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Relative influence of soil- vs. biochar properties on soil phosphorus retention

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ABSTRACT

Properties of biochar are thought to determine whether phosphorus (P) sorption or increased P availability occur following biochar application to sandy acidic soil; the effect of soil properties on P retention in biochar-amended acid soils remains largely unexplored. Our objective was to determine effects of hardwood biochar and poultry litter biochar on P sorption and release from two soils differing in P retention properties at three rates of biochar addition. Soils as well as soil + biochar mixtures were treated with 12 levels of solution P concentrations. Phosphorus concentration and the amount of P sorbed for each level of P addition at the end of the incubation showed that after P addition corresponding to the soil P storage capacity (SPSC) as determined prior to biochar application, P retention abruptly declined for all treatments irrespective of biochar type. Biochar did not diminish the capacity of the two soils to tenaciously bind P added as a soluble inorganic source. Also, the maximum P retention capacity of the soil (S_{max}) increased as amount of biochar applied increased. Biochar-enhanced P sorption at high solution concentrations would be environmentally beneficial only if the sorption were strongly hysteretic such that subsequent P release is minimal as concentrations approach background levels. X-ray diffraction analysis of the biochar after incubating at high P solution concentration did not reveal formation of a stable crystalline P phase. This study provides evidence that the amount of P that can be "safely" added to soils amended with biochar depends significantly upon the P retention property of the soil, and not only the biochar characteristics.

1. Introduction

Biochar is a product of either thermal pyrolysis (temperature range of 300–1000 °C) or gasification created by heating carbon-rich biomass (feedstock) under conditions of limited or no air (Lehmann, 2007a). It is reported to have several functions including carbon (C) sequestration (and thus climate change mitigation), soil amendment and management, environmental remediation, waste management and renewable energy generation (Barrow, 2012). During the past few years, biochar has attained considerable importance as an easily accessible input for agriculture (Biederman and Harpole, 2013) and as an amendment for achieving environmental objectives (Chen et al., 2011). Biochar is not only rich in C but also plant nutrients (Ippolito et al., 2012); one of the most important aspects of biochar use is its ability to supply nutrients to plants in nutrient-deficient, low-fertility and degraded soils (Novak et al., 2009; Woolf et al., 2010).

The consequences of biochar application on nutrient retention (Spokas et al., 2009; Kloss et al., 2014) and/or nutrient availability (Laird et al., 2010a; Wang et al., 2012), are recognized as potentially important. However, studies have shown inconsistent results as to whether biochar application enhances P sorption or release (Atkinson et al., 2010; Yao et al., 2012; Xu et al., 2014). Numerous studies have reported that P availability was enhanced by biochar application (Lehmann et al., 2003; Kloss et al., 2014; DeLuca et al., 2015), but it has also been reported that biochar could sorb phosphates (Lehmann, 2007b; Chintala et al., 2014; Schneider and Haderlein, 2016). Biochar has also been suggested as a P-retaining fertilizer with potential to release P in soils (Peng et al., 2012; Streubel et al., 2012; Yao et al., 2013). The retention and release of P from soil with biochar application might depend on chemisorption among soil and biochar particles (Zhang et al., 2016) or geo-chemical processes such as solubilization or adsorption beyond electrostatic attraction or repulsion. Among these complex processes, retention of P is often best described by sorption mechanism which might improve the availability and plant uptake of P due to higher anion exchange capacity in soil (DeLuca et al., 2015; Novak et al., 2009). Other researchers have reported that P retention in biochar-amended soils can relate to P adsorption by calcium carbonate associated with the biochar (Zhang et al., 2016; Kumari et al., 2014). The availability of P by biochar application in soils has been attributed to a biochar-induced pH change in

Abbreviations: EPC_0, equilibrium phosphorus concentration; HWB, hardwood biochar; PLB, poultry litter biochar; PSR, phosphorus saturation ratio; S_{max}, phosphorus sorption maximum; SPSC, soil phosphorus storage capacity; XRD, X-ray diffraction analysis.

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soils (DeLuca et al., 2015) and strong competition between electrostatic repulsive forces induced by biochar dissolved organic matter and P sorption sites in soils (Schneider and Haderlein, 2016). Long-term studies are not available that clearly define the fate and transport of nutrients following biochar addition to a soil (Jeffery et al., 2011) and its associated trade-off with environmental pollution (eutrophication) (Jeffery et al., 2015). In addition, there is a need to account for the variability in P retention and release characteristics among biochars from diverse feedstocks.

The underlying mechanisms of P adsorption and release from soil due to biochar application need to be investigated further. The hypotheses of this research are that i) additions of biochar with EPC_0 greater than that of soil will not contribute to P retention at environmentally relevant solution P concentrations, and ii) increases in P sorption maximum (S_{max}) of a soil will depend on the amount of biochar added and the specific biochar feedstock. The objective of this study was to determine the effects of commercially available hardwood biochar (HWB) and poultry litter biochar (PLB) added at varying rates (1%, 2%, and 5%) on P sorption and release from two soils with differing P-retention capacities.

2. Materials and methods

2.1. Soil sampling and preparation

Two types of soil samples were collected from relatively un-impacted sites in Florida with respect to P fertilizer and/or manure application. One of them, an E horizon of a Candler soil (Hyperthermic, uncoated Typic Quartzipsamments), generally has low P retention capacity. The other, with a higher P retention capacity, is from the Bt horizon of the Apopka soil series (Loamy, siliceous, subactive, hyperthermic grossarenic Paleudults). The soil profiles sampled were representative of these series. They were sampled at locations within the University of Florida Ordway-Swisher Biological Station in Putnam County, Florida, USA. After collection, samples were mixed thoroughly, air-dried and passed through a 2-mm sieve before use. The air-dried soil samples were further used for the biochar batch experiments.

2.2. Biochar feedstocks and production

Two different types of commercially available biochar were used for the batch experiment. One was a pure coarse biochar obtained from Charcoal Green. It was made from the wood of trees such as maple (*Acer* spp.), oak (*Quercus* spp.), and pine (*Pinus* spp.), slowly pyrolyzed at 650–700 °C (Bakshi et al., 2014). The deciduous trees (maple and oak; "hardwoods") were main contributors for this biochar preparation compared to pines, hence the product was labelled "hardwood biochar" (HWB). The term "HWB" is maintained in this article, with the above qualifications, to maintain consistency with the product label. The HWB was crushed, homogenized, and sieved through a 2-mm sieve before use. The other type of biochar was from poultry litter (the term "PLB" is maintained in this article), a granular activated biochar produced from broiler manure and bedding materials used in poultry operations, including wood shavings, saw dust, straw, and other materials as described by Lima et al. (2014).

The PLB was produced utilizing broiler manure litter obtained from United States Department of Agriculture, Agriculture Research Services (USDA-ARS) and Poultry Research Unit (Starkville, MS, USA) by Lima and her co-workers. The original litter materials serving as the PLB feedstock used in this study had up to 30% of wood shavings (Lima and Marshall, 2005). The ash content of the original feedstock was 21.2% in broiler litter. The poultry litter was pyrolyzed at 700 °C for 1 h followed by a 45 min steam activation at 800 °C at different water flow rates from 1 to 5 mL min^{-1}. A detailed description of biochar activation is available in Lima et al. (2014).

2.3. Experimental design

The HWB and PLB were added to samples from each of the two soils (Candler and Apopka) at rates of 1, 2 and 5% (w/w). Soil and each mixture (in triplicate) were incubated at 25 °C for 14 days. A constant moisture content (60%) was maintained throughout the whole incubation period. The incubation period of 14 days was used to obtain stabilized pH values (by measuring the pH values of soil and biochar mixtures at each day starting from the first day of incubation). At the end of the incubation period, 12 concentrations of P in the form of KH_2PO_4 solution were added to each of the treatments. Various chemical analyses and P sorption isotherms were conducted on the biochars, and the incubated soil-biochar mixtures.

2.4. Chemical analyses of biochar and soil-biochar mixtures

The HWB and PLB samples were both characterized for selected chemical properties (Tables 1 and S1). We used parameters as reported by Bakshi et al. (2014) and Lima et al. (2014) since the biochar in our study were subsamples from the Bakshi et al. (2014) and Lima et al. (2014) studies. The two biochars were analyzed for pH, electrical conductivity (EC), total P (TP) and water soluble P (WSP). The pH was determined using a standard pH meter in saturated paste (Mukherjee et al., 2011) of 0.5 g of biochar in 50 mL of deionized water and allowing

Table 1
Mean values (values in parentheses represent the standard error) of selected properties of the biochars used in the study.

Property	HWB	PLB	Source
Pyrolysis temperature (°C)	650–700	700–800	Bakshi et al. (2014), Lima et al. (2014)
pH[a]	9.3 (0.6)	9.8 (0.9)	This study
EC (μS cm^{-1})	443 (4.8)	565 (8.5)	This study
CEC ($Cmol_c$ kg^{-1})	33.8 (18.3)	N/A	Bakshi et al. (2014), Lima et al. (2014)
AEC ($Cmol_c$ kg^{-1})	3.5 (1.3)	N/A	Bakshi et al. (2014), Lima et al. (2014)
Total C (g kg^{-1})	720 (21)	338.1 (13.2)	Bakshi et al. (2014), Lima et al. (2014)
Total oxygen (g kg^{-1})	N/A	107.9 (2.1)	Lima et al. (2014)
Total hydrogen (g kg^{-1})	N/A	11.9 (0.4)	Lima et al. (2014)
H/C	N/A	0.04	Lima et al. (2015)
Total N (g kg^{-1})	10.2 (1.6)	32.6 (2.1)	Bakshi et al. (2014), Lima et al. (2014)
Total P (g kg^{-1})	1.9 (0.2)	25.6 (1.8)	This study
WSP (mg kg^{-1})	2.30 (0.9)	1.10 (0.5)	This study
Ash content (%)	18.8 (0.3)	60.9 (0.7)	Bakshi et al. (2014), Lima et al. (2014)
Volatile matter (%)	13.2 (1.2)	17.3 (2.3)	Bakshi et al. (2014), Isabel Lima, personal communication
Surface area (m^2 g^{-1})	0.78 (0.03)	274 (8.2)	Bakshi et al. (2014), Lima et al. (2014)
Mineralogy	Calcite, quartz	Sylvite, whitlockite & quartz	This study

HWB, hardwood biochar; PLB, poultry litter biochar; EC, electrical conductivity; CEC, cation exchange capacity; AEC, anion exchange capacity; WSP, water soluble P.
N/A = not available.
[a] After 72-h equilibration.