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Research article

Effects of biochar on availability and plant uptake of heavy metals – A meta-analysis

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ABSTRACT

Biochar can be an effective amendment for immobilizing heavy metals in contaminated soils but has variable effects depending on its chemical and physical properties and those of the treated soil. To investigate the range of biochar's effects on heavy metal accumulation in plants in responses to the variation of soil, biochar and plant, we carried out a meta-analysis of the literature that was published before March 2016. A total of 1298 independent observations were collected from 74 published papers. Results showed that across all studies, biochar addition to soils resulted in average decreases of 38, 39, 25 and 17%, respectively, in the accumulation of Cd, Pb, Cu and Zn in plant tissues. The effect of biochar on heavy metal concentrations in plants varied depending on soil properties, biochar type, plant species, and metal contaminants. The largest decreases in plant heavy metal concentrations occurred in coarse-textured soils amended with biochar. Biochar had a relatively small effect on plant tissue Pb concentrations, but a large effect on plant Cu concentrations when applied to alkaline soils. Plant uptake of Pb, Cu and Zn was less in soils with higher organic carbon contents. Manure-derived biochar was the most effective for reducing Cd and Pb concentrations in plants as compared to biochars derived from other feedstock. Biochar having a high pH and used at high application rates resulted in greater decreases in plant heavy metal uptake. The meta-analysis provides useful guidelines on the range of effects that can be anticipated for different biochar materials in different plant-soil systems.

1. Introduction

Soil contamination with heavy metals is a major environmental concern that has emerged with the rapid development of industrial activities in the world over the last century. Heavy metals that are subsequently taken up by plants enter into the food chain and accumulate in animals and humans where they can cause toxicity (Dudka and Miller, 1999; Reeves and Chaney, 2008; Singh et al., 2010). Many factors affect the uptake process of metals by plants, such that remediation of heavy metal polluted soils presents a considerable challenge. Various methods for treatment of contaminated soils include phytoextraction (Kumar et al., 1995), chemical stabilization (Kumpiene et al., 2008), and soil washing (Abumaizar and Smith, 1999). In-situ immobilization of metals via chemical stabilization is a particularly convenient and cost-effective way to reduce heavy metal bioavailability and uptake by plants (Guo et al., 2006; Martin and Ruby, 2004). Among the amendments that are used to adsorb heavy metals and decrease their potential bioavailability, biochar has been shown to be particularly effective (Beesley et al., 2011; Houben et al., 2013).

Biochar is a carbon rich material produced by pyrolysis of straw, manure, wood, and other agricultural wastes under oxygen-limited conditions (Lehmann and Joseph, 2009). Under current agricultural and environmental practices, improper disposal or burning of agricultural organic wastes is a waste of resources and cause of environmental pollution (Segat et al., 2015; Zhang et al., 2016), while conversion of agricultural wastes into biochar is a multi-win strategy that is beneficial for soil carbon storage (Bolan et al., 2013), mitigation of greenhouse gases emissions (Zhang et al., 2010), improvement soil

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fertility (Doan et al., 2015), and immobilization of organic and heavy metal pollutants (Inyang et al., 2016; Lehmann and Joseph, 2015). Studies have shown that biochar is effective for reducing the bioavailability of heavy metals (Ahmad et al., 2014), thereby reducing plant uptake (Fellet et al., 2014) and food chain transfer (Khan et al., 2013). Biochar has highly condensed aromatic structures that make it resistant to microbial decomposition, which allows it to persist for decades to centuries, as evidenced by the anthrosol soils where charcoal was used as a soil amendment (Kuzyakov et al., 2014; Lehmann et al., 2006). Ageing of biochar also may enhance its ability to stabilize heavy metals in soil. Biochar undergoes oxidation over time, which promotes increases in carboxyl groups and the net negative charge that generates its cation exchange capacity (Bian et al., 2014). Thus there may be a long term effect of biochar on stabilizing heavy metals depending on its persistence in soil and increase in charge over time. Variations in the efficacy of biochar for immobilization of heavy metals can be attributed to differences in pH that affect the pH dependent charge (Yuan et al., 2011), as well as the pyrolysis temperature and feedstock that affect the abundance of functional groups that form metal complexes (Uchimiya et al., 2011). Immobilization of heavy metals is also affected by the mineral content of the associated ash in most biochar products (e.g. phosphate) (Cao et al., 2009) and by differences in the surface area and porosity of biochar (Harvey et al., 2011). These properties are dependent not only on the feedstock material, but can be manipulated by controlling the pyrolysis temperature, and other production conditions (e.g. heating rate and residence time) (Kloss et al., 2012; Zhao et al., 2013). The efficacy of particular biochar materials will further depend on soil properties (Ahmad et al., 2014), the specific heavy metals that are targeted (Beesley et al., 2011), and differences among plant species in their root growth patterns and in their abilities to take up and accumulate heavy metals (Rizwan et al., 2016).

To quantitatively and systematically examine the range of biochar's effects on soil heavy metal availability and plant uptake, we carried out a meta-analysis of data from previously published studies. Variables that were considered included soil physical and chemical properties, the type and application rate of biochar and crop type. The results provide useful insights into which biochars are most effective, and the extent to which heavy metal uptake may be affected by different biochar types and soils.

2. Materials and methods

2.1. Data sources and compilation

Relevant scientific articles were collected using the search terms “biochar” or “bio-char” to search for articles in the databases at the Web of Science, Elsevier, Springerlink, Wiley online, and Google Scholar. The search included all relevant articles up until March 1, 2016. Although the terms “char”, “black carbon” and “charcoal” have commonly been included in some former meta-analysis, here we mainly focused on “biochar” as this term intentionally denotes its use for agricultural and environmental applications (Lehmann et al., 2006; Lehmann and Joseph, 2009), as opposed to studies on naturally occurring black carbon. The definition of “biochar” was formally established in 2006 (Lehmann et al., 2006), therefore, the studies including “biochar” were published mainly after that year. The title and abstract of each article were examined and the articles relevant to heavy metal uptake by plant in soils treated with and without biochar were selected.

Data were compiled from the literature reporting the most common heavy metals of concern (Pb, Cd, Cu and Zn) in studies that specifically compared plant uptake of these metals in soils with and without a biochar amendment. Although of interest, there were too studies on the effect of biochar on arsenic uptake, which was not included in this meta-analysis because of the insufficient sample size. If the results were presented in figures, the data were numerically extracted using GetData software (version 2.26). In total, data were extracted from 74 scientific papers containing a total of 1298 individual observations comparing control (no biochar treatments) and biochar-amended treatments (see Supplementary Material 1). The basic properties of the soils and biochars were collected along with descriptions of the soil chemical and physical properties, and the crop type. Soil properties included soil organic carbon (SOC), total nitrogen, pH, cation exchange capacity (CEC), and texture. Biochar variables included feedstock, pyrolysis temperature, total organic carbon, total nitrogen, pH, and the amount applied. Experimental type included pot study and field study. Data collection also included the contents of heavy metals in the studied soils and biochars. Detailed description of the variables are listed in Supplementary Table 1.

The experiments that were evaluated in the present study were mainly conducted in China and Europe, accounting for 34 and 31% of the total studies, respectively (Fig. S1). Other reports were from South Korea (7%), Australia (7%), New Zealand (3%), and other areas (18%). Most of the studies (85%) employed pot trials, and 15% were conducted using field experiments.

2.2. Data normalization

Standard deviation (SD) was used as a measure of variance, and was calculated from the measured variance in each published study (Abalos et al., 2014). When standard errors (SE) were provided, they were transformed to standard deviations according to the following equation:

$$\mathrm{SD} = \mathrm{SE}\sqrt{\mathrm{n}} \tag{1}$$

where n is the number of replications. If the pH was measured with $CaCl_2$ solution, the values were transformed to acidity values predicted to be measured with deionized water using the following formula (Biederman and Harpole, 2013; Cayuela et al., 2014):

$$\mathrm{pH}_{[\mathrm{H2O}]} = 1.65 + 0.86{*}\mathrm{pH}_{[\mathrm{CaCl2}]} \tag{2}$$

Soil organic matter (SOM) values were converted to SOC content by multiplying them by the Bemmelen index value of 0.58 (Liu et al., 2015). Soil texture was classified into three categories of coarse (sandy loam, sandy clay loam, loamy sand and sand), medium (clay loam, loam, silty clay loam, silt, silt loam) and fine (clay, silt clay, loamy clay, sandy clay) according to the methods described in prior former studies (Cayuela et al., 2014; Liu et al., 2015).

2.3. Meta-analysis

Meta-analysis estimates the magnitude of change in a property (also named “effect size”) in response to an experimental treatment across a wide range of variables (Hedges et al., 1999; Kelley and Preacher, 2012). The *response ratio* (R), which is the ratio of measured quantity in experimental and control groups, is usually used to measure the effect size because it quantifies the proportionate change resulting from an experimental manipulation (Hedges et al., 1999). R was normally transformed to its natural logarithms (ln) to obtain a near normal distribution of data according to the following equation:

$$\mathrm{R} = \ln(\mathrm{X_t}/\mathrm{X_c}) = \ln(\mathrm{X_t}) - \ln(\mathrm{X_c}) \tag{3}$$

where X_t and X_c are means of the variable in biochar treatment and control groups, respectively. Its variance (υ) was estimated as:

$$\upsilon = \frac{S_t^2}{n_t x_t^2} + \frac{S_c^2}{n_c x_c^2} \tag{4}$$

where n_t and n_c are the sample sizes for the treatments and control groups, respectively; S_t and S_c are the standard deviations for the treatment and control groups. The Q statistic was used to measure the heterogeneity of effect sizes among studies (Zhou et al., 2016). The total heterogeneity (Q_t) of R among studies consists of within-group (Q_w) and between-group (Q_b) heterogeneity (Wang et al., 2016). A Q_b larger than a critical value indicates significant difference between groups