



Biochar application does not improve the soil hydrological function of a sandy soil



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ABSTRACT

Biochar application to soil is currently being widely posited as a means to improve soil quality and thereby increase crop yield. Next to beneficial effects on soil nutrient availability and retention, biochar is assumed to improve soil water retention. However, evidence for such an effect in the primary literature remains elusive. Therefore, we studied the effect of biochar on soil hydrological characteristics in two separate field experiments on a sandy soil in The Netherlands. In Experiment I, biochar produced through slow pyrolysis of herbaceous feedstock at two temperatures (400 °C and 600 °C) was applied to soil at a rate of 10 t ha⁻¹. In Experiment II, the 400 °C biochar was applied at rates of 1, 5, 20 and 50 t ha⁻¹. Soils were analysed for soil water retention, aggregate stability and other soil physical parameters after three growing seasons and one growing season for Experiment I and Experiment II, respectively. We characterised the pore structure of the biochar using X-ray computed micro-tomography (XRT) and hydrophobicity using contact angle measurements.

We found no significant effects of biochar application on soil water retention in either experiment. Aggregate stability was also not significantly affected, nor was field saturated hydraulic conductivity. XRT analysis of the biochars showed that they were highly porous, with 48% and 57% porosity for the 400 °C and 600 °C biochar respectively. More than 99% of internal pores of the biochar particles were connected to the surface, suggesting a potential role for biochars in improving soil water retention. However, the biochars were highly hydrophobic. We postulate that this strong hydrophobicity prevented water from infiltrating into the biochar particles, prohibiting an effect on soil water retention. Our results suggest that, in addition to characterising pore space, biochars should be analysed for hydrophobicity when assessing their potential for improving soil physical properties.

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1. Introduction

Biochar application to soil has been widely propagated in recent years because of its supposed ability to sequester carbon (C) (Woelf et al., 2010; Gurwick et al., 2013), while concurrently improving crop yields (Crane-Droesch et al., 2013; Liu et al., 2013; Kauffman et al., 2014). However, negative effects have also been reported including reductions in yields and increased greenhouse gas emissions (Mukherjee and Lal, 2014). Evidently published results can be contradictory and the mechanisms underlying most observed effects remain unclear (Jeffery

et al., 2015). Therefore, elucidation of these mechanisms is needed to make robust predictions and decisions regarding when and where to apply biochar to soil.

A commonly reported effect of biochar application to soil is an improvement in soil water retention (e.g., Sohi et al., 2009; Verheijen et al., 2010; Abel et al., 2013). This was first reported by Glaser et al. (2002) who found that Terra preta soils (i.e., anthropogenic soils in the Amazon basin that are enriched with charcoal) had increased water retention capacity compared to adjacent soils. Gaskin et al. (2007) confirmed that biochar can improve soil water retention, reporting a doubling in the mean volumetric water content of a loamy sandy soil at −2 kPa following the addition of peanut hull biochar applied at a rate of 88 t ha⁻¹. Other studies have corroborated these results for different soils (Asai et al., 2009; Sun and Lu, 2014) and for biochars produced from different feedstocks and under different production conditions (e.g., Karhu et al., 2011; Masulili et al., 2010; Basso et al., 2013). However, Hardie et al. (2014) reported no significant

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effects on soil moisture release characteristics or plant available water following application of a green waste biochar applied to a clay loam soil.

Biochar also affects saturated hydraulic conductivity, although contrasting results have been reported. For example, [Asai et al. \(2009\)](#) found significant increases in saturated hydraulic conductivity following biochar application to a clay loam soil in an upland rice paddy field in Laos. [Hardie et al. \(2014\)](#) reported a significant increase in near saturated hydraulic effects of soil in an apple orchard following biochar application to sandy loam Planosol ([WRB, 2006](#)). However, [Major et al. \(2012\)](#) reported no significant effect on either the water holding capacity or the saturated hydraulic conductivity of a clay soil following the addition (20 t ha^{-1}) of a biochar produced from wood. It is important to note that some of these studies which report positive effects have used biochar application rates which are likely to be far higher than what is possible for large scale field applications, such as 195 t ha^{-1} as reported by [Yu et al. \(2013\)](#).

Despite this growing body of literature, the potential mechanisms behind observed effects remain largely untested. Identification of such mechanisms may aid understanding of the contrasting effects discussed above. One currently hypothesised mechanism for the increase in soil water retention is that water is stored within the pore space of the biochar ([Basso et al., 2013](#)), which is generally highly porous ([van Zwieten et al., 2009](#)). Alternatively, [Masulili et al. \(2010\)](#) and [Sun and Lu \(2014\)](#) attributed their observed increase in soil water retention after biochar application to increased aggregate stability. However, aggregate stability was not measured in either study.

Characterising the pore structure of biochar is problematic; pore sizes can span five orders of magnitude, ranging from sub-nanometre to tens of micrometres ([Brewer et al., 2014](#)). There is currently no single method to quantify and characterise the pore structure of biochar particles across such a large range of scales. Mercury infiltration is seen as the benchmark technique for pore size characterisation ([Brewer et al., 2014](#)). However, this technique is unable to distinguish between the intra- and inter-pore space and is therefore prone to error for granular samples such as powdered or ground biochar. Furthermore, results can be affected by the surface chemistry of biochar particles ([Giesche, 2006](#)). Gas sorption methods combined with Brunauer–Emmett–Teller (BET) analysis ([Brunauer et al., 1938](#)) have also been applied to characterise biochar porosity. However, such techniques are usually applied to milled samples to reduce inherent heterogeneity. Therefore, they only allow characterisation of micropores (i.e., those in the nm range), which are of little relevance to plant water uptake ([Hughes and Mason, 2001](#)). X-ray computed tomography (XRT) provides a non-destructive means of quantifying and characterising the pore space of biochar particles in the ~ 1 to $100 \mu\text{m}$ range. As such, this technique allows investigation of the pore space at hydrologically relevant scales in terms of water being plant available. Furthermore, it does not require pre-analytical steps such as milling. It, therefore, addresses the need for a quantitative technique to characterise large ($>0.1 \mu\text{m}$) pores within intact (i.e., non-milled) biochar particles as stated by [Kinney et al. \(2012\)](#).

Despite its generally high porosity, biochar does not always affect soil moisture characteristics (e.g., [Major et al., 2012](#); [Hardie et al., 2014](#)). Recent work by [Gray et al. \(2014\)](#) has suggested that the hydrophobicity of biochars may impede uptake of water into the pore space of biochars regardless of pore size and structure. Further, they reported that production temperature of the biochars is positively correlated with water uptake. They attributed this to a negative relationship between biochar production temperature and hydrophobic compounds remaining on the surface of the biochars. However, the magnitude of this effect was feedstock dependent.

To determine whether biochar affects soil water retention and elucidate the mechanisms behind any effects, we examined the impacts of application of a biochar produced from herbaceous feedstock on the hydrology of a dry sandy soil in a semi-natural grassland in The Netherlands. [Atkinson et al. \(2010\)](#) predicted that positive effects should occur following biochar application to sandy soil due to slower

draining and hence increased plant available water. To test this we conducted two field experiments: an ongoing field experiment in which the effects of biochars produced at two different pyrolysis temperatures are tested ([Van de Voorde et al., 2014](#)), and a field experiment in which different biochar application rates were tested. The field measurements were combined with lab analyses of biochar pore space characterisation (via computed X-ray tomography) and hydrophobicity (via contact angle measurements).

2. Materials and methods

2.1. Experimental field site

Two field experiments were performed for this study. Both were set up in a nature restoration grassland of 180 ha near Ede, The Netherlands ($+52^{\circ}3'34.03''$, $+5^{\circ}45'2.81''$). Experiment I was set up in October 2010. Full details of the experimental set-up can be found in [Van de Voorde et al. \(2014\)](#). In short, the experimental site is located on an ice pushed ridge formed during the Saalien Ice Age. The soil is characterised as a “holtpodzol” on coarse sand (gY30; [Stiboka, 1975](#): map 40 W). The area was used as arable field until 1995 and had last been used to grow maize in 1995. Previous to that cropping had included cycles of sugar beet, potatoes and oats ([van der Putten et al., 2000](#)). Mean annual temperature is 9.4°C and average rainfall was 0.84 m year^{-1} . The area is surrounded by forest and, after cessation of agriculture, has been managed as natural grassland. Since that time it has been grazed by free roaming cattle and horses. The experimental area was fenced in 2010. Key soil characteristics can be found in [Table 1](#). The experiment consists of six replicates of four treatments in a randomised block design, with the blocks running perpendicular to a slight slope ($\sim 1^{\circ}$). Individual plots measure $4 \times 4 \text{ m}$ with a 1 m buffer in between. The treatments consisted of two biochars (produced at 400°C and 600°C ; hereafter Biochar 400 and Biochar 600 respectively), both from the same feedstock of herbaceous plant cuttings; a control with no amendment and a positive control to which the unpyrolysed feedstock was applied (hereafter “Hay”). Both types of biochar and the unpyrolysed feedstock were applied at a rate equivalent to 10 t ha^{-1} , and incorporated into the top $\sim 10 \text{ cm}$ of the soil with a rotovator. This is in line with application rates often reported in the literature (e.g., [Liu et al., 2013](#)). The non-amended control was also rotovated. All plots were then seeded with a seed mixture of 18 species that are commonly found in northern European grasslands ([Table S1](#)).

Experiment II was set up in April 2013 alongside the first experiment. This experiment consisted of different application rates of the 400°C biochar used in Experiment I: 1, 5, 20 and 50 t ha^{-1} . This is in line with the “maximum sustainable technical potential” biochar application rate, as defined by [Woolf et al. \(2010\)](#). A control with no addition, as well as a positive control containing unpyrolysed feedstock (hay) applied at a rate equivalent to 20 t ha^{-1} were also included. Each treatment was replicated four times in plots $1 \text{ m} \times 1 \text{ m}$ with a 1 m buffer in between. Plots were set up following a randomised block design

Table 1
Selected soil characteristics of the semi-natural grassland soil used in both experiments.

Soil characteristics	
Sand (%)	89.6
Silt (%)	6.8
Clay (%)	3.6
pH	5.2
Soil organic carbon (%)	2.7
N-NH ₄ (mg N kg ⁻¹)	2.5
N-NO ₃ + NO ₂ (mg N kg ⁻¹)	20.0
N-DON ¹ (mg N kg ⁻¹)	4.0
P-PO ₄ (mg P kg ⁻¹)	3.2
K ⁺ (mg K kg ⁻¹)	29.1
EC (dS m ⁻¹)	0.08

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