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Long-term effects of biochar on soil physical properties

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ABSTRACT

A growing body of research into the effects of biochar on soil physical characteristics suggests that it is most effective in coarse-textured soils. In this study, we set out to test this theory by comparing the effects of a woodchip biochar on a Chernozem, Cambisol and a coarse-textured Planosol in a pot experiment. We also compared the effect of different biochars on the Planosol, including woodchip biochar, straw biochar, and two vineyard-pruning biochars produced at different pyrolysis temperatures. Three characteristics were measured as indicators of good soil structure: bulk density, soil aggregate stability and plant available water.

The woodchip biochar induced greater decreases in bulk density in the coarse textured Planosol than in the other soils. It also had a greater effect on soil aggregate stability in the Planosol than in the Cambisol, but had no effect on the Chernozem. Woodchip biochar had no effect on plant available water in any of the three soils. Straw biochar was the most effective at improving soil aggregate stability in the coarse-textured Planosol, with a 98% increase. Straw biochar also improved plant available water in the Planosol by 38% relative to the control, compared with 24% and 21% increases in the vineyard-pruning biochars, produced at 525 °C and 400 °C, respectively.

Our study supports the theory that coarse-textured soils have the most to gain structurally from biochar amendments. We also show that straw biochar was the most effective at improving soil aggregate stability and plant available water in a coarse-textured Planosol.

1. Introduction

Meeting increasing global demand for food in the context of constrained resources and changing climate means that our agricultural systems must be both more productive and resilient (FAO, 2004). Innovative tools are required to help deal with these complex challenges, which has fuelled interest in biochar as a potential soil amendment to improve soil quality and crop productivity (Lehmann et al., 2006). Biochar is a porous, carbon-rich material produced by heating organic matter to temperatures of between 300 °C and 1000 °C in an environment with limited or no oxygen (Verheijen et al., 2010). Research into biochar as a soil amendment has been wide-ranging and results have been mixed due to the complexity of interactions between biochar, soils and crops (Lychuk et al., 2014). Meta-analysis of the effects of biochar suggests that it is most effective in acidic, degraded and coarse-textured soils (Jeffery et al., 2011; Crane-Droesch et al., 2013). The benefits are suspected to be derived from a liming effect, increases in cation exchange capacity, sorption of organic matter, and changes in soil structure (Liu et al., 2012).

Research into the effects of biochar on soil physical characteristics can be divided into two main concepts. The first is that by adding a porous substance to soil, it will inevitably have a direct effect on soil physical properties (de Melo Carvalho et al., 2014; Peake et al., 2014). Underpinning this theory are cases where total porosity, water-holding capacity or bulk density of biochar-amended soils have improved (Basso et al., 2013; Kammann et al., 2011).

For example, Devereux et al. (2012) found that biochar added at a rate of 5% (w/w) decreased average pore size in the soil from 0.07 mm^2 to 0.046 mm^2. In their short run experiment, they also observed improvements in bulk density, as did Githinji (2014) and Mukherjee et al. (2014).

Ulyett et al. (2014) attribute their observed reductions in bulk density to the lower density of biochar added to two coarse-textured soils. Quin et al. (2014) and Castellini et al. (2015) also suggest that this direct effect on soil bulk density explained observed increases in soil water retention close to saturation.

Hardie et al. (2014) tested this direct effect theory in a 30-month-long field experiment. They expected that biochar would increase plant available water in the soil through the addition of pores with a diameter of between 30 μm and 0.2 μm. However, they could not attribute

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any observed changes in the soil to the internal porous structure of the biochar. In their case, improvements in near-saturated hydraulic conductivity and soil water content at −0.1 kPa were attributed to increased earthworm activity.

This leads us to the second concept, which is that the addition of biochar can support soil structure building processes via indirect means. These processes may include: providing improved habitat for soil microorganisms (Pietikainen et al., 2000; van Zwieten et al., 2009), through favourable association with soil organic matter and improved aggregation (Lehmann et al., 2011; Fletcher et al., 2014), or by improving plant growth thereby enhancing rhizosphere effects (Joseph et al., 2010). An increase in soil aggregate stability was reported by Herath et al. (2013) and Lu et al. (2014) when analysing different biochars added to different soils. The authors attributed these effects to biochar-carbon combining with clay mineral phases to form macro-aggregates. This is to say that although the catalyst for these processes may come from a direct effect such as a change in bulk density, the processes that follow may be of more importance in the long-term.

The inherent complexity of biochar, which can change dramatically depending on feedstock and pyrolysis parameters (Verheijen et al., 2010; Demirbas, 2004), makes it difficult to isolate interactions with dynamic soil processes. However, this complexity also lends support to both concepts being relevant, perhaps at different points throughout an experiment or field trial.

For example, a short-run pot experiment may be useful for determining the initial direct effects, such as changes in water holding capacity (Novak et al., 2009). However, changes induced by cropping, consolidation, biochar hydrophobicity, weathering of biochar particles, and washout of ash and soluble elements are unlikely to be captured in this type of study. Conversely, long-term field trials are much more likely to yield results that represent these indirect effects over time. A general disadvantage is that they are usually adversely impacted by environmental variability (Liu et al., 2013).

In order to limit some of these methodological issues for this study, we chose to take samples from an old biochar pot experiment that had involved several cropping cycles (Kloss et al., 2014) and then been left to fallow outside over two years. As the soil/biochar mixtures had a chance to equilibrate, it is hoped that the measurements are more representative of the long-term effects of biochar, and that the issues of disturbance should be minimised. The exposure to the outside environment and vegetative effects means that some of the factors included in field trials are also captured without the variability. Using this resource meant we were able to take advantage of existing data to deepen our analysis and include temporal factors.

Our study had two main objectives. The first was to test the idea that biochar has the most positive effect on the physical properties of sandy acidic soils. We did this by comparing the effect of a typical woodchip biochar on three very different agricultural soils. Our second objective was to test whether there are characteristics of different types of biochars that make them more effective amendments in coarse-textured soils. We chose three indicators of good soil structure for our two comparisons: bulk density, soil aggregate stability and plant available water.

2. Materials and methods

2.1. Soils and biochars

Three agricultural soils were used for the study from a prior project (see Kloss et al., 2014); a Planosol (N48°46′32.9″, E15°14′28.6″), a Chernozem (N48°19′52.6″, E15°44′20.5″) and a Cambisol (N47° 13′46.0″, E15°50′40.6″) (see Table 1). The soils were originally taken from the top 30 cm of each profile, air-dried and homogenised. Large aggregates were broken down and rocks >3 cm were excluded.

Four biochars were selected from three feedstocks including mixed woodchips (pyrolysis temp. 525 °C), wheat straw (*Triticum aestivum* L., pyrolysis temp. 525 °C) and vineyard-prunings (*Vitis vinifera* L., pyrolysis temp. 525 °C and 400 °C) (see Table 2). Basic measurements such as pH (in $CaCl_2$), cation exchange capacity, electrical conductivity (ratio 1:10) and water-soluble cations (ratio 1:20) were taken as per standard methodologies (see Kloss et al., 2012). Biochar was mixed with soils at a rate of 3% by weight, and soil-biochar mixtures were filled into 17 litre pots (diameter: 23.5 cm, height: 40 cm) at a defined bulk density. The pots were planted with three consecutive crops — mustard (*Sinapis alba* L.), barley (*Hordeum vulgare* L. cv. Xanadu) and red clover (*Trifolium pratense* L.) — between November 2010 and December 2011, and fertilised according to common agricultural practice (see Kloss et al., 2014). The experiment was run in a glasshouse for this period and pots were then left to fallow outside for two years.

2.2. Soil physical characteristics

In November 2013, the clover was removed from the pots and both disturbed soil samples and undisturbed 200 cm^3 cores were taken at a depth of 15 cm. Three main parameters were chosen as indicators for changes in soil physical characteristics: bulk density, soil aggregate stability and plant available water.

Plant available water was measured using the pressure chamber method (according to Richards, 1948). Four undisturbed cores from each treatment type were saturated, weighed, and pressure applied at 6 kPa, 30 kPa and 1.5 MPa. Samples were weighed between each pressure step and then oven dried at 105 °C for 24 h. Gravimetric water content was determined as the difference between the dried and wet weights at each pressure step and converted to volumetric water content. Plant available water was taken as the water held between 6 kPa and 1.5 MPa.

Soil aggregate stability was determined using a wet sieving device (according to Murer et al., 1993). Fine earth (<2 mm) was air-dried for seven days and sieved to collect aggregates of between 1 mm and 2 mm in diameter. Four grams of aggregates were weighed and placed on a 0.25 mm sieve which was mechanically raised and lowered (42 cycles/min) for 5 min in distilled water. Weakly aggregated material fell through the sieve, leaving the stable aggregates, sand, organic particles and biochar. These materials were then oven-dried at 105 °C for 24 h and weighed. Samples were then immersed in 0,1 mol $Na_4P_2O_7 \cdot H_2O$ for 5 min to breakdown the stable aggregates and sieved again, leaving only the sand, organic particles and biochar. Samples were then dried at

Table 1
Basic soil characteristics, measurements and analyses undertaken by Kloss et al. (2014).

Soil type	pH ($CaCl_2$)	CEC (mmolc kg^{-1})	Carbonate (w.-%)	OC (w.-%)	clay (w.-%)	silt (w.-%)	sand (w.-%)	Texture class
Planosol	5.4 ± 0.0a	75.1 ± 0.0a	0.0 ± 0.0a	1.64 ± 0.02b	10.7	19.6	69.8	Sandy loam
Chernozem	7.4 ± 0.1c	208.6 ± 2.3b	15.8 ± 0.1b	1.50 ± 0.01a	16.9	61.4	21.6	Silt loam
Cambisol	6.6 ± 0.1b	209.4 ± 1.2b	0.0 ± 0.0a	2.36 ± 0.02c	32.7	37.6	29.7	Clay loam

Different letters indicate significant difference within one column (P < 5%; Tukey's test). ± corresponds to standard error. CEC: cation-exchange capacity; OC: organic carbon.