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Assessing potential of biochar for increasing water-holding capacity of sandy soils

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Abstract
Increasing the water-holding capacity of sandy soils will help improve efficiency of water use in agricultural production, and may be critical for providing enough energy and food for an increasing global population. We hypothesized that addition of biochar will increase the water-holding capacity of a sandy loam soil, and that the depth of biochar incorporation will influence the rate of biochar surface oxidation in the amended soils. Hardwood fast pyrolysis biochar was mixed with soil (0%, 3%, and 6% w/w) and placed into columns in either the bottom 11.4 cm or the top 11.4 cm to simulate deep banding in rows (DBR) and uniform topsoil mixing (UTM) applications, respectively. Four sets of 18 columns were incubated at 30 °C and 80% RH. Every 7 days, 150 mL of 0.001 M calcium chloride solution was added to the columns to produce leaching. Sets of columns were harvested after 1, 15, 29, and 91 days. Addition of biochar increased the gravity-drained water content 23% relative to the control. Bulk density of the control soils increased with incubation time (from 1.41 to 1.45 g cm−3), whereas bulk density of biochar-treated soils was up to 9% less than the control and remained constant throughout the incubation period. Biochar did not affect the CEC of the soil. The results suggest that biochar added to sandy loam soil increases water-holding capacity and might increase water available for crop use.

Keywords
biochar, Gardner's function, sandy soils, water balance, water retention curves, water-holding capacity

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Assessing potential of biochar for increasing water-holding capacity of sandy soils

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Abstract

Increasing the water-holding capacity of sandy soils will help improve efficiency of water use in agricultural production, and may be critical for providing enough energy and food for an increasing global population. We hypothesized that addition of biochar will increase the water-holding capacity of a sandy loam soil, and that the depth of biochar incorporation will influence the rate of biochar surface oxidation in the amended soils. Hardwood fast pyrolysis biochar was mixed with soil (0%, 3%, and 6% w/w) and placed into columns in either the bottom 11.4 cm or the top 11.4 cm to simulate deep banding in rows (DBR) and uniform topsoil mixing (UTM) applications, respectively. Four sets of 18 columns were incubated at 30 °C and 80% RH. Every 7 days, 150 mL of 0.001 M calcium chloride solution was added to the columns to produce leaching. Sets of columns were harvested after 1, 15, 29, and 91 days. Addition of biochar increased the gravity-drained water content 23% relative to the control. Bulk density of the control soils increased with incubation time (from 1.41 to 1.45 g cm^{-3}), whereas bulk density of biochar-treated soils was up to 9% less than the control and remained constant throughout the incubation period. Biochar did not affect the CEC of the soil. The results suggest that biochar added to sandy loam soil increases water-holding capacity and might increase water available for crop use.

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Introduction

The global energy demand is growing rapidly and it is estimated that approximately the 88% of this demand is satisfied with fossil fuels. Different scenarios have shown that the energy demand will increase by a factor of two or three during this century (O'Gallagher, 2006). Moreover, increasing population, economic growth, energy demand, and climate change are putting substantial stress on the world's water resources (Brown, 2010). The agricultural sector is estimated to account for 70% of total global water withdrawals, the vast majority of which is used for irrigation. Only about 20% of the world's cropland is irrigated, however, these irrigated lands contribute 40% of total food production (FAO, 1998). The UN has projected a need to double global food production by 2050 to keep up with growing demand driven by both population and economic growth. Water use efficiency (WUE) greatly depends on nutrient and cropping management (Angus & Van Herwaarden, 2001; Hatfield *et al.*, 2001). In dryland agriculture, WUE ranges from 0.25 to 1.5 kg m^{-3}, whereas in irrigated agriculture it ranges from 0.5 to 1.7 kg m^{-3}, depending on the crop (Howell, 2001; Deng *et al.*, 2006). Water use efficiency in both dryland and irrigated agriculture will need to be substantially improved if we are going to meet this growing demand for food and fuel (Oki & Kanae, 2006).

Recently, researchers have found that biochar additions have the potential to increase soil water-holding capacity. This implies that soils amended with biochar could retain more water from rainfall, which should increase crop production in non-irrigated dryland regions (Jeffery *et al.*, 2011), and reduce the amount of irrigation water needed to grow crops in irrigated regions. Novak *et al.* (2009a) found that addition of switchgrass biochar (made at 500 °C) to a sandy Ultasol increased soil water retention by 15.9% relative to no-biochar controls. Chan *et al.* (2007) applied biochar made from greenwaste at 450 °C by slow pyrolysis to an Alfisol. They detected significantly more water retained by soils at field capacity in the biochar-amended soils relative to control soils for biochar application rates of 50 and 100 Mg ha^{-1}. Addition of 1–2% hardwood slow pyrolysis biochar to a Mollisol increased gravity-drained water retention by 15% relative to no-biochar controls, but did not affect moisture content at −0.33 bars (field capacity) or −15 bar (wilting point) soil water potentials (Laird *et al.*, 2010a). However, significant increases in soil water content at −1 and −5 bars water potentials were

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observed for the 1% and 2% (w/w) biochar treatments compared with no-biochar controls. Moreover, the authors stated that the ability of biochar to increase moisture retention capacity of soils has the potential to increase yields for crops exposed to water stress during critical periods of the growing season.

The depth and method of biochar incorporation into soils has the potential to influence soil water retention. So far, two biochar application strategies have been studied: uniform top mixing and deep-banding. Blackwell *et al.* (2010) evaluated banded application of biochar on dryland wheat (*Triticum* spp.) production in Western and South Australia. They used banding to reduce wind erosion and to place biochar close to crop roots. They found that banding biochar can reduce fertilizer requirements without affecting yields.

Bulk density is one of the most important soil characteristic affecting rainfall infiltration (Ueckert *et al.*, 1978), and recent research has found a decrease in soil bulk density after biochar additions (Oguntunde *et al.*, 2008; Laird *et al.*, 2010a). Decreasing soil bulk density increases soil porosity and soil aeration, and may have a positive effect on root and microbial respiration.

Despite insights from previous studies, there are still several gaps in understanding the impact of biochar additions on water retention and water partitioning in sandy soils. Previous studies have evaluated biochars made by slow pyrolysis. Evaluation of the impact of biochars made by fast pyrolysis on soil water relations, however, needs to be assessed. In addition, an evaluation of the relative impact of uniform surface and deep-banding biochar applications on water-holding capacity of sandy soils and the partitioning of added water between storage, drainage, and evaporation may also be valuable. We hypothesize that the addition of biochar to sandy soil will increase soil water content because evaporation and/or drainage will be reduced. Moreover, we hypothesize that deep-banding of biochar will increase soil water retention relative to uniform mixing of biochar with topsoil because less water will evaporate from the surface.

Fresh biochar tends to be hydrophobic, however, as biochar surfaces are oxidized on contact with air and water, biochar surfaces become hydrophilic. Carboxylate and other ionizable functional groups are believed to form on the surfaces of biochar as it oxidizes leading to an increase in cation exchange capacity (CEC) of biochar with time after being incorporated into the soil (Cheng *et al.*, 2006, 2008; Liang *et al.*, 2006). We hypothesized that the water-holding capacity of biochar-amended soil will increase over time because of these chemical changes on the surface of biochar particles. Furthermore, we hypothesize that CEC can be used as an indirect measure of the extent of surface oxidation and hence water retention capacity of soils amended with biochar. To test these hypotheses we carried out a soil incubation study. The specific objectives of the study were:

1) Assess the capacity of biochar for increasing water-holding capacity of a sandy soil.
2) Test biochar placement effect on soil water partitioning (amount of water retained by the soil, evaporated, and drained).
3) Estimate biochar effects on soil water retention curve parameters.
4) Determine changes in bulk density after biochar addition to the soil.

Materials and methods

Soil

The soil used in this study was a sandy loam (68.2% sand, 25.1% silt, and 6.7% clay) collected from the surface of 15 cm of a field on the Iowa State University Agronomy and Agricultural Engineering Research Farm in Boone County, Iowa, USA. Particle size analysis was carried by the Department of Agronomy Landscape Analysis Laboratory following Gee & Bauder (1986). Soil was air dried then passed through a 6-mm sieve and stored in closed plastic containers until used. Characteristics determined by the Soil and Plant Analysis Laboratory (Agronomy Hall, Iowa State University, Ames) are presented in Table 1. Soil pH was assessed with a pH meter using a 1 : 1 wt/wt soil/water slurry (Watson & Brown, 2011). Plant available P was estimated using the Bray 1 method (Bray & Kurtz, 1945). Plant available micronutrients (Zn, Cu, Fe, and Mn) were

Table 1 Chemical properties of the sandy loam soil, including Bray 1 P, DTPA extractable Cu, Fe, Mn, and Zn, and 1 M ammonium acetate extractable Ca, Mg, Na, and K. Values are in ppm units unless otherwise noted. Mean (n = 2) ± SD

P	K	Ca	Mg	Na	Zn	Cu	Fe
27 ± 1	117.5 ± 0.5	1871.5 ± 11.5	261 ± 1	3.5 ± 0.5	0.4 ± 0.0	0.7 ± 0.0	30 ± 0
Mn	NH_4-N	NO_3-N	Total C (%)	Total N (%)	OM (%)	pH	ECEC* (meq/100 g oven-dry soil)
20.5 ± 0.5	2.5 ± 0.5	13.5 ± 0.5	1.372 ± 0.011	0.1148 ± 0.0007	2.5 ± 0.0	7.3 ± 0.0	11.85 ± 0.05

*Sum of NH_4OAc extractable cation equivalents.

assessed by extraction with a DTPA solution (Lindsay & Norvell, 1978), and analysis using inductively coupled plasma-atomic emission spectroscopy (ICP). Exchangeable base cations (K, Ca, Mg, and Na) were determined by extraction with an 1 M ammonium acetate followed by ICP analysis (Warncke & Brown, 2011). Effective cation exchange capacity was calculated as the sum of exchangeable K, Ca, Mg, and Na (Warncke & Brown, 2011). Soil organic carbon and total nitrogen were determined by thermal combustion analysis, whereas the organic matter was estimated by multiplying soil organic carbon by 1.72 (Combs & Nathan, 2011). Extractable (2 M KCl) inorganic nitrogen was determined using a colorimetric method (Mulvaney, 1996).

Biochar

Avello Bioenergy, Inc. (BioCentury Research Farm, 1327 U Avenue, Boone, Iowa, USA) provided the biochar used for this experiment. The biochar was produced using red oak (*Quercus rubra*) feedstock by fast pyrolysis (500 °C) in a 6 inch bubbling fluidized bed reactor, using nitrogen (183 L min^{-1}) as the fluidizing gas. The average biomass feed rate was 5.0 kg hr^{-1}. After production, the biochar was stored in a sealed container for 3 months before it was used in this study. The biochar was characterized using ultimate (ASTM-D3176, 2009) and proximate (ASTM-D3172, 2007) analyses conducted by Hazen Research, Inc. (4601 Indiana Street Golden, Colorado 80403, USA).

Characteristics of the biochar are provided in Tables 2 and 3. The biochar used in this study had high ash content (Table 2), 21.6% compared to the 13.9% found in a slow pyrolysis biochar made of hardwood used in another study (Laird *et al*., 2010a, b). This high ash content may contribute to increases in the soil pH after dissolution of carbonates and oxides present in the ash fraction (Joseph *et al*., 2010). Some of the sand that was used as a heat carrier in the fast pyrolysis reactor was likely transferred into the biochar. Any such sand contamination would have increased the apparent ash content of the biochar.

Table 2 Ultimate and Proximate analysis of the hardwood (red oak) fast pyrolysis (500 °C) biochar following ASTM standard methods (ASTM-D3172 2007; ASTM-D3176 2009)

	As received,%	Dry,%	Air Dry,%
Ultimate			
Moisture	1.45	0.00	1.45
Ash	21.58	21.90	21.58
Sulfur	0.005	0.005	0.005
Carbon	84.97	86.22	84.97
Hydrogen	3.45	3.50	3.45
Nitrogen	0.08	0.08	0.08
Oxygen	<0.01	<0.01	<0.01
	100.00	100.00	100.00
Proximate			
Moisture	1.45	0.00	1.45
Ash	21.58	21.90	21.58
Volatile matter	15.75	16.01	15.78
Fixed carbon*	61.19	62.09	61.19
	100.00	100.00	100.00

*By difference.

Table 3 Elemental analysis of ash from the hardwood (red oak) fast pyrolysis (500 °C) biochar following ASTM standard methods (ASTM-D3172 2007)

Component	Percentage (%)
SiO_2	91.82
Al_2O_3	1.38
TiO_2	0.02
Fe_2O_3	0.32
CaO	4.17
MgO	0.33
Na_2O	0.10
K_2O	2.24
P_2O_5	0.26
SO_3	0.44
Cl	0.03
CO_2	0.35
Total	101.46

The volatile fraction and fixed carbon represent the available and recalcitrant fraction of carbon, respectively. The value of these parameters, along with the percentage of carbon are similar to values found in other biochars (Table 2) (Novak *et al*., 2009a; Laird *et al*., 2010a).

Incubation

The soil incubation was carried out in PVC columns of 18 cm height and 7 cm external diameter. To build the columns, individual 18 cm length PVC pipes were cut longitudinally and then joined together with two hose clamps to avoid leaks. The purpose of cutting the pipe was to allow access to the soil for sampling with minimal disturbance. A PVC end cap on the bottom of each column had a drain hole (3 mm) with an attached tube (4.3 mm i.d.) for collecting water draining out the bottom of the columns. The concave portion of the end cap was filled with approximately 100 g of coarse sand (4–7 mm). The total mass of oven dry soil in each column was 994 g.

Biochar was applied in two different ways, either in the bottom 11.4 cm or at the top 11.4 cm, to simulate deep-banding in rows (DBR) and uniform topsoil mixing (UTM) applications, respectively. To complete the column filling, 5 cm of soil without biochar was placed either on the top (DBR) or the bottom (UTM) of the column. There were three rates of biochar application, 0% (control), 3%, and 6% (w/w). These percentages were calculated in the section of column where there was biochar, excluding the portion of column where there was soil without biochar. For the 3% biochar treatment, each column contained 20 g of biochar and 974 g of soil, whereas columns with the 6% biochar treatment contained 40 g of biochar and 954 g of soil. All columns were packed to similar bulk densities ranging from 1.31 to 1.41 g cm^{-3}, depending primarily on the biochar application rate.

The four sets of 18 columns were incubated at 30 °C and 80% RH in a dark room. Column sets were destructively

harvested at different times during the incubation: the first set was harvested 1 day after the start of the incubation, whereas sets 2, 3, and 4 where harvested 15, 29, and 91 days after the start of the incubation, respectively. Each set of columns had three rates of biochar application (0%, 3%, and 6%), two biochar placements (DBR and UTM), and three replicates. The 72 columns were randomly distributed in two square tables, each containing 36 holes for mounting the columns.

During the incubation, the columns were watered every 7 days with 0.001 M $CaCl_2$ to induce a leaching event. On day 0, the columns were leached with 350 mL of solution; all other leaching events were completed using 150 mL of solution. The solution was introduced on the top of each column at approximately 3.75 mL min^{-1}, using a dropper system. A piece of fiberglass filter paper was placed at the soil surface to help disperse solution drops as they impacted the soil. Leachate was collected for approximately 24 h after the beginning of each leaching event in plastic bottles placed below each column and connected with the drainage tube.

Water partitioning

Water partitioning was assessed for every leaching event during the incubation by measuring the mass of water draining out the bottom of the column, water retained within the column, and water evaporated out the top of the column. The weight of each column was determined before the start of a leaching event and the mass of water retained within the column was determined by subtracting the initial dry column weight. Drainage was measured by weighing the leachate collected for approximately 24 h after each event. Evaporation was assessed by computing the difference between the mass of water added and drainage plus or minus any change in soil water content.

The mass of water retained in the columns was the gravity-drained water content after 7 days of the watering events. Water potentially available for evapotranspiration (ET) right after each watering event was considered equal to the sum of each component of the water partitioning except drainage.

ECEC and gravimetric water content

Gravimetric water content and effective cation exchange capacity (ECEC) were determined for soil samples collected at three depths (depth 1 = 0–1.3 cm, depth 2 = 5.05–6.35 cm, and depth 3 = 13.94–15.24 cm) in each column at the time of sampling (Fig. 1). The second set of columns was harvested 48 h after watering, whereas the other three sets of columns where harvested 24 h after watering. Because of this difference in harvest timing, values from the second set of columns were not used for interpreting water partitioning. Gravimetric water content was determined by the difference between moist and oven-dried (105 °C for 24 h) sample weights. The remaining soil in each sample was air dry and stored in a sealed plastic bag for later ECEC determination following Sumner & Miller (1996) with the following modification: prior to extraction with NH_4Cl, the soil was washed with Milli-Q water to remove any excess salt. Concentrations of Ca, Mg, Na, and K were determined by inductively coupled plasma-atomic emission spectroscopy (ICP).

Soil water retention curves

Soil water retention curves were determined using soil from the 6.35–11.4 cm depth increment collected during destructive sampling of the columns (Fig. 1). A cylinder of intact soil, 5 cm high and 7 cm diameter, was collected during the destructive sampling for matric potential analysis. A pressure chamber was used for determination of water held at matric potentials of −0.01, −0.025, −0.05, −0.1, −0.2, −0.33, and −0.5 bar (Klute, 1986). The intact soil cylinders held in PVC rings were initially saturated from the bottom up with 0.001 M $CaCl_2$ for 24 h at 20 °C. The average matric potential of the saturated soil sample was −0.0013 bars. The saturated samples were placed into a pressure chamber and pressure was incrementally increased. At each step, the pressure was held constant until all samples stopped draining water. Equilibrium water content of the individual cores was determined by recording the volume of water

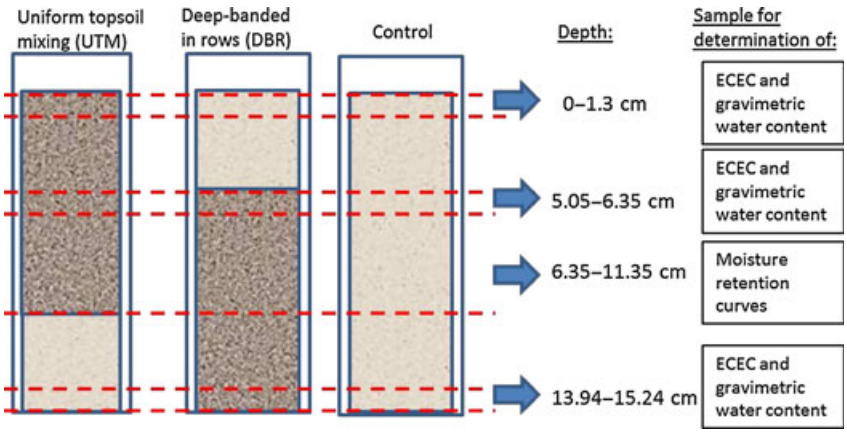

Fig. 1 Graphical representation of the column soil sampling strategy for the different measurements. Dark-textured color represents biochar plus soil and light-textured color represents soil only. At the end of the incubation period, the columns were dismantled and samples at different depths were obtained.

released at each pressure. Water retained at −1 and −15 bars matric potential was determined by the pressure plate method (Klute, 1986) using a Ceramic Plate Extractor (Soil Moisture Equipment Corp., Santa Barbara, CA, USA). Rubber rings (1 cm thick by 3 cm diameter) were filled with soil and saturated from the bottom with 0.001 M $CaCl_2$ at 20 °C. After 7 days of pressure, the soil was weighed, oven dried at 105 °C for 24 h, and reweighed to determine water content. Available water-holding capacity of each sample was determined by calculating the difference in volumetric water content held at −0.10 and −15 bars.

Evaporative demand

The average temperature in the room where the columns were incubated was 30 °C. Nevertheless, there were differences in temperature across the room and evaporative demand was also influenced by proximity to overhead air circulation fans. In to take into account these differences, evaporative demand was determined for each column. For this, PVC cups were filled with a known amount of water and placed above each column. The PVC cups were weighed several times over the next 3 days to determine the average rate of water loss for each column (evaporative demand). Evaporative demand was used as a covariate in the statistical analysis.

Bulk density

Bulk density was determined on days 0, 21, 63, and 90 of incubation for the fourth set of columns. The distance from the top of the soil surface to the top of the column was measured to estimate the headspace volume of each column and then the soil volume was determined by difference from the total column volume. Bulk density was calculated by dividing the initial oven-dry mass of soil by the soil volume. This approach assumes no changes in soil mass during the incubation and the value obtained was the average bulk density of the column.

Statistical analysis

A linear mixed model was used to analyze water partitioning, water available for ET, bulk density, gravimetric water content, and ECEC (Proc Mixed, SAS 9.2, SAS Institute Inc., Cary, NC, USA). The terms in the model used for water partitioning, water available for ET, and bulk density analysis were incubation day (1, 15, 29, and 91 days), biochar treatment (control, DBR_3, DBR_6, UTM_3, and UTM_6), and the interaction term between incubation day and biochar. In addition to these terms, for the gravimetric water content and ECEC analysis, the term depth (depth 1 = 0–1.3 cm, depth 2 = 5.05–6.35 cm, and depth 3 = 13.94–15.24 cm) and the interaction between biochar, incubation day, and depth were included. To account for the correlation of residuals in variables that were measured repeatedly over the duration of the experiment the covariance structure of the residuals was modeled. The structures chosen (based on AIC criteria) were "First order ante-dependence covariance structure" for ECEC and gravimetric water content and "Variance components" for bulk density, water partitioning, and water available for ET. Evaporative demand was used as a covariate in each model. Mean separation was conducted based on linear contrasts at an alpha of 0.05.

Gardner's function was used to estimate parameters of the water retention curves:

$$\theta_{(h)} = \theta_r + (\theta_s - \theta_r)[1 + (\alpha h)^n]^{-1}$$

Where:

- θr = Residual water content
- θs = Saturation water content
- $\alpha \sim 1/P$ (Pressure at which slope is the steepest)
- 'n' is related to slope at P (greater slope, greater 'n')

(Parameter explanation was extracted from van Genuchten (1980)).

The analysis of the water retention curves was carried out using a nonlinear mixed model (HydroMe R package (Omuto & Gumbe, 2009)). Available water-holding capacity was analyzed using a linear model (Proc Mixed, SAS 9.2, SAS Institute Inc.), where the terms in the model were incubation day (1, 15, 29, and 91 days), biochar treatment (control, DBR_3, DBR_6, UTM_3, and UTM_6), and the interaction between incubation day and biochar treatment. Mean separation was conducted based on linear contrasts at an alpha of 0.05.

Results

Water partitioning

Biochar-amended columns had a significant increase of 23% in gravity-drained water content (Fig. 2), relative to the control, calculated based on the difference in mass

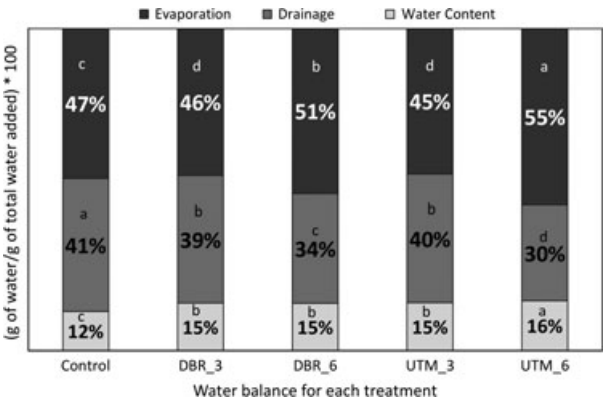

Fig. 2 Water partitioning for each treatment averaged across 91 days of incubation. Biochar rates (3 and 6% wt/wt) were applied in the bottom 11.4 cm or in the top 11.4 cm, to simulate deep-banding in rows (DBR_3 and DBR_6) and uniform topsoil mixing (UTM_3 and UTM_6) applications, respectively. Treatment means within each component of water partitioning with different letters indicate statistically significant differences ($P < 0.05$).

of water retained per gram of oven-dry soil by each treatment (0.1943 and 0.1583 average water retained by biochar and control treatments, respectively). Differences in water content between biochar treatments were not significant except for the UTM_6 treatment, which showed slightly higher water content ($P < 0.01$) than the other biochar treatments. From the total amount of water added during the 91 days of incubation, an average of 15.5% was retained by columns receiving the biochar treatments, and the remaining 84.5% was either drained or evaporated (Fig. 2). Columns receiving the 6% biochar treatment lost significantly ($P < 0.05$) less water to drainage and more water to evaporation compared with columns receiving the 3% biochar treatment. There were no significant differences in evaporation and drainage between DBR_3 and UTM_3 treatments. On the other hand, values of drainage observed in the UTM_6 treatment were significantly ($P < 0.01$) less than the values of drainage for the DBR_6 treatment.

A comparison between water content of the different methods of biochar application is shown in Fig. 3. Significantly less water evaporated from soil amended with 6% (w/w) biochar applied as a deep-band (DBR_6) than when it was uniformly mixed with the top soil (UTM_6). Significantly more water was held in UTM_6, however, because it had significantly less water loss to drainage than did the DBR_6 treatment.

Soil water content of columns treated with biochar measured 1 week after a leaching event was relatively constant during the incubation period, whereas the water content of the control columns slowly decreased from day 7 to day 91 of the incubation (Fig. 4). In comparing days 14 and 91 in Fig. 4, there were no significant decreases in water content for columns that received biochar, whereas water content of control columns decreased significantly ($P < 0.05$) during the same period. This was probably due to the increase in soil bulk density observed for the control columns (Fig. 5).

Available water for ET for each treatment at incubation day 91 was 0.242, 0.274, 0.285, 0.276, and 0.302 g of water per g of oven-dry soil for the Control, DBR_3, UTM_3, DBR_6, and UTM_6 treatments, respectively. These values represent significant increases in water available for ET of 13%, 18%, 14%, and 25% for DBR_3, UTM_3, DBR_6, and UTM_6 treatments, respectively, relative to the controls.

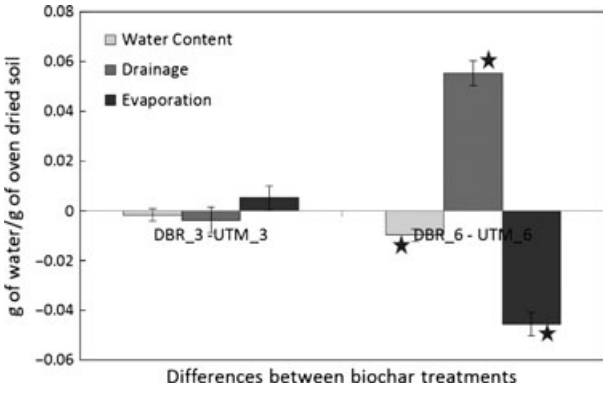

Fig. 3 Differences in water content between biochar treatments after 91 days of incubation. Biochar rates (3 and 6% wt/wt) were applied in the bottom 11.4 cm or in the top 11.4 cm, to simulate deep-banding in rows (DBR_3 and DBR_6) and uniform topsoil mixing (UTM_3 and UTM_6) applications, respectively. Each column represents the difference between treatments for each component of water partitioning. Star denotes statistically significant differences ($P < 0.05$) from 0. Error bars show standard error of the difference.

Bulk density

Bulk density of the control columns increased significantly during the incubation from 1.41 to 1.45 g cm^{-3} for incubation days 0 and 90, respectively (Fig. 5). On the other hand, changes in bulk density for the biochar treatments were not significant along the incubation period (Fig. 5). The DBR_3 treatment did not have significant effect on bulk density, compared with the control on incubation day 0. At the end of the incubation, bulk density was 1.43 (control), 1.42 (DBR_3), 1.36 (DBR_6), 1.37 (UTM_3), and 1.32 (UTM_6) g cm^{-3} (Fig. 5). On incubation day 90, however, we observed significantly ($P < 0.05$) lower bulk densities of 1.6%, 5.1%, 6.2%, and 9.0% for DBR_3, UTM_3, DBR_6, and UTM_6 treatments, respectively, relative to the control.

Water retention curves

The UTM_6 treatment significantly ($P < 0.05$) increased, compared with the control, the amount of water held at tensions of saturation point (θs) after 29 and 91 days of incubation (second and fourth set of column, respectively) and significantly ($P < 0.05$) increased θr after 91 days of incubation (Fig. 6). Moreover, DBR_3 significantly ($P < 0.05$) increased θs compared with the control in the fourth set of columns. UTM_3 showed larger water content retained at the lower tensions than the other treatments for incubation day 29. Available water-holding capacity (AWHC) on incubation day 15 was not significantly different between the control and biochar treatments. By incubation day 29, however, all of the biochar treatments showed greater AWHC than the control, and for UTM treatments this difference was statistically significant. By incubation day 91, all of the biochar treatments had significantly ($P < 0.05$) larger AWHC relative to the controls. Values of AWHC for each treatment at incubation day 91 were 0.14, 0.25, 0.19, 0.17,

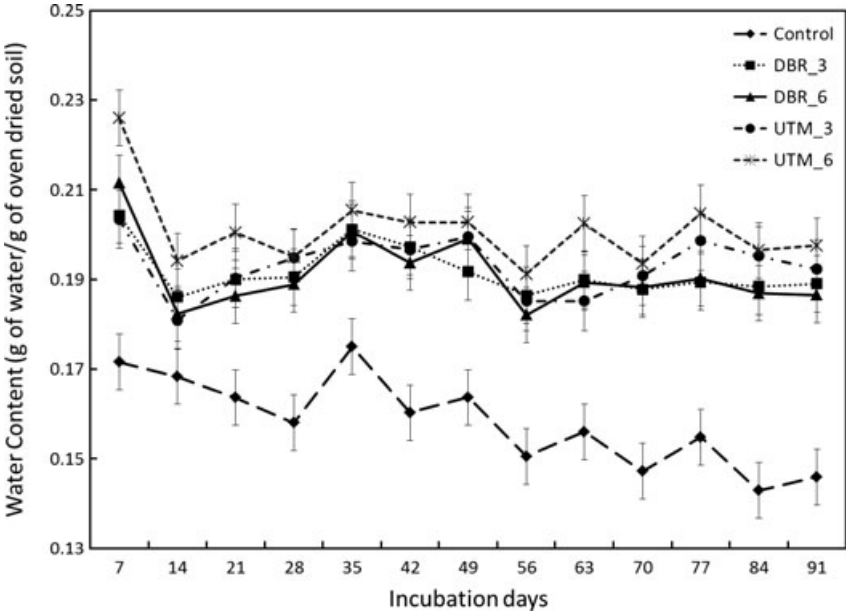

Fig. 4 Temporal dynamics of gravimetric water content for each treatment during the 91 days of incubation. Biochar rates (3 and 6% wt/wt) were applied in the bottom 11.4 cm or in the top 11.4 cm, to simulate deep-banding in rows (DBR_3 and DBR_6) and uniform topsoil mixing (UTM_3 and UTM_6) applications, respectively. Error bars are the standard error of the mean.

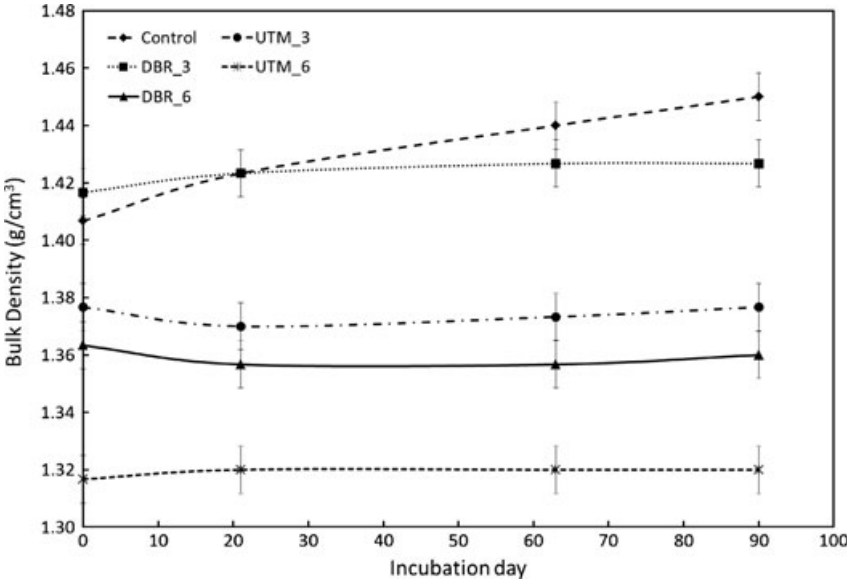

Fig. 5 Temporal dynamics of bulk density for each treatment during the 91 days of incubation. Biochar rates (3 and 6% wt/wt) were applied in the bottom 11.4 cm or in the top 11.4 cm, to simulate deep-banding in rows (DBR_3 and DBR_6) and uniform topsoil mixing (UTM_3 and UTM_6) applications, respectively. Error bars are the standard error of the mean.

and 0.19 cm^3 of water per cm^3 of soil for the Control, DBR_3, UTM_3, DBR_6, and UTM_6 treatments, respectively. These values represent an increase in AWHC for the biochar treatments relative to the control of 84%, 44%, 29%, and 38% for DBR_3, UTM_3, DBR_6, and UTM_6 treatments, respectively.

Biochar treatments did not show significant differences in AWHC among them, except for DBR_3, which showed significantly greater AWHC than the others. We did not observe a significant increase in AWHC for the UTM_3, DBR_6, and UTM_6 biochar treatments from incubation days 15 to 91.

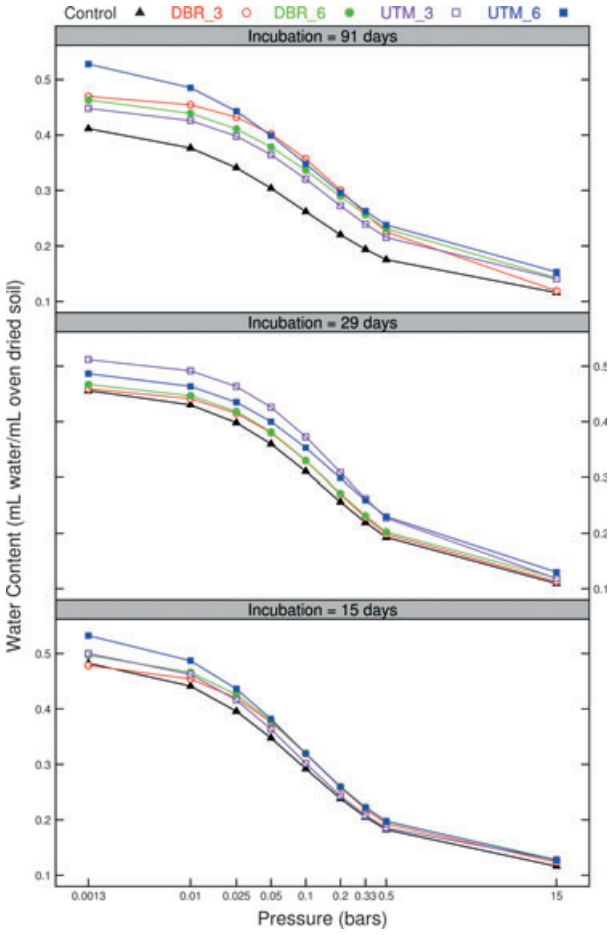

Fig. 6 Water retention curves for biochar treatments at different times during the incubation. Biochar rates (3 and 6% wt/wt) were applied in the bottom 11.4 cm or in the top 11.4 cm, to simulate deep-banding in rows (DBR_3 and DBR_6) and uniform topsoil mixing (UTM_3 and UTM_6) applications, respectively.

Gravimetric water content and ECEC

The distribution of biochar within the columns influenced the gravimetric water content distribution within the columns (Fig. 7). For the UTM treatments, depths 1 and 2 had greater water content than depth 3, coincident with the fact that samples taken at depths 1 and 2 had biochar whereas those taken at depth 3 did not. Similarly, for DBR treatments, water content for depths 2 and 3 were greater than water content at depth 1. In DBR treatments, samples taken at depths 2 and 3 had biochar, but those taken at depth 1 did not. Moreover, treatments that received 6% wt/wt of biochar had greater gravimetric water content than those receiving 3% wt/wt biochar. Unlike samples having biochar, water content of the control significantly decreased from harvesting time 1 toward harvesting time 4.

The incorporation of biochar did not increase the ECEC of the soil (Fig. 8). Figure 8 shows that ECEC was not related to biochar placement. Moreover, there was not a clear trend in ECEC along the different columns' harvesting time and the different depths (Fig. 8).

Discussion

Water partitioning

The results of this study showed that biochar addition to a sandy soil significantly increase gravity-drained water content, relative to the no-biochar controls. Biochar increased gravimetric water content in other experiments (Tryon, 1948; Novak *et al.*, 2009a; Laird *et al.*, 2010a). The difference observed in drainage between the 6% biochar treatments might be due to the fact that UTM_6 columns had slower water infiltration rates during most of the

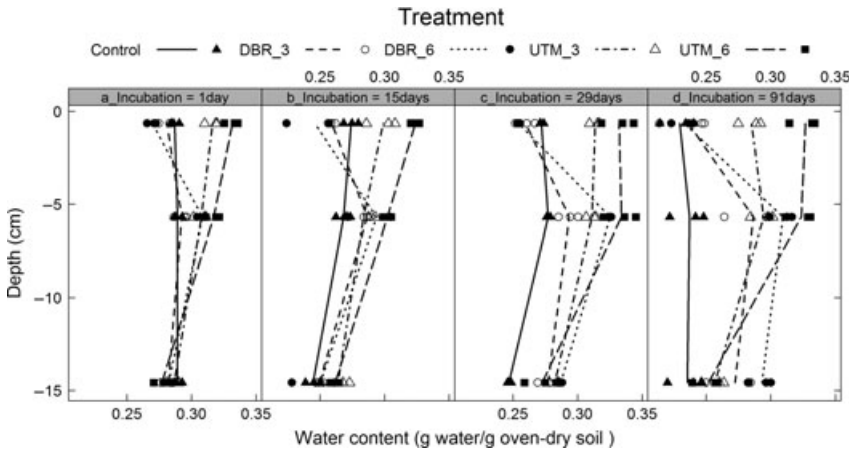

Fig. 7 Distribution of water content by depth and incubation day for soil columns containing biochar treatments. Biochar rates (3 and 6% wt/wt) were applied in the bottom 11.4 cm or in the top 11.4 cm, to simulate deep-banding in rows (DBR_3 and DBR_6) and uniform topsoil mixing (UTM_3 and UTM_6) applications, respectively.

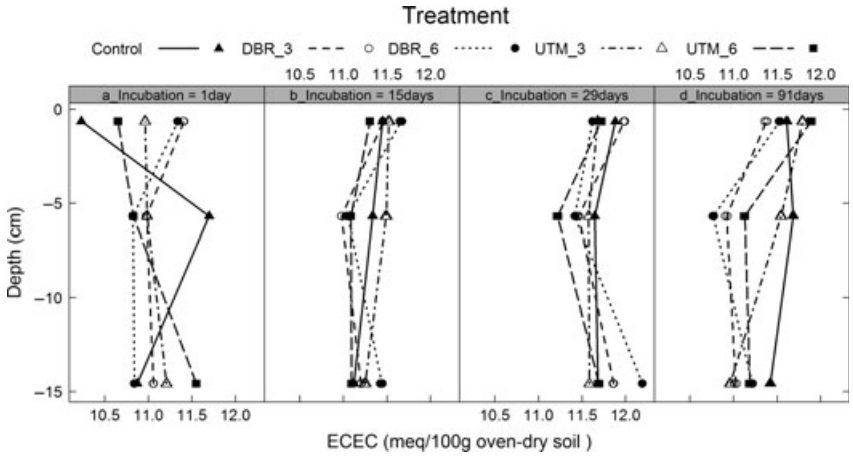

Fig. 8 Distribution of effective cation exchange capacity (ECEC) by depths and incubation day for soil columns containing biochar treatments. Biochar rates (3 and 6% wt/wt) were applied in the bottom 11.4 cm or in the top 11.4 cm, to simulate deep-banding in rows (DBR_3 and DBR_6) and uniform topsoil mixing (UTM_3 and UTM_6) applications, respectively.

incubation time compared with the others treatments, resulting not only in the least drainage but also in greater evaporation due to ponding of water. Moreover, the water was concentrated close to the soil surface in the UTM_6 columns (see Fig. 6), therefore more water was readily available for evaporation between watering events than in the DBR_6 columns, where most of the water was in the bottom of the column. Tryon (1948) observed that addition of charcoal to soil reduced slightly the loss of moisture by evaporation, and that the effect was more pronounced when a sandy soil was used instead of a clayey soil. In this study, we observed a reduction in evaporation relative to the controls only for the 3% wt/wt biochar treatments. However, in the experimental setup that Tryon (1948) used to determine evaporation there was no possibility for drainage and the quantities of biochar used were much greater than in the present experiment. During most of the incubation time, water infiltration was very slow in the columns of the UTM_6 treatment, requiring approximately 40 min for all of the added water to infiltrate. In all the other treatments, around 10 min was sufficient for all of the water to infiltrate. The infiltration rate of the UTM_6 columns, however, increased with time and became similar to the infiltration rate of the other treatments by the end of the incubation period. Infiltration rate was not measured in this experiment; these values are estimates from observation made during the incubation. However, this observation suggests that the biochar used might be hydrophobic when it is fresh and that it become more hydrophilic after prolonged contact with soil, air, and watering solution, as observed in other studies (Cheng *et al.*, 2008; Joseph *et al.*, 2010).

We observed that uniform top mixing 6% (w/w) of biochar within the soil (UTM_6 treatment) might reduce water infiltration in the soil, creating a water layer on the soil surface, which if projected to a field situation could potentially result in runoff and soil erosion during the initial period after biochar application when it remains hydrophobic. Studies have shown that water flowing over the land surface is one of the most important driving forces for soil erosion (Renard & Foster, 1983; Moore & Singer, 1990). Water films covering the soil surface, however, might moderate the impact of water drops (rainfall drops, for example), reducing soil erosion (Moore & Singer, 1990). Moreover, factors like crop residue and landscape slope influence not only soil erosion but also runoff and rate of intake of water by soils (Duley, 1939). As these factors were not taken into account in the present laboratory experiment, further research is needed to fully understand the effects of biochar on soil water infiltration.

Bulk density

Biochar addition to sandy soil significantly reduced the bulk density of the soil after 91 days of incubation. The increase in bulk density in the control was likely responsible for the decrease in water content compared with the stable water content in the columns that received biochar. However, this result along with those observed in water partitioning need to be confirmed in the field where soil structure is not disturbed and crops and crop residues are present, as interactions among many factors influence soil water infiltration, drainage, and bulk density.

Other researchers have also found a decrease in soil bulk density after biochar additions (Oguntunde *et al.*, 2008; Laird *et al.*, 2010a), probably due to the low bulk density of the biochar itself (Downie *et al.*, 2009).

Decrease in bulk densities may promote plant root elongation (Siemer & Grable, 1968) and root density (Thompson *et al*., 1987).

Water retention curves

The greatest differences in water content between the biochar-treated columns and the controls occurred mainly at large matric potentials and these differences increased as the incubation advanced (Fig. 6). The amount of water retained at matric potentials between 0 and 1 bar, which describe the shape of the water retention curve, depends mainly on the capillary effect and the pore-size distribution (Hillel, 1998; Jury & Horton, 2004). Parameters 'α' and 'n' in the Gardner function determine the shape of the water retention curve. In this study, no significant changes in 'α' or 'n' were found for different harvesting times when comparisons between control and biochar treatments were made. So, incorporation of 3% or 6% (w/w) of this particular type of biochar does not appear to affect capillarity and pore-size distribution of the soil. The differences observed in water content between biochar treatments and the control in this study appear to be mostly due to higher total porosity of the biochar-treated soil, which allowed more water to be physically retained (Downie *et al*., 2009).

The water content of the control decreased proportionally at each matric potential value compared with the biochar treatments (Fig. 6). This observation is consistent with the observation that water retention by biochar-treated columns was relatively constant during the incubation period (Fig. 4). The reason for the differences in water content between treatments at the saturation point was probably due to the differences in bulk density between treatments. The bulk density of the control columns increased during the incubation (reducing the space where water could be retained) whereas bulk density of the biochar-treated columns remained relatively constant during the incubation (Fig. 5). We do not, however, have a clear explanation for the larger water content at lower tension observed for UTM_3 at incubation day 29 compared with the other treatments.

Biochar addition significantly increased AWHC of the sandy soil. Considering a soil with an average AWHC of 0.14 $cm^3\ cm^{-3}$, adding a layer of 10 cm of biochar-amended soil (average AWHC of 0.20 $cm^3\ cm^{-3}$) into a root zone of 150 cm depth, represent an increase of 3% in equivalent depth of water in the 150 cm soil depth. This 3% is the extra amount of water that will be available in the root zone for crops by adding biochar, and could represent the amount of irrigation water that a producer will save.

The reason why we did not observe a significant increase in AWHC for all the biochar treatments except DBR_3, from incubation days 15–91, might be due to the fact that the volumetric water content retained at -15 bars matric potential (permanent wilting point, WP) increased in a greater proportion than the volumetric water content retained at −0.1 bars (field capacity, FC). On the other hand, AWHC for the DBR_3 significantly increased between incubation days 15–91. For this treatment, we observed a decrease in water content at WP from incubation day 15–91 whereas water content at FC increased during the same period. These differences in water content at FC and WP between the biochar treatments are the reason for the greatest AWHC of DBR_3 treatment.

The increase in volumetric water content retained at −15 bar matric potential (WP) observed for the UTM_3, DBR_6, and UTM_6 treatments might be due to the opening of obstructed capillary pores by dissolution of oxides that were blocking them. Another reason could be a change in the nature of biochar surfaces from hydrophobic to hydrophilic as was evidenced by an increase in infiltration rate for the UTM_6 columns as noted earlier in the Water Partitioning discussion. These processes did not affect the DBR_3 columns in the same way as columns receiving the other biochar treatments. These results need to be investigated further as there is no obvious explanation why the DBR_3 columns should have responded differently from the other columns.

Gravimetric water content and ECEC

The gravimetric water content distribution observed in Fig. 7 is consistent with what was observed in Fig. 4, where water content of columns with biochar showed little variation during the incubation period, whereas the water content of the control significantly decreased during the 91-day incubation.

Biochar addition to soil has been shown to increase the ECEC of soils (Cheng *et al*., 2006; Chan *et al*., 2007; Van Zwieten *et al*., 2009; Laird *et al*., 2010a), although in other studies biochar did not have a measurable effect on the capacity of the soil to retain positively charged ions (Novak *et al*., 2009a,b). Researchers have found an increase in ECEC values of biochar with time which has been attributed to surface oxidation and creation of carboxylic and phenolic surface functional groups (Cheng *et al*., 2006, 2008; Liang *et al*., 2006). In this study, the relationship between biochar placement and ECEC was expected to be similar to what was observed for water content, with higher ECEC values where biochar was located, in addition to increasing ECEC during incubation due to oxidation of biochar surfaces. Moreover, we also expected greater surface oxidation on biochar of UTM treatments compared with biochar of DBR treatments. We observed that the ECEC of biochar-amended

soils, however, was not significantly different from that of the control, and this variable did not explain the increase in water-holding capacity of the sandy soil after biochar addition during 91 days of incubation. The 91-day incubation time may not have been long enough for surface oxidation to generate carboxylate groups under the conditions of the study or the analytical procedure may not have been precise enough to detect minor changes in ECEC. Regardless of the reason we did not detect an increase in ECEC, our results indicate that factors other than ECEC influence water adsorption by biochar.

In summary, the major impact of adding biochar to the sandy loam soil was an increase in water-holding capacity. Our results suggest that addition of this type of biochar (red oak, fast pyrolysis, 500 °C) has the potential to increase total water retained against gravity by the soil, as well as to maintain this water in the soil for an extended period of time. There were no significant differences in water partitioning (water retention, evaporation, and drainage) between biochar application methods at 3% wt/wt biochar addition rate. Uniform top mixing of 6% wt/wt biochar (UTM_6), however, significantly increased water retention relative to deep-banding 6% wt/wt biochar (DBR_6). Biochar application did not increase ECEC of the soil during the 91-day incubation, thus demonstrating that the transformation from hydrophobic to hydrophilic biochar surfaces observed in this study was not accompanied by a measureable increase in ECEC. Another interesting finding from this study is that biochar addition maintained bulk density relatively constant during the incubation, whereas bulk density for the controls significantly increased during the same period of time. The analysis of the water retention curves suggested that differences observed in water content between biochar treatments and the controls were mostly due to the large porosity of the biochar that could have allowed more water to be physically retained which is consistent with the lack of a change in ECEC. Addition of biochar significantly increased available water-holding capacity of the soil after 91 days of incubation. Overall, biochar could be added to sandy soils to increase water-holding capacity and thereby to retain greater amounts of plant available water for crops for longer periods of times. However, field research is still needed to assess the crop response to biochar along with experiments to determine specific mechanisms by which water is retained in biochar-amended soils.

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