Biochar

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Overview

Biochar is a type of black carbon produced from a carbonaceous material through the application of heat or chemicals (Lehmann, 2007b; Novak et al., 2009). Black carbon in soils can be a result of anthropogenic activities like fire pits or natural occurrences like volcanic activity or forest fires (Spokas et al., 2012). Biochar is differentiated from black carbon in that it is created with the intent to be used as a soil ameliorant (Barrow, 2012). Specifically, biochar is a stable substrate created from organic material that has been combusted under low or no oxygen conditions through the process of pyrolysis (Atkinson et al., 2010; Karhu et al., 2011). Biochar may increase soil pH, nutrient retention, cation exchange capacity (CEC), crop biomass, and many other variables important to soil quality and agriculture (Schnell et al., 2012; Xu et al., 2012) in addition to increased soil C sequestration (Lehmann, 2007a).

This ability of biochar to amend soil quality issues, in conjunction with sequestering C, has contributed to a surge in biochar interest. Prior to 2000, a Google Scholar search of "biochar" returned 595 papers. Between 2000 and 2010 there were 4,340 papers, and within the past 6 years there were 15,400 papers published, an almost 2,500% increase from pre-2000 levels. Despite this spike in published papers, the concept of incorporating biochar into soil for agriculture is not new. Areas in the Amazon have soils rich in black carbon that date back to between 450 BC and AD 950 (Barrow, 2012). It is unclear whether the Amazonian dark earths, also known as Terra Preta, were anthropic (unintentionally formed by humans) or anthropogenic (intentionally formed by humans), but the source material it is most likely a mixture of ash from fires, midden waste, and slash and burn practices (Barrow, 2012; Spokas et al., 2012). Terra Preta soil is characterized by increased amounts of C, nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg), compared to the surrounding soil (Glaser et al., 2001; Pagano et al., 2016). Terra Preta sites are several times higher in soil C with large amounts of stable soil organic matter (Glaser et al., 2001) and harbor-specific soil biota that are thought to be responsible for the ability of the soil to maintain its higher quality (Barrow, 2012).

Biochar is currently promoted as a way to initiate a "doubly green revolution" (Barrow, 2012) by potentially addressing soil organic matter GHG emissions and food insecurity concurrently (Jones et al., 2012; Lehmann et al., 2006; Mukherjee and Lal, 2013; Sohi et al., 2010). Specifically, biochar is being targeted in tropical soils. Sustainable agriculture in the tropics is difficult because of the rapid degradation of soil organic matter in some soils as a result of limited stabilizing minerals in a hot and rainy climate (Glaser et al., 2001). In addition, the lack of stabilizing minerals means that fertilizer application is only effective for a short-time postamendment (Glaser et al., 2001). The stable nature of biochar (Kuzyakov et al., 2014) could make it a more effective long-term soil conditioner. In particular, one study found a single biochar application resulted in increased crop yields 4 years postamendment (Major et al., 2010).

Impacts of Biochar on Soil Chemical and Physical Properties

Biochar improves the physical aspects of soil, including the bulk density, particle size distribution, porosity, structure, and texture (Ding et al., 2016; Manyà, 2012; Xu et al., 2012). The chemical properties of soil are also impacted including an increase in soil carbon, pH, and CEC (Laghari et al., 2016). The large surface area of biochar and its porous nature partly explain increased retention of nutrients and water (Atkinson et al., 2010; Barrow, 2012; Xu et al., 2012). The application of biochar can reduce ammonia volatilization and increase the immobilization of inorganic N (McHenry, 2011). However, there are very few studies on soil properties in long-term field scale trials, so more research needs to be done to investigate these changes and elucidate the mechanisms (Atkinson et al., 2010). In addition, while biochar impacts on soil have been documented, less is known about how

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biochar changes in the soil environment (McHenry, 2011). Another important aspect of understanding how biochar impacts the soil is how it affects soil microbial communities and biogeochemical cycles (Xu et al., 2012).

Impacts of Biochar on Soil Biota

Biochar is considered recalcitrant due to its resistance to microbial decay (Lehmann et al., 2011). However, the high porosity can provide additional niches for microorganisms (Barrow, 2012; Pietikäinen et al., 2000). Depending on the biochar and soil type, biochar may also reduce changes within the microbial community structure and function (Anderson et al., 2011), have no effect on species richness or diversity (Rutigliano et al., 2014), or increase microbial abundance (Ding et al., 2016). Biochar application has also been found to increase the amount of bacteria with decreased fungi abundance (Chen et al., 2013) or by increasing k-strategist microbial biomass and increasing species richness (Liang et al., 2010; O'Neill et al., 2009). It may also increase plant root colonization by ectomycorrhizal fungi and arbuscular mycorrhizal fungi (Warnock et al., 2007) or shift the microbial community to one that prefers aromatic C (Bamminger et al., 2014). Additionally, biochar can affect the activity of soil enzymes by inhibiting or increasing the contact with SOM (Thies et al., 2015). The variety of different biochars, with varying chemical and physical properties, in conjunction with varying soil environments likely causes the wide range of microbial responses to biochar-amended soils.

Biochar and Greenhouse Gas Emissions

The biochar-induced changes in soil microbial community structure and function may result in altered C and N cycling and a subsequent change in soil respiration and N_2O flux. It can decrease emissions of GHG, including CO_2 (Case et al., 2014), CH_4 (Karhu et al., 2011), and N_2O (Wang et al., 2012; Zhang et al., 2016). However, some studies have also found a lack of significant differences for GHGs (Xiong et al., 2007) or increases in soil respiration (Deng et al., 2016). Biochar can influence how C is stabilized within soils (Chen et al., 2013) and change the mineralization of native soil C (Liang et al., 2010). Biochar may also alter the N cycle within soils by increasing the relative abundance of microbial communities involved in the reduction of N_2O to N_2 and the fixation of N_2 to NH_4^+ (Anderson et al., 2011). However, it is possible that microbial changes are short term due to the small amount of labile C in biochar (Ding et al., 2016). It is important to consider these changes in GHG emissions from soils when considering biochar as a way to mitigate climate change.

Biochar and Environmental Remediation

The properties of biochar make it an ideal candidate for environmental remediation of organic and inorganic pollutants for both contaminated water and soils due to the high surface area, microporosity, and the negatively and positively charged surface functional groups (Ahmad et al., 2014). Biochar can be used to sorb organic compounds like pesticides and herbicides; however it reduces the ability of microbes to break down these substances and thereby increasing the longevity of these contaminants in the environment (Xie et al., 2015). For inorganic ions, metals can be physically entrapped or chemically sorbed onto the biochar (Inyang et al., 2016). Unlike with organic compounds, biochar is not inhibiting microbial breakdown of inorganic pollutants while trapped within the micropores (Beesley et al., 2011). Additionally, biochar is alkaline and therefore the increase of soil pH stabilizes metals, with the exception of arsenic (Ahmad et al., 2014; Beesley et al., 2011). The alkalinity may also cause some metals to precipitate out of solution and onto the surface of the biochar (Inyang et al., 2016). This can reduce the availability of these metals to plants (Zhang et al., 2013).

There are unknowns associated with the use of biochar as a remediation tool, including the saturation point of biochar and the longevity of metal immobilization (Beesley et al., 2011). Additionally, different biochars created at different temperatures had varying responses to metals although high pyrolysis temperature and an animal-derived biochar tend to be the most effective (Higashikawa et al., 2016).Optimizing feedstock and pyrolysis factors and matching them to specific environmental contaminants require further testing. The success of field trials (Zhang et al., 2013) and the economic feasibility of large-scale applications also need to be considered (Higashikawa et al., 2016). Lastly, the combination of biochar with phytoremediation or the growth of a bioenergy crop also needs to be further explored (Paz-Ferreiro et al., 2014).

Biochar Production

Biochars are heterogeneous in their properties due to the wide variety of feedstocks that can be used and pyrolysis technologies. Some common feedstocks include switchgrass, hardwoods, peanut hulls, corn hulls, pecan shells, bark, rice, sugarcane, leaves, paper sludge, cow manure, poultry manure, poultry litter, sewage sludge, and aquaculture waste (Atkinson et al., 2010; Barrow, 2012; Manyà, 2012; Spokas et al., 2012; Xu et al., 2012). Biochar can help eliminate the reluctance people may have to waste stream products by removing both the wetness and the odor through the process of pyrolysis (McHenry, 2011). Once the feedstock is established, there are many different types of pyrolysis, including slow pyrolysis, fast pyrolysis, flash pyrolysis, vacuum pyrolysis, hydropyrolysis, intermediate pyrolysis, and microwave-assisted pyrolysis (Manyà, 2012; Tripathi et al., 2016). In addition to the solid biochar, bio-oil and bio-syngas are also products of pyrolysis (Tripathi et al., 2016). Other methods to create biochar include torrefaction, flash carbonization, hydrothermal carbonization, and gasification (Cha et al., 2016). The combination of many feedstocks and several pyrolysis technologies makes for a plethora of biochars all varying in physicochemical properties. Once the biochar is created, other variables need to be documented. For instance, it is also important to maintain records of how the biochar was stored and if any chemical or thermal activation occurred as these factors can affect the surface chemistry of the biochar as well as how resistant it is to decay within soil (Spokas et al., 2012).

Importance of Characterization

However, it is this versatility that also makes it difficult to establish experimental repeatability. The starting stock properties of biochar greatly influence the characteristics of the final product (Atkinson et al., 2010; Barrow, 2012; Ippolito et al., 2012). Biochar properties can be influenced by the pyrolysis process and the different variables within the process. These variables include how quickly the organic matter is heated, to what temperature it is heated to, how long it remains at that temperature, what the pressure is during this process, and what happens to the biochar postpyrolysis (Ippolito et al., 2012; Manyà, 2012). Manipulating these variables can lead to a biochar with specific characteristics, which would be useful to amending soil in a precise manner.

It is important to have a well-characterized biochar for studies in order to begin making meaningful comparisons between studies. This will help provide more insight into how the different properties of biochar translate to changes in agriculture and carbon sequestration. The growth of this body of knowledge as well as advances in pyrolysis technology and other ways to modify biochar will allow the deliberate control of the biochar production variables which allows for the creation of a biochar with specific properties (Rajapaksha et al., 2016; Spokas et al., 2012). While it is still a poorly understood process, some relationships between conditions and properties have been established; these relationships include increasing temperatures which result in lower yield, greater surface area, lower oxygen content, and higher fixed carbon (Manyà, 2012). The temperature can also affect Ca, Mg, and NO_3 leaching, with lower temperatures resulting in less leaching (Ippolito et al., 2012). High pyrolysis temperatures usually result in higher pH biochars, lower ash contents, and higher $CaCO_3$ equivalence (Singh et al., 2010). Higher temperature biochar also usually has lower CEC (Ippolito et al., 2015). It also increases electrical conductivity (Kloss et al., 2012). These high temperatures increase the aromatic structure of the biochar, which can allow it to better resist microbial mineralization and therefore improve C sequestration (Kloss et al., 2012; Spokas et al., 2012). Given the wide range of biochar starting materials and the multitude of variables that can be manipulated during the process of pyrolysis, it is clear why there are inconsistent results in agricultural field and greenhouse trials with biochar. However, the ability to tailor biochar, either through feedstock or through pyrolysis manipulation, offers considerable opportunity for the use of biochar as a soil ameliorant or crop enhancer. As more characterization studies, field trials, and greenhouse trials are undertaken, trends on how different biochars and their specific properties impact soils and crop growth can be ascertained. With this information, a soil with a deficiency or problem can be matched with a biochar that was created from a specific feedstock and under certain pyrolysis conditions to amend that precise problem (Ippolito et al., 2015).

Potential Drawbacks of Biochar

Despite the ability of biochar to improve a number of soil problems, it is not a straightforward process. An issue with the creation of biochar is choosing a feedstock with low moisture content. While there are some methods that work well with wetter feedstocks, the biochar they create has a high oxygen-to-carbon ratio, which results in a lower aromatic structure that is easier to degrade in soil (Spokas et al., 2012). Due to the difference in structure, these types of biochar are less suited to carbon sequestration compared to a more recalcitrant biochar. While it is possible to dry out wetter feedstock, this can add onto the cost and time of production. Another important initial feedstock characteristic is the concentration of its elemental makeup, as the concentration of these elements is often magnified in the final product (Spokas et al., 2012). Therefore, a feedstock high in elements known to cause plant toxicity would not make a biochar that is ideal for crop production. The process of pyrolysis may also produce harmful byproducts such as polycyclic aromatic hydrocarbons (Laghari et al., 2016).

Another variable to the complex issue of biochar as a soil amendment is the wide variety of agriculture management practices that impact how soils function. This includes what tillage practices are used, the type of fertilizer, the rate of fertilizer, the type of crop rotation, and the agricultural history of the land under cultivation (Karhu et al., 2011; Major et al., 2010). Even when biochar and fertilizer are applied, crop yields do not always increase; therefore it is not just increasing nutrient availability that is responsible for increased crop yields, and other variables are also responsible (Spokas et al., 2012). It is important to establish what biochar does within the soil because it is very stable and nearly impossible to remove from the soil (Barrow, 2012; Jones et al., 2012). Therefore, if adverse effects were to occur, little could be done to quickly remedy the situation.

Future Research

While biochar has been the topic of much research, there are still large knowledge gaps that need to be addressed. The longevity of biochar in field conditions and the long-term impacts of biochar are two unknowns. The mechanisms behind how biochar impacts the soil environment, including changes in soil physical and chemical properties as well as the impact of biochar on the soil microbial communities, need to be further explored especially in regards to changes in biogeochemical cycles (Ding et al., 2016; Thies et al., 2015). More research is needed to find ways to alter biochar to further reduce GHG emission when amended into soils, especially in field experiments (Mandal et al., 2016). Additionally full-scale outdoor trials of biochar as a way to restore contaminated soils and assess how long biochar retains the metals as it ages in the field (Zhang et al., 2013). Lastly, increased understanding in the creation of designer biochars to target specific soil deficiencies using tailored biochar feedstocks and pyrolysis processes (Ding et al., 2016). As biochar continues to be utilized as a soil conditioner, these unknowns need to be addressed given the difficulty of removing biochar from the environment.

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