



# Sensitivity of soil water retention and availability to biochar addition in rainfed semi-arid farmland during a three-year field experiment



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## ABSTRACT

Aridity and water stress limit the productivity of rainfed dryland agriculture, and one possible solution to this problem is the application of biochar, a highly porous, pyrolysed biomass material that has been well documented to improve soil quality. The objectives of this study are to investigate whether straw-biochar can be beneficial for improving soil hydraulic properties, explore how biochar affects the temporal and spatial distributions of soil moisture, and ultimately determine whether biochar impacts soil water availability. A 3-year field experiment was conducted on the semi-arid Loess Plateau in northern China, and biochar derived from maize-straw feedstock was applied to a spring maize monoculture cropping system at rates of 0, 10, 20 and 30 t ha<sup>-1</sup>. The results of two sampling campaigns of undisturbed soil indicated that the incorporation of biochar reduced the soil bulk density and increased the total pore volume at depths of 0–10 and 10–20 cm. In addition, a significant negative linear correlation was observed between the rate of biochar addition and the soil bulk density. The incorporation of biochar into the soil not only increased the soil permeability (higher saturated hydraulic conductivity) but also improved the water retention capacity of the mixed soil (higher saturation, readily available and estimated available water contents), particularly when biochar was added at 30 t ha<sup>-1</sup>. The soil water contents following rainfall in the biochar-amended plots were consistently greater than the soil water contents in the control (BC0) throughout the entire 5-day monitoring period, and both irregular precipitation and crop water utilization resulted in temporal and spatial variations in soil water contents throughout the crop growing seasons. Biochar-amended soils were more sensitive to rainfall variations, and the variations in water across the soil profile mainly occurred at depths of 0–40 cm. Compared with the control, the soil permeability was obviously enhanced by the addition of 30 t biochar ha<sup>-1</sup>, which resulted in water infiltration at a depth of 0–60 cm. Biochar application increased the crop yields and water use efficiency (WUE). The average yields during the 3 studied years were 10.2% and 14.2% higher in BC20 and BC30, respectively, than in the control, and the average WUEs were 9.4% and 12.3% higher in BC20 and BC30 than in the control, respectively. These results indicate that biochar amendment could improve the physical and hydraulic status of semi-arid agricultural soils, thereby leading to an increase in plant available water.

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## 1. Introduction

Rainfed farming accounts for approximately 25 Mha of arable land in China, which is mainly located in the semi-arid Loess Plateau (Deng et al., 2006; Zhang et al., 2011), where recurrent droughts and water deficiency are the most important constraints for dryland

agricultural production (Zhang et al., 2014) and soil degradation due to accelerated soil erosion further aggravates water scarcity. Insufficient and erratic rainfall is the main source of water in the region; thus, soil moisture conservation is vital for crop production (Bu et al., 2013). Climate change strongly affects precipitation patterns and consequently soil water resources (Haider et al., 2015). Thus, in the future, declining precipitation is likely to threaten crop yields and food supply in semi-arid areas (Milly et al., 2005; Lobell et al., 2008). One innovation to mitigate these negative impacts is to use biochar, which has received widespread and increased attention around the world in recent years.

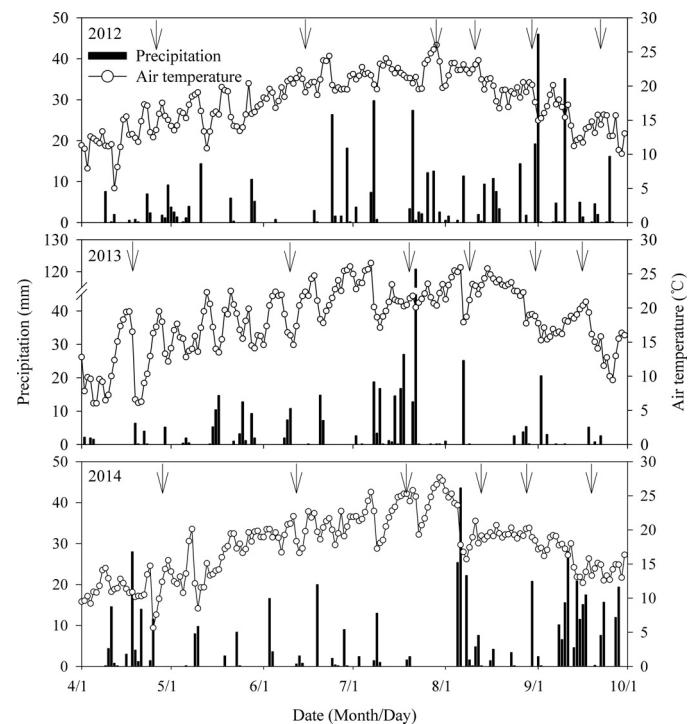
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Biochar is a porous, low-density and carbon-rich product of organic feedstock that is produced from pyrolysis at a set temperature in the presence of no or low amounts of oxygen (Novak et al., 2009; Sun and Lu, 2014; Bayabil et al., 2015). The application of biochar to agricultural soils has been proposed as a potential method for improving soil quality and mitigating climate change by reducing greenhouse gas emissions (Jeffery et al., 2011; Lehmann et al., 2011). Because it contains large amounts of carbon, biochar has the potential to significantly increase soil organic matter contents, which are in critical decline in many regions of the world, particularly in regions containing farmland (De la Rosa et al., 2014). Biochar can increase the soil ion exchange capacity, which improves nutrient adsorption and soil nutrient availability and reduces nutrient losses due to leaching (Knowles et al., 2011; Dong et al., 2015). A previous review indicated a mean increase in crop productivity of approximately 10% following biochar addition (Jeffery et al., 2011; Liu et al., 2013). The beneficial effects of biochar are attributed to its impacts on physical, chemical and biological characteristics of soils (Glaser et al., 2002; Laird et al., 2010; Biederman and Harpole, 2013), which synergistically improve crop performance (Rogovska et al., 2014). However, the effects of biochar addition on the physical and hydrological properties of soils have received less attention than the effects of biochar addition on the chemical and biological properties of soils (Obia et al., 2016).

Biochar application can affect soil quality and crop performance in different ways depending on its characteristics and application rate and the soil type (Glaser et al., 2002; Fan et al., 2015). Biochar has a high surface area due to its porous structure, and studies have indicated that the application of biochar to soils can reduce soil bulk density (Asai et al., 2009) and soil compaction (Olmo et al., 2014) and influence soil surface area (Lehmann et al., 2011), soil porosity (Githinji, 2014) and pore size distribution (Sun and Lu, 2014). In addition, the improved soil aggregate stability resulting from biochar amendment (Ouyang et al., 2013) can increase soil organic carbon stabilization (Zhang et al., 2015). All of these changes potentially affect aeration, water percolation (Bell and Worrall, 2011) and the ability of a soil to retain plant available water (Herath et al., 2013). The addition of biochar to soils with different textures has different effects on soil permeability, causing lower infiltration in sandy soils, higher infiltration in clay soils and no change in infiltration in fine-loamy soils (Laird et al., 2010; Barnes et al., 2014; Xiao et al., 2015). Under an electron microscope, the structure of biochar exhibits a high pore density of 0.2–50 µm, which is related to the storage of plant available water (Abel et al., 2013). Several authors have reported increased soil water holding capacities and available water contents in mixed soils following biochar addition (Glaser et al., 2002; Laird et al., 2010; Rogovska et al., 2014; Gul et al., 2015); however, Major et al. (2012) demonstrated that the addition of biochar at 20 t ha<sup>-1</sup> did not have a pronounced influence on water percolation and retention. Most previous studies have been conducted using laboratory incubations and pot trials with highly weathered tropical or degraded soils (Rogovska et al., 2014), and a few peer-reviewed reports have focused on the influences of biochar on soil water properties in field studies. In addition, the effects of biochar on soil physical properties and hydrological characteristics in temperate regions have not been well investigated to date.

The Loess Plateau is a typical arid and semi-arid region in China dominated by dryland agriculture with a cropland area of 16 million ha (Zhang et al., 2011). Therefore, it is important to evaluate the influences of different rates of biochar application on plant-soil moisture relationships on the semi-arid Loess Plateau. A long-term experiment is also needed to understand soil water dynamics during periods of crop growth under natural conditions and the interactions between crop growth and soil moisture status. Therefore, a field experiment was designed and conducted over



**Fig. 1.** Daily rainfall (vertical bars) and mean air temperature (line) during the monitored growth seasons in 2012, 2013 and 2014. Arrows indicate the sampling times of the soil moisture profiles.

3 consecutive years with the following objectives: (i) to explore the responses of physical and hydraulic soil properties to different rates of biochar addition in a mixed soil layer, (ii) to investigate the temporal and spatial variations of soil water contents affected by biochar amendment at soil depths of 0–200 cm, and (iii) to assess the effects of different biochar treatments on maize productivity and water use efficiency. The results generated from this research could help increase the understanding of how biochar amendment alters soil water properties in dryland agricultural systems.

## 2. Materials and methods

### 2.1. Site description

The field experiment was conducted from 2012 to 2014 at the Changwu Agricultural and Ecological Experiment Station (35.28°N, 107.88°E; 1200 m elevation) on the Loess Plateau. The climate is semi-arid with an average annual temperature of 9.1 °C and an average annual rainfall of 555 mm (previous 20 yr), of which 73% falling during the maize growth season. But the mean value of open pan evaporation is as high as 1565 mm. The daily rainfall and mean air temperatures during the observation period from April to September in 2012, 2013 and 2014 are presented in Fig. 1. During the growing season, 403, 421, and 375 mm of rainfall occurred in 2012, 2013, and 2014, respectively, accounting for 84%, 73% and 66% of annual rainfall, respectively. The mean air temperatures during the maize growing season were 18.9, 19.5 and 19.1 °C in 2012, 2013 and 2014, respectively. The soils at this site are Cumuli-Ustic Isohumosols (Gong et al., 2007). Analyses of soil samples taken from the experimental field before planting in 2012 indicated that the soil properties in the top 0–20 cm were a pH (1: 2.5 H<sub>2</sub>O) of 7.89, a bulk density of 1.36 g cm<sup>-3</sup> and 19.9 g kg<sup>-1</sup> of soil total carbon, 0.99 g kg<sup>-1</sup> total nitrogen, 6.56 mg kg<sup>-1</sup> available phosphorus (Olsen-P), 127.12 mg kg<sup>-1</sup> available potassium (NH<sub>4</sub>OAc-K), and 9.96 mg kg<sup>-1</sup> mineral N (NO<sub>3</sub><sup>-</sup>-N and NH<sub>4</sub><sup>+</sup>-N).

## 2.2. Biochar

The biochar used for the field experiment was produced by pyrolysis of maize-straw at 400 °C at the Sanli New Energy Company in Henan, China. Biochar was surface applied by hand in April 2012 before the maize sowing and immediately incorporated into 0–20 cm soil depth with basal fertilizers utilizing both rotary and moldboard plow tillage. Biochar had C, N and H contents of 59.16%, 0.98% and 1.69%, respectively, as well as a pH of 9.8, a bulk density of 0.4 g cm<sup>-3</sup> and a specific surface area (Brunauer-Emmett-Teller) of 53.03 m<sup>2</sup> g<sup>-1</sup>.

## 2.3. Experimental design and treatments

Four biochar application rates (0, 10, 20 and 30 t ha<sup>-1</sup>) were labeled as the control (BC0), BC10, BC20 and BC30, respectively. Each treatment plot was 7 m × 8 m in area and the field plots were arranged in a randomized complete block design with three replicates. Approximately 10 cm high ridges were located around each plot and the experimental topography was flat. Urea was applied to achieve a total N application of 225 kg N ha<sup>-1</sup>, with 40% applied before sowing, 30% top-dressed at the jointing stage, and 30% top-dressed at the silking stage. Phosphorus and potassium were applied as calcium superphosphate and potassium sulphate at rates of 40 kg P ha<sup>-1</sup> and 80 kg K ha<sup>-1</sup>, respectively. The same rates and timing of N, P and K fertilization were used in all plots.

## 2.4. Soil sampling and analyses

Six (November 2012) and 24 months (April 2014) after biochar incorporation, three replicated, undisturbed soil samples were collected at depths of 0–10 and 10–20 cm from each plot by using metal rings (an inner diameter of 5 cm and a height of 5 cm) after removing all plant debris. The means of the three replicate samples were calculated as one value per plot. The soil bulk density was calculated from the oven-dried (105 °C) mass and volume of the undisturbed soil sample, and the total porosity was determined from the bulk density, assuming a particle density of 2.65 g cm<sup>-3</sup>. Saturation water content (SWC) of the soil was determined by saturating the undisturbed soil samples for 24 h (Sun and Lu, 2014), and the saturated hydraulic conductivity ( $K_s$ ) was determined using the constant head method (Wang et al., 2008). Three soil samples were used per treatment to measure the soil water retention at different matric potentials using a high-speed refrigerated centrifuge (Model CR21G, Hitachi Co., Ltd., Japan; Gao and Shao, 2015), and the readily available water content (RAWC) of the soil was determined by calculating the differences in soil water retention at matric potentials of -10 and -100 kPa (Rogovska et al., 2014). To analyse the effects of biochar on soil water retention characteristics, we used the Van Genuchten (1980) soil moisture retention model (Eq. (1)) in RETC hydrologic software (the U.S. Salinity Laboratory, California) to fit the measured soil water contents corresponding to the matric potentials of -1 to -1000 kPa (Gao and Shao, 2015). The available water content (AWC) of the soil was calculated as the difference in moisture retention between -33 and -1500 kPa as estimated by Eq. (1).

$$\theta(h) = \theta_r + (\theta_s - \theta_r) / [1 + (\alpha|h|)^n]^m \quad (1)$$

where  $\theta(h)$  is the measured volumetric water content at a matric potential  $h$  (cm),  $\theta_r$  and  $\theta_s$  are the residual and saturated volumetric water content, respectively,  $\alpha$  is related to the inverse of the air entry matrix potential,  $n$  is a curve shape parameter related to soil pore size distribution and  $m$  is set equal to  $1 - 1/n$ .

The standard system for maize developmental stages was used to identify the crop growth stages (Ritchie et al., 1992). Field soil samples were obtained at 10-cm intervals from one core obtained

from each plot for the 0–100 cm core and at 20-cm intervals for the 100–200 cm core obtained at planting time (PT), the sixth leaf stage (V6), silking stage (R1), milk stage (R3), dent stage (R5) and physiological maturity (R6) each year (Fig. 1). Each soil sample was oven-dried at 105 °C for 24 h until a consistent weight was achieved to determine the soil water content (gravimetric water content, % g/g). Using the time domain reflectometry (TDR) method (Field Scout TDR 300, Soil Moisture Meter, USA), the soil water contents (volumetric water content, % v/v) were measured following rainfall events at depths of 0–3.8, 0–7.6, 0–12 and 0–20 cm (from 11 May 2014 to 15 May 2014). Four measurements were collected in each plot and each soil layer, and the measurements were averaged for each plot and for each soil layer.

The maize grains harvested from four rows in each plot with an area of 10 m<sup>2</sup> were first oven-dried at 105 °C for 30 min and then oven-dried at 80 °C to constant weight, and grain yield was calculated at 15.5% moisture content. Seasonal evapotranspiration (ET, mm) during the growth stage of spring maize was calculated as the total seasonal rainfall (P, mm) during the crop growing season plus the difference in soil water storage within the 200 cm profile between the beginning and end of the experiment ( $\Delta W$ , mm), i.e.,  $ET = P + \Delta W$ . The water use efficiency (WUE, kg ha<sup>-1</sup> mm<sup>-1</sup>) for grain yield was determined using the formula  $WUE = Y/ET$ , where  $Y$  (kg ha<sup>-1</sup>) is the grain yield.

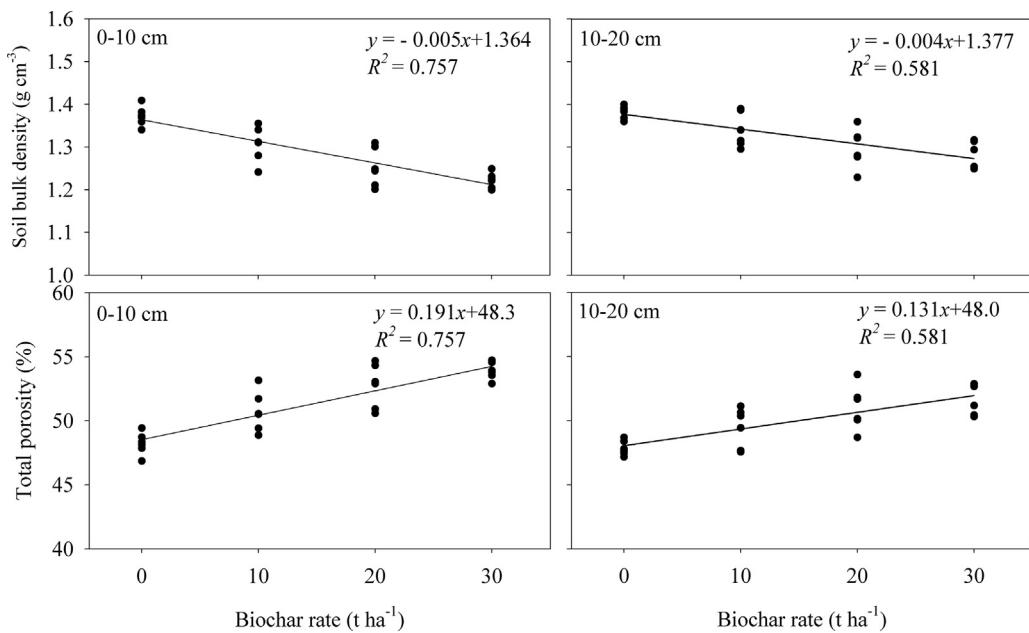
## 2.5. Statistical analyses

One-way analysis of variance (ANOVA) was used to evaluate the effects of different biochar application rates on the measured parameters, and differences between the treatment means were compared using least significant difference testing (LSD) at  $P < 0.05$ . The relationship between soil bulk density (total porosity) and biochar application rate was tested by linear regression (Proc REG). Two-way analysis of variance was used to evaluate the changes in ET, grain yield and WUE with different biochar application rates and the sampling years as two fixed factors. Statistical analyses were performed using IBM SPSS 19.0 statistics software (SPSS Inc., Chicago, USA) for Windows, and plots were developed using SigmaPlot 10.0 (Systat Software Inc., California, USA).

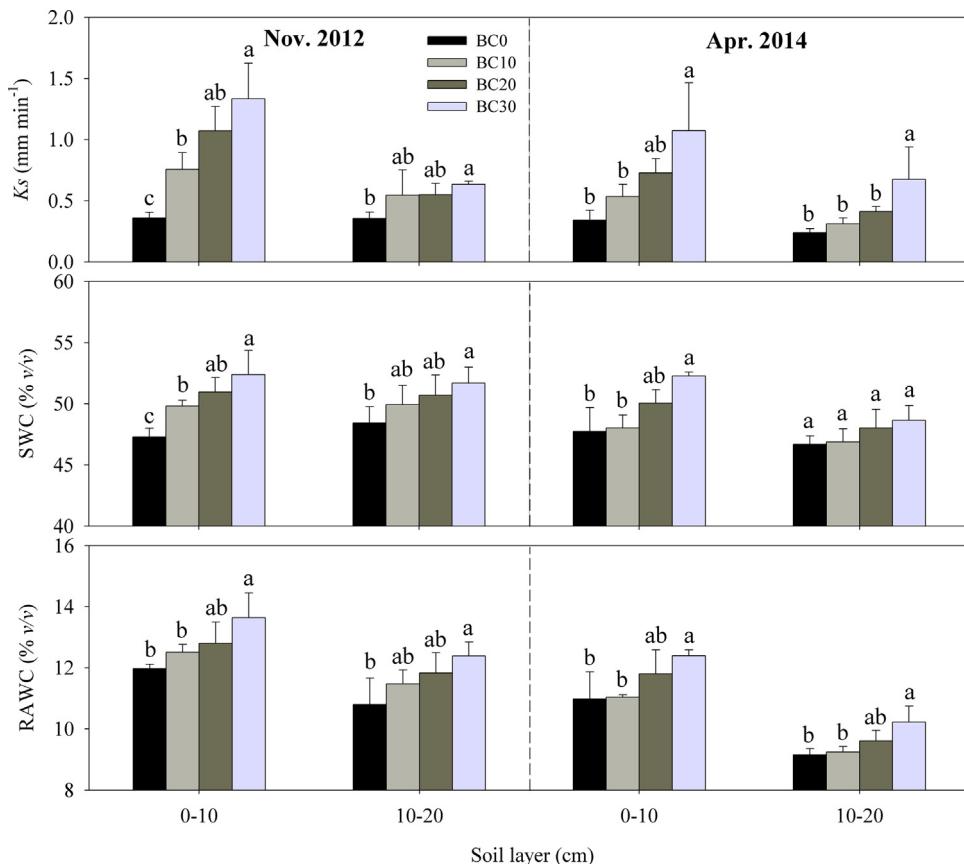
## 3. Results

### 3.1. Physical and hydrological properties

The physical and hydrological properties of the undisturbed soils are shown in Figs. 2 and 3. The differences in the soil bulk density and total porosity between the first sampling and second sampling were not statistically significant ( $P < 0.05$ ). The regression lines between the parameters (soil bulk density and total porosity) and the biochar application rates showed significant linear relationships ( $P < 0.001$ ). When averaging the values from the two samplings, biochar application decreased the bulk density in the 0–10 and 10–20-cm layers from 1.37 and 1.38 g cm<sup>-3</sup> in the control to 1.22 and 1.28 g cm<sup>-3</sup> in the treatment amended with 30 t biochar ha<sup>-1</sup>, respectively. In addition, the total soil porosity was generally inversely correlated with the soil bulk density. Significant increases ( $P < 0.05$ ) in the average total soil porosity from 48.23 and 47.86% in BC0 to 53.91 and 51.7% in BC30 were observed at depths of 0–10 and 10–20 cm, respectively. Although BC10 had higher  $K_s$ , SWC and RAWC than the control, the differences were not significant, except for the SWC at a depth of 0–10 cm in Nov. 2012. The BC20 treatment only had significantly higher  $K_s$  and SWC values than the control for the first sample at a depth of 0–10 cm. Compared with the control, the application of 30 t biochar ha<sup>-1</sup> significantly increased the  $K_s$  and SWC of the



**Fig. 2.** Soil bulk density and total porosity of both samplings (Nov. 2012 and Apr. 2014) in response to different biochar application rates at depths of 0–10 and 10–20 cm.



**Fig. 3.** Saturated hydraulic conductivity ( $K_s$ ), saturation water content (SWC) and readily available water content (RAWC) of the 0–10 and 10–20 cm soil layers with different biochar application rates in Nov. 2012 and Apr. 2014. Bars (standard deviation) followed by different letters are significantly different at  $P < 0.05$ .

soils. However, two years after biochar incorporation, no difference in SWC was observed at a depth of 10–20 cm among all of the treatments. The retention of water was obviously higher in the soil amended with 30 t biochar  $\text{ha}^{-1}$  at 10 kPa than in the control,

which eventually resulted in significantly higher RAWCs (retained tensions of between  $-10$  and  $-100 \text{ kPa}$ ) in BC30 than in the control.

The significance values of the estimated hydraulic parameters at a soil depth of 0–10 cm using the van Genuchten hydrologic model are shown in Table 1. Comparing the values between treatments, no

**Table 1**

Summary statistics of the van Genuchten model fitting parameters and the estimated AWC for the biochar treated and control soils of 0–10 cm layer in Nov. 2012 and Apr. 2014.

Sampling time	Treatment	$\theta_r$ (cm <sup>3</sup> cm <sup>-3</sup> )	$\theta_s$ (cm <sup>3</sup> cm <sup>-3</sup> )	$\alpha$ (cm <sup>-1</sup> )	n	AWC (% v/v)
Nov. 2012	BC0	0.053a	0.473c	0.026a	1.216b	14.29a
	BC10	0.056a	0.497b	0.031a	1.216b	14.61a
	BC20	0.101a	0.510ab	0.023a	1.285a	14.74a
	BC30	0.089a	0.523a	0.028a	1.270a	15.10a
Apr. 2014	BC0	0.045a	0.477b	0.042a	1.201a	13.53b
	BC10	0.041a	0.481b	0.041a	1.193a	13.65b
	BC20	0.064a	0.498b	0.038a	1.216a	13.89ab
	BC30	0.049a	0.522a	0.038a	1.205a	14.87a

Numbers in each column in the same sampling time followed by different letters indicate significant ( $P < 0.05$ ) differences between treatments according to LSD tests.

significant differences were observed among any of the estimated model parameters, except for  $\theta_s$  and  $n$ . The estimated  $\theta_s$  values were similar to the measured SWC values in Fig. 3. With regard to the values of  $n$ , the BC20 and BC30 soils only appeared markedly different from the control in Nov. 2012, and no significant differences were observed in Apr. 2014. The estimated AWCs in the biochar treatments were slightly higher than that in the control in Nov. 2012; however, in Apr. 2014, the estimated AWC in BC30 was significantly higher than that in the control (by 9.85%).

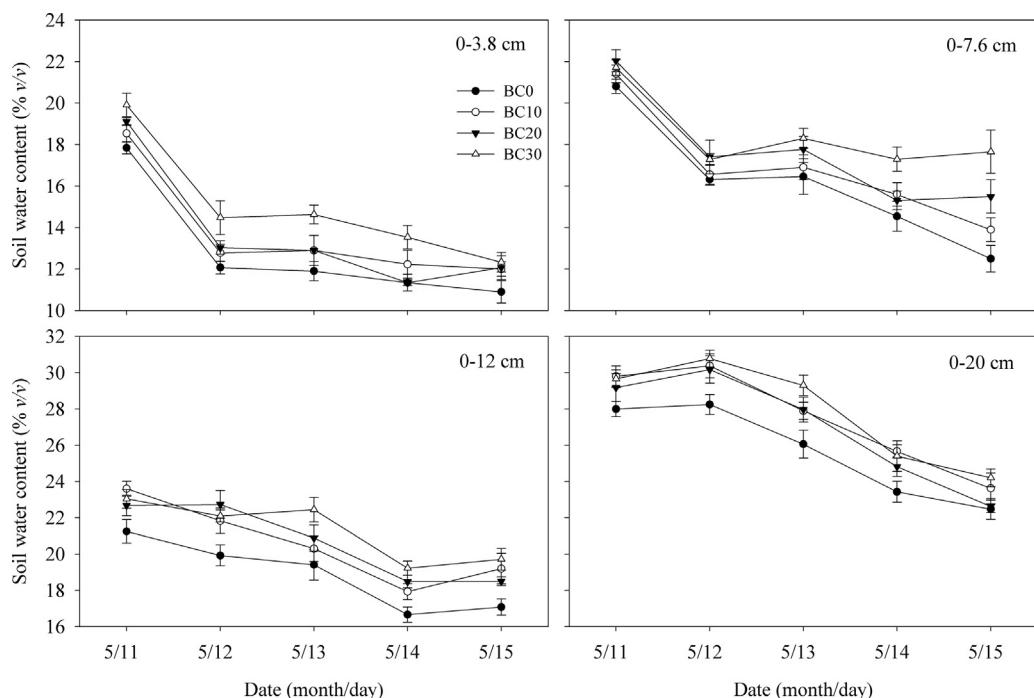
### 3.2. Temporal variation of the soil water content

During the third growing season, the soil water contents at depths of 0–3.8, 0–7.6, 0–12 and 0–20 cm were monitored daily from May 11–15 following an 8.0 mm rainfall event on May 9 and a 9.8 mm rainfall event on May 10 (Fig. 4). The successional data showed that the soil water content was higher in the biochar-amended treatments than in the control; however, this difference was not always significant. The average soil water content over the five monitoring days in BC10 was markedly higher than the control by 9.04% at a depth of 0–12 cm. Similar results were observed in BC20, in which the average soil water contents over the five monitoring days were 9.18 and 9.49% markedly higher than the

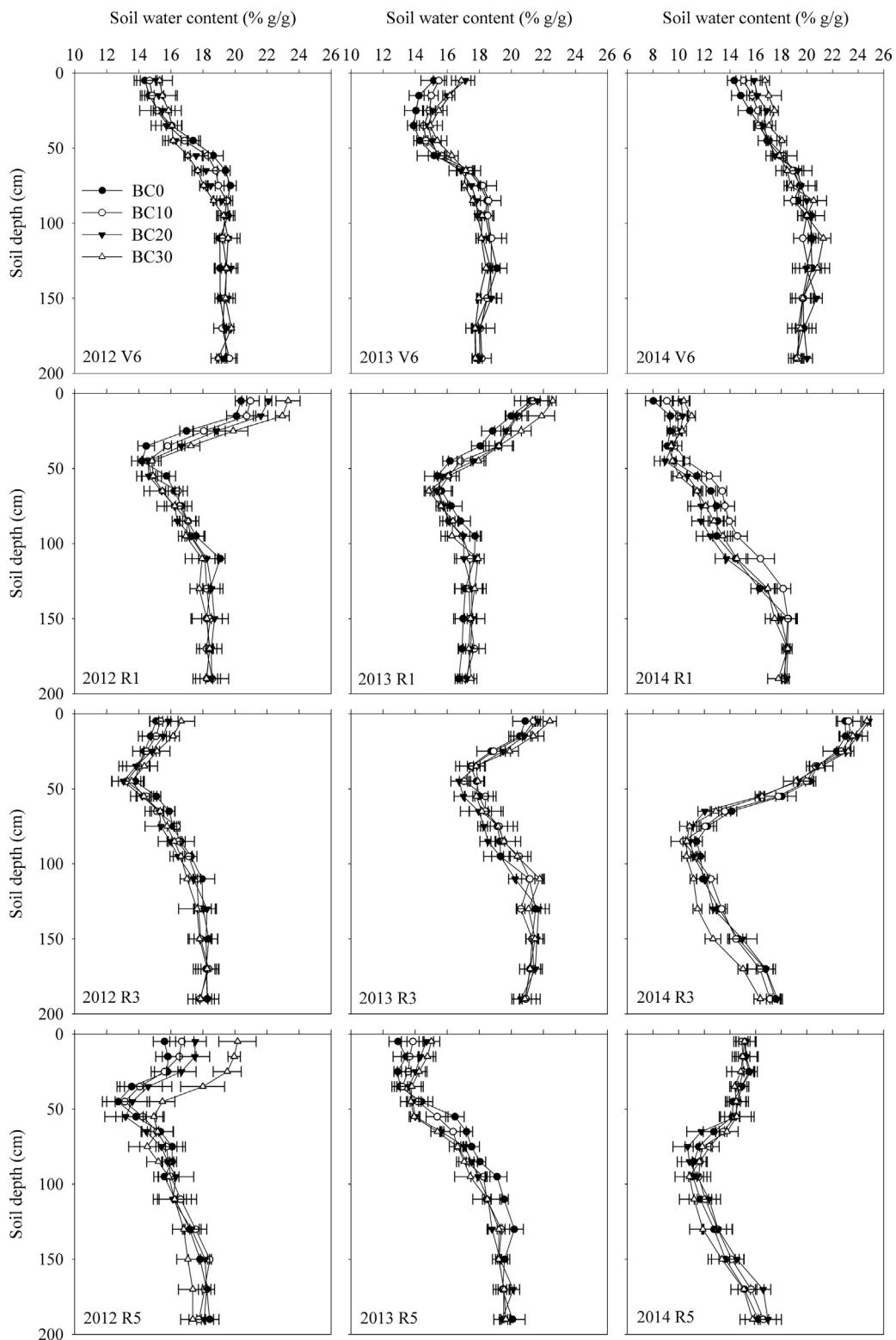
soil water contents of the control at depths of 0–7.6 and 0–12 cm, respectively. With a few exceptions, the application of biochar at 30 t ha<sup>-1</sup> significantly increased the soil water contents at all four depths, and the difference between BC30 and the control at 0–7.6 cm gradually increased from 4.4% on the first day after rainfall to 41.2% on the fifth day after rainfall. Compared with the first day after rainfall, the soil water content in the topsoil at depths of 0–3.8 and 0–7.6 cm rapidly decreased on the second day after rainfall. No clear difference between the two days was found at a depth of 0–12 cm, and a small increase was observed at a depth of 0–20 cm.

### 3.3. Soil water distribution profile in the field

The water contents across the 0–200 cm soil profile during different crop growth periods and the three growing seasons of maize for each treatment are shown in Fig. 5. Higher frequency rainfall events occurred before samplings during the first two growth seasons. No rainfall occurred for 16 days before collecting samples at V6 in 2012, and the water contents in the biochar-added plots were lower in the 40–80 cm soil layer than in the control, especially in BC30. The distributions of the water contents in the R1, R3 and R5 profiles were similar; i.e., the water contents decreased



**Fig. 4.** Temporal variations of the soil water content after rainfall at soil depths of 0–3.8, 0–7.6, 0–12 and 0–20 cm as affected by biochar application rates. (Observation period: 11–15 May 2014).



**Fig. 5.** The water contents across the 0–200 cm soil profile under different biochar treatments at sixth leaf stage (V6), silking stage (R1), milk stage (R3) and dent stage (R5) in 2012, 2013 and 2014.

from 0 to 50 cm and then increased from 50 to 120 cm. Compared with the control, the water contents of R1 (with 12.6 mm of rainfall before sampling) in BC20 and BC30 were significantly higher at a depth of 0–40 cm; the water contents of R3 (with 11.4 mm of rainfall three days before sampling) in BC30 were significant higher by 10.35 and 9.48% in the 0–10 and 10–20 cm soil layers, respec-

tively; and the water contents of R5 (with rainfalls events of 1.8 and 14.4 mm occurring one and three days before sampling, respectively) in BC30 were significantly higher by 29.18, 26.17, 23.59, 32.68 and 21.64% in the 0–10, 10–20, 20–30, 30–40 and 40–50 cm soil layers, respectively. The water contents of R1 and R3 in BC20

**Table 2**

Seasonal evapotranspiration (ET), spring maize grain yield (Y) and water use efficiency (WUE) across the 0–200 cm soil profile in various treatments during the 3-year field experiment.

Year	Parameter	Treatment			
		BC0	BC10	BC20	BC30
2012	ET (mm)	362b	370ab	372ab	379a
	Y ( $t\text{ha}^{-1}$ )	10.2b	10.9ab	11.1a	11.5a
	WUE ( $\text{kg ha}^{-1} \text{mm}^{-1}$ )	28.3a	29.5a	29.9a	30.4a
2013	ET (mm)	410a	408a	407a	407a
	Y ( $t\text{ha}^{-1}$ )	9.8c	10.4bc	10.8ab	11.1a
	WUE ( $\text{kg ha}^{-1} \text{mm}^{-1}$ )	23.8b	25.5ab	26.7a	27.3a
2014	ET (mm)	347a	358a	347a	350a
	Y ( $t\text{ha}^{-1}$ )	8.9c	9.5bc	9.9ab	10.3a
	WUE ( $\text{kg ha}^{-1} \text{mm}^{-1}$ )	25.6c	26.6bc	28.4ab	29.5a
	Source of variation	ET	Y	WUE	
	Biochar (B)	ns	***	***	
	Year (Y)	***	***	***	
	B × Y	ns	ns	ns	

Numbers in each row followed by different letters indicate significant ( $P < 0.05$ ) differences between treatments according to LSD tests.

\*\*\*Significant at  $P < 0.001$ ; ns, Nonsignificant.

and BC30 were slightly lower in the 50–120 cm soil layer than in the control.

In 2013, compared with the control, the average water contents of V6 (with 9.4 mm of rainfall before sampling) in BC20 and BC30 were significantly higher by 9.94 and 9.52% at soil depths of 0–40 and 0–60 cm, respectively. Biochar addition slightly increased the R1 water contents (with rainfall events of 27 and 16.8 mm occurring one and two days before sampling) at a depth of 0–60 cm, but the water contents only significantly increased by 9.5, 9.37 and 11% in the 10–20, 20–30 and 40–50 cm soil layers, respectively, of BC30. Biochar addition slightly increased the R3 water contents (with 25.2 mm of rainfall one day before sampling) at a depth of 0–40 cm, but only BC30 significantly increased the water content by 7.34% at a depth of 0–10 cm; and the water contents in BC20 were slightly lower in the 40–120 cm layer than those in the control. The water contents of R5 (with 9.4 mm of accumulated rainfall before sampling) in the biochar-added plots were higher at soil depths of 0–40 cm and were lower at soil depths of 40–160 cm.

In 2014, small rainfall events occurred before sampling during the third growing season. Compared with the control, the water contents of V6 (without rainfall for 7 days before sampling) in BC20 and BC30 were significant higher by 10.72 and 16.67, 8.78 and 14.75, and 8.49 and 12.29% in the 0–10, 10–20 and 20–30 cm layers, respectively. The water contents of R1 (without rainfall for 7 days before sampling) in BC20 and BC30 were 27.02 and 29.53, 10.08 and 17.72, and 8.89 and 9.89% higher in the 0–10, 10–20 and 20–30 cm layers, respectively, but slightly lower in the 40–90 cm layer. The water contents of R3 (with 36.4 mm of accumulated rainfall five days before sampling) in BC20 and BC30 were 8.03 and 7.28% higher, respectively, in the 0–10 cm layer; however, BC20 and BC30 had lower water contents in the 40–100 cm layer and in the 40–200 cm soil layer, respectively. No significant differences were observed among all of the treatments in the soil water contents of R5 (with 3.6 mm of accumulated rainfall ten days before sampling) at soil depths of 0–200 cm.

### 3.4. Grain yield, evapotranspiration (ET) and water use efficiency (WUE)

Analysis of variance indicated that the biochar application rates and sampling years significantly influenced maize grain yields and WUE (Table 2). The maize grain yields varied among the three experimental years, with the highest yields recorded in 2012 and

the lowest yields recorded in 2014. The grain yields in the biochar treatments were higher than the grain yields in the control across all three years, and no significant difference was found when biochar was added at  $10\text{ t ha}^{-1}$ . In 2012, the ETs in the biochar treatments were higher than in the control (significantly only in BC30 by 5%), and in the following two years, the ETs in the biochar treatments were not different from the ET in the control. Biochar addition slightly increased the WUE in 2012 and significantly increased the WUE in the next two years.

## 4. Discussion

### 4.1. Soil physical and hydrological properties

Soil physical properties have important effects on plant growth and water management, and the application of biochar decreases the soil bulk density. In our study, the soil bulk density decreased as the amount of biochar amendment increased. A similar reduction in Midwestern Mollisols following biochar addition was reported by Rogovska et al. (2014), and biochar amendments have been shown to increase the total soil porosity and macroporosity (Nelissen et al., 2015). In the present study, the total pore volume of the biochar-treated soils was observed to increase, possibly due to the high internal porosity of biochar (Peterson and Jackson, 2014) or the creation of large soil macropores surrounding the biochar particles (Hardie et al., 2014). The lower soil bulk density resulting from biochar addition may decrease the degree of compaction, and the changes in porosity could affect the aeration and moisture retention capacity of soils (Lehmann et al., 2011).

The application of biochar improved the soil water retention properties, especially in BC30, over different soil sampling times (short or long periods). Previous studies, mainly of sandy soils, have indicated that the incorporation of biochar reduces the soil infiltration capacity and the effects of soil erosion (Novak et al., 2009; Barnes et al., 2014) or does not affect the field saturated hydraulic conductivity (Jeffery et al., 2015). However, higher  $K_s$  values were observed (a loamy soil) with biochar addition in this study. One possible explanation for this observation may be that the clay particles in the soils were directly substituted by relatively larger biochar particles, increasing the macroporosity and the soil permeability (Bayabil et al., 2015). These findings are in agreement with the work presented by Oguntunde et al. (2008) and Asai et al. (2009), who reported that biochar increased the soil infiltration capacity and reduced surface runoff. In addition, biochar increased the maximum soil water holding capacity, i.e., higher amounts of biochar resulted in higher SWCs. Similar improvements due to biochar addition were reported by Sun and Lu (2014). Readily available water is the water that a plant can easily extract from the soil, and available water is the amount of water held between the field water holding capacity and the permanent wilting point. In our study, soil amended with biochar at  $30\text{ t ha}^{-1}$  exhibited increases in the RAWC and AWC, both of which are available to crops and potentially improve crop performance, and the increased water may be related to microporosity and mesoporosity. Biochar can physically adsorb water on the exterior surface and/or inside these pores and hold water between biochar-soil particles by capillary force. Additionally, the increased water may contribute to mitigating the problem of uncertain rainfall patterns under field conditions. The higher values of  $n$  observed in the biochar-added soils of BC20 and BC30 at the first sampling revealed steeper water characteristic curves, which indicated a rapid decrease in soil water content as the matric potential increased (Hodnett and Tomasella, 2002). The release of more water from soils will provide more water for plants. Stronger effects of biochar addition on the physical and hydrological soil parameters were observed in the 0–10 cm soil layer than in the 10–20 cm

soil layer, probably due to the nonuniform distribution of biochar to a depth of approximately 20 cm.

#### 4.2. Temporal and spatial soil water content variations

The temporal variations of the soil water content after rainfall events indicated that biochar incorporation improved the water content of the topsoil, which is consistent with the results reported by Rogovska et al. (2014), who found that the water contents in the 0–3 cm surface soil layer were higher in biochar-amended plots throughout the monitoring period (each day over 2 weeks). Similarly, Chen et al. (2010) conducted an outdoor lysimeter experiment and observed the changes in soil water content after 10 weeks of cultivation, which showed that the soil moisture in the bagasse-biochar plots was significantly higher than in the other plots. The soil water contents obviously increased in all of the treatments after rainfall events, but the responses were different between the biochar treatments and the control. The average soil water contents with biochar addition over five days were significantly higher at the 0–7.6 and 0–12 cm depths than in the control. This result is consistent with the hydrological properties of the undisturbed soil, which showed that the soil water holding capacity was greater at a depth of 0–10 cm than at a depth of 10–20 cm. Over time, the differences in the soil water contents between BC30 and the control gradually increased, revealing that biochar can maintain more moisture in the soil, which may delay evaporation and provide available water for plant absorption. As the amount of biochar addition increases, biochar can hold more moisture in the same layer and maintain much of the moisture in the deeper soil. Moreover, the changes in the soil moisture content in response to rainfall were different in varying soil layers, especially on the second day after rainfall. The soil moisture content in the shallow soil layer decreased rapidly due to the rapid evaporation caused by lower atmospheric water vapour pressure, while the subsoil moisture was not obviously reduced, and even increased in some areas. This result potentially occurred due to the movement of water from deeper soil to the topsoil through capillarity and vapour transfer (Zhou et al., 2009).

Our results indicated that biochar addition could alter the distribution of soil moisture in the soil profile (Fig. 5). Incorporation of biochar had succeeded in improving the water retention capacity of the undisturbed mixed soil in the laboratory study, and the field moisture conditions below the mixed soil were also influenced by the upper soil texture when other materials were added. Rainwater enters larger pores more easily; thus, it may take less time for water to infiltrate the soil when larger soil pores are present (Asai et al., 2009). In the present study, the higher porosity and saturated hydraulic conductivity of biochar-mixed soils promoted the flow of more rainwater into the subsoil, which increased the rainfall harvest and soil water storage. Due to the inherent soil water status, soil water content and infiltration depth responded to rainfall differently. The comprehensive analysis of the temporal and spatial variations of soil water content in the soil profile revealed that the soil moisture in the biochar-amended treatments exhibited frequent and large changes at a depth of 0–40 cm, which was similar to the finding reported by Chen et al. (2013), who indicated that the upper 0–40 cm of soil is an active layer regarding water and temperature variations. The application of biochar could improve not only the water condition of the 0–20 cm mixed-soil layer but also the subsoil layers of 20–40 cm via water infiltration of the upper soil in the semi-arid region. In the 30 t biochar  $\text{ha}^{-1}$  treatment, the depth of water infiltration even reached up to 60 cm below the horizon, but the lower rate of biochar addition (10 t  $\text{ha}^{-1}$ ) had almost no influence on soil water infiltration after rainfall, which verified the lack of a clear effect of biochar addition on the hydraulic conductivity of the 0–20 cm soil layer in BC10 (Fig. 3). Data analysis of all of the samples revealed that the soil water contents in the biochar

treatments were not always higher than the soil water contents in the control when considering crop absorption and soil evaporation. Soils amended with biochar maintain more moisture in the topsoil, and the larger canopy induced by biochar addition, in turn, gathers more rainwater that flows to the roots of the planted maize. The larger canopy can also shade more of the soil surface and may reduce the water loss that results from evaporation due to direct solar radiation (Li et al., 2013). In addition, the favourable environment caused by the addition of biochar induced more and thicker individual maize roots as shown by our previous study (Xiao et al., 2016), which could retain more moisture in the root zone which supply much available water to the crop (Bruun et al., 2014; Olmo et al., 2014).

During some growing stages, the water contents of the deeper soil layer (below 40 cm) in the biochar-amended treatments were lower than the water contents in the control in the absence of adequate rainfall. For example, no rainfall occurred for 16 days before V6 in 2012 and, compared with the control, biochar addition increased the consumption of soil water at depths of 40–80 cm. During the silking to maturity period (the critical period for kernel formation), crops require sufficient water to sustain reproductive growth. However, in 2013, the accumulated rainfall that occurred during the R3–R5 growth stages was 12 mm, and water stress stimulated soil water depletion below 40 cm, especially in the treatments amended with biochar. During the R1–R3 growth stages in 2014 and due to a 25-day dry period (only 4 mm of rainfall) before a heavy rainfall event, soil water depletion also occurred below 40 cm at rates of 20 and 30 t biochar  $\text{ha}^{-1}$  to maintain a larger canopy in the treatments with biochar amendment (Xiao et al., 2016). Throughout the region, the upper soil water contents in the biochar plots met the water requirements for normal crop growth when rainfall was sufficient. However, the deeper soil water was used as a supplement to support the canopy during drought. Rainfall events increased the soil water contents of biochar-added treatments much more than the control (Figs. 1 and 5), which led to the absorption of more water by the crop. Additionally, the consumption of water from deeper soil layers induced by biochar addition also occurred, particularly during the grain-filling period, during which biochar can improve the efficient uptake of water by roots in deeper soil layers. This result agrees with previous findings (Li et al., 2016) that have shown crops can exploit deep soil water to support shoot biomass production.

#### 4.3. Grain yield, evapotranspiration (ET) and water use efficiency (WUE)

The interannual variations in rainfall frequency and intensity eventually led to differences in yearly grain production. The grain yields in the third year were the lowest among the three years, probably due to insufficient precipitation close to the critical period of kernel number determination (Fig. 1). Lehmann et al. (2011) and Novak et al. (2016) reported positive effects of biochar addition on crop yield and soil productivity, which were mainly attributed to the favourable physical, chemical and biological soil environment and the improved soil nutrient levels and soil water availability that resulted from biochar addition. Our study showed that grain yields significantly increased following the biochar addition at rates of 20 and 30 t  $\text{ha}^{-1}$  each year, which could partly be attributed to the fact that biochar addition resulted in the maintenance of greater water contents in the upper soil, as reported by Chen et al. (2010) and Rogovska et al. (2014). Our previous study has shown that biochar addition can improve soil nutrient levels, facilitate root growth and increase the number of fine roots (Xiao et al., 2016), which could promote water absorption. Similarly, Jeffery et al. (2011) concluded that enhancing the soil water holding capacity through biochar addition may be a primary mechanism for improving crop yield.

Besides, the increase in soil water depletion in the deeper soil layers at some stages maybe another of the reasons to explain the increases in grain yields observed in our study. In 2012, the low but significant seasonal ET increments induced by biochar addition were mainly attributed to greater ET during the grain-filling to maturity period (data not shown). Although biochar addition significantly enhanced grain yields, no significant differences in WUE were observed due to the higher seasonal ET that occurred in 2012. In the next two years, the obviously higher WUEs under biochar-added treatments were found due to the greater yield achievement compared with the control (Table 2). Most likely due to lower soil evaporation and increased crop transpiration, biochar addition potentially had no effect on seasonal ET in 2013 and 2014. However, biochar addition increased the depletion of water in the deeper soil layers (i.e., greater ET) during the early and middle grain-filling periods (Fig. 5), which could be attributed to the greater soil water extraction capacity of the maize roots and/or the greater transpiration capacity of the maize canopy due to biochar addition (Chen et al., 2010), which increased the yields and WUEs. Corresponding with our results, increased WUEs with biochar addition were reported by Kammann et al. (2011) and Akhtar et al. (2014), who observed that biochar addition improved the physiological responses of plant under drought stress (e.g., greater leaf photosynthesis and/or greater leaf stomatal conductance), thereby increasing the ratio of yield to water consumption (WUE). Hence, more research is needed to establish the relationship between plant photosynthesis, transpiration and biomass accumulation in the dryland farming. Overall, biochar application improved soil available water in the root zone, and increased grain yield and WUE.

## 5. Conclusion

Our results imply that the application of biochar has beneficial effects on some special soil physical properties and hydrology characteristics in the medium-textured, semi-arid agricultural soil examined in this study. With added biochar, the soil bulk density decreased and the total porosity increased with increasing biochar mixing rate. Biochar can improve the soil water retention capacity, allowing for the retention of more moisture in the soil layer mixed with biochar (i.e., increases in saturation, readily available and available water contents). The successively higher water contents in the soils amended with biochar after rainfall events also indicated that biochar can hold more soil moisture under natural conditions. The variations of the soil water contents across the soil profile in the biochar treatments was collectively affected by rainfall and crop growth and mainly occurred at a soil depth of 0–40 cm. Relative to the control, the depth of water infiltration in the 30 t biochar ha<sup>-1</sup> treatment reached up to 60 cm below the horizon due to an obvious increase in the soil infiltration capacity following biochar addition. Eventually, the application of biochar enhanced the crop grain yields and water use efficiency. Nevertheless, additional studies are needed to clarify the effects of the addition of biochar to different soil types on the soil moisture status and plant available water contents in the presence of different rainfall frequencies and intensities.

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