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Broadcast woody biochar provides limited benefits to deficit irrigation maize in Colorado

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ABSTRACT

Biochar soil amendments have been widely promoted for their ability to improve soil fertility in degraded tropical soils, and irrigation and fertilizer use efficiency in fertile temperate agricultural systems. Here, we evaluate if a woody biochar can produce both agronomic and environmental benefits in deficit irrigation systems by ameliorating water stress, improving crop N uptake and mitigating greenhouse gas emissions. To evaluate these responses, we established a maize field trial in northern Colorado under deficit irrigation treatments with a woody biochar amendment. Irrigation treatments included recommended irrigation (Full), recommended irrigation except during non-essential growth phases (Limited) and 50% of recommended irrigation (Drought). We measured crop biomass, grain yield, grain N uptake, mineral N availability, soil water content, soil field capacity, soil C sequestration and N_2O emissions. Drought treatments reduced both grain and biomass yield while Limited irrigation showed no significant yield reduction relative to Full irrigation. Biochar amendments did not provide any yield improvements. Biochar also did not alter mineral N availability within the soil profile or grain N uptake. Biochar amendments increased gravimetric soil water content by 9.7% over the field season and increased water retention by 7.4%. However, these increases failed to alleviate the water stress coefficient, an index of how much the water content has dropped below the maximum soil water depletion acceptable between irrigation applications, which was correlated with yield. Biochar sequestered C primarily as coarse biochar particles with significant losses, likely a result of erosion. Across irrigation treatments biochar treatments trended towards a lower mean cumulative N_2O emissions over the growing season, but such effect was not significant due to high spatial variability in N_2O fluxes. Both biochar amendments and Limited irrigation treatments did not significantly impact yield-scaled cumulative N_2O emissions or irrigation water-use efficiency. This research highlights the importance of targeting the deficit irrigation treatment timing and amount to maximize biochar's improved water retention in order to reduce crop water stress. It also confirms the diminished biochar N_2O emission reductions in the field relative to most lab incubations due to drier field conditions and crop N uptake.

1. Introduction

Agriculture is one of the most vulnerable sectors to changing temperature and precipitation regimes, yet also contributes to the problem itself generating 24% of greenhouse gas (GHG) emissions globally (Smith and Bustamante, 2014). In the context of climate change, identifying agricultural practices that increase water and nutrient use efficiency while decreasing GHG impacts is essential for developing sustainable agricultural systems. Dryland and irrigated systems are especially sensitive to changes in precipitation and the resulting impacts on water supply, thus promoting water-use efficiency in agricultural practices is critical in managing these increasingly limited water resources (Kang et al., 2009). Increasing soil organic matter is one strategy to help improve the available water capacity of soils (Hudson, 1994), to help manage crop water stress while also providing climate benefits through carbon (C) sequestration (Smith et al., 2008). Soil moisture regime also interacts with soil nitrogen (N) cycling to impact crop productivity, affecting N availability, transformation and losses (Gonzalez-Dugo et al., 2010). Sustainable agricultural practices must consider interactions with soil water dynamics to maximize fertilizer N delivery to crops while minimizing environmental losses from N leaching or gaseous N production, including the important GHG,

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nitrous oxide (N_2O). Biochar soil amendments are one agricultural technology with potential to deliver improved water and N retention while decreasing GHG emissions (Atkinson et al., 2010), but few field studies have evaluated biochar's agronomic and environmental benefits in combination with reducing irrigation inputs (Foster et al., 2016; Kangoma et al., 2017).

With shifting climate patterns and growing demands on water supplies, producers in arid to semi-arid climates must consider new strategies for water conservation and increasing water productivity. Irrigation systems are generally designed to supply water to match the demands of evapotranspiration (Allen et al., 1998). With increasing competition for water resources and variable water supply, farmers may resort to deficit irrigation strategies to maintain yields while decreasing irrigation water use. Deficit irrigation strategies might include not irrigating crops during the early vegetative growth phases, which are less sensitive to water stress, or reducing total irrigation water throughout the growing season (Geerts and Raes, 2009; Sudar et al., 1981). Soil amendments, such as biochar, offer opportunities for improving water productivity by potentially increasing water storage while reducing evaporative losses. Biochar's porous structure has been shown to increase the water holding capacity of soils (Ali et al., 2017; de Melo Carvalho, 2014; Omondi et al., 2016), but this effect varies with soil texture, with more heavily textured soils showing diminished effects (Dan et al., 2015). Combining strategies of deficit irrigation while increasing water storage through biochar amendments may minimize crop water stress and reduce total water inputs.

Changes to soil moisture due to irrigation and soil organic matter management will also influence N availability, including soil N transformation and delivery to the crops (Barakat et al., 2016; Gonzalez-Dugo et al., 2010). N requirements are largely supplied through passive water uptake into roots, therefore higher irrigation has been shown to significantly increase N use efficiency across cropping systems (Aulakh and Malhi, 2005). Modeling studies also suggest that soils with greater water holding capacity have greater potential for improved N use efficiency (Asseng et al., 2001). Soil moisture levels and dynamics not only impacts crop N uptake but also microbial N cycling, as soil water content controls N diffusion, mineralization, immobilization, nitrification and denitrification (Barakat et al., 2016). Biochar may alter mineral N availability through its high ion exchange capacity (Gai et al., 2014), direct impacts on microbial N transformation (Clough et al., 2013; Nguyen et al., 2017) and interactions with soil hydraulic properties affecting mineral N transport through the soil profile (Sun et al., 2015). Previous research demonstrated that biochar reduces mineral N leaching in irrigated systems (Gai et al., 2014), but the dynamics for mineral N transport and transformation with biochar addition in deficit irrigation systems requires further study.

Lab incubations have shown that biochar can substantially reduce N_2O emissions by 54% across studies (Cayuela et al., 2014, 2015), yet the degree to which biochar mitigates N_2O emissions under field conditions remains uncertain (Verhoeven et al., 2017). Exploring interactions with irrigation regimes may help resolve some of those outstanding discrepancies. Assessing the impact of management practices on N_2O emissions in the field presents numerous challenges due to extensive temporal and spatial variability (Parkin and Venterea, 2010). Soil moisture is a key control on soil redox status, which moderates nitrification and denitrification rates, the two primary sources of N_2O in soils (Baggs and Bateman, 2005; Linn and Doran, 1961), although other N transformation processes may also contribute to N_2O production (Butterbach-Bahl et al., 2013). Deficit irrigation regimes with different soil moisture dynamics may alter biochar's impact on N_2O emissions. Some field studies indicate that soil moisture moderates biochar's ability to reduce N_2O, but more research is needed to understand these impacts (Angst et al., 2014; Saarnio et al., 2013; Scheer et al., 2011).

In addition to N_2O reduction, biochar also reduces GHGs by sequestering C in soils. Biomass pyrolysis generates a condensed aromatic C structure that is more resistant to microbial decomposition, allowing for C sequestration in soils on the century to millennia timescales (Spokas, 2010). When sourced from sustainable feedstocks, biochar has potential to deliver significant GHG benefits up to 12% of global anthropogenic CO_2-eq emission annually (Woolf et al., 2010). Biochar's effects on the priming of native soil organic matter must also be considered when calculating its full impact on GHG emissions, but a recent meta-analysis suggests such effects are minimal (Wang et al., 2016).

Here we assessed both the agronomic and environmental benefits of a beetle-killed pine biochar soil amendment relative to unamended soils under conventional and deficit irrigation management in a maize production system. This study explored three agronomic and environmental benefits biochar may provide across different irrigation regimes: 1) improved soil water retention, 2) reduced mineral N losses, and 3) increased GHG benefits through soil C sequestration and decreased soil N_2O emissions. We hypothesize that in irrigated maize biochar will:

1) Increase soil water retention throughout the growing season, translating to yield benefits under deficit irrigation;
2) Mobilize nutrients in the rooting zone and decrease N leaching through the soil profile leading to improved crop N uptake, with less of an effect in deficit irrigation due to less mineral N leaching;
3) Provide significant GHG benefits by retaining the biochar C added to soils without increasing soil respiration and reducing soil N_2O emissions from N fertilizer application, with less of an effect in deficit irrigation due to intrinsically lower N_2O emissions.

2. Materials and methods

2.1. Site description and experimental design

We tested biochar's impact on soil moisture dynamics, mineral N availability and GHG benefits in a maize system with irrigation manipulation at the Agricultural Research Development and Education Center in northeastern CO (40°39′6″ N; 104°59′57″ W). The site receives 27.3 cm precipitation annually with a mean annual temperature of 8.9 °C (CoAgMet weather station, 1993–2016 annual average, retrieved 2017). The 2016 field season (April to October) recorded a mean temperature of 15.9 °C (ranging from -4.9 to 37.0 °C) and received 14.1 cm precipitation, in addition to the irrigation treatments described below (CoAgMet weather station, retrieved 2017). The soil at the site is a Fort Collins loam (mesic Aridic Haplustalfs; Natural Resources Conservation Service, 2017) with a clay loam texture (34.7% sand, 31.6% silt, 33.7% clay), 1.19 g cm^{-3} bulk density, pH 7.99 (5:1 water:soil, w/w), 1.49% C, and 0.12% N.

The experiment was a randomized block design with four blocks, three irrigation treatments (Full, Limited and Drought irrigation) and two soil amendments (biochar and control), for a total of 24 plots. Experimental plots were 4.5 × 4.5 m, each planted with six rows of Dupont® Pioneer maize hybrid (P9697 A). Irrigation treatments included Full irrigation (irrigation amounts designed to meet crop requirements (50.8 cm)), Limited irrigation (stopping irrigation during the non-essential growth phases V5 to V10 (42.5 cm; Table 1)), and Drought irrigation (half the rate of the Full irrigation treatment (25.4 cm)). Irrigation was applied weekly throughout the irrigation periods specified in Table 1. Such irrigation treatments were applied each year starting with the 2014 growing season, as described in Foster et al. (2016). Within each irrigation treatment, we established two soil amendment treatments: 1) a coarse-sized, slow pyrolysis woody biochar treatment, and 2) a no amendment control.

2.2. Biochar and fertilizer application

The woody biochar was produced using a beetle-killed lodgepole pine feedstock, under slow pyrolysis, reaching temperatures of 550 °C, sieved to the chip size fraction (> 3 mm) by Biochar Now (Berthoud, CO). Biochar treatments were applied in April 2015 at a rate of 25 Mg ha^{-1} to