The emerging biochar industry

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Introduction

Biochar is basically charcoal. The term "charcoal" is preferred when the material is use as a fuel for cooking or heating, whereas the term "biochar" is appropriate when the material is use as a soil amendment. In recent years there has been rapid growth in interest in biochar among soil scientists, environmentalists, and entrepreneurs. Soil scientists have recently recognized that 10 to as much as 50% of the carbon in soil organic matter is in fact biochar, a legacy of natural vegetation fires (Skjemstad et al., 2002). Soil scientists are seeking to understand how both native and added biochar impacts soil quality, the leaching of nutrients and pesticides, and agricultural productivity. Environmentalists see biochar as a highly effective means of sequestering atmospheric carbon. Plants remove CO_2 from the atmosphere through photosynthesis. When the plant dies, decomposition of the plant residue quickly returns most of the biomass C back to the atmosphere as CO_2. If, however, the plant residue is pyrolyzed such that 20 to 50% of the biomass C is turned into biochar and that biochar is incorporated into the soil, then the C will be preserved for hundreds if not thousands of years (Lehmann et al., 2006). Entrepreneurs see an emerging industry with untapped markets and large growth potential due to the synergism of positive environmental and agronomic impacts. This article reviews the basic nature of biochar, it's impact on soil properties and crop yields, the status of the emerging biochar industry, and the potential for a future role of biochar in the emerging cellulosic bioenergy industry.

Biochar is highly diverse

Biochar is not a single material, but rather a highly diverse group of materials that are made through the incomplete combustion, gasification, or pyrolysis of biomass (Laird et al., 2009). Properties of the biomass feedstock and the thermochemical conditions during the pyrolysis reaction have a big influence on the properties of the resulting biochar (Singh et al., 2010). Low temperature biochars (peak pyrolysis temperature <400°C) contain relatively high levels of O, N, S, and H in addition to C. As a general rule, low-temperature biochars have high cation exchange capacities, low internal porosity, low surface areas, and contain at least some biologically available C. The half-life of low-temperature biochar C in soils ranges from 10s to 100s of years. By contrast, high-temperature biochars (peak pyrolysis temperature >600°C) have high levels of biologically inert C and low levels of other elements; they also have low cation exchange capacities, high internal porosity, and high surface areas. The surfaces of high temperature biochars are typically hydrophobic when freshly prepared. The half-life of C in high-temperature biochars is >1000 years. All biochars contain at least some ash when freshly prepared, which consists primarily of carbonates, oxides and hydroxides of the various inorganic elements that were present in the biomass at the time of pyrolysis. Biochars made from herbaceous biomass, such as corn stover and switch grass, typically contain high levels of ash dominated by silica (SiO_2) and carbonates of Ca, Mg, and K. Biochars made from hardwood and especially softwood contain low levels of ash, which is mostly present as carbonates of base cations. The ash content of biochars increases with the peak pyrolysis temperature.

Biochar reactions in soils

Once in the soil biochars evolve or "age" with time. Although we have incomplete knowledge of the aging process some aspects are known. The carbonates in the ash associated with biochar react with soil acidity; and because of this reaction, most biochars are weak liming agents. The reaction involves the release of CO_2, which may diffuse out of the soil or move with groundwater as bicarbonate, and base cations primarily Ca, Mg, and K which are available as nutrients for plant uptake. Oxidation of biochar surfaces is another major aging reaction. Oxidation slowly enriches the concentration of oxygen containing organic functional groups on biochar surfaces, which transforms the surfaces from hydrophobic to hydrophilic and adds cation exchange capacity primarily in the form of carboxylate groups. There is some question as to how fast carboxylate functional groups form on the surfaces of biochars, with some authors arguing that it may take decades for cation exchange capacity to develop (Cheng et al., 2008), however we clearly measured an increase in cation exchange capacity after a 500 day laboratory incubation (Laird et al., 2010). A third and very important aging process is the adsorption of dissolved organic molecules on biochar surfaces. Organic molecules released to the soil solution during the decomposition of plant and animal residues are readily adsorbed through both hydrophobic and various polar interactions. These molecules may act as surfactants further transforming the biochar from hydrophobic to hydrophilic and may add cation exchange capacity and other properties to the biochar. A fourth aspect of aging is the colonization of biochar surfaces by soil microorganisms (Lehmann et al., 2011). The C of high-temperature biochars is biologically unavailable; however, low-temperature biochars are a potential source of metabolic energy for microorganisms. Most studies have shown increases in fungi and actinomycetes populations relative to bacteria, however bacteria clearly live in biochar pores where they may find refuge from predation. Fungi and actinomycetes may be better adapted for utilizing the C and nutrients of low-temperature biochars as a substrate. Although high-temperature biochar C is either unavailable or only very slowly available to microorganisms, biogenic organic compounds adsorbed on biochar surfaces provide a source of substrate to sustain microbial activity.

The potential for biochar amendments to improve soil quality has been well documented in the soil science literature (Laird et al., 2010: Atkinson et al., 2010). Biochar is a low density highly porous material; when added to the soil it acts as a conditioning agent reducing bulk density and increasing porosity, aeration, and drainage. These changes in soil physical properties have been consistently measured in both soil column incubation studies and in the field at least three years after a biochar application. As noted above, biochar is transformed from hydrophobic to hydrophilic after residing in the soil for a relatively short period of time. This transformation together with the high internal porosity of biochar and lower bulk densities increases the capacity of biochar amended soils to retain water. Increased water retention may be agronomically important, especially for coarse textured soils. In fine textured soils, the ability of biochar amendments to increase porosity, aeration, and drainage is often more important than the increase in water retention capacity. The high cation exchange capacity of aged biochars increases the capacity of soils to retain cationic nutrients. Ortho phosphate, which is negatively charged, is retained on biochar surfaces through anion exchange or ligand exchange reactions. Nitrate, however, does not appear to be strongly adsorbed on biochar surfaces. However, the adsorption of NH_4^+ and organic molecules that contain N may slow rates of nitrification and mineralization, respectively, and hence reduce the leaching of nitrate. In summary, biochar amendments improve the physical properties of both coarse and fine textured soils and increase the nutrient and water retention capacity of most soils.

Impact of biochar on crop yields

Field trials assessing the impact of soil biochar amendments on crop yields are currently under way in many parts of the world (Spokas et al., 2012). The results to date are highly variable. Some studies have reported spectacular yield increases, but these tend to be studies that involved poor quality soils that initially have very low yields. Most reports of yield trials on high-quality soils have found only small yield increases or no yield response due to biochar applications. A few studies have also reported negative yield responses due to biochar applications. The reason for these negative responses is not always clear. However, some biochars contain significant levels of phytotoxic polycyclic aromatic hydrocarbons. Other studies have reported physiologic changes in some plant species, which are consistent with plant hormone activity. The presence of phytoactive compounds is associated primarily with high-temperature biochars. The results demonstrate the critical importance of biochar quality; hence anyone interested in experimenting with biochar is advised to use a proven product.

Across the Midwest Corn Belt biochar applications are anticipate to have little or no impact on crop yields for high-quality well-managed soils. However, on coarse textured soils where yields are limited by low nutrient and water holding capacities and on fine textured soils where yields are limited by poor aeration and drainage, biochar may help. Biochar may also be effective for solving compaction problems in some soils. A one-time deep injection of biochar into soils with hard setting E horizons, for example, could permanently eliminate the need for frequent deep ripping. Thus we see little benefit from uniform applications of biochar on Midwestern corn and soybean fields, rather agronomic value is more likely to be associated with site-specific applications designed to alleviate a specific soil problems.

The emerging biochar industry

At this time, the nascent biochar industry in the US consists of a handful of entrepreneurs selling biochar in small quantities to home gardeners for use in their back yards, to the horticulture industry for use as a component of soil-less potting media and as a soil conditioning agent, to corporations and government agencies for reclamation of contaminated soils including mine lands and urban brown fields (Beesley et al., 2011), and for use in systems designed to capture and temporarily retain urban storm runoff. What these markets have in common is high value and the need for relatively small quantities of biochar. The current price of biochar is approximately $1000 per ton. At such high prices, biochar is cost prohibitive for most Midwestern corn and soybean farmers. To reduce the price to a level that would be affordable will require a large increase in the supply of biochar. The most likely scenario that could lead to a large increase in supply is the production of a biochar co-product in the emerging cellulosic bioenergy industry.

Biochar potential in the emerging cellulosic bioenergy industry

Pyrolysis of corn stover, switch grass, hardwood and other forms of biomass produces three products, syngas, bio-oil, and biochar (Wright et al., 2010; Laird et al., 2009). Syngas is a combustible gas with only about one tenth the energy density of natural gas; none-the-less, syngas can be burned to produce heat, steam, and/or power. The syngas produced during pyrolysis can conveniently be burned to provide some of the heat needed to operate a pyrolysis plant. Bio-oil is a liquid energy raw material with about half the energy density of petroleum. Bio-oil is not an ideal fuel as it is acidic, contains various amounts of water, and has a tendency to gel; however, bio-oil mixed with 20% ethanol can be used as boiler fuel. The use of corrosion resistant fuel injectors, storage tanks, and other components is necessary for this application. Alternatively, bio-oil can be refined through the use of hydrocracking to produce diesel and other products currently produced from petroleum. Pyrolyzers can also be designed to separate aqueous and non-aqueous bio-oil fractions through differential condensation of the pyrolysis vapors. This process produces a superior "biocrude" that can be mixed with petroleum and processed at existing US oil refineries. The acidic aqueous phase is of relatively low value, but potentially could be steam reformed to produce H_2 gas.

Gassification is an alternative thermochemical technology for transforming diverse biomass feedstocks into syngas and biochar. Gasification is exothermic, which means it generates excess heat through the partial combustion of the biomass feedstock. The process heat and heat generated from combustion of the syngas can be used to generate steam for a coupled industrial process or to generate electric power. An obvious example for the Midwest would be to couple a biomass gasifier with and existing grain ethanol plant. In this scenario, the gasification of corn stover would generate the heat and power needed to run the ethanol plant replacing coal or natural gas while generating a biochar co-product.

Syngas can also be transformed directly into synthetic liquid transportation fuels and other products through the Fischer-Tropsch (FT) process. The FT process is used at an industrial scale by Sasol in South Africa to produce synthetic fuels from coal. The industrial scale production of FT synthetic fuels from biomass is technologically doable; however high startup costs and the relatively low energy conversion efficiency have so far been prohibitive. The coupling of a biomass gasifier with an industrial plant, such as the grain ethanol plant scenario discussed above, and the development of stand alone or coupled fast pyrolysis plants are seen as attractive small or medium scale alternatives to large-scale FT plants for the thermochemical production of biofuels from biomass. A distributed network of small and medium scale gasifiers and/or pyrolyzers addresses many of the logistic challenges associated with the handling, storage, and transportation of biomass. At this time numerous small and medium sized industrial gasifiers are operating in the US, commonly using municipal solid waste as a fuel. While this is an efficient way to turn waste into usable energy, the ash or char generated by these systems is generally not suitable for use as a soil amendment, due to the presence of heavy metals or other contaminants. Only a couple of industrial scale biomass pyrolyzers are currently operating in the US, and these are targeting the production of high-value specialty products. However, there is considerable interest among both small entrepreneurial companies and large multinational corporations in the development of industrial biomass pyrolysis for the production of liquid transportation fuels. For example, Kior inc. (http://kior.com) is building one of the first industrial pyrolyzers in Columbus Mississippi, which is targeting Southern Yellow Pine as a biomass feedstock. Whether or not corn stover based thermochemical bioenergy industry develops in the Midwest will depend on the price of petroleum, the price of natural gas, and the political fate of government regulations designed to encourage renewable energy production.

The sustainability of harvesting crop residues for use as a feedstock in bioenergy production is a significant concern. Most crop residues are currently returned to the soil where they provide substrate for the microorganisms responsible for nutrient cycling and contribute to the formation of biogenic soil organic matter. If crop residues were harvested year after year the quality of Midwestern soils would degrade and ultimately soil productivity would decline. Thus any reliance of the emerging cellulosic bioenergy industry on crop residues as feedstock for either enzymatic or thermochemical processing must be coupled with new agricultural management systems that add carbon to the soil. Such management systems may include greater use of cover crops, no-tillage, crop rotations that include forages, and both manure and biochar applications. Biochar applications in particular will return most of the inorganic nutrients that are removed from the soil when the biomass is harvested (Schnell et al., 2012), add a highly stabilized form of C to soils, and build soil quality.

Summary

In summary, biochar applications are not expected to improve crop yields on high-quality Midwestern soils, but are of potential agronomic value when targeted to solve specific soil quality problems such as low nutrient and water holding capacity, poor drainage, and compaction. Biochar quality is critical; some biochars contain phytoactive compounds, which can adversely affect crop growth. At this time the cost of biochar is prohibitive for large scale production agricultural. Because of the high cost the emerging biochar industry is targeting high-value low-volume applications in horticulture and land reclamation. The best chance for reducing the price of biochar to a level that would be affordable for Midwestern grain and soybean farmers is to increase the supply through the thermochemical conversion of biomass to bioenergy and biochar, co-products. Under such a scenario the use of biochar as a soil amendment would help to enhance sustainability of biomass harvesting by recycling nutrients, sequestering C, and building soil quality.

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