Geoderma 307 (2017) 114–121

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Impacts of fresh and aged biochars on plant available water and water use efficiency

Deborah Aller[a], Samuel Rathke[b], David Laird[a,*], Richard Cruse[a], Jerry Hatfield[c]

[a] Department of Agronomy, Iowa State University, Ames, IA 50011, USA
[b] Department of Soil, Water and Environmental Sciences, University of Arizona, Tucson, AZ 85721, USA
[c] National Laboratory for Agriculture and the Environment, Ames, IA 50011, USA

ARTICLE INFO

Handling Editor: Morgan Crisitne L.S.

Keywords:
Biochar
Biochar age
Soil water retention
Rainfed agriculture
Water stress

ABSTRACT

The ability of soils to hold sufficient plant available water (PAW) between rainfall events is critical to crop productivity. Most studies indicate that biochar amendments decrease soil bulk density and increase soil water retention. However, limited knowledge exists regarding biochars ability to influence PAW and water use efficiency (WUE), and even less is known about the effects of aged biochars on PAW and WUE. This greenhouse study investigated the influence of six fresh and six aged biochars on PAW and WUE for three soils of contrasting texture. PAW and WUE were assessed by growing maize in repacked soil columns (1 kg soil). Plant and water data were collected from the V1 growth stage until the plants died of water stress. Relative to the controls, both fresh and aged biochars increased soil moisture retention in the clay loam soil, had no impact in a silt loam soil, and had variable effects in a sandy loam soil. Final biomass weight increased with the addition of fresh biochar in the sandy loam and silt loam soils and decreased in the clay loam soil, while aged biochar increased biomass weight in the silt loam soil. Both fresh and aged biochars decreased PAW in the clay loam soil and had no impact on PAW in the silt loam soil. Fresh biochar increased PAW, while aged biochar had no effect on PAW for the sandy loam soil. WUE decreased in response to both fresh and aged biochars in the clay loam soil and was variable for the other two soils. Results of this experiment indicate that biochar type and biochar age have variable impacts on PAW and WUE, indicating that biochar amendments can improve soil water relations and crop growth under water limited conditions for some but not all soils.

1. Introduction

Over 80% of cropland and 60% of food produced globally is the result of rainfed agricultural production (FAO, 2011). This makes getting ‘more crop per drop’ (FAO, 2003) in a period of rapid population growth, increasing environmental degradation, and greater climatic variability a high priority. Managing water efficiently in rainfed systems to maintain high productivity will be essential in order to meet food, fiber, and fuel demands of a growing global population with increasingly variable rain events (IWMI, 2007). Rainfall patterns are expected to change in terms of intensity, frequency, and distribution as the global climate changes (IPCC, 2007). Water is already considered the limiting factor for attaining the maximum yield potential in areas where rainfed agriculture is practiced (Rockström et al., 2010). Hence, technologies that improve not only soil water retention but water use efficiency (WUE) and plant available water (PAW) in rainfed systems are critically needed to increase the resilience of food production. This is especially true during critical periods of the growing season when significant yield declines may occur due to limited water availability. One technology currently available that has the potential to improve water management in rainfed agriculture is biochar. Biochar, the solid co-product of biomass pyrolysis, is a soil amendment effective at improving soil water retention while simultaneously sequestering carbon and enhancing soil quality (Lehmann and Joseph, 2009).

Numerous studies indicate that biochar impacts soil water retention and other hydrologic functions, but due to different experimental conditions (including soil type and biochar treatments), results have been variable (Glaser et al., 2002; Major et al., 2012; Jeffery et al., 2015; Hardie et al., 2014; Obia et al., 2016; Lim et al., 2016). Nevertheless, due to the high internal porosity and the large surface area of biochars studies in general support decreased soil bulk density and increased porosity and water retention (Novak et al., 2009; Streubel

---

Abbreviations: SP, slow pyrolysis; FP, fast pyrolysis; SG, switchgrass; CS, corn stover; SB, soybean; HW, hardwood; PAW, plant available water; WUE, water use efficiency; PWP, permanent wilting point; FC, field capacity; BD, bulk density; WDPT, water droplet penetration test

[*] Corresponding author at: 2505 Agronomy Hall, Iowa State University, Ames, IA 50011, USA.
E-mail address: dalaird@iastate.edu (D. Laird).

http://dx.doi.org/10.1016/j.geoderma.2017.08.007
Received 11 May 2017; Received in revised form 1 August 2017; Accepted 4 August 2017

et al., 2011; Artiola et al., 2012; Basso et al., 2013; Abel et al., 2013; Rogovska et al., 2014; Ma et al., 2016). These many studies have investigated the effects of different biochar and soil mixtures on water retention and soil physical properties but only more recently have a few studies examined biochars influence on PAW and WUE. Quantifying WUE and PAW impacts of biochar in addition to water retention is essential because more water retained in the soil profile does not necessarily equate to more water for a growing plant (Verheijen et al., 2010) and in order to achieve maximum yield potentials plants must be able to access the water.

Very little is known about how biochar aging (weathering) influences PAW and WUE. Although considerable knowledge now exists about how biochar properties change over time, and was recently summarized in Mia et al. (2017), knowledge of how aged biochars in diverse soils influences PAW and WUE remains limited. Biochar age should be considered in biochar studies because although biochars are inherently more recalcitrant than other forms of organic matter, biochar properties still change over time (Downie et al., 2009; Kasozi et al., 2010; Kuzyakov et al., 2014). These changes have been shown to influence biochars' impact on agroecosystem functions (Seredych and Bandosz, 2007; Major et al., 2010; Wang et al., 2012; Borchard et al., 2014; Rajapaksha et al., 2016).

The aging of biochar can be broadly classified as either short- or long- term aging. Short-term aging refers to the hydration and oxidation of biochar surfaces that occurs after exposure to air and moisture (IBI, 2014). Long-term aging results from the physical and biochemical breakdown of biochar particles, dissolution of soluble salts and organic compounds, sorption of dissolved compounds from the soil solution, and the neutralization of alkalis over time in soil environments (Mia et al., 2017). Natural field aging of biochar can take decades to centuries so rapid laboratory aging procedures have been developed to mimic long-term field weathering processes. These artificial procedures often include a combination of acidification, oxidation, and incubations of different biochars (Hale et al., 2011; Uchimiya et al., 2011; Liu et al., 2013; Shi et al., 2015; Bakshi et al., 2016). The presence of aged biochars in soils may be more beneficial than fresh biochars as the changes in physicochemical properties of the biochars that occur on aging may increase the capacity of soils to retain water and nutrients (Mia et al., 2017).

This study was undertaken to assess the impact of artificially aged biochars on soil water relations and crop growth in diverse soils. While we recognize that artificially aged biochars may not be fully representative of naturally aged biochars, they provide a basis for assessing the direction and potential impact of aging on water relations. The objectives of this study were to investigate the influence of biochar age, biochar type, and their interaction on PAW and WUE in maize for three soils with contrasting textures. We hypothesized that biochar amendments would increase PAW and WUE in all three soils and that aged biochars would lead to a greater increases in PAW and WUE than their fresh counterparts.

2. Material and methods

This greenhouse column experiment was conducted at Iowa State University during the winter of 2015/2016. It involved 39 different treatments with four replicates totaling 156 columns in a complete randomized design. Treatments included 12 different biochars, three soil types, one biochar application rate, one crop, and one watering regime.

2.1. Soils

The soils used in this study were collected from three different locations across the state of Iowa and included a sandy loam, a silt loam, and a clay loam (USDA textural classification). Silt loam and clay loam soils were collected from agricultural fields in southwest and central Iowa, respectively, and the sandy loam from a river flood plain in central Iowa. Chemical and physical properties of the three soils are provided in Table 1. Following collection, soils were air dried, sieved to < 2 mm, and stored in sealed plastic containers until the start of the experiment.

Table 1
Soil chemical and physical properties.

Property	Soil type		
	Sandy loam	Silt loam	Clay loam
pH	7.34	6.80	6.92
EC (μs cm^{-1})	154.3	417	29.1
Extractable P (mg kg^{-1})	39.11	169.60	79.49
Extractable K (mg kg^{-1})	59.48	536.03	369.25
NH^{4+}-N (mg N kg^{-1})	1.90	5.77	7.17
NO^{3-}-N (mg N kg^{-1})	0.37	3.84	3.77
Total C (%)	1.25	2.89	4.86
Total N (%)	0.08	0.29	0.37
% Sand	77.6	14.3	40.7
% Silt	12.5	59.8	29.8
% Clay	9.9	25.9	29.5

2.2. Biochars

The biochars used in this study were produced by either fast pyrolysis (FP) or slow pyrolysis (SP) using corn stover (CS), switchgrass (SG), soybean (SB), and hardwood (HW) feedstocks. A subsample of each biochar was aged in the laboratory using acidification and oxidation treatments, followed by incubation with dissolved organic carbon (Bakshi et al., 2016). Briefly, fresh biochars (sieved < 1 mm) were incubated for one month at 40 °C in 1 M HCl (biochar: 1 M HCl = 1:5) with weekly additions of 30% H_2O_2. Following this incubation period biochars were washed twice with 1 M $CaCl_2$, washed with double deionized water, and then incubated for another month at 40 °C in an aqueous solution of dissolved organic carbon extracted from compost. Lastly, the incubated biochars were washed again with double deionized water, air dried, and stored for later use. A brief description of the 12 biochars (six fresh and six aged) used is provided in Table 2. For the complete physiochemical properties of the fresh and aged biochars please refer to Bakshi et al. (2016).

2.3. Experimental design

Previously constructed soil columns made of PVC pipe were used. Each column had dimensions of 14.1 cm high and 10.3 cm diameter, and was fitted with an endcap containing a 12.7 mm diameter hole. Prior to the experiment, the mass of all empty columns was recorded and a small piece of landscape fabric was placed on the underside of each column to allow water flow but prevent any loss of soil material. A Whatman 42 filter paper was placed inside the bottom of the each column to trap soil particles and 100 g of coarse sand (2–5 mm) was added on top of the filter paper to maintain adequate drainage out the bottom of each column. Individual masses of fabric and filter paper were recorded for all columns. The soil and biochar for each treatment were mixed together in a rotary cement mixer for 5 min. Biochar was incorporated at a rate of 1% w w^{-1} for all treatments (field application rate of ~22 t ha^{-1}), after taking into account the moisture content of each soil and biochar. All columns were packed with 1 kg of soil + biochar mixture and manually tapped down to consolidate the soil.

After all 156 columns were packed, they were placed into plastic bins and saturated from the bottom-up with distilled water. Complete saturation was assumed after a head of water was visible on the soil surface. Once saturated, columns were removed from the bins and left to freely drain until the head of water had disappeared (< 30 mins). Extenders, 5 cm high and of a known mass, were secured to the top of