Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data

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A B S T R A C T
The use of biochar as a soil amendment had been increasingly advocated for its effects on carbon sequestration and greenhouse gas emission mitigation as well as on improvement of soil fertility. However, lack of a general assessment of biochar effects on soil physical properties made it difficult for the recommendations for its practical use for soil quality improvement in global agriculture. In this study, we performed a meta-analysis of literature data published by October 2015 and quantified biochar effects on selected soil physical properties. The literature data covered a range of feedstocks, pyrolysis temperature, soil and experimental conditions. Results showed that biochar amendment significantly improved all the soil physical properties tested. On average, soil bulk density was significantly reduced by 7.6% whereas soil porosity significantly increased by 8.4%, aggregate stability by 8.2%, available water holding capacity (AWC) by 15.1% and saturated hydraulic conductivity by 25.2%. Furthermore, the changes in soil bulk density were negatively correlated to porosity and AWC. In addition, these effects were greater in coarse textured soils than in fine textured soils. While the size of biochar effect on soil physical properties varied with the amount of biochar added, changes in bulk density only was correlated to application rates of crop residue and wood biochar. Overall, biochar amendments could likely improve soil hydrological properties though varying with biochar and soil conditions. Use of biochar thus could offer a viable option to improve moisture storage and water use efficiency for soils poor in organic carbon in arid/semiarid zones. More studies on dynamics of soil hydrological behaviors following biochar amendment should be deserved in field conditions for a sound understanding of biochar’s potential in world agriculture.

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1. Introduction

The use of biochar as a soil amendment had been on the increase recently for its effects on C sequestration, greenhouse gas emission reduction, improvement of crop yield and soil quality (Atkinson et al., 2010; Koide et al., 2014; Lehmann et al., 2006; Mukherjee and Lal, 2013). Soil amendment with biochar had been shown affecting soil physical properties such as texture, structure, porosity and pore size distribution, available water capacity and soil drainage properties (Glaser et al., 2002; Deverueux et al., 2012; Herath et al., 2013). These effects could further affect plant growth and development, via mediating water uptake and root respiration processes. It became crucial for upscaling biochar use in agriculture in arid/semiarid zone to characterize the biochar-induced changes in soil physical properties with both biochar conditions related to feedstock and pyrolysis temperature as well as application rate, and soil conditions related mainly with soil texture and organic matter content.

Biochar soil amendment had been shown reducing bulk density in many studies (Laird et al., 2010; Tammeorg et al., 2014a; Herath et al., 2013). The decrease in bulk density had been observed in line with increased soil porosity and aeration, which mediates biophysical environment for root and microbial respiration (Basso et al., 2013). The extent of such changes, however, varied with the application rate, feedstock and soils tested. Biochar amendment at 10 t ha⁻¹ significantly reduced soil bulk density in an Alfisol poor in organic carbon but not in an Andosol high in organic carbon (Herath et al., 2013). Enhancing soil organic matter through organic amendment had been concerned as a key option to promote soil aggregate formation and stabilization as well as soil microbial activity (Six et al., 2004). Being a key indicator of soil quality, soil aggregate stability represented generally by a mean weight diameter (MWD) could influence water infiltration and thus soil erosion. Biochar addition helped to improve soil structure by increasing aggregate stability through promotion of macro aggregate formation (Herath et al., 2013; Ouyang et al., 2013). Porosity had been accepted as an important soil property affecting the root zone processes such as respiration and water uptake (Hillel, 2004). Both soil porosity (Tammeorg et al., 2014b; Abel et al., 2013) and structure (Jen and Wang, 2013; Ouyang et al., 2013) had been shown improved with biochar soil amendment. The extent by which
these properties were improved, however, varied with soil conditions and feedstocks of biochars tested. For example, bulk density, porosity and water content was significantly improved in a sandy clay loam soil (Tammeorg et al., 2014b). Whereas, r bulk density while structure and porosity improved significantly in clay soils, following biochar amendment (Jien and Wang, 2013). The highly porous structure of biochar helped improve soil water retention (Devereux et al., 2012) though did not necessarily improve available water capacity (Herath et al., 2013).

Furthermore, biochar addition led to an increase in soil water content at any given matric potential (Devereux et al., 2012). In coarse textured soils, biochar significantly increased the available water capacity (AWC), with the extent varying with pyrolysis temperature of the biochar used (Uzoma et al., 2011). However, this effect varied with soil texture (Abel et al., 2013). Soil hydraulic conductivity had also been considered an important soil property that governing water infiltration and movement within soil profile, thus influencing the likelihood of soil run-off after a heavy rainfall or irrigation event. Use of biochar could lead to an increase in soil saturated hydraulic conductivity (Ksat) (Uzoma et al., 2011; Herath et al., 2013). However, such changes were not observed in a typical Midwestern agricultural soil from US (Laird et al., 2010).

While much attention had been focused on changes in plant growth and productivity (Liu et al., 2013) and soil organic carbon mineralization (Wang et al., 2015), there had been relatively few studies on biochar effects of on soil physical properties (Devereux et al., 2012; Atkinson et al., 2010). Moreover, the changes in soil physical properties with biochar were found inconsistent or even contrasting across the few existing studies, varying with a wide range of soil conditions and biochar conditions. Unfortunately, there had been no quantitative assessment of biochars effect on soil physical properties, especially on soil hydrological properties. This limited our general understanding of biochar’s role in improving soil fertility in arid/semiarid zone around the world.

Thus, in this study was performed a meta-analysis of literature data published up to October 2015 and drew a general quantification of biochar’s effect on improving soil physical properties. We aimed to provide recommendations both for future biochar studies and for potential use of biochar in right soils around world. The quantified effects would also be important in assessment of the economic value of biochar application for sound policy formulation.

2. Materials and methods

2.1. Data collection

Literature search of published articles was performed via Web of Science and Chinese magazine net CNCK. While in searching, key words used were of biochar and soil physical properties, and/ or hydraulic conductivity, and/or aggregate stability, and/or available water capacity, and/or porosity or bulk density. Only the biochar soil studies that compared the changes between the control (without biochar) and biochar amended soils were collected to form a literature data base (Supplementary Table S1). The information or data retrieved from the published articles included measured soil physical properties mentioned above, location of the study, soil texture and organic carbon level, and biochar condition (feedstock, pyrolysis temperature or application rate). For cases where data was provided as graphs, data extractor software was used to extract data points. We excluded the studies without replicated treatments and data pairs. Where specific information was not available, the datasets were characterized as unspecified. For aggregate stability, only those studies that measured MWD by wet sieving were included in the study. Where the water content was presented as gravimetric content, these were converted to volumetric by multiplying by the reported soil bulk density. The available water holding capacity (AWC) in the studies used was defined as the water held between field capacity and permanent wilting point. In addition, porosity in this study was the total porosity measured in the retrieved studies. Overall, 34 published articles were collected of biochar soil physical studies that covered 128 datasets on bulk density, 74 datasets on available water content (AWC), 38 datasets on porosity, 24 datasets on saturated hydraulic conductivity (Ksat) and 10 datasets on aggregate stability (MWD) (Supplementary Table S1). The collected datasets were from studies located mainly in the continents of Asia, Europe and America but most of these studies were conducted in greenhouse pot experiments and laboratory incubations. However, the fewer field experiments in the study covered a range of climatic zones from temperate to tropical and subtropical environments, of which quantification was not allowed due to the very limited data available.

2.2. Data category and treatment

The extracted analytical data were standardized to the same metric for each property to allow for comparison among different studies. A response ratio from the treatment and control means were calculated before performing the meta-analysis. For meta-analysis, biochar was categorized in terms of feedstock as wood biochar (pyrolyzed from wood residues), crop residue biochar (feedstocks of wheat—Triticum aestivum L., Maize—Zea mays L., Rice husk—Oryza sativa L. and switch grass—Panicum virgatum L.), manure biochar pyrolyzed of dairy or poultry waste and sludge biochar pyrolyzed of sewage sludge. Biochar pyrolysis temperature condition was categorized into low (<250 °C), medium (250–500 °C) and high (>500 °C) temperature biochar. Biochar application rates were grouped into low (~20 t ha⁻¹), medium (21–40 t ha⁻¹), high (41–80 t ha⁻¹) and very high (>80 t ha⁻¹) dosage. Soil texture class was categorized, according to the USDA Soil Classification System, into fine (clay, clay loam, silty clay loam and silty clay), medium (loam, silt loam and silt) and coarse (sandy loam, sandy clay loam, loamy sand and sand) texture classes.

2.3. Meta-analysis

Meta-analysis allowed for comparison of results of different studies after standardization to establish hidden information not apparent in conventional studies (Borenstein et al., 2009). Paired values of means of the control and biochar treatment were recorded for individual studies after a standardization process. The standard deviations of the control and biochar treatment were recorded for individual studies after standardization to establish hidden information not apparent in the tested variable. The standard error reported in an individual study was converted to standard deviation by multiplying by the square root of the replications of that study. Following Borenstein et al. (2009), an ‘effect size’ (the measure of the magnitude of effect of a treatment on a soil property being investigated or the impact of an intervention), was the natural log value of the response ratio (r) calculated as:

\[ r = \frac{X_t}{X_C} \]

The calculated response ratio was log-transformed with an equation:

\[ \ln r = \ln X_t - \ln X_C \]

where, \( X_t \) is the mean of biochar treated group and \( X_C \) the mean of control group for a given experiment. The log transformed values were used for meta-analysis in calculation of summary effects and confidence limits. A response ratio greater than 1 indicated an increase while those less than 1 indicated a decrease, in the tested variable.

2.4. Data treatment and statistics

Data treatment and processing were performed with Microsoft Excel 2010. All figures were expressed as the mean response factor and 95%
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