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Biochar reduced nitrate leaching and improved soil moisture content without yield improvements in a four-year field study

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ABSTRACT

The use of biochar (BC) is discussed as a strategy to sequester carbon in soils, to reduce GHG emissions and improve soil fertility. However, the responses of crop yields to biochar amendments in agricultural ecosystems, specifically under temperate field conditions, are still uncertain. Furthermore, results obtained under field conditions are often differing from laboratory studies. Therefore, the establishment of long-term studies under field conditions is mandatory to provide the base for recommendations. We carried out a two-factorial split-plot field experiment over four years (2012–2015, *still in progress*) to compare the effects of BC on crop yields, mineral nitrogen (NO_3^- and NH_4^+) dynamics, soil moisture and initial soil CO_2 efflux. A temperate sandy soil was amended with BC (0, 15 and 30 Mg ha^{-1}) with the second factor being watering regime (irrigated or rainfed). The soil CO_2 efflux was increased only for a short time following BC amendments. Freshly incorporated BC (30 Mg ha^{-1}) initially induced manganese (Mn) deficiency at the vegetative stage of the first crop maize (*Zea maize* L.). Biochar amendments significantly reduced NO_3^- leaching, as indicated by greater NO_3^- stocks in the topsoil and reduced stocks in the subsoil (0–15, BC amendment zone and 60–90 cm respectively). In BC treatments a higher soil moisture and higher NO_3^- amount was observed, however, this did not translate into higher yields. Rather, grain yields of maize (year I) and summer barley (*Hordeum vulgare* L., year III, no nitrogen (N) fertilization) were significantly reduced (1–11 and 5–26% respectively) due to N deficiency with BC amendment or (non-alleviated) drought stress. A prolonged drought spell in 2015 (year IV) drastically reduced the grain yield of maize (5 and 0.7 Mg ha^{-1}) and N uptake (96 and 11 kg ha^{-1}) in the irrigated and rainfed treatments respectively, without any alleviating effects of biochar amendment. We conclude that application of large amounts of pure, non-nutrient-loaded biochar to temperate sandy soils may provide environmental benefits, such as carbon sequestration and reduction of nitrate leaching, but without an economic incentive for implementing biochar use, at least for the initial few years of application.
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1. Introduction

Global population is continuously increasing and is expected to reach 9 billion by 2050 (Food and Agriculture Organization (FAO), 2011). Therefore, the pressure on natural resources (land and freshwater) will continue to rise because of increasing demands for higher caloric food, feed, fiber and energy (Pfister et al., 2011; Zabel et al., 2014). On the other hand, the total current cropland area which is already intensively used (Wani et al., 2015), and which is likely to decrease will have to provide the food for the growing population (FAO, 2009). This might lead to overexploitation of land resources in terms of monoculture and heavy use of mineral fertilizers (Zuo and Zhang, 2009). Specifically, soil quality degradation and greenhouse gas (GHG) emissions (agriculture contributing 13.5% of global GHG emissions) are likely to increase (FAO, 2011; Lal, 2009, 2010).

Global warming itself may further increase soil aridity/water scarcity problems due to shifts in global precipitation patterns and increase in the frequency of extreme weather events including

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heat waves (IPCC, 2015; Giorgi et al., 2004; Lenderink et al., 2007; Mulcahy et al., 2013; Sheffield and Wood, 2008). Hence, the identification and implementation of adaptation measures aimed to enhance the resilience of agroecosystems to climate change impacts are mandatory.

One potential option is to enhance the productivity of degraded, carbon-poor, arid and sandy soils under changing climate, via an increase of the soil carbon content (Lal, 2004; Smith and Gregory, 2013). Particularly the fertility of sandy soils will benefit from an increase in soil organic carbon (SOC) mainly via the improvement in soil aggregation and water holding capacity (WHC; Mulcahy et al., 2013). In addition, sandy soils can exhibit lower crop productivity due to limited nutrient and water retention capacity. As a consequence, they can show rapid N leaching losses especially via nitrate (Jovanovic et al., 2009; Liu et al., 2012). Therefore, improving the WHC of sandy soils may enhance their water use efficiency and agricultural productivity (Basso et al., 2013; Oki and Kanae, 2006).

In recent years, biochar "the product of heating biomass in the absence of or in limited air to above 250 °C, a process called charring or pyrolysis" (Lehmann and Joseph, 2015) has gained interest in public and private sectors because of its potential benefits as an option to improve degraded land resources (Beesley et al., 2011; Glaser, 2007; Zhang et al., 2016b). It has been claimed that depending on feedstock properties and pyrolysis conditions (Antal and Grønli, 2003; Chan and Xu, 2009) biochar amendments may achieve various sustainability goals in terms of carbon sequestration (Glaser et al., 2002; Lehmann et al., 2006; Lehmann, 2007; Sombroek et al., 2003; Stavi and Lal, 2013), reductions in GHG emissions (Cayuela et al., 2014; Harter et al., 2014; Sohi et al., 2010; Kammann et al., 2012), reduced nutrient leaching (Haider et al., 2016; Kammann et al., 2015; Lehmann et al., 2011; Oram et al., 2014; Ventura et al., 2013; Yuan et al., 2016), enhanced nutrient uptake (Lehmann et al., 2003), improved soil fertility (Glaser et al., 2002; Liu et al., 2014; Sombroek et al., 2003; Spokas et al., 2012; Zhang et al., 2016b), agronomic performance (Biederman and Stanley Harpole, 2013; Liu et al., 2013), energy production and climate change mitigation (Woolf et al., 2010). Biochar possesses the potential to ameliorate soil moisture conditions and hence ecosystem functioning by increasing the amount of plant available water (i.e. the amount stored in a soil between the permanent wilting point and field capacity; Basso et al., 2013; Jeffery et al., 2011; Masiello et al., 2015). Improved WHC is often but not always an indicator for an increase in the plant-available water (Cornelissen et al., 2013; Kammann and Graber, 2015; and citations therein).

A potential benefit of BC in temperate sandy/coarse textured soils could be increased WHC and plant available water (Rogovska et al., 2014). For instance, biochar applied at 96 Mg ha^{-1} in Midwestern Mollisol improved readily plant available water content (i.e. available −10 kpa and −100 kpa) and improved maize grain yield by 11–55% over the control during the first year of application (Rogovska et al., 2014). A 10% yield increase of barley (*Hordeum sativum*) with biochar amendment in a chernozem region under prolonged drought stress was attributed to increased water availability (Karer et al., 2013). Similarly, Basso et al. (2013) found in a soil column study with hardwood biochar a significant increase in soil WHC and predicted that the increased WHC may enhance available water capacity (AWC = available water between field capacity and permanent wilting point) for crops. Tomato seedlings were protected from wilting due to improved soil moisture content with higher (30% v/v) rates of biochar amendments in sandy soil (Mulcahy et al., 2013). Structural properties of biochar can help to retain more water and nutrient concentrations under drought conditions (Major et al., 2010; Novak et al., 2009) in sandy soils. It has been frequently demonstrated that biochar amendments may enhance crop productivity via improving soil water and nutrients availability especially under sandy soil conditions (Jeffery et al., 2011; Tryon, 1948). However, there are some reports where crop yield did not improve after biochar amendments. For instance, a soft wood biochar applied at 5–10 Mg ha^{-1} increased relative moisture contents of amended soil but the increased water availability was not sufficient to cause yield improvements of wheat, turnip and faba bean (Tammeorg et al., 2014).

Thus, the effects of BC amendments on the soil-plant system may vary widely depending on BC or soil properties, crop species and climatic and environmental conditions. For instance, biochar has been found to show its beneficial effects in the presence of balanced fertilization, especially nitrogen, as indicated by a 10% increase in grain yield of barley with 72 Mg ha^{-1} biochar amendment in combination with the standard required nutrients for the crop (Karer et al., 2013). The findings of Asai et al. (2009) further support the idea that biochar amendments without additional fertilization may even decrease crop yields, most probably due to N immobilization (Bruun et al., 2012; Novak et al., 2010; Tammeorg et al., 2014). Haider et al. (2015) found increased maize biomass yield and nitrogen use efficiency with wood chip sieving biochar at addition rates of 1.5 and 3% (w/w). However, the yield increase was rather attributed to soil moisture improvement than increased N availability to plants. In this study a retention of nitrate in biochar-amended soils has been observed (Haider et al., 2015) which was understood only later when studied in more detail (Haider et al., 2016). A substantial increase in quinoa (*Chenopodium quinoa* L.) yield was observed by Kammann et al. (2015) when co-composted biochar was used in a greenhouse pot study; the co-composted biochar was clearly nutrient-loaded and had captured considerable amounts of nitrate. However, it is unclear how field aging of biochar may influence its yield improvement potential, because there was no yield improvement of maize during the second year of biochar addition under drought stress conditions (Rogovska et al., 2014).

Hence, there are varying results of BC amendments in soil-plant systems observed under greenhouse, laboratory or tropical-environment conditions (Jeffery et al., 2011). A recent review of 798 biochar studies until August 2015 revealed that only 26% of all biochar studies were performed under field conditions (Zhang et al., 2016b), and temperate regions particularly lack in biochar field trials (Hammond et al., 2013). Moreover, field studies often showed contrasting findings compared to greenhouse studies (Glaser et al., 2015; Liu et al., 2012). In particular results from long-term field studies are needed to predict effects and likeliness of biochar use on a global scale (Woolf et al., 2010) and to provide insights into the effect of changing soil properties or plant growth processes after biochar amendment (Ernsting and Smolker, 2009; Lehmann et al., 2015).

In this study a four-year field experiment was conducted to quantify the effects of biochar on cereal crop production in a rainfed sandy soil managed according to conventional standard practices. Sandy soils – relying on rainfall for water supply – are about 75% of global cropland area and are usually less fertile but still contributing 58% to global food production (Portmann et al., 2010; Rosegrant et al., 2002). Cereals were used in this study because of their economic importance in global food security. Biochar was applied at increasing rates up to 0, 15 and 30 Mg ha^{-1} following the findings of Vaccari et al. (2011) who found (∼31%) grain yield improvement of wheat either with biochar application of 30 or 60 Mg ha^{-1}. Likewise, Liu et al. (2012) found substantial crop growth improvement in a sandy soil with biochar amendments in East Germany (but using a combination of biochar and compost). Therefore we used BC application rates below or up to 30 Mg ha^{-1} of Vaccari et al. (2011) who did not achieve further

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