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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^{-1}. 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^{-1}. 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^{-1}, 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.

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^{-1} 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 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.

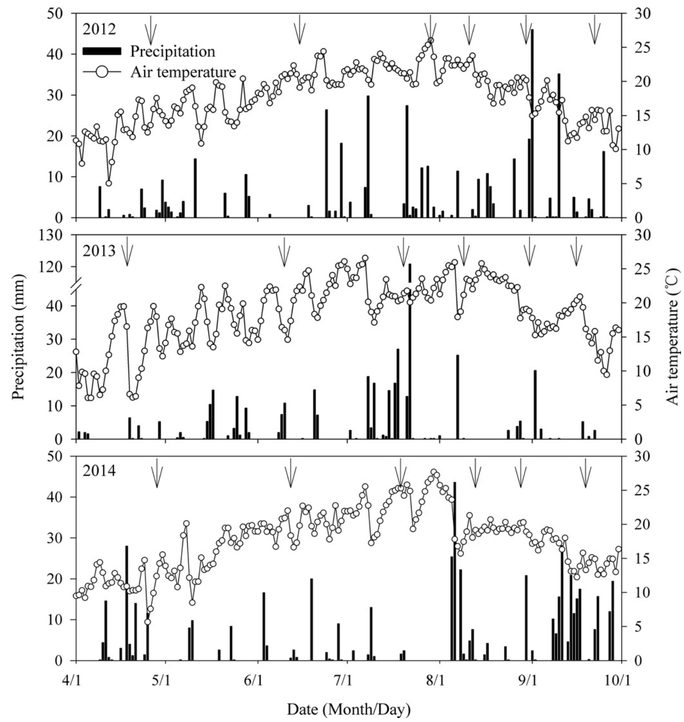

Fig. 1. Daily rainfall (vertical bars) and mean air temperature (line) during the monitored growth seasons in 2012, 2013 and 2014. Arrows indicate the sampling times of the soil moisture profiles.

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_2O) of 7.89, a bulk density of 1.36 g cm^{-3} and 19.9 g kg^{-1} of soil total carbon, 0.99 g kg^{-1} total nitrogen, 6.56 mg kg^{-1} available phosphorus (Olsen-P), 127.12 mg kg^{-1} available potassium (NH_4OAc-K), and 9.96 mg kg^{-1} mineral N (NO_3^--N and NH_4^+-N).

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