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EDITORIAL

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Introduction

Over the past decade, biochar soil management has seen a surge in activities related to both research and development (Lehmann and Joseph 2015; Ok et al. 2015). Even though our knowledge has considerably advanced, the effects of biochars on crop growth still appear unpredictable, with in some instances increasing while in others decreasing yield responses (Liu et al. 2013; Jeffery et al. 2015a). To a large extent, this is a result of widely varying biochar properties (Enders et al. 2012; Schimmelpfennig and Glaser 2012) as well as of variable soil properties and environmental plant requirements. Some biochars may increase crop yield, whereas others may decrease yield for reasons that are readily explainable using known responses of crops to for example altered pH or salt contents (Van Zwieten et al. 2010; Rajkovich et al. 2012) and short-term N limitation in N deficient soil (Clough et al. 2013). However, we also observe a distinct lack of mechanistic insight into how properties that are shared by many biochars affect plant growth. This special issue focuses on identifying and explaining the mechanisms by which certain biochar properties affect plant performance through rhizosphere interactions.

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The biochar-soil-plant interface

In our opinion, at least two linked reasons for the observed knowledge gap in process information about effects of biochars on plants exist: (1) the biophysicochemical interactions between biochar particles, the soil, and the roots on the one hand; and (2) their distinct spatial distribution on the other hand affect what micro-environment the roots are exposed to. In most conceptual models (and most experiments), the plant is thought to interact with a mixture of biochar and soil (Fig. 1a), when in fact there could in many instances be important three-way interactions between biochar particles, soil, and plant roots (Fig. 1b). These can be bidirectional and encompass many different effects; these may include but are not limited to changes in

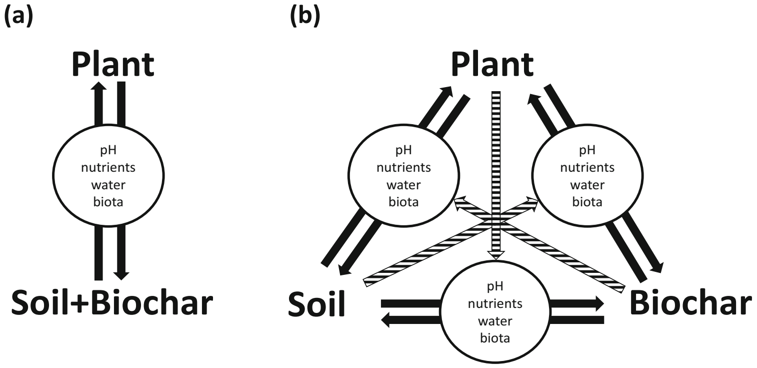

Fig. 1 Conceptual sketch of (**a**) a one-dimensional view of the interaction between plants and biochar added to soil; and (**b**) a two-dimensional view of how biochars affect, and is affected by, both soil and plants (*solid arrows*), and how biochars will influence the interaction between plant and soil (*hashed arrows*); the strength of the effects is variable in time and space and differs depending on the type of soil, plant and biochar (*arrows* are meant to indicate effects, not mass flow)

pH, metabolizable organic substances, signaling molecules, plant nutrients and toxins, water, and soil biota (Fig. 1b, solid arrows). In addition, biochars may influence how plants interact with the soil surrounding the biochar particles (Fig. 1b, hashed arrows). For example, biochars may affect growth of roots or mycorrhizae in the soil and thereby the extent to which the plant takes up water or nutrients from the soil surrounding the biochar particles that is not directly influenced by the added biochar. This interaction may also occur in reverse when alkaline biochars increase the pH of an acid soil; this may in turn enhance photosynthesis and could alter the way plants explore the pores of biochar particles.

Biochars are known to alter in many instances a wide variety of soil properties, such as pH, bulk density, soil aggregation, water holding capacity, nutrient availability and organic carbon availability. However, because roots can explore biochar pores directly and the biochars are particulate in nature, the spatial arrangement of the biochar-soil-plant interface warrants recognition. Further, the roots, root hairs, and mycorrhizal hyphae that grow in the pores or on the surfaces of biochar particles may be exposed to a chemical and physical and biological environment that is very different from the soil environment surrounding it. For example, the pH of the biochar particles (9.2) may be much higher than that of the surrounding soil (4.2) and the mixture of 2 % *w/w* biochar may show an intermediate pH (5.9) (Fig. 2). However, this average pH does not reflect the pH environment the roots are actually exposed to, which could be higher or lower than the composite pH and depend on the proximity to the biochar particles (Fig. 2). In addition, the distribution of biochar particles and thereby its influence on soil properties, is not homogeneous on a fine scale. This may question the utility of examining how biochars influence the bulk soil properties and could motivate investigation of the biochar-plant or biochar-biota-plant interface at a scale that is relevant to its interaction. It also illustrates the large environmental changes that roots (and by extension also microorganisms) may be exposed to in the vicinity of biochar particles; these changes are not limited to pH but may also include changes in electric conductivity (and thereby osmotic potential), concentrations of specific salts (including nutrients and heavy metals) or organic compounds and many other factors.

Even though roots and microorganisms growing on and in biochar particles have been visualized for some time (Ogawa 1994), quantitative evidence of whether there are more or less roots and microorganisms growing in biochar particles is virtually non-existent (Lehmann et al. 2011). Even less is known about the reasons why roots or microorganisms would prefer the biochar spaces, beyond well-known effects of nutrients, water or metabolizable carbon as energy sources. This special issue attempts to provide insight into these interactions and to advance our understanding of the mechanisms that operate at the scale of the biochar-soil-plant interface.

Probing the interface

This special issue contains articles that examine how and through what mechanisms biochars influence

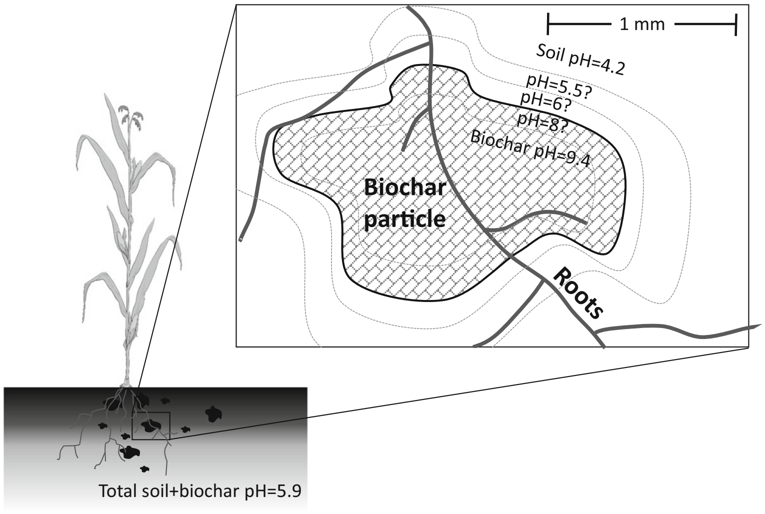

Fig. 2 Illustration of the strong pH gradient that plant roots may need to overcome, depending on their proximity to a biochar particle. *Inset* shows the fine-scale environment of a biochar particle. Example with values from Van Zwieten et al. (2010) (pH values with question marks are hypothetical values; biochar particles are less than 2 mm)

rooting (Abiven et al. 2015; Graber et al. 2015); plant access to water (Haider et al. 2015) and nutrients through either increased mycorrhizal abundance (Vanek and Lehmann 2015) or biological nitrogen fixation (Van Zwieten et al. 2015); disease resistance and tolerance (Jaiswal et al. 2015; Mehari et al. 2015); contaminant phytoavailability (Rees et al. 2015; Williams et al. 2015); and microbial community composition (Wang et al. 2015).

The size of maize root systems significantly increased after 4 Mg ha^{-1} of biochar (produced from maize cobs) were added to various deeply weathered soils in Zambia (Abiven et al. 2015). The authors were not only able to show that the root architecture was markedly influenced by the biochar additions but also that the root-shoot ratio increased. This observation differed from those obtained by pot studies, where mostly reductions in root-shoot ratios were found (Lehmann et al. 2011). The authors could not resolve whether the added biochar increased the root system which enabled more nutrients to be taken up to increase crop growth; or whether the added biochar increased nutrient availability in the soil directly which improved both below and above ground crop growth. Causal relationships appear to be particularly difficult to discern in such cases. An experiment with Arabidopsis seedlings (Graber et al. 2015) revealed that root hair abundance decreased in the presence of alkaline extracts of the studied biochar, regardless of whether or not inorganic P was added. This finding shows that root growth may be influenced independent of large changes in nutrient availability (without any observed changes in aeration, pH, moisture), possibly by plant perception of its environment. A related observation was reported for mycorrhizae (Vanek and Lehmann 2015); greater plant P uptake was not related to greater P additions through the biochar, but rather the biochar-induced increase in mycorrhizae led to greater P uptake from the soil (and not from the biochar). In the study by Wang et al. (2015), the bacterial community structure was not affected by additions of biochar in the presence of plants (that on their own showed a major imprint on community structure), and even without plants was only minimally influenced by additions of biochar. Possibly only observations of specific organisms and their abundance generates mechanistic insights into biochar effects on plant-microbe interactions, as shown here with pathogen responses (Jaiswal et al. 2015; Mehari et al. 2015). The spatial distribution of microorganisms may be especially revealing, as with the observed greater mycorrhizal abundance within the biochar than in the surrounding soil (Vanek and Lehmann 2015) that confirms earlier visual analyses (Lehmann et al. 2011). The reasons for such a preference of microorganisms or roots to grow near biochar particles or even in their pores remain unclear: are these related to nutrients, water or pH (which was excluded as an explanation in the paper by Vanek and Lehmann 2015), and if not, what other reasons may exist?

The importance of pH correction in overall effects of biochars on plant performance is often observed and was also important for increasing biological N fixation in a field setting (Van Zwieten et al. 2015). Soil pH effects were also a major contributor to the way in which biochars influenced heavy metal uptake by plants (Rees et al. 2015). Indications for specific effects of organic substances found in biochars on pathogens could not be substantiated (Jaiswal et al. 2015).

Interestingly, adding a greater amount of biochars often did not lead to a linear increase in plant responses. Rather, plant-water relations (Haider et al. 2015) or disease suppression (Jaiswal et al. 2015) improved by what these studies considered to be intermediate biochar application rates of 0.5–1.5 % *w/w* and decreased beyond that. It is tempting to interpret such results with an optimum response to the target effect, but it is equally possible (and given the multitude of effects of different biochars on plant-soil interactions even more likely) that cause and effect are not always discernable, with negative effects emerging at high application rates. Therefore, the mechanisms of interactions still remain a challenge to predict the effects of different biochars.

The way forward

The need for recognizing the wide variety of biochars with often diametrically opposing characteristics in terms of physical and chemical properties has been amply stated (Novak et al. 2009). This variety not only requires inclusion of detailed characterization of the myriad different biochars in scientific publications, but also classification systems that allow more productive communication in the sciences (Camps-Arbestain et al. 2015). The argument for including appropriate experimental controls in research on biochars that go beyond a no-biochar treatment has also been made (Jeffery et al. 2015b) but appropriate experimental designs are only slowly implemented. Even less recognized is the topic of this special issue: the emergent evidence shows that processes occur on surfaces of biochar particles and in their pore spaces that are relevant to plant growth. Relating the effects of biochars on plant growth to observations in the bulk soil blurs causal relationships. Conversely, investigating the plant-soil interface in a spatially-explicit manner by observing the contribution that areas within and around biochars make brings critical mechanisms into focus. What if biochar particles constitute an important plant-soil interface, the biocharsphere (Lehmann et al. 2011) providing hotspots of microbial and root activities (Kuzyakov and Blagodatskaya 2015)? This warrants spatially-explicit observations at the relevant spatial and temporal scales. In most cases, we will face significant methodological hurdles to examine for instance the pH around and in those pores of biochars that root hairs or mycorrhizal hyphae experience. Soil minerals interacting with biochar particles may create a different interface than exposed biochar surfaces and may warrant separate consideration. Resolving these issues and, especially, generalization of such spatially resolved observations is extremely rewarding and highlights the importance that the spatial architecture of soil plays for plant growth.

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