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Short-term effects of biochar on soil properties and wheat yield formation with meat bone meal and inorganic fertiliser on a boreal loamy sand

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ABSTRACT

Poor water retention capacity (WRC) and nutrient deficiency commonly limit crop yields in sandy soils. The use of biochar as a soil amendment has been previously reported to improve these limiting factors in subtropical and temperate soils. We studied the effects of biochar on soil properties and yield formation of spring wheat (*Triticum aestivum* L.) when applied together with inorganic fertiliser or meat bone meal (MBM) to an Endogleyic Umbrisol with a loamy sand texture in boreal conditions. In a two-year field experiment, biochar was applied at 0, 5, 10, 20 and 30 t ha^{-1} combined with three fertiliser treatments (unfertilised control, MBM and inorganic fertiliser) providing equal amounts of nitrogen (N), phosphorus (P) and potassium (K). Soil WRC and fertility as well as wheat yield, yield components and quality were analysed. Soil moisture content, leaf area index and leaf chlorophyll values (SPAD) were monitored during the experiment. Biochar increased the plant-available water content of the topsoil in the first year and reduced the bulk density in the second year after application. It also increased the contents of easily soluble K and soil organic C (SOC) in the 20 cm of topsoil, but had no effects on other soil nutrients, pH or moisture content. Biochar amendment decreased the soil NO_3^--N content below control values in the first year but increased it significantly in the second year. The addition of biochar did not significantly affect the nitrogen uptake, grain yield or quality of wheat, possibly because of its low nutrient availability and the high organic matter content of the soil.

1. Introduction

The combination of biomass pyrolysis and use of the resulting biochar as a soil amendment simultaneously provides bioenergy, carbon (C) sequestration and soil conditioning (Lehmann et al., 2008; Verheijen et al., 2009; Woolf et al., 2010). The long-term C sequestration potential of such biochar practices relies on the recalcitrance of the biochar-C to microbial decomposition (Lehmann et al., 2008; Singh et al., 2012). The improvement of soil fertility is considered a further benefit of biochar application to acid or nutrient-deficient (sub-) tropical soils (Steiner et al., 2008; Major et al., 2010; Vaccari et al., 2011; Zhang et al., 2012). In addition to the liming effect of certain biochars (Major et al., 2010; Van Zwieten et al., 2010; Vaccari et al., 2011), the enhancement of soil fertility has been attributed to increased cation exchange capacity (Liang et al., 2006), fertilisation by nutrients contained in the biochar (Major et al., 2010; Quilliam et al., 2012; Xu et al., 2013) and enhanced arbuscular mycorrhizal (AM) colonisation leading to increased nutrient availability (Blackwell et al., 2010; Solaiman et al., 2010). Furthermore, the improved water retention capacity (WRC) of the soil (Eastman, 2011; Liu et al., 2012) may explain some of the previously reported increases in the activity of soil biota (Chan et al., 2008; Lehmann et al., 2011), enhanced nutrient use efficiency (Chan et al., 2007; Steiner et al., 2008) and crop yields (Major et al., 2010; Vaccari et al., 2011; Zhang et al., 2012) on subtropical soils.

The effects of biochar on soil and plant properties vary widely, depending on the characteristics of both the underlying soil and the biochar. This is demonstrated by the lack of significant changes

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in crop yields 1–4 years after biochar application to fertile mineral soils in temperate (Güereña et al., 2012; Jones et al., 2012) and boreal climates (Karhu et al., 2011; Tammeorg et al., 2014a), in spite of improvements in nutrient and water status of the soils. The challenges in scaling up the now rather sporadic use of biochar as a soil amendment relate largely to the uncertainties concerning its long-term effects on soil quality, as it cannot practically be removed from soil after application (Jones et al., 2012). The possible negative effects of biochar soil addition include short-term reductions in mineral nitrogen (N) availability in soils (Novak et al., 2010; Bruun et al., 2012; Tammeorg et al., 2012), decreased performance of crops on calcareous soils (Kishimoto and Sugiura, 1985; Van Zwieten et al., 2010), increased loss of native soil C (Wardle et al., 2008; Zimmerman et al., 2011), and decreased availability of soil-applied herbicides (Graber et al., 2012). Furthermore, little is known about the biochar-mediated changes on soil and plant properties in boreal soils affected by freeze-thaw cycles (Karhu et al., 2011), and considering the high availability of different biochar raw materials in northern countries (e.g., forestry residues), there is an urgent need for scientific evidence on both the positive and negative long-term effects of biochar on the soil-plant-atmosphere system in this region.

A few studies have been published on the interactive effects of biochar and organic fertilisers applied together (Lehmann et al., 2003; Steiner et al., 2007, 2008; Schulz and Glaser, 2012; Tammeorg et al., 2012). The importance of nutrient recycling through amplified use of organic fertilisers is increasingly acknowledged (Roy et al., 2002; Römer, 2009; Fischer and Glaser, 2012) as the inputs for inorganic fertiliser production (e.g., phosphorus (P) rocks) become depleted (Cordell et al., 2009) and the prices of inorganic fertilisers increase (Silva, 2011; USDA, 2013). The interactive mechanisms between biochar and organic fertilisers have been associated with increased contents of SOC and black carbon that could enhance the nutrient retention capacity of the soil (via increased cation exchange capacity and forming of organo-mineral complexes; Glaser et al., 2002) and improve the sorption capacity of phytotoxic substances (Hille and Den Ouden, 2005; Schulz and Glaser, 2012). A greater increase in biomass of oat (*Avena sativa* L.) was reported from a biochar-compost mixture than from pure compost addition under tropical conditions (Schulz and Glaser, 2012). In boreal conditions, the effects of soil-applied biochar on N mineralisation dynamics depended greatly on the C:N ratios of the organic fertilisers (Tammeorg et al., 2012). Understanding the effects of using biochar together with organic fertilisers is particularly important when biochar is used as a soil amendment in organic farming systems.

One of the organic fertilisers at present increasingly used in Europe is a co-product of the meat processing industry, meat bone meal (MBM), which has a low C:N ratio (about 4.5) facilitating faster N mineralisation than many other organic fertilisers (Salomonsson et al., 1994; Tammeorg et al., 2012). Similarly to biochar, it has been associated with enhanced activity of soil microbes (Mondini et al., 2008), increments in the N and P use efficiencies of crops (Ylivainio et al., 2008; Jeng and Vagstadt, 2009) and improved crop yields (Jeng et al., 2004, 2006; Chen et al., 2011). Thus, if MBM is applied together with biochar, it is possible that certain interactive mechanisms leading to agronomic benefits may follow.

It has been suggested that the effects of biochar in temperate soils would be most evident in coarse-textured soils by mediation of their nutrient deficiency and poor WRC (Atkinson et al., 2010; Liu et al., 2012). In our previous laboratory study (Tammeorg et al., 2012), the application of biochar together with MBM to a loamy sand in boreal conditions facilitated initial N immobilisation in a dose-dependent manner. To gain further insights into the mechanisms of the effects of biochar in combination with organic and inorganic fertiliser treatments on the physicochemical properties of soil and crop performance on a field scale, a field experiment with five biochar application rates was started on the same nutrient-deficient, coarse-textured soil as used in the laboratory study. The specific aims of this study were to determine the short-term effects of different biochar application rates on (i) the physicochemical properties of soil; (ii) the growth dynamics, N uptake (NU), yield and quality of spring wheat (*Triticum aestivum* L. emend Thell.), as well as (iii) to evaluate whether the effects of biochar application on wheat growth and soil properties depend on the type of the fertiliser.

2. Materials and methods

2.1. Experimental site and soil

The field experiment was conducted over two consecutive growing seasons (2011 and 2012) at the Viikki Experimental Farm, University of Helsinki, Finland (60°13′42″ N 25°2′34″ E). For the preceding six years, the field was cropped with spring wheat and barley (*Hordeum vulgare* L.) with conventional mouldboard ploughing to 20–25 cm depth and inorganic fertiliser application. The soil was classified as an Endogleyic Umbrisol (WRB, 2007) with a loamy sand texture with 83% sand, 15% silt and 2% clay (Soil Survey Division Staff, 1993) at 0–30 cm depth. The original content of soil organic matter (SOM) was 63.4 g kg^{-1}, assuming a 50% C content for the SOM (Pribyl, 2010). Before the start of the experiment, the soil had a sufficient level of easily soluble P (21 g m^{-3} soil, extraction with 0.5 M ammonium acetate, pH 4.65), whereas the levels of easily soluble Ca, K, Mg and S were deficient according to the Finnish classification of arable soils (Viljavuuspalvelu Oy, 2008).

The growing season of 2011 was notably warmer than the 30-year average in Helsinki, especially in July and August (Table 1). The temperatures in 2012 were close to the long-term mean. August 2011 and May, June and September 2012 were much wetter than the long-term means.

2.2. Biochar

The biochar was obtained by pyrolising chips of debarked spruce (*Picea abies* (L.) H. Karst.) in a continuously pressurised carboniser (Preseco Oy, Finland) at 550–600 °C. Air-dried chips were fed into the reactor tube via an airtight system and subsequently moved by a screw conveyor through the hot region of the reactor tube in 10–15 min. The biochar was cooled overnight in an airtight silo and then ground in a roller mill. Before application to the soil, the biochar was wetted to 25% (w/w) to moderate dust problems. The biochar had a pH$_{H_2O}$ of 8.1, a specific surface area of 265 m^2 g^{-1} and contained 122 g kg^{-1} of volatile matter (VM) and 27 g kg^{-1} of ash. It comprised 883 g total C kg^{-1}, 4.66 g Ca kg^{-1}, 4.52 g K kg^{-1} and 3.5 g N kg^{-1}. Additional details about the physicochemical properties of the biochar are presented in Tammeorg et al. (2014b).

Table 1
Mean air temperature (°C) and precipitation (mm) in Helsinki for growing seasons 2011–2012 and the long-term (1971–2000) averages at Helsinki Kaisaniemi (FMI, 2012, 2013).

Month	Mean temperature (°C)				Precipitation (mm)		
	1971–2000	2011	2012		1971–2000	2011	2012
May	9.9	9.9	10.9		32	27	65
June	14.8	16.7	13.7		49	49	88
July	17.2	20.6	17.7		62	56	54
August	15.8	17.5	16.0		78	173	39
September	10.9	13.6	12.5		66	88	160
Mean	13.7	15.7	14.2	Sum	287	393	406