Soil Biology & Biochemistry 103 (2016) 1–15

Contents lists available at ScienceDirect

Soil Biology & Biochemistry

journal homepage: www.elsevier.com/locate/soilbio

Review Paper

Biochemical cycling of nitrogen and phosphorus in biochar-amended soils

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ARTICLE INFO

Article history:
Received 7 April 2016
Received in revised form
30 July 2016
Accepted 1 August 2016

Keywords:
Black carbon
Soil microbial community
Mineralization
Solubilization
Crop yield
Extracellular enzymes

ABSTRACT

There is global interest in understanding the prospects for biochar application to agricultural soils. If biochar enhances the availability of nitrogen (N) and phosphorus (P) to crops, this could be pivotal in reducing N and P fertilizer inputs to agricultural soils. This review evaluates the soil biochemical cycling of N and P as influenced by biochars with diverse characteristics, and describes the consequences for plant nutrition with respect to the N use efficiency (NUE) and P use efficiency (PUE) of crops grown in biochar-amended soils. Fundamentally, biochar can alter microbial-mediated reactions in the soil N and P cycles, i.e. N_2 fixation, mineralization of N and P, nitrification, ammonia volatilization and denitrification. As well, biochar provides reactive surfaces where N and P ions are retained in soil microbial biomass and in exchange sites, both of which modulate N and P availability to crops. Distinctions must be made between biochars derived from manure- and crop residue-based feedstocks versus biochars derived from ligno-cellulosic feedstock, as well as biochars produced at a lower production temperature (<400 °C) versus biochars generated at a higher production temperature (≥600 °C). These factors determine the nutrient retention capacity of biochars when they are applied to soil. For example, low bioavailable N and P concentrations are expected when coarse-textured soil is amended with biochar having a high surface area, necessitating fertilizer application to avoid N and P deficiencies in the crop. Since the biochemical cycling of N and P in biochar-amended soil is affected strongly by biochar × soil interactions, detailed assessment of biochar-induced changes in soil physico-chemical properties and biological processes may improve predictions of how diverse biochars will affect soil fertility and crop nutrition under site-specific conditions.

1. Introduction

Most agricultural soils are limited in their ability to supply adequate N and P to crops, mainly due to the fact that the plant-available ionic forms of these nutrients are susceptible to loss via leaching (i.e., NO_3^- and the ortho-P ions $H_2PO_4^-$ and HPO_4^{2-}), conversion to gaseous forms (e.g., NH_3, NO, N_2O and N_2), and fixation or precipitation reactions (i.e., NH_4^+ fixation in clays, precipitation of ortho-P ions with calcium carbonate in alkaline soils and with aluminum and iron oxides in acidic soils). Inorganic N and P fertilizers are used to meet crop demands, but inefficient nutrient recovery from fertilizers has environmental consequences such as eutrophication, global acidification and global warming (Galloway et al., 2014). Rational use of inorganic N and P fertilizers requires consideration of the inherent reserves of plant-available N and P that are supplied to crops through internal recycling in the soil environment.

Biochar is a soil amendment with potential to improve N and P recycling in the soil-plant system. This carbonaceous solid residue is produced by heating biomass under oxygen-deficient conditions through slow and fast pyrolysis, gasification and hydrothermal carbonization. The latter three methods are suitable for energy and bio-oil generation at the industrial scale, whereas slow pyrolysis is a traditional method of charcoal production that generates more biochar than the other pyrolysis methods (Brewer and Brown, 2012). The important characteristics of pyrolyzed biochars affecting the biochemical cycling of N and P are: high surface area, pH and nutrient content. These characteristics vary among biochars depending on their source (feedstock) and production temperature. Manure- and crop residue-based biochars are richer in nutrients,

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http://dx.doi.org/10.1016/j.soilbio.2016.08.001
0038-0717/

tend to have higher pH and greater surface area than the biochars produced from ligno-cellulosic feedstocks such as wood (Gul et al., 2015; Mohanty et al., 2013; Novak et al., 2013; Singh et al., 2010). Likewise, slow pyrolyzed biochars produced at a higher production temperature (≥550 °C) tend to have greater surface area and higher pH values, but have lower plant-available nutrient concentrations than those produced at a lower production temperature (Al-Wabel et al., 2013; Cantrell et al., 2012; Mukherjee et al., 2011; Singh et al., 2010).

The diverse physico-chemical properties of biochar exert a variable influence on soil N and P cycling (Biederman and Harpole, 2013; Lehmann et al., 2011). Moreover, the soil physico-chemical properties affect the N and P cycling rates in biochar-amended soil (Biederman and Harpole, 2013; Lehmann et al., 2011). For instance, biochars that have greater surface area have greater adsorption capacity for ionic forms of N and P. Thus, biochars with low nutrient content (e.g., wood-based biochars) may be beneficial to reduce NO_3^- and ortho-P leaching in nutrient-rich soil, but their application in nutrient-poor soil may reduce the concentration of bioavailable N and P (Fig. 1) and have consequences for microbially-mediated reactions in the soil N and P cycles (Cayuela et al., 2013; Hussain et al., 2016; Lehmann et al., 2011). In contrast, biochars produced from manure feedstock have high pH values, 5–6 times greater nutrient content than residue-based biochars and >10 times higher nutrient content than wood-based biochars, and so are less likely to cause nutrient limitation in soil (Gul et al., 2015). However, high concentrations of base cations in some biochars can cause a significant increase in soil pH and contribute to soil salinity, which impaired crop growth in a poorly-buffered acidic soil (Sigua et al., 2016a) but had no negative impact on crop performance in well-buffered acidic soils (Murray et al., 2015; Subedi et al., 2016).

Biochar application to agricultural fields for soil fertility improvement is gathering momentum in many parts of the world (Jirka and Tomlinson, 2014). Generalizations about biochar performance must be balanced against the realization that biochars are highly heterogeneous in their form and reactivity in soil, which affects soil N and P dynamics, crop nutrition and yield. If a particular biochar can enhance internal N and P recycling in soil, it may also increase the N and P use efficiency of crops. Therefore, information on the biochemical cycling of N and P in the soil and plant compartments of biochar-amended agroecosystems is required to evaluate the prospect of using biochar to reduce our reliance on N and P fertilizer inputs. This fundamental knowledge is essential to develop guidelines for the selection and appropriate use of biochars to achieve desired agronomic outcomes.

The objective of this review is to examine how biochar types, determined by the feedstock source and production temperature affect (1) biochemical cycling of N, (2) biogeochemical cycling of P and (3) crop performance, namely N and P acquisition from biochar-amended soils. To compare data from diverse studies, we converted volumetric biochar applications (e.g., % or g biochar 100 g^{-1} soil) to a mass basis (i.e., t ha^{-1}) using the conversion factors of Ameloot et al. (2014) and indicate these estimated values with a tilde (~) symbol.

2. Nutrients in biochar

Biochars contain various organic and inorganic forms of N and P including NO_3^-, NH_4^+, ortho-P and amide groups (Kookana et al., 2011; Jindo et al., 2014). Concentration of these nutrients depends on the source and production temperature, as summarized by Gul et al. (2015). Biochars produced from nutrient-rich feedstocks like manure and crop residues generally have higher nutrient content than biochars generated from ligno-cellulosic feedstocks. Nitrogen forms in biochar are affected by the production temperature, such that biochars produced at higher temperatures have more NO_3^- while biochars produced at lower temperatures have more NH_4^+ (DeLuca et al., 2009). Azuara et al.

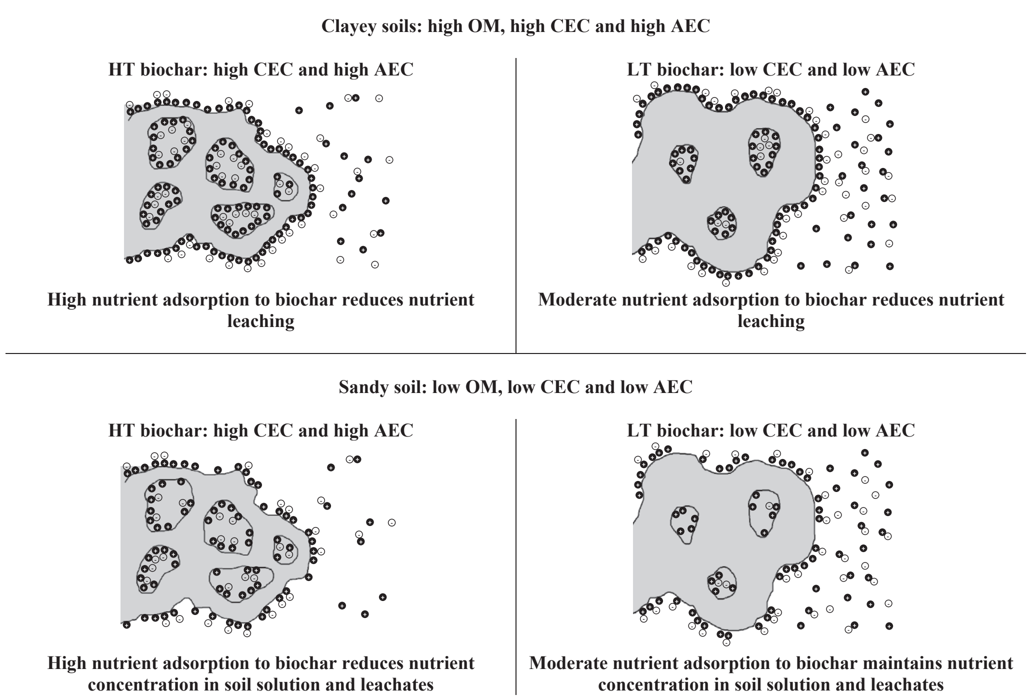

Fig. 1. Conceptual model of the cation exchange capacity in clayey (fine-textured) and sandy (coarse-textured) soils as influenced by slow pyrolyzed biochars produced at high and low production temperatures. The circles with + and − signs indicate cation and anions. The largest particle represents a soil organo-mineral surface while the smaller irregular greytone/hatched structures are biochar. OM: organic matter; CEC: cation exchange capacity; AEC: anion exchange capacity; HT: high production temperature; LT: low production temperature.