0.21
pH (H_20)	6.8
Organic Carbon (%)	53.00
CEC (cmolc kg^{-1})	19.71

TABLE 3
Greenhouse seasonal water balance components as affected by BC application mode and rates

Treatment	I	Dr	R	ET	θv	Dr/I	R/I
	….……………………mm………………………				$cm^3\ cm^{-3}$	%	
First irrigation regime (I1)							
NB I1	610	192.9 ±2.10 a	323.30 ±1.63 a	64.86 ±1.08 a	0.17 ±0.01 a	32	53
FM3 I1	610	212.2 ±0.98 b	302.20 ±1.17 b	63.49 ±0.94 ab	0.19 ±0.00 a	35	50
FM6 I1	610	238.2 ±1.30 c	279.80 ±1.10 c	59.41 ±1.73 abc	0.19 ±0.01 a	39	46
C3 I1	610	292.9 ±0.38 d	229.40 ±0.73 d	52.00 ±1.02 bc	0.21 ±0.01 a	48	38
C6 I1	610	317.6 ±1.70 e	202.40 ±1.73 e	51.03 ±0.78 c	0.23 ±0.02 a	52	33
Second irrigation regime (I2)							
NB I2	452	141.5 ±0.42 a	237.10 ±0.24 a	44.44 ±0.24 a	0.17 ±0.01 a	31	53
FM3 I2	452	150.2 ±0.36 b	226.20 ±0.36 b	43.22 ±0.47 a	0.19 ±0.01 a	33	50
FM6 I2	452	156.1 ±0.12 c	221.30 ±0.82 c	43.83 ±0.22 a	0.18 ±0.02 a	35	49
C3 I2	452	193.4 ±0.32 d	184.70 ±0.56 d	42.69 ±0.53 a	0.18 ±0.02 a	43	41
C6 I2	452	217.8 ±0.89 e	162.40 ±0.89 e	42.77 ±0.68 a	0.17 ±0.04 a	48	36

I = the total irrigation amount (mm) applied over the regime; **Dr** = total drainage (mm) over the regime; **R** = total runoff (mm) over the regime; **ET** = total evapotranspiration (mm) over the regime; **θv** = average moisture content ($cm^3\ cm^{-3}$), **Dr** (%) and **R** (%) = proportion of irrigation lost via **Dr** and **R**; ± = standard error of means; Mean values with the identical letters show no significant differences

different from the rest of the treatments. There was a statistical difference ($p < 0.001$) between ***C***3 and ***C***6, with ***C***3 having about 5% more runoff for the first irrigation water regime. Treatment effects and trends for drainage ($p < 0.001$) and runoff ($p < 0.001$) on all the treatments under the second irrigation regime (I2) were similar to those observed under the first irrigation water regime (Table 3).

The mode of BC application significantly affected the *ET* under the first irrigation regime. The *ET* under the ***NB*** treatment was significantly ($p < 0.001$) higher than those obtained under the ***C*** treatments. For the second irrigation watering regime (I2), the trend of the *ET* values was similar, with the lowest *ET* observed in treatment under ***C***3 I2 as shown in Table 3.

Maize growth

Maize growth under the various treatments was reflected in the leaf area development, shoot, and root growth. As observed in Figure 2, the patterns of the average leaf area (LA) (cm^2) were somewhat similar over time. In all the treatments, LA increased monotonously,

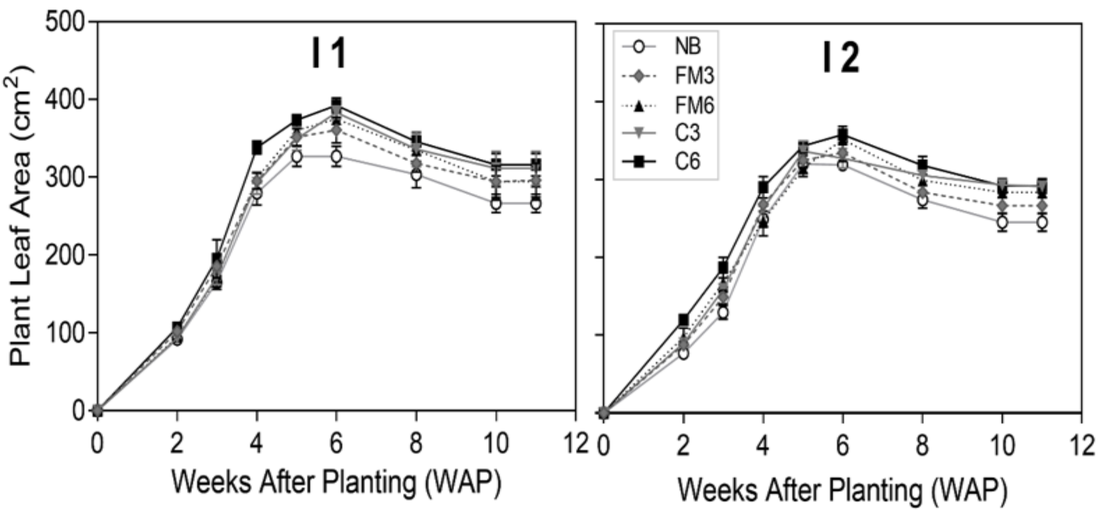

Figure 2 Time-course of maize leaf area (LA) for different modes of biochar application under the first (left) and second (right) water regimes. I1= first irrigation season (610 mm); I2 = second irrigation season (452 mm)

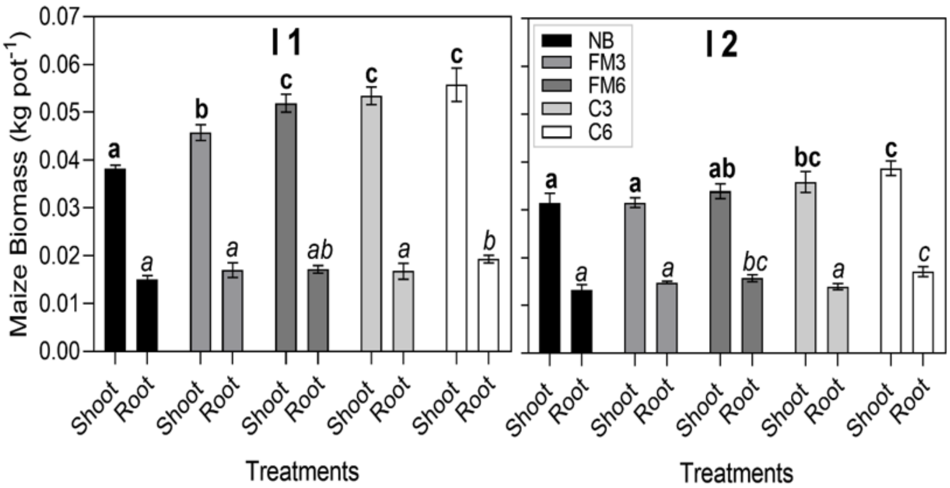

Figure 3 Biomass of maize as affected by BC application mode grown under greenhouse conditions. I1= first irrigation regime (610 mm); I2 = second irrigation regime (452 mm)

reaching a peak at about 6 WAP and thereafter showed declining trends till maturity. The latter decline could be attributed to senescence. At 6 WAP, the order of the LA was ***C***6 (392.43 cm^2) > ***C***3 (378 cm^2) > ***FM***6 (374.30 cm^2) > ***FM***3 (360.60 cm^2) > ***NB*** (326.78 cm^2) for I1. Despite the decline in LA in all treatments after 7 WAP, ***C*** treatments still dominated.

The trends of LA observed for the second water regime were similar to those of the first water regime. The maximum LA at the vegetative stage of the maize was recorded under treatment ***C***6, followed by ***C***3 > ***FM***6 > ***FM***3 > ***NB***. Some of the treatment means were significantly different. For example, the LA for ***C***6 was significantly different from ***NB*** at 11 WAP under both watering regimes.

Maize shoot and root biomass at maturity (14 WAP) depended on the treatments (Figure 3). The mode of BC application significantly influenced shoot and root biomass at maturity. The ***C***6 treatment produced the highest shoot biomass, which was almost 32% higher than that obtained for NB. The differences in growth under the various treatments narrowed somewhat under the lower watering regime, but the ***C*** treatments still produced the highest biomass (Figure 3).

Grain yield and water use efficiency (WUE)

Figure 4 shows the yield and water use efficiency (WUE) of the maize under both water regimes as affected by the mode of BC application. The mode of BC application significantly ($p = 0.003$) influenced grain yield under the first irrigation regime. The ***NB*** treatment obtained the least grain yield, while the ***C***6 obtained the highest grain

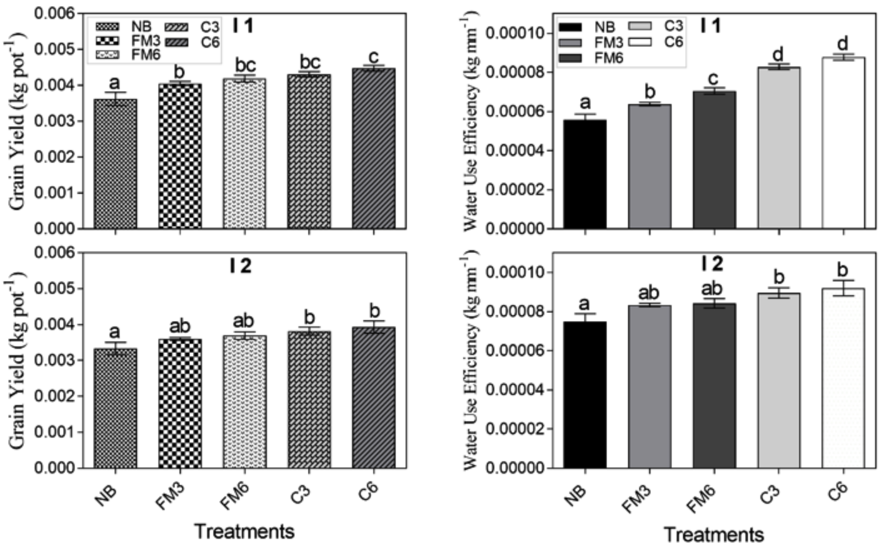

Figure 4 Grain yield and water use efficiency (WUE) of maize as affected by ***BC*** application mode. ***I***1= first water regime (610 mm); ***I***2 = second water regime (452 mm)

yield increase of 19% over NB (Figure 4). The ***C***6 yields were, however, statistically similar to those obtained under ***C***3 and ***FM***6. The ***FM***3 was also similar to ***FM***6 and ***C***3, but significantly different from ***NB*** and ***C***6. Similar observations were also made for the lower watering regime. The ***NB*** treatment obtained the least grain yield while the ***C***6 obtained the highest grain yield, but ***C***6 was similar to those obtained from ***C***3, ***FM***3, and ***FM***6. Grain yield obtained from ***FM***3 and ***FM***6 were similar, but statistically ($p < 0.05$) different from that obtained from ***NB***.

The mode of BC application also influenced ($p < 0.001$) the ***WUE*** in the first irrigation regime. As with grain yield, the WUE of the ***NB*** treatment was the least, whereas that of the ***C***6 was the highest and was significantly similar to that of ***C***3, but different from the rest of the treatments. The WUE of the ***C*** treatments were 24 and 28% (***C***3 and ***C***6, respectively) higher than that of the ***NB*** treatment. As with the high watering regime, the mode of BC application significantly ($p = 0.019$) influenced the WUE of the low watering regime. The ***NB*** treatment recorded the lowest ***WUE***, but this was not different from the ***FM*** treatments. The ***FM*** treatments were similar, while the ***C*** treatments were also similar ($p = 0.019$) as shown in Figure 4.

Discussion

Impact of BC application mode on water balance components

The general observation was that the mode of biochar application to the Vertisols is a major determinant of the water balance. The traditional approach of broadcasting and mixing into the topsoil (***FM***) has a limited effect on water intake, even though the impact was better than the control (NB). In general, applying the same quantity as "in-crack" filling enhanced water entry significantly, as hypothesized in this study. Though drainage may be considered as a loss term in water balance computations, the increased drainage recorded in the buckets could not be strictly considered as loss, given that the depths were only 22 cm. On the contrary, the increased drainage under the ***C*** treatments indicate that more water would be admitted into deeper soils. Indeed, the lower runoff determined under the ***C*** treatments compared to the control and ***FM*** treatments all gives further credence to the superiority of the C mode of biochar application to improve water relations of Vertisols.

The higher drainage and lower runoff in C treatments can be attributed to two main effects, namely (i) the maintenance of the macropore structure by the BC in filled cracks, serving as locations of weakness, fractures, and fissures on the soil surface that enhanced preferential flow for the excess water movement (Gerke and van Genuchten, 1993; Jarvis et al., 2012; Jarvis et al., 2016), and (ii) the vastly porous, and high infiltration capacity of the carbon-rich BC in the "cracks" (macropores) that enhanced rapid infiltration (Jones et al., 2010; Masulili et al., 2010; Herath et al., 2013; Lim et al., 2016). Under these conditions, water on the soil surface would be directed into the BC infilled cracks, by-passing the main soil matrix (Hendrickx and Flury, 2001; Jarvis et al., 2016). It is also worth noting that the increased drainage under ***C*** treatments would not imply loss under field conditions where the soils are deeper than the small buckets used in this study. Obviously, the increased drainage under the ***C*** treatments would imply greater admission of water into the lower zones of the soil profile, thereby increasing the overall soil water storage. Yet, despite the higher drainage for the ***C*** treatments, the overall soil water availability appeared to be similar to the other treatments. Furthermore, the drastic reduction in runoff loss under ***C*** treatments shows that ponding would be unlikely. For field conditions where soils are deep, the reduction in the runoff by the ***C*** treatments or "in-crack" BC application is desirable, as it not only reduces the surface loss but also prevented ponding, which may impair the aeration of upland crop roots.

Overall, whereas this study clearly demonstrated that applying biochar in cracks improved soil water relations, the practical question remains as to how this finding could be operationalized in the field, where the creation of "artificial cracks" may not be feasible. Conceivably, natural cracks develop in the field during the dry seasons, and these can be infilled with biochar before the onset of the rainy season. Continually repeating the process over several years could lead to the "creation" of a modified composite soil with improved water relations. The validity of the approach is yet to be demonstrated in the field.

Impact of biochar application mode on maize growth and water use efficiency

How the plant responds to the changes induced by the treatments would determine the relevance of the treatments. It was observed that the root/shoot ratio changed in favour of shoot growth for the ***C*** treatments, but to root growth for the other treatments. Increased root growth may suggest that the plant invests more in roots to explore water or and nutrients under limiting water/nutrient conditions. It can thus, be inferred that relatively less soil water was available under ***NB*** and ***FM*** treatments compared to ***C*** treatments. Plant water use is expressed in terms of evapotranspiration (ET). Our computations indicated that ET was generally higher for ***NB*** and ***FM*** treatments. However, since we were unable to separate the ET into transpiration and soil water evaporation, we only conjecture that in treatments where less water infiltrated the soil, the major part of the ET would be attributed to soil evaporation more than the more productive transpiration. The higher LA observed for the ***C*** treatments would also reduce the soil evaporation component under ***C*** treatments. Results by Gale and Thomas (2019) indicated that biochar addition at 8 and 30 t biochar ha-1 increased the LA growth by 30 and 33% respectively than the NB treated soil. A recent study by Faloye et al. (2019) also showed that a higher leaf area index (LAI) reduced moisture loss via evaporation and limits it to the subsurface layer where plants make use of moisture in the root zones. Since ET is related to LA (Al-Kaisi et al., 1989; Kar and Verma, 2005), it is plausible to imply that treatments that improved LA would also improve water use and hence cop growth.

The main hypothesis of this study was that the in-filling of Vertisol cracks with biochar would minimize ponding that handicaps upland crop production on the Vertisols, as well as keep the cracks open "permanently". Indeed, the non-ponding conditions that prevailed under ***C*** treatments throughout the greenhouse study support this assertion. The increased drainage observed indicates less water accumulation on the soil surface.

Overall, there was better maize growth per unit water for the ***C*** treatments than for the other treatments. The ***WUE*** determined were of the increasing order ***C***6 > ***C***3 > ***FM***6 > ***FM***3 > ***NB***. Faloye et al. (2019) indicated that in a water-limited condition, biochar application to soils enhanced the water use efficiency of maize and limited the adverse impact of drought on its yield. In this current study, it has been shown that not only BC application but also the mode of application was also important in enhancing the growth and yield of maize under limiting soil water conditions. Though not significant, the ***C*** treatments led to increased water storage and higher water use efficiency than the ***FM*** treatments and the control.

Emphatically, we have not found any studies to date that investigated the use of biochar to enhance water entry into heavy crack-swell clayey soils in the manner described in this study, even though the knowledge of preferential flow in Vertisols has been long known (Anderson et al., 2009; Cey and Rudolph, 2009; Kurtzman et al., 2011; Baram et al., 2012).

Conclusion

This study investigated the possibility of in-crack fill biochar amendment of Vertisols as a means of enhancing deep infiltration and reduction of ponding. The study has shown that biochar can be used as a soil physical amendment agent to enhance upland crop production on Vertisols, whose use in Ghana has hitherto been limited to lowland rice and cane sugar production. This current study investigated the impact of biochar application mode on soil water relations as well as maize productivity. The application of biochar into "cracks" created in Vertisols, instead of fully mixing into the topsoil, increased the overall infiltration, reduced runoff and ponding, and improved infiltration on the Vertisol. The quantities of biochar applied into cracks could be lower than full topsoil mixed options and still, be far more effective in enhancing infiltration of water into the soil. Additionally, direct unproductive water loss by evaporation could be reduced when biochar is applied to the cracks. The influence of the relative area of the cracks on the overall infiltration was not critical. Overall, the water use efficiency of maize was significantly higher for treatments where the biochar was applied into the cracks. The application of biochar into soil cracks on Vertisol provides a new and effective technology that would improve infiltration and reduce ponding and flooding, enabling upland crop production on heavy clayey soils such as the Vertisols. Though this has been demonstrated under greenhouse conditions, the lingering question is how to actualize it under field conditions. Conceivably, cracks developed naturally in Vertisols during the dry period could be periodically filled in with biochar. Repeating this practice over several years could help "develop" a composite soil with improved physical conditions that would enhance water intake and reduce runoff.

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Declaration of interest

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

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