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Authors
Wang, Daoyuan
Li, Chongyang
Parikh, Sanjai J
et al.

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Impact of biochar on water retention of two agricultural soils – A multi-scale analysis

Daoyuan Wang*, Chongyang Li, Sanjai J. Parikh, Kate M. Scow

Department of Land, Air and Water Resources, University of California, Davis, CA 95616, USA

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A B S T R A C T

The ability of soil to retain water under drought and other extreme hydrological events is critical to the sustainability of food production systems and preserving soil ecosystem services. We investigated the impact of biochar on water retention properties in California agricultural soils in a series of column, lab incubation, and field studies. Results from studies based on similar variables (soil, biochar) were used to demonstrate the impact of biochar on soil-water relations at different scales. The influences of biochar type (softwood, 600–700 °C, low surface area; walnut shell, 900 °C, high surface area), application rate (0, 0.5, 1% wt.), and particle diameter (0–0.25, 0.25–0.5, 0.5–1, 1–2 mm) were investigated. Only the higher surface area biochar increased the field capacity of a sandy soil. Neither biochar, altered the field capacity of the higher clay content soil. The walnut shell biochar with 1–2 mm particle diameter was more effective at increasing field capacity in sandy soils compare to smaller biochar size fractions. Neither biochar affected the wilting point in either soil. Neutron imaging was used to explore potential mechanisms involved in water retention by observing the spatial and temporal distribution of water in and surrounding biochar particles (~ 2 mm diameter). After wetting, water retained in the internal pores of biochar was continuously released to surrounding space (~ 2.2 mm sphere) during a 7-day air drying at room temperature, suggesting that soil water retention is improved via the biochar's intraparticle structure. In the field trial, (6 yr., corn-tomato rotation), neither walnut shell biochar amendment (10 t/ ha, equivalent to 0.5% wt. in lab scale experiments) nor agricultural management practices (organic, conventional) altered the water retention capacity of a silty clay loam soil. These data suggest that biochars with a high pore volume can temporarily increase the field capacity and plant available water in a coarse-textured soil, until biochar internal pores are filled by clay and soil organic matter. Our results suggest that biochar can have a limited impact on soil water retention when biochar pore volume is low, or soil texture is fine. High dosage (≥ 10 t/ha) of high pore volume biochar with bulky particle size (≥ 1 mm) can improve water retention of coarse-textured soil with limited capacity of water storage and may improve soil's resilience during hydrological extremes.

1. Introduction

Global climate change has increased extreme hydrological events, such as long-term drought, extreme precipitation, and frequent wet-dry cycles (Trenberth et al., 2015). This can lead to greater uncertainty in agricultural production globally (Lesk et al., 2016). Improving soil water retention capacity can increase the resilience of agroecosystems (Post et al., 2008) and the soil microbial communities on which they depend (Manzoni et al., 2012). As a by-product of biomass pyrolysis under oxygen limited conditions (Lehmann and Joseph, 2009), biochar soil amendments provide a potential soil carbon sequestration technology to help mitigate global climate change (Woolf et al., 2010). Adding biochar can provide other agricultural benefits, such as reducing nutrient leaching (Knowles et al., 2011) and increasing soil cation exchange capacity (Liang et al., 2006).

Previous research on the impact of biochar on soil water retention is inconsistent in its outcomes. Because biochar physical characteristics vary depending on feedstock and pyrolysis conditions (Mukome et al., 2013), its capacity to modify soil water retention depends on the combination of biochar and soil properties. Comparing biochars prepared from straw and pine wood at different temperatures, Burrell et al. (2016) found no consistent impact on plant available water in three

Abbreviations: WA, walnut shell; SW, softwood; FC, field capacity; PWP, permanent wilting point; PAW, plant available water

* Corresponding author at: Department of Land, Air and Water Resources, University of California, Davis, 3314 PES Building, One Shields Ave., Davis, CA 95616, USA.

E-mail address: dyuwang@ucdavis.edu (D. Wang).

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agricultural soils. However, Hansen et al. (2016) found that two gasification biochars improved plant available water in two coarse-textured soils. Biochar soil amendment can influence soil water retention properties by decreasing soil bulk density (Abel et al., 2013), increasing total soil pore volume and altering the pore-size distribution (Obia et al., 2016), increasing soil surface area, especially in coarse-textured soil (Laird et al., 2010), and increasing soil aggregation (Herath et al., 2013). However, many of these proposed mechanisms have not been validated based on direct evidence.

Observation of soil moisture distribution in biochar-amended soil at a finer resolution can provide direct information about potential mechanisms. The investigation of water movement and distribution in porous media using traditional methods, such as a pressure plate (Richards, 1948; Richards and Fireman, 1943), is challenging since pressure plate can only measure water retention capacity when the internal moisture distribution has reached equilibrium. Neutron imaging technology, a non-destructive method, provides the possibility to observe moisture distribution in undisturbed porous media. Neutron imaging can measure the spatial and temporal moisture distributions with a high resolution (Kang et al., 2014; Tumlinson et al., 2008) and is sensitive to minute changes in soil volumetric water content. This tool enabled us to investigate biochar's potential impact on soil water retention and water movement between biochar and supporting material in a defined system, e.g., organic matter free silica sand.

An area that has not received much research attention is how biochar aging after application to soil may lead to changes in its properties over time. Most studies of biochar and soil water retention measure impacts in freshly amended systems; however, biochar soil amendment is considered to be a long-term practice (Lal, 2016). Interactions between biochar particles and soil components will gradually alter the biochar surface, especially under field conditions (Mia et al., 2017). For example, fresh biochar has a relatively high surface area associated with its internal micro- and macropores (Rajapaksha et al., 2016), however over time particles of soil organic matter fill biochar pore space and decrease its specific surface area (Martin et al., 2012). Ren et al. (2018) found that biochar surface area increased after aging for 0.5 year in an agricultural soil and decreased during the following 1.5 years. A three-month lab incubation experiment also showed application of in-situ aged biochar had a greater impact on soil water holding capacity than did fresh biochar (Paetsch et al., 2018). The results are inconsistent in part because they are conducted under different, sometimes artificial, conditions and do not reflect the realistic aging processes that occur in agricultural fields subjected to physical disturbance, UV exposure and wet-dry cycles. Thus, long-term field studies are needed to better understand impact of biochar on soil water retention capacity in agricultural systems with different management practices.

The objective of our study was to investigate the influence of biochar on soil water retention properties. We compared the impacts of two chemically different biochars on water retention in agricultural soils of different textures, observed water movement in a biochar-amended sample during a drying process, and examined biochar's impact on soil water retention under different management practices in a field trial six years after biochar amendment. We hypothesized that: (1) Biochar can hold water as a porous material and may improve water retention when amended to soils with limited water holding capacity; (2) biochar's impact on soil moisture retention properties depends on biochar's pore volume and pore size distribution, and it has a greater impact in coarser textured soils; (3) biochar can supply water to surrounding soil during a drying event, while the water movement from biochar decreases over time due to the reduction of difference in matric potential between biochar and supporting material; (4) impact of agricultural management practices (i.e., compost amendment, cover crop) on soil water retention capacity is larger than biochar amendment. These hypotheses were tested at different spatial (lab and field scale) and temporal scales.

2. Materials and methods

2.1. Soil and biochar

In February 2013, the top 15 cm of two soils were sampled: a Yolo silt loam soil (Yolo soil, 29.5% sand, 42.5% silt, 29.0% clay, bulk density 1.3 g cm^3) from the Russell Ranch Sustainable Agricultural Research Facility (ltras.ucdavis.edu) and a Reiff very fine sandy soil (Reiff soil, 62.9% sand, 24.1% silt, 13.0% clay, bulk density 1.4 g cm^3) from a vineyard at the University of California, Davis. Soil samples were air dried, sieved to pass through a 2-mm sieve, sealed in plastic bags, and stored at room temperature until use.

The commercially available biochars tested were: 1) a walnut shell (WA) biochar produced by Dixon Ridge Farms in Winters, CA and 2) a commercially available softwood based (SW) biochar, produced by Algae Aqua Culture in Whitefish, MT. Detailed information on biochar characteristics and methods of analysis have been presented elsewhere (Mukome et al., 2013). Briefly, the WA biochar was produced from walnut shell at a pyrolysis temperature of 900 °C, with 40% ash content, 33.4 cmol g^{-1} cation exchange capacity, and pH of 9.7. The SW biochar was produced from a mix of conifers species (ponderosa pine, Douglas fir, larch, lodgepole pine, spruce, and alpine fir) via pyrolysis between 600 and 700 °C and then mixed with algal digestate, and had 6.4% ash content, 67.0 cmol g^{-1} cation exchange capacity, and pH of 6.8. The biochars were processed the same as the soil process described above before use.

Biochars with particle diameter of 0–2 mm were further divided into 4 ranges: 1–2, 0.5–1, 0.25–0.5 and 0–0.250 mm. Full range (0–2 mm) or sub-divided biochars with different diameter ranges were well mixed with soil samples to reach three dose rates: 0, 0.5, and 1% (on a mass basis, equivalent to 0, 10 and 20 t/ ha in the field trial).

2.2. Biochar surface area and pore volume analysis

Biochar surface area was determined via the Brunauer, Emmett, and Teller (BET) method (Brunauer et al., 1938) with nitrogen gas as the adsorbate (with a 0.162 nm^2/molecule sectional area). Approximately 0.2 g of biochar (sieved through 0.25 mm screen) was outgassed at 120 °C for 16 ± 0.5 h and then analyzed on an Autosorb-1 Surface Area Analyzer (Quantachrome Instruments) at 77.3 K. Eleven data points, with relative pressures of 0.05 to 0.35, were used to calculate the surface area. The R^2 values were > 0.99 and the BET constants (C) were > 100.

The Non-Local Density Functional Theory (NLDFT) method was used to characterize the micro- and meso-porosity (ISO-15901-3, 2007). The Generalized Adsorption Isotherms (GAI) were obtained via selecting the kernel "NLDFT-N_2-carbon equilibrium transition kernel at 77 K based on a slit-pore model" in AS1 WIN (version 1.53) software (Quantachrome Instruments). The pore size distribution was then derived by solving the GAI equation numerically via a fast non-negative least square algorithm with the pore width range from 0.35 nm to 40 nm.

2.3. Neutron imaging method and image analysis

The neutron imaging equipment was at McClellan Nuclear Research Center in Sacramento, CA and was setup as described as Tumlinson et al. (2008). Based on our preliminary study, biochar amended samples were saturated for 48 h before taking images to reach full saturation. The raw neutron imaging radiographs were analyzed on a pixel-by-pixel basis. The moisture distributions in the biochar amended sand column were calculated according to transmission of neutrons through the sample column, which can be described using the Lambert-Beer law (Berger, 1971):

$$\frac{I}{I_0} = \exp(-\tau\mu) \quad (1)$$

where I is the transmitted intensity, I_0 is the original intensity, τ is the effective water thickness, and μ is the attenuation coefficient of the medium, which includes water, air, silica sand, and the sample container. The attenuation coefficient for air is very small and can be neglected. Measurements of the attenuation coefficients for sample container and silica sand showed that they are both small compared with that for the hydrogen in water. The raw neutron imaging radiographs were first γ filtered and then normalized according to reference images of the open beam (shutter opened without a sample) and dark field (shutter closed, no neutron illumination) using

$$\frac{I}{I_0} = \frac{I_{(raw\ image)} - I_{(dark\ field)}}{I_{(open\ beam)} - I_{(dark\ field)}} \quad (2)$$

The water thickness τ_{ij} was then calculated using combined Eq. [1] and Eq. [2] by assuming $\mu = \mu w + \beta\tau$ on a pixel-by-pixel basis:

$$\tau_{ij} = -\frac{\mu_w}{2\beta} - \sqrt{\left(\frac{\mu_w}{2\beta}\right)^2 - \frac{1}{\beta}\ln\left[\frac{I}{I_{0(i,j)}}\right]} \quad (3)$$

where μ_w is the linear attenuation coefficient for water and β is a beam hardening correction coefficient for the detector used (Cheng et al., 2012).

Since the sample was packed in a column, the moisture thickness was corrected for variations in sample thickness according to the following equation:

$$C_{ij} = 2\sqrt{r^2 - a_{(i,j)}{}^2} \quad (4)$$

where r is the radius of the sand column (cm) and $a_{(i,j)}$ is the distance from the center of the column to the pixel (i, j) (cm). The relative water content at pixel (i, j), θ_{ij}, was then calculated as below:

$$\theta_{ij} = \frac{\tau_{ij}}{C_{ij}} * \frac{pixel\ area}{pixel\ area} = \frac{\tau_{ij}}{C_{ij}} \quad (5)$$

2.4. Soil field capacity (FC), permanent wilting point (PWP) and plant available water (PAW)

FC and PWP of soil or biochar and soil mixtures were determined by measuring the water retention at −33 and −1500 kPa, respectively (Ratliff et al., 1983) using a pressure plate apparatus (Dane and Hopmans, 2002). PAW is defined as the water content difference between FC and PWP. Samples with biochar amendment were saturated in pressure plate for 48 h. All measurements were conducted in triplicate.

2.5. Biochar field trial and soil water retention characteristics measurements

A long-term farm experiment was initiated starting May 2012 at the Russell Ranch Sustainable Agricultural Research Facility, University of California, Davis (Griffin et al., 2017). The aim of the field trial was to investigate long-term impacts of a WA biochar amendment. Biochar rates were 0 or 10 Mg ha^{-1} and it was applied once and disked in with finish disk to a depth of 15 cm. Two management practices were compared: i) organic with poultry manure compost, an incorporated winter cover crop, along with any crop residues and ii) conventional with mineral fertilizer and only crop residues. Equivalent amount of nitrogen was applied to each management during each growing season. Surface soil (0–15 cm) in organic treatments receives winter cover crop and approximately 1000 ppm carbon as poultry manure compost. The soil was a Rincon silty clay loam (fine, smectitic, thermic Mollic Haploxeralfs, 20% sand, 49% silt and 31% clay; 20 g C kg^{-1}C content; 1.3 g cm^{-3} bulk density). The crop rotation was processing tomato (*Lycopersicon esculentum* Mill.) and corn (*Zea mays* L.) and the farm was managed using the same practices and equipment as local commercial growers. Four treatments were arranged by a randomized complete block design and each treatment had 4 replicates. Soil samples were taken from the top 15 cm of the field in October 2017, six years after biochar amendment, to evaluate long-term impacts of a one-time biochar amendment on the water retention capacity of an agricultural soil under field conditions. Soil FC, PWP, and plant available water (PAW) were measured using the pressure plate method described above. The soil properties of Rincon soil were similar to those of Yolo soil, which is one of the soils tested in the lab. The Yolo soil was taken from a field adjacent to this field trial.

2.6. Data analysis

Neutron imaging radiographs analysis was performed using the MATLAB (Windows R2012b V7.15, The MathWorks) software packages. Soil water retention and infiltration data were subjected to statistical analysis with Microsoft Excel for Windows 2010 add-ins with XLSTAT Version 2017.6 (Addinsoft, New York, NY, USA). Statistically significant differences between treatments were analyzed using analysis of variance (ANOVA) and Tukey's range test at 5% significance level.

3. Results

3.1. Biochar surface characteristics

Differences in biochar surface and structural characteristics (surface area, pore volume and pore size distribution) correlates with their differences in impacting soil water retention. WA biochar had a much higher BET surface area than did SW biochar (Table 1). Pore volume of the WA biochar micropore (0–2 nm) was 13-fold higher than that of SW biochar and WA mesopore (2–50 nm) volume approximately doubled that of SW (Table 1). The WA biochar had a narrow pore size distribution over 90% of the pore volume was attributed to pores under 10 nm. In contrast, SW biochar had a more even size distribution compared to WA and micropores contributed less 15% to the total pore volume.

3.2. Immediate impacts of biochar on soil water retention capacity after amendment

The short-term impact of adding biochar to soil on its water retention capacity depended on the type of biochar and soil type. The SW biochar amendment did not significantly impact the FC of either the fine or coarse texture soil. Adding the WA biochar at 1%, however, significantly increased the FC of the coarse- but not fine-textured soil (Fig. 1). When we fractionated the WA biochar into large and small particles, application of the larger particles of WA biochar (1–2 mm) at

Table 1
BET surface area and pore volume of walnut shell biochar and softwood biochar.

Biochar	BET surface area ($m^2 g^{-1}$)	Mesopore volume ($cm^3 g^{-1}$)	Micropore volume ($cm^3 g^{-1}$)
Walnut shell biochar	57.5	1.60×10^{-2}	1.55×10^{-2}
Softwood biochar	2.0	0.78×10^{-2}	0.12×10^{-2}

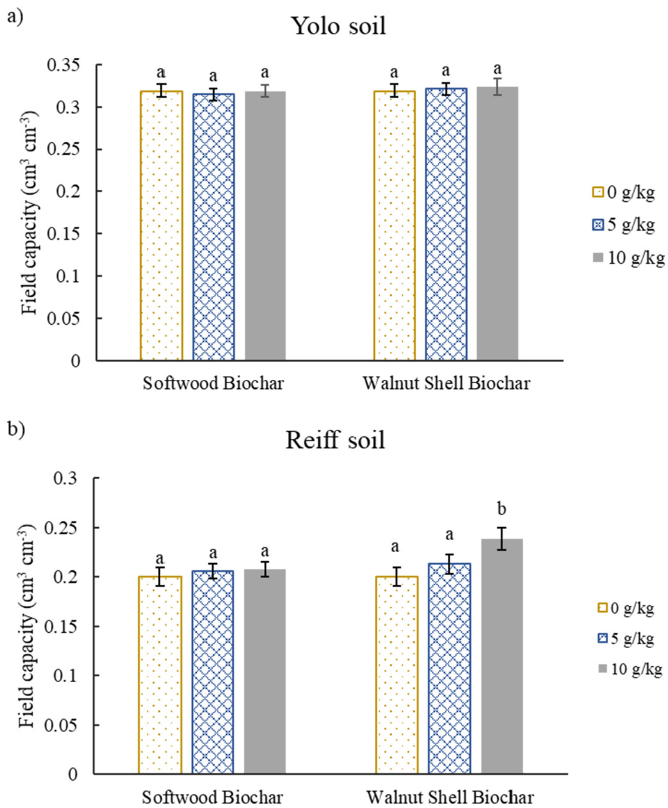

Fig. 1. Impact of biochar on field capacity of different agricultural soils (in $cm^3\,cm^{-3}$, Reiff = very fine sandy loam, Yolo = silty loam), with and without the addition of two biochar types at varying application rates (doses). The error bars represent standard errors and bars with different letters indicate statistically significant ($P < 0.05$) differences.

both 0.5% and 1% significantly increased the FC of the Reiff soil. Neither application rate of the smaller particles of WA biochar (< 1 mm) had any impact (Fig. 2).

Adding either WA or SW biochar had no influence on the PWP of either Reiff or Yolo soil (Fig. S1). Adding WA biochar at both the 0.5% and 1% rates increased PAW of the Reiff soil (Fig. 3). Biochar amendment did not impact soil water retention characteristics in other soil-biochar combinations.

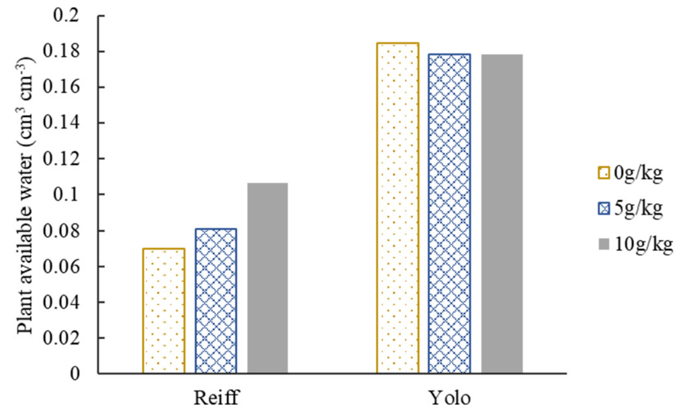

Fig. 3. Impact of walnut shell biochar on plant available water of different agricultural soil (in in $cm^3\,cm^{-3}$, Reiff = very fine sandy loam, Yolo = silt loam), with and without the addition of walnut shell biochar at varying application rates (doses). Values represent differences between triplicate means for difference between field capacity and permanent wilting point.

3.3. Moisture distribution in biochar-sand mixed sample during a 7-day drying process

To test the hypotheses that biochar can hold water as a porous material and can release water to surrounding space during a drying event, we conducted an experiment using neutron imaging of soil, in this case sand, amended with biochar. Neutron imaging can provide nondestructive, continuous and accurate observations of the distribution of water in a porous medium. Unfortunately, it was not possible to use either of our test soils because the soil organic matter also contributes to neutron attenuation and can obstruct measurement of water distribution. Instead silica sand was used to provide a matrix in which it was possible to quantify the impact of added biochar on moisture dynamics over time (Gu et al., 2011; Harvey et al., 2010; Tumlinson et al., 2008). Similar to silica sand, biochar itself has minimal neutron attenuation (Fig. 4a).

We observed water release from wetted biochar into the matrix immediately surrounding the biochar particles. In pre-saturated WA biochar (2-mm diameter) amended silica sand, the moisture content was measured over the course of a 7-day air drying period at three locations: inside the biochar particle, at the biochar-sand interface, and surrounding the biochar particle (Fig. 4b). We observed higher neutron attenuation, which indicated higher moisture content, inside biochar particle than surrounding sand from day 0 (saturated) to day 7 (air-

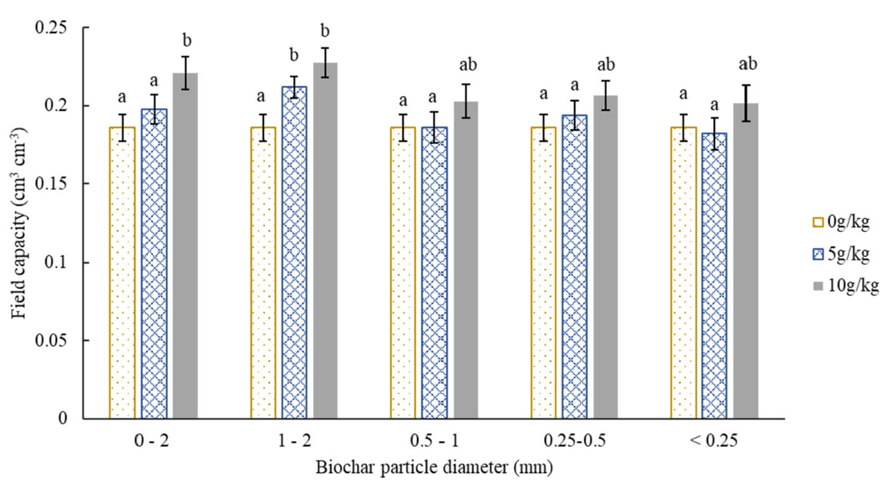

Fig. 2. Impact of walnut shell biochar with different diameter range on field capacity of Reiff soil (in $cm^3\,cm^{-3}$, Reiff = very fine sandy loam), with and without the addition of walnut shell biochar. The error bars represent standard errors and bars with different letters indicate statistically significant ($P < 0.05$) differences.

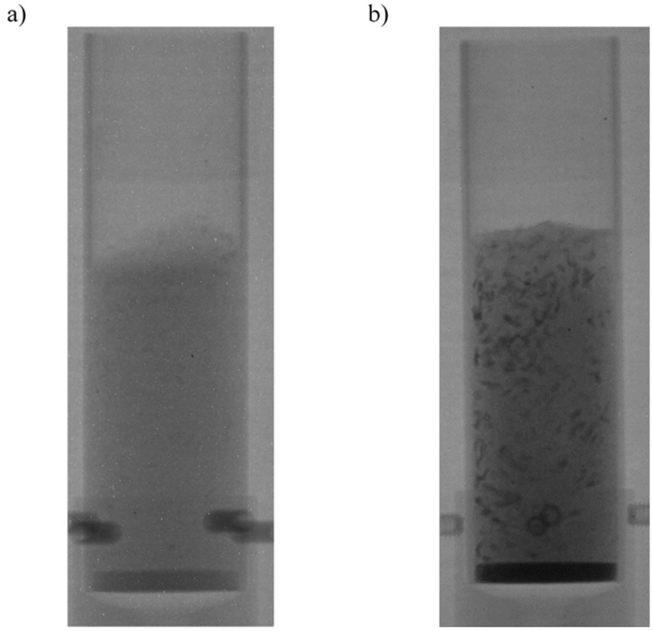

Fig. 4. Comparison of neutron tomography images of walnut shell biochar amended sand column after (a) 48 h oven dry at 105 °C and (b) 168 h air dry at room temperature. Darker areas represent material with relative higher water content, with water content proportional to degree of darkness.

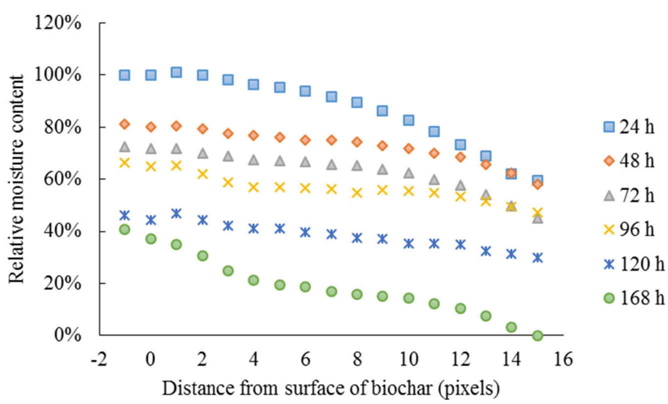

Fig. 5. Relative moisture content within a sand column amended with walnut shell biochar as a function of distance from the biochar particle surface (−1 = inside biochar, 0 = surface of biochar, 1 pixel is 0.1 mm approximately). The calculation based on neutron radiography imaging.

dried for 7 days) due to biochar's inherent porous structure. The WA biochar was a continuous source of water to the surrounding space for 7 days while maintaining its higher internal moisture content. The difference in soil moisture between biochar and sand reduced over time. As shown in Fig. 5, a saturated 2-mm diameter biochar particle released water to surrounding space, 2.2 mm sphere diameter from biochar surface, and raised sand water content for at least 7 days (room temperature, air-dry process).

3.4. Biochar's long-term impact on soil water retention capacity

A one-time application of WA biochar did not have any effect on the water retention capacity of Rincon silty clay loam soil 6 years after amendment in soils that differed in their organic matter inputs. Both biochar amendment and management practices did not significantly influence soil FC and PAW (Table 2). Soil PWP in conventional without biochar treatment was significantly lower than organic treatments (both with and without biochar amendment).

The field experiment results were consistent with lab study. We found that 0.5% and 1% WA biochar (wt.) amendment (equivalent to approximately 0, 10, 20 Mg ha^{-1}) did not impact FC, PWP and PAW of Yolo silt loam soil, which was similar textured soil to Rincon silty clay soil. Thus, we speculate WA biochar (10 t/ha) did not impact soil water retention capacity since the field trial established.

4. Discussion

4.1. Biochar's short-term impact on soil water retention capacity

Targeted use of biochar can improve soil water retention capacity. We found that, of the two biochars studied, the biochar with the higher pore volume increased FC and PAW of coarse textured soils in the short term (Table 1 and Figs. 1 & 3). This impact of biochar may not be substantial if either the biochar surface area or pore volume is low or the soil texture is fine, as in soils with higher clay content (Hansen et al., 2016). A biochar with a high surface area and pore volume can benefit soil water retention capacity in several ways: by reducing soil bulk density (Abel et al., 2013), increasing total average pore size (Obia et al., 2016) and the surface area of soil (Laird et al., 2010). Optimizing biochar surface characteristics can maximize biochar's capacity to improve soil water retention (Gray et al., 2014).

Biochar can improve soil PAW by raising soil intraparticle porosity, especially intraparticle mesopore and macropore volume. Both interparticle and intraparticle pore structure can be altered by biochar amendment, while interparticle pore structure generated by irregular-shaped biochar particles (Liu et al., 2017) can be readily filled with soil particles (Lehmann and Joseph, 2015). High soil intraparticle mesopore and macropore volume can increase soil PAW associated regions in soil water retention curve (Kerre et al., 2017; Mollinedo et al., 2015). The larger particle sizes of WA biochar potentially has a greater relative proportion of mesopores and macropores (Table 1) than the smaller particle material, which may be why it had a greater impact on the FC of a coarse textured soil (Fig. 2). Hansen et al. (2016) also found that 1% straw gasification biochar, which has a similar surface area as the WA biochar, increased both the FC and PAW of a sandy loam soil and coarse sand, but did not impact PWP. In contrast, biochar amendment led to a large increase of soil micropore structure, increasing both FC and PWP, and thus there was no net effect on the PAW (Abel et al., 2013; Hansen et al., 2016). We speculate biochar with high hydrophobicity can prevent water entering its internal structure thus limiting its potential impact on soil PAW (Głąb et al., 2016; Jeffery et al., 2015; Kameyama et al., 2016).

4.2. Water movement from biochar to surrounding space during soil drying

The neutron imaging data suggest that water retained in the internal pores of biochar can be released to surrounding soil as it dries out. Biochar particles increased the moisture content of the porous media immediately surrounding them, impacting a soil volume similar in magnitude to its internal volume (Figs. 4 and 5). The spatial range of the biochar's influence on soil moisture decreases as the biochar's moisture content decreases. Our results confirm that high intraparticle structure, instead of interparticle structure, can improve water holding capacity (Fig. 4). Implications of this are that, over time, as biochar ages in the field and its internal porosity starts to fill with fine grained soil material, its impact on soil water retention will diminish (Lehmann and Joseph, 2015).

4.3. Biochar's impact on soil water retention capacity under long-term field condition

The field scale study revealed that biochar did not impact the water retention capacity of a silty clay loam soil six years after biochar amendment. Results of our field and lab scale results were similar and

Table 2
Plant available water, field capacity, and permanent wilting point of top 15 cm soil in biochar field experiment six years after walnut shell biochar amendment (Organic = receives poultry manure compost and winter cover crop, Conventional = receive mineral fertilizer).

Agricultural management	Biochar amendment	Field capacity	Permanent wilting point	Plant available water
	(t/ ha)	($cm^3\ cm^{-3}$)		
Organic	0	0.353 ± 0.005 (a)	0.213 ± 0.006 (a)	0.141 ± 0.009 (a)
	10	0.354 ± 0.012 (a)	0.215 ± 0.004 (a)	0.138 ± 0.009 (a)
Conventional	0	0.351 ± 0.014 (a)	0.204 ± 0.004 (a)	0.147 ± 0.013 (a)
	10	0.364 ± 0.021 (a)	0.207 ± 0.004 (a)	0.156 ± 0.019 (a)

comparable because the textures of Yolo silt loam and Rincon silty clay soil are so similar (Fig. 1b and Table 2). Neither biochar amendment rate nor agricultural management practice altered soil water retention parameters due to decreased biochar porosity under field conditions. Joseph et al. (2010) found that the biochar internal pores started to fill in with organic and mineral matter after 1 year and most pores were filled after 2 years in a field experiment. Similarly, Hardie et al. (2014) reported that biochar did not influence either soil water retention capacity or soil porosity in a sandy loam soil after four year amendment. In another study the impact of biochar on the PAW of a sandy loam soil diminished by 30 days after application in greenhouse soil columns (Aller et al., 2017). Biochar may also have an indirect impact on water retention via improving soil aggregation in finer textured soil, through which organic matter rich low pore volume biochar can also have the potential to influence soil water dynamics in the long term (Burrell et al., 2016; Wang et al., 2017). Overall, more attention is needed to understand the interaction of biochar with soil particles and, in turn, how this impacts soil structure and water dynamics.

5. Conclusions

Our results suggest that biochar with high interporosity can raise both FC and PAW in coarse textured soils immediately after application, and the mechanism involved appeared to be water held in relatively large biochar particles (1–2 mm diameter). Moisture initially retained within biochar can become available to the surrounding soil matrix as the soil dries, but only for a short time (7 days at room temperature) until it became depleted. In a long-term field trial, however, the impact of biochar on soil water retention was limited, in part because the soil was finer textured. Lack of effect was also seen in the lab study with same biochar and similar textured Yolo silt loam soil. If either biochar pore volume is low or soil texture is fine, biochar's impact on soil water retention would be limited. High dosage (≥ 10 t/ha) of large pore volume biochar amendment, preferably with large particle size (≥ 1 mm), can help enhance water retention in soil with limited capacity to store water and improve soil's resilience during extreme hydrological events in the short term.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geoderma.2019.01.012.

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