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Effects of gasification biochar on plant-available water capacity and plant growth in two contrasting soil types

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ABSTRACT

Gasification biochar (GB) contains recalcitrant carbon that can contribute to soil carbon sequestration and soil quality improvement. However, the impact of GB on plant-available water capacity (AWC) and plant growth in diverse soil types still needs to be explored.

A pot experiment with spring barley (*Hordeum vulgare* L.) was conducted to investigate the effect of soil amendment by 1% straw and wood gasification biochar (SGB and WGB), respectively, on AWC and plant growth responses under two levels of water supply in a temperate sandy loam and a coarse sandy subsoil. In the sandy loam, the reduced water regime significantly affected plant growth and water consumption, whereas the effect was less pronounced in the coarse sand. Irrespective of the soil type, both GBs increased AWC by 17–42%, with the highest absolute effect in the coarse sand. The addition of SGB to coarse sand led to a substantial increase in plant biomass under both water regimes: shoot growth by 40–165% and root growth by 50–57%. However, no positive effects were achieved by the addition of WGB. In the sandy loam, soil application of GB had no or negative effects on plant growth.

Our results suggest that SGB has considerable potential for enhancing crop productivity in coarse sandy soils by increasing soil water retention and improving root development.

1. Introduction

An improvement in soil quality and an increase in soil organic matter reduce the exposure and vulnerability of crops to extreme events such as drought (Altieri et al., 2015). The annual soil application of agriculture residues is one of the management tools available for increasing soil organic matter content (Reeves, 1997). However, at the same time the demand for biomass for bioenergy production is growing, putting even more pressure on plant production and the utilization of agriculture and forestry residues (Powlson et al., 2011). Thermal gasification of these residues not only produces sustainable bioenergy (Ahrenfeldt et al., 2013), but also a by-product, gasification biochar (GB), a potentially valuable soil amendment (Müller-Stöver et al., 2012). Depending on the feedstock and specific thermal technology used, GB may contain up to 60% carbon, which has been shown to be stable toward microbial degradation after soil application and may stay in the soil carbon pool for decades (Hansen et al., 2015). Soil application of GB has the potential to increase the soil organic carbon content, thereby having a beneficial impact on climate change mitigation and soil quality (Sohi et al., 2010).

However, very little research has been undertaken so far on the effect of GB soil amendment on physical soil properties and plant growth. The majority of studies available have been conducted with pyrolysis biochar, the main product of a pyrolysis process conducted under low-oxygen conditions at temperatures of between 400 and 750 °C (Kammann et al., 2011; Baronti et al., 2014; Abel et al., 2013). Pyrolysis biochar typically contains 50–80% carbon, often including a labile carbon fraction that can stimulate microbial activity influencing initial mineralization processes (Bruun et al., 2011). On the other hand, GB is produced at higher temperatures (700–1200 °C), resulting in a by-product with a lower C content (20–60%) but higher stability toward microbial

Abbreviations: GB, gasification biochar; SGB, straw gasification biochar; WGB, wood gasification biochar; AWC, plant-available water capacity; WHC, water holding capacity.

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degradation (Müller-Stöver et al., 2012; Bruun et al., 2014; Hansen et al., 2015).

Biochar has a significant adsorbing ability due to its high specific surface area, and its internal porosity may contribute to increasing the water holding capacity (WHC) (Uzoma et al., 2011; Kammann et al., 2011; Bruun et al., 2014) and plant-available water capacity of soil (AWC) (Abel et al., 2013). Especially coarse sandy soils have poor water and nutrient retention, resulting in a risk of drought in dry periods and nutrient losses in wet periods. Hence, large proportions of hydrophilic micropores (0.2–30 μm) in biochar, potentially retaining plant-available water, may have the ability to improve AWC in coarse sandy soils (Hardie et al., 2014). Furthermore, decrease in soil bulk density is often reported after biochar application (Rogovska et al., 2014) along with an increase in total porosity (Abel et al., 2013), which may improve the soil structure, resulting in better water retention (Sun and Lu, 2014) and improved root growth (Bruun et al., 2014). Thus, improvement of AWC in biochar-amended soil is apparently not straightforward, but rather a combination of several factors such as soil type, biochar amendment rate and biochar properties (Barnes et al., 2014). In a vineyard field experiment, Baronti et al. (2014) reported that biochar application increased the available water content and leaf water potential during dry periods. In contrast, Jeffery et al. (2015) found that biochar had no effect on soil water retention, which they attribute to the hydrophobicity of the biochar used. Similarly, Hardie et al. (2014) found that acacia biochar had no effect on plant-available water capacity in a sandy loam soil, partly due to the high natural variation in soil physical properties. Biochar amendment has also shown the ability to increase plant root and shoot growth and drought tolerance without increasing soil water availability, improving plant ecophysiological responses related to water status such as leaf osmotic potential, stomata resistance and water use efficiency (Kammann et al., 2011; Haider et al., 2014).

An improvement in soil structure may be especially beneficial in coarse sandy soils showing high mechanical resistance to root growth due to low compressibility and high friction (Bruun et al., 2014). Rooting depths of only 50–70 cm are reported in soils with coarse sandy subsoil, while in loamy soils located under the same climatic growing conditions roots may reach depths of >140 cm (Madsen, 1985). Consequently, the yield potentials of crops can generally not be fully exploited in coarse sandy soils. However, the particle size and pore structure of the specific biochar material may play a significant role when aiming for soil structure improvement (Abel et al., 2013; Sun and Lu, 2014).

Further information about the effects of specific GBs on the properties of different soil types as well as on plant growth under drought stress is required to learn more about how to optimize the use of a limited amount of GB material to improve soil quality and increase crop yields. The overall aim of this study was therefore to evaluate the effects of two contrasting GB materials on the capacity of plant-available water (AWC) and plant growth responses (shoot and root biomass, leaf water potential, stomatal conductance and carbon isotope discrimination) of spring barley (*Hordeum vulgare* L.) grown in two different soil types under sufficient and reduced water supply.

2. Materials and methods

2.1. Biochar

Two biochar materials were used in this study: wood gasification biochar (WGB) and straw gasification biochar (SGB). SGB was produced in a Low Temperature Circulating Fluidized Bed gasifier (LT-CFB) at 750 °C using winter wheat (*Triticum aestivum* L.) as a feedstock. WGB was produced in a TwoStage gasifier at 1200 °C from pine wood (*Pinus* spp.) (Ahrenfeldt et al., 2013). A number of physicochemical characteristics were determined for the GB produced and are shown in Tables 1 and 2. The total content of organic C was measured on an elemental analyzer (FLASH 2000 Organic Elemental Analyzer, Thermo Scientific, Cambridge UK). The elemental composition was determined by ICP-OES after acid digestion (ISO 11885). The specific surface area was determined by the Brunauer–Emmett–Teller (BET) method by nitrogen gas sorption at 77 K (Quantachrome instruments, Boynton Beach, USA). The pH of the biochar was measured in a 1:5 (w/v) biochar/Milli-Q water suspension by using a pH meter (Mettler-Toledo AG, Switzerland). More details about the production processes, analytical methods and further characteristics of both SGB and WGB can be found in Hansen et al. (2015).

Table 1
Chemical characterization and particle size distribution of the SGB (straw gasification biochar) and WGB (wood gasification biochar) materials (modified from Hansen et al., 2015).

Parameter	Unit	SGB	WGB
C	$g\,kg^{-1}$	468	653
P	$g\,kg^{-1}$	4	3.4
K	$g\,kg^{-1}$	72	25
S	$g\,kg^{-1}$	1.2	0.17
Mg	$g\,kg^{-1}$	4.6	5.9
Ca	$g\,kg^{-1}$	18	52
Fe	$g\,kg^{-1}$	1.7	16
Zn	$mg\,kg^{-1}$	64	160
Cu	$mg\,kg^{-1}$	13	55
pH (water)		11.6	11.1
Particle size distribution	% of dry mass		
<0.045	mm	89.3	33
0.045–0.125	mm	10.3	13.7
>0.125	mm	0.3	53.3

2.2. Soils

The soils used in this study were sandy loam and sandy soils (USDA textural classification). The sandy loam soil was collected from the Ap horizon (0–25 cm) of a conventional agricultural field on the Bregentved Estate in Zealand, Denmark (55°22′N, 12°05′E). The sandy soil was collected on the Jyndevad Research Station of Aarhus University, Denmark (54°53′N, 9°07′E) from the B horizon (25–100 cm depth) and is further termed coarse sandy soil. Both soils were air-dried and sieved to obtain a fraction ≤ 2 mm. The soil properties are shown in Table 3.

2.3. Experiment setup

The experiment was conducted in the Risø Environmental Risk Assessment Facility (RERAF) phytotron at the Technical University of Denmark, Roskilde campus, Denmark. The experiment involved 12 treatments with four replicates: two soil types, three GB amendments (control without GB, 1% WGB and 1% SGB respectively) and two water regimes (70% and 30% of the water-holding capacity (WHC) of the control treatment respectively). It was decided to base the water supply on the WHC of the control treatment to avoid effects simply caused by a higher water supply

Table 2
Brunauer–Emmett–Teller (BET) specific surface area (SSA) and pore volume of straw gasification biochar (SGB) and wood gasification biochar (WGB). WGB was divided into two size fractions (modified from Hansen et al., 2015).

Biochar	Particle size (mm)	SSA ($m^2\,g^{-1}$)	Pore volume ($cm^3\,g^{-1}$)
SGB	0–1	75	0.04
WGB	0–0.5	426	0.52
WGB	0.5–1	1027	0.58