

# Biochar amendment of soil improves resilience to climate change

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## Abstract

Because of climate change, insufficient soil moisture may increasingly limit crop productivity in certain regions of the world. This may be particularly consequential for biofuel crops, many of which will likely be grown in drought-prone soils to avoid competition with food crops. Biochar is the byproduct of a biofuel production method called pyrolysis. If pyrolysis becomes more common as some scientists predict, biochar will become more widely available. We asked, therefore, whether the addition of biochar to soils could significantly increase the availability of water to a crop. Biochar made from switchgrass (*Panicum virgatum* L.) shoots was added at the rate of 1% of dry weight to four soils of varying texture, and available water contents were calculated as the difference between field capacity and permanent wilting point water contents. Biochar addition significantly increased the available water contents of the soils by both increasing the amount of water held at field capacity and allowing plants to draw the soil to a lower water content before wilting. Among the four soils tested, biochar amendment resulted in an additional 0.8–2.7 d of transpiration, which could increase productivity in drought-prone regions or reduce the frequency of irrigation. Biochar amendment of soils may thus be a viable means of mitigating some of the predicted decrease in water availability accompanying climate change that could limit the future productivity of biofuel crops.

**Keywords:** available soil water, biochar, bioenergy, climate change, field capacity, pressure plate, soil texture, switchgrass, transpiration, wilting point

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## Introduction

Soil moisture limits plant productivity in many areas of the world (Seneviratne *et al.*, 2010). In some regions, this limitation may be exacerbated by predicted climate change as a consequence of elevated temperature, reduced rainfall, changing seasonal rainfall patterns, or reduced availability of irrigation water (Schlenker *et al.*, 2007; Vano *et al.*, 2010; O'Neill & Dobrowolski, 2011). Insufficient soil moisture may become particularly problematic for biofuel crops; to reduce competition with food crops, biofuel crops may have to be planted preferentially on sites that are not highly productive for food crops (Vuichard *et al.*, 2009; Cai *et al.*, 2011; Niblick *et al.*, 2013), where some of the challenges include shallow and excessively draining soils. Improving the availability of water in these chal-

lenging soils will be of great importance to biofuel production.

An increase in the soil available water content is possible by their amendment with hydrogels, polymers that can hold water at hundreds of times their own weight (Abedi-Koupai *et al.*, 2008). However, the cost and longevity (Frantz *et al.*, 2005) of such materials make their use at the field-scale very unlikely. In this contribution, we ask whether amendment of soils with biochar can similarly increase available water content. In contrast to hydrogels, biochar (one of a continuum of thermal conversion products of organic materials) may be far more temporally stable in soil and, because it is a byproduct of the production of biofuels via pyrolysis, its application may become cost-effective as syngas and bio-oil production increase (Laird, 2008). Considerable interest already exists in the amendment of soils with biochar because it can stably sequester significant amounts of carbon (Nguyen *et al.*, 2014) and, under certain circumstances, significantly improve crop yield (Spokas *et al.*, 2012).

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Some research indicates that amendment of coarse-textured soils with biochar increases their capacity to absorb water (Laird *et al.*, 2010; Karhu *et al.*, 2011; Novak *et al.*, 2012; Novak & Watts, 2013). The ability to absorb water is important in situations, where excess drainage leads to loss of soil or nutrients. But simply holding more water does not necessarily result in more water being available to the plant, particularly if the water is held so tightly that the plant has no access to it. Thus, in situations in which water stress limits crop yield, the effect of biochar on soil water-holding capacity per se is less relevant than the effect of biochar on the amount of water that is actually available to the plant, the so-called available water content. There is frequently a positive relationship between soil available water content and plant yield, particularly in arid climates (Wong & Asseng, 2006; Lawes *et al.*, 2009).

Available water content is defined as the difference in water content held at field capacity and at the permanent wilting point of the plant. Increased available water content due to biochar amendment can result from either improved water content at field capacity or reduced water content at permanent wilting point, or both. Most biochars made from plant materials have a high porosity and surface area (Downie *et al.*, 2009) and thus a large capacity to hold water at field capacity (Glaser *et al.*, 2002). It is not clear what to expect from biochar near the wilting point. Therefore, the current study was conducted to examine the effects of switchgrass derived biochar on the water content of soils at both field capacity and the wilting point. We determined available water content using a bioassay. While it is common to use the pressure plate apparatus for this purpose, we showed that it may not be appropriate for soils containing biochar. Because soil texture is known to influence soil hydraulic properties, we added biochar to four soils varying significantly in texture. Finally, because biochar is significantly less dense than mineral soil, biochar addition to soil can appear to increase the water content of soil on a weight basis merely by decreasing its density. Therefore, we determined available soil water content on the basis of soil volume rather than weight.

## Materials and methods

### Soils

The effect of biochar on the water-holding properties of soils is likely dependent on several factors including soil texture (and thus inherent water-holding capacity). Therefore, we chose to study four soils that varied significantly in texture. Soils were collected from four sites across the Appalachian Plateau and Ridge and Valley Physiographic Provinces in Pennsylvania, United States, which are currently part of a regional study on the use of biochar to produce switchgrass (*Panicum virgatum* L.) in soils from sites that are marginally productive for row crops. Two soils, the Edom (collected at 77°54'32.848"W 40°36'56.727" N) and Wharton (78°9'41.034"W 41°1'55.388"N) silty clay loams, are from sites that frequently experience extended periods of excessive wetness. The other two soils, the Morrison sandy loam (77°53'55.5"W 40°49'34.062"N) and the Weikert loam (77°53' 38.94"W 40°39'8.106"N) are from excessively drained sites. Soils were sampled in September 2011 from the plow layer (A over Ap, or Ap horizon) to a depth of 0.15 m. Seven to ten positions at each site were sampled, and the samples were combined. All soils were air-dried in a greenhouse and passed through a 2 mm sieve. Soil C concentration was determined using an Elementar Vario-Max instrument on soils that were finely ground using mortar and pestle. Soil pH was measured with a standard glass electrode using a 1 : 1 soil:distilled water (w : v) ratio following a 30 min equilibration. The soils are further described in Table 1.

To determine the moisture release characteristics of the soils, we used pressure plate extractors (Soilmoisture Equipment Corp, Santa Barbara, CA, USA) to assess the relationship between tension and water content for the four soils. Gravimetric water content was determined at tensions of  $-0.010$ ,  $-0.033$ ,  $-0.100$ ,  $-0.300$ ,  $-0.500$ ,  $-1.00$ , and  $-1.50$  MPa (Dane & Hopman, 2002). Briefly, rubber rings (5 cm diameter by 1 cm high) were placed on porous, ceramic plates of the appropriate bubbling pressure and filled with 2 mm sieved, air-dried soils. The ceramic plates were placed in plastic pans and a sufficient quantity of deionized water was added to cover the surface of the plates. Plates were left in the pans overnight to allow soil to saturate by capillary action. Once the soils were saturated, the ceramic plates were transferred to pressure chambers. The desired pressure was exerted on each chamber until outflow of water from the pressure chamber was no longer observed. This usually required at least several hours, but the chamber was

**Table 1** Mean (SEM) of some characteristics of the four soils used in this study.  $n = 4$

Soil series	Sand (%)	Silt (%)	Clay (%)	Total C* (%)	pH†
Edom silty clay loam (Typic Hapludalf)	6 (0.1)	62 (0.5)	32 (0.3)	3.8 (0.3)	6.0 (0.08)
Weikert loam (Lithic Dystrudept)	44 (0.7)	40 (0.6)	16 (0.3)	4.0 (0.2)	6.0 (0.03)
Morrison sandy loam (Ultic Hapludalf)	61 (0.2)	27 (0.2)	12 (0.1)	1.7 (0.1)	5.9 (0.02)
Wharton silty clay loam (Aquic Hapludult)	15 (0.3)	58 (0.3)	27 (0.1)	4.1 (0.6)	5.4 (0.03)

\*Total C is assumed to be equivalent to organic C at the given pH values.

†In water.

allowed to equilibrate in each case for 24 h. In any case, the criterion for equilibrium was no further water loss. Upon reaching equilibrium, the plates were removed from the chambers and the gravimetric water contents of soil samples were determined from the wet weights and dry weights (assessed after heating to 105 °C for 24 h). There were three replicates at each tension for each soil.

### Biochar

Switchgrass is a perennial grass, and a potentially important bioenergy crop (Parrish & Fike, 2005). It has been grown successfully on sites that are marginally productive for row crops (Keshwani & Cheng, 2009). Biochar was produced from shoots of harvested switchgrass (*P. virgatum* var. Cave-In-Rock) by the torrefaction facility at North Carolina State University (Raleigh, NC, USA). The switchgrass had been produced by Ernst Conservation Seeds (Meadville, PA, USA). Approximately 4.5 dry weight units of air-dry grass shoots were used to produce one dry weight unit of biochar. Biochar production consisted of several steps. First, the switchgrass biomass was preheated to about 100 °C in a hopper before being transferred to and held in the torrefaction chamber by constant stirring with an auger for 1–1.5 min. The torrefaction chamber had a low oxygen environment and was held between 375 and 475 °C. The biochar was then cooled in an exit auger for about 3 min, achieving a near ambient temperature (35 °C). Finished biochar was hydrated to 60% water content by weight to prevent self-heating. After allowing it to stand for 24 h to reach hydration/oxidation equilibrium with the atmosphere, the biochar was packaged and shipped to our research facility in Pennsylvania. Biochar pH was measured with a standard glass electrode using a 1 : 20 biochar:distilled water (w : v) ratio following a 30 min equilibration. Ash content was determined by weighing the residue after heating to 550 °C for 4 h. Total C and N concentrations were determined using an Elementar Vario-Max elemental analyzer. Bulk density was calculated from the dry weight (105 °C) of known volumes.

The mean (se) biochar bulk density was approximately 0.083 (0.004) g cm<sup>-3</sup> ( $n = 9$ ), the ash content was 10.2 (0.9)% of dry weight ( $n = 3$ ), the C concentration was 74.6 (1.2)% of dry weight ( $n = 9$ ), the N concentration was 1.16 (0.02)% of dry weight ( $n = 9$ ), the C : N ratio was 64.8 (2.1,  $n = 9$ ), and the pH in water was 9.5 (0.1,  $n = 16$ ). Only 3% of the biochar (by weight) was >2.0 mm diameter, while 93% was in the 0.05–2.0 mm fraction, and 4% was <0.05 mm.

The procedure used to determine the moisture release curves of the soils was also used for whole biochar pieces, biochar that was finely ground, and ground biochar mixed with whole biochar pieces (1 : 1 weight ratio), with three replicates at each tension.

### Soil-biochar mixtures

Soils were compared with mixtures of soil with 1% biochar by weight. To prepare the mixtures, each soil was mixed with 1% biochar by weight, equivalent to approximately 10 tonne ha<sup>-1</sup> to a depth of approximately 15 cm. Although the biochar was

1% of soil dry weight, it comprised approximately 10–13% by volume depending on the soil and experiment (see Results).

### Available water content

We calculated available water content as the difference in water content of the media when allowed to drain by gravity to field capacity, and at the permanent wilting point, as in Meyer & Green (1980). Four subsamples from each of four unamended soils, biochar and the soil-biochar mixtures (1% biochar by weight) were taken for measurement of water content at field capacity using the Büchner funnel method (Veihmeyer & Hendrickson, 1949) with some modifications. A 186 ml Nalgene Büchner funnel was used for the measurement with Whatman filter paper No. 2 to cover the funnel to prevent soil loss during drainage. A 53.1 cm<sup>3</sup> PVC ring (5.2 cm diameter × 2.5 cm height) was placed on the filter. Fifty to seventy grams of medium, depending on the medium, were weighed and packed into the PVC ring to the bulk densities given in Table 2. To saturate the soil, the removable top portion of the funnel was then placed overnight in a plastic tray containing distilled water to the level of half the ring's height. On the following day, the top portion of the funnel was attached to the bottom portion and allowed to stand for 48 h to permit free water drainage (Sarkar & Haldar, 2005). The top of the funnel was covered with parafilm to prevent evaporation. The media in the rings were collected for determination of water content by weighing both before and after overnight drying at 105 °C.

A completely randomized experiment with four replicates was designed to determine medium water content at the permanent wilting point. The soils, biochar and their mixtures were packed into 1.67-l standard plastic pots, tapping the pot vigorously on a hard surface on five or six separate occasions during the filling process. To compact the medium to the bulk densities given in Table 2. The pots were then randomly placed in plastic trays, and 3–5 cm of water was added to the trays to moisten the media. Maize (*Zea mays* L.) seeds (Pioneer P0891AM1 Des Moines, IA, USA) were pregerminated on moist filter paper. Seedlings were transplanted into the pots (five seedlings per pot) and given Hoagland's nutrient solution (Machlis & Torrey, 1956) daily to maintain rapid growth. All trays were placed randomly in one growth chamber with a constant 50% relative humidity and a thermal cycle of 30/22 °C day/night with a 14 h photoperiod. The maximum photosynthetically active radiation flux density was approximately 700 μmol m<sup>-2</sup> s<sup>-1</sup> at plant height. Approximately 2 weeks after transplanting, watering was stopped to allow the plants to wilt. To prevent the media from losing water by direct evaporation, the drainage holes at the bottom of each pot were covered with polyethylene, and the surface of the soil, biochar or soil-biochar mixture was covered with a 2.5 cm layer of horticultural perlite. To determine the permanent wilting point, we started to track transpiration rates as soon as water was withheld, before the leaves wilted (data not shown). Transpiration rates were determined using a steady state porometer (LI-1600, LI-COR, Lincoln, NE, USA) for several days, 2 h after the initiation of the light period on a recently fully expanded leaf. When

**Table 2** Mean bulk densities and volumetric proportions of biochar in the soil-biochar mixtures used in the wilting point and field capacity determinations of water content.  $n = 4$ 

Soil	Biochar*	Wilting point		Field capacity	
		Bulk density (g cm <sup>-3</sup> )	Volumetric proportion biochar	Bulk density (g cm <sup>-3</sup> )	Volumetric proportion biochar
Edom	no	1.05	0.00	1.07	0.00
Edom	yes	0.94	0.10	0.97	0.11
Wharton	no	1.23	0.00	1.07	0.00
Wharton	yes	1.11	0.12	1.01	0.11
Weikert	no	1.05	0.00	1.01	0.00
Weikert	yes	0.94	0.10	0.99	0.11
Morrison	no	1.37	0.00	1.31	0.00
Morrison	yes	1.17	0.12	1.22	0.13
Experimental SEM		0.01	0.001	0.01	0.001

\*1% of dry weight.

transpiration rate was nil, the pot was transferred to a dark growth chamber to allow leaf water potential to equilibrate with soil water potential. After four hours in the dark, the plants were visually examined to determine if the leaves had regained turgor. Pots with leaves that recovered turgor were placed back in the lighted growth chamber. Pots with leaves that had not regained turgor had leaf water potential measured using a pressure chamber. Three subsamples of the medium in the pot were taken for water content determination by weighing the subsamples before and after 105 °C overnight drying. Leaf water potentials at the wilting point were less than  $-1.9$  MPa for all soil  $\times$  biochar treatment combinations (including 100% biochar). The average was  $-2.2$  MPa (SE = 0.5). Volumetric water content (g cm<sup>-3</sup>) was calculated by multiplying bulk density by gravimetric water content.

We calculated the available water content of biochar, soils, and soils mixed with biochar as the difference in water content between field capacity and wilting point.

### Statistical analysis

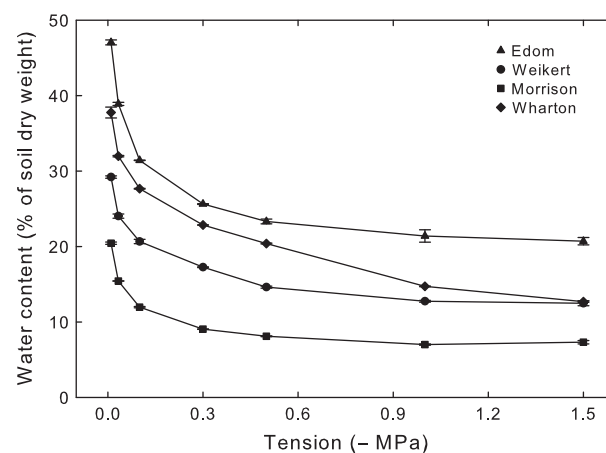
**Available water content.** There were four replicate measurements of water content at field capacity and four replicates at the permanent wilting point. Available water content is the difference between field capacity and permanent wilting point water contents. To determine the means and standard deviations for the differences in each treatment combination (four soils with and without biochar), frequency distributions of the differences were constructed in the following way. For a given treatment combination, the differences were calculated for all possible combinations of the four replicate water contents at wilting point and the four replicate water contents at field capacity. These 16 differences were then randomly sampled (four at a time) 1000 times with replacement. The 1000 means of the four drawn samples were then taken to bootstrap a frequency distribution of the differences, and the mean and standard deviation were determined. Single factor analyses of variance were performed according to Cohen (2002), and means were separated using the 95% confidence intervals.

**Field capacity and permanent wilting point water contents.** The interactive effects of four soils and two biochar treatments (0% or 1% by weight) on field capacity and wilting point water contents were determined using the analysis of variance procedures in the Statgraphics programs (STSC, 1991).

### Results

As expected based on soil textural properties, the four soils exhibited very different moisture release properties (Fig. 1). At any given tension, the sandiest soil (Morrison) had the lowest water content, while the most clayey soil (Edom) had the highest water content. The soils of intermediate texture (Weikert and Wharton) had intermediate moisture release curves.

Whole biochar particles (size range given above) exhibited a moisture release curve that suggested, contrary to expectations, that the least amount of water was



**Fig. 1** Moisture release curves for the four soils (unmixed with biochar). Error bars are  $\pm 1$  SEM. In some cases, errors are smaller than symbols.  $n = 3$ .

held at lower tensions ( $-0.033$  and  $-0.100$  MPa) and the most at higher tensions ( $-0.300$  to  $-1.50$  MPa) (Fig. 2), suggesting that the pressure plate method may not be useful in describing the moisture release characteristics of this particular biochar. We hypothesized that for whole biochar pieces in the pressure plate apparatus, hydraulic connection was lost either among the individual pieces of biochar, or between the pieces of biochar and the ceramic plate. To test that hypothesis, we used biochar that had been ground to readily pass through a 1 mm sieve using a mortar and pestle as we felt this material would not suffer from the loss of hydraulic connection. We subsequently refer to this as powdered biochar. When powdered biochar was used, the moisture release curve was far closer to what might be expected, with ever-decreasing water contents as tensions increased. When whole and powdered biochar was mixed 1 : 1 (w : w), the moisture release curve was intermediate. This would only be possible if some water were not draining from the whole biochar, suggesting that some loss of hydraulic connectivity does occur in the pressure plate apparatus with whole biochar. Thus, we chose an alternative method to determine available water content of soil and soil-biochar mixtures.

The available water content of biochar, calculated from field capacity and permanent wilting point water contents, was significantly greater than for any of the soils (Fig. 3). The soils themselves varied significantly ( $P < 0.05$ ) in available water content, blending this particular biochar into the soils at 1% of dry weight significantly ( $P < 0.05$ ) increased available water content of all the soils, and the magnitude of the effect of the biochar depended ( $P < 0.05$ ) on the soil (Fig. 3). The increases in available water content due to this biochar were  $0.0157$ ,  $0.0165$ ,  $0.0263$ , and  $0.0549$   $\text{g cm}^{-3}$  for the Edom, Wharton, Weikert, and Morrison soils, respectively.

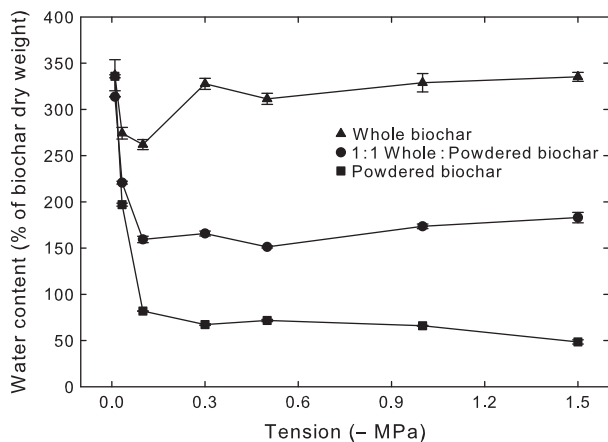


Fig. 2 Moisture release curves of whole and powdered biochars, and a 1 : 1 mixture of the two. Error bars are  $\pm 1$  SEM. In some cases, errors are smaller than symbols.  $n = 3$ .

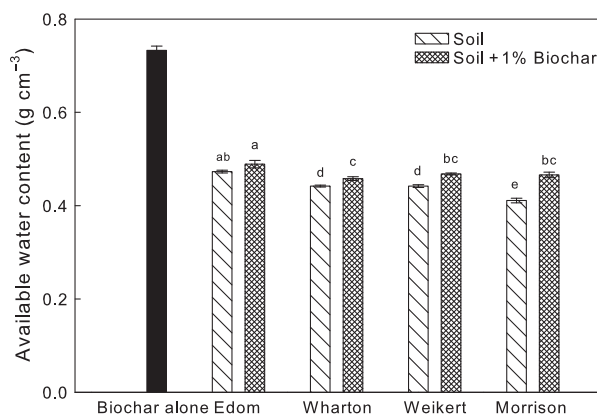


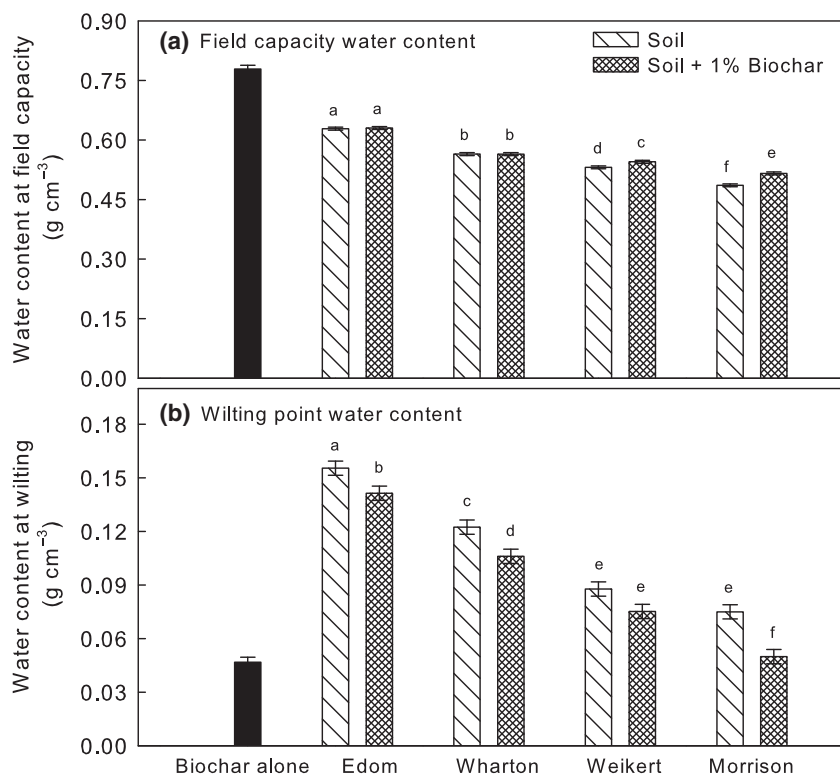
Fig. 3 Mean available water content ( $\text{g cm}^{-3}$ ) of soils and soils mixed with biochar (1% by weight). Available water content was calculated as the difference between water content at field capacity and water content at permanent wilting point. Error bars are  $\pm 1$  SEM.  $n = 4$ . Different letters indicate significantly different means according to 95% confidence intervals.

The available water contents of the soils were influenced by mixture with this biochar in two ways. The biochar significantly ( $P < 0.0005$ ) increased the water content at field capacity. The average increase for the four soils was  $0.011$   $\text{g cm}^{-3}$ , although the effect of the biochar depended ( $P < 0.005$ ) on the soil (Fig. 4a). For example, the biochar effect was large for the Morrison soil ( $0.0298$   $\text{g cm}^{-3}$ ) and small for Wharton soil ( $0.0002$   $\text{g cm}^{-3}$ ). The biochar also significantly ( $P < 0.0001$ ) decreased the water content at the permanent wilting point, indicating that, prior to wilting, the plants were able to extract more water from soil when it was mixed with the biochar. Overall, the decrease in water content at permanent wilting due to the biochar amendment was  $0.017$   $\text{g cm}^{-3}$ , (Fig. 4b). In the case of permanent wilting point water content, there was no significant interaction ( $P = 0.413$ ) between soil and biochar amendment.

## Discussion

Our goal was to determine the effect of the switchgrass biochar on soil available water content. We utilized four soils that differed significantly in their moisture release characteristics. The addition of the biochar at the rate of 1% by weight (equivalent to between 10% and 13% biochar by volume, or  $10$  tonne  $\text{ha}^{-1}$ ) resulted in significant increases in available water content.

The increase in available soil water content due to the biochar amendment was biologically significant. This is readily illustrated using the results for the Morrison soil. The biochar amendment increased the available water content of this soil by  $0.0551$   $\text{g cm}^{-3}$ . If the biochar were tilled in to a depth of 15 cm in the field,



**Fig. 4** Water content at field capacity (a) and at wilting point (b) for biochar, the four soils, and the four soils mixed with biochar (1% by weight). Error bars are  $\pm 1$  SEM.  $n = 4$ . Different letters indicate significantly different means according to 95% confidence intervals.

which is a common depth for tillage implements, the increase in available soil water in the top 15 cm of soil would amount to  $8270 \text{ g m}^{-2}$  ( $0.0551 \text{ g cm}^{-3} \times 150\,000 \text{ cm}^3 \text{ m}^{-2}$ ). Maximal transpiration rates from a mature switchgrass canopy in Pennsylvania during the summer have been documented from eddy covariance measurements to be approximately  $3 \text{ mm d}^{-1}$  or  $3000 \text{ g m}^{-2}$  (Skinner & Adler, 2010). Thus, for a single drying event the increase in available soil water in the Morrison soil due to biochar amendment would amount to 2.7 additional days of full transpiration. Even for the Edom soil, for which the biochar had the least effect on available water content, the biochar amendment would provide approximately 0.8 additional days of full transpiration. This suggests that if water shortage occurred frequently enough, soils amended with this biochar might allow plants to have a significant advantage in terms of photosynthesis (Seneviratne *et al.*, 2010) as well as lessening plant stress, consistent with the relationship between available water content and crop yield in arid climates (Wong & Asseng, 2006; Lawes *et al.*, 2009). In some regions of the United States, there may be both more frequent and longer lasting periods of drought (Cook *et al.*, 2004). The resilience of agricultural systems to that kind of climate change may be improved by

addition to the soil of biochars with similar properties to the one used in this study. While many have considered biochar amendments to be primarily a means of sequestering C in soils over the long term (Nguyen *et al.*, 2014), they may have the additional benefit of making more water available to the crop. In this study, the biochar amendment increased soil available water content in two ways. It increased soil water content at field capacity and allowed plants to draw the soil to lower water content before wilting.

Several studies have investigated the effects of biochar amendment on soil hydraulic properties but, for a variety of reasons, most of them are difficult to interpret. A common difficulty stems from expressing water content on a gravimetric basis, i.e. g water per g soil (see Ulyett *et al.*, 2014; Novak & Watts, 2013; Briggs *et al.*, 2012; Novak *et al.*, 2012; Karhu *et al.*, 2011; Laird *et al.*, 2010). That is problematic when dealing with biochar because, owing to its very low bulk density, when added to soil it significantly increases the volume of a given weight. Thus, because a gram of soil and a gram of soil-biochar mixture are not equivalent in volume, the very basis for the comparison is called into question.

The works by Pereira *et al.* (2012) and Abel *et al.* (2013) are exceptional in that they characterized

available water on a volumetric basis. As did we, they both found that addition of biochar to soil increased the water available to a plant, the difference between water content at field capacity and at the wilting point. We found that the biochar effect on available water was more pronounced in a coarsely textured soil than in the more finely textured soils as did Abel *et al.* (2013). That stands to reason as fine-textured soils may already have high available water content mainly due to the increased water content at field capacity. Abel *et al.* (2013) found that biochar made from *Zea mays* (whole shoots) increased soil available water mainly because it increased soil water content at field capacity. In contrast, we found that our switchgrass biochar both increased water content at field capacity and caused the soils to retain less water at the wilting point. This difference may have to do with distinct hydraulic properties of different biochars or different soils.

Methodology has also made it difficult to assess the effect of biochar on water availability from soils. For most soils, the pressure plate method is adequate to determine both field capacity (frequently estimated at  $-0.033$  MPa) and wilting point (frequently estimated at  $-1.5$  MPa) water contents. We found, however, that our switchgrass biochar did not produce the expected shape of the moisture release curve, particularly at the greater tensions (toward the wilting point), possibly because of the loss of hydraulic connectivity among biochar particles and/or between the biochar particles and the porous ceramic plate. Mixing whole biochar particles in a matrix of powdered biochar produced a moisture release curve that had a shape closer to what was expected. Thus, it is possible that in a matrix of soil the moisture release curve of biochar-soil mixtures would be acceptable. However, there is no way to determine that. Instead, we determined wilting point water content based on a bioassay. In the field, after all, it is the ability of the plants to extract water from the soil that will determine how much is available for their use.

We conclude that addition of our switchgrass biochar to a variety of soils, from the fine-textured Edom and Weikert soils, to the coarse-textured Morrison and Wharton soils, significantly increased available water content, even with as little as 1% biochar by weight (as in this study). While we cannot yet speak to the economics of this approach, biochar amendment may be a viable means of mitigating current water shortages on drought-prone soils and future water shortages accompanying climate change.

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