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Progressing from Terra Preta de Índios to the Whole World

Biochar: a review

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Climate change mitigation

In the context of this abstract, carbon sequestration is the primary driver for considering the application of biochar to soil. Policy makers charged with meeting greenhouse gas emission targets and addressing public concern over increasingly evident climate change may recognize the potential for biochar-based strategies. The land-owner or farmer is likely to have a more practical or financial perspective. A particular combination of feedstock, pyrolysis technology, energy conversion and byproduct usage can comprise a biochar-based system. Alternative systems have different greenhouse gas balances. Additionally, economically and politically conceivable systems for different regions of the world must be considered. The future price of carbon and the inclusion of biochar in carbon-trading schemes is a key factor as well the likely additional benefits of biochar to agricultural production. These factors are critical since they dictate whether relevant practices are adopted on a large scale through their effect on the decision making of individual farmers. From a global and policy perspective the potentially negative impacts of biomass use on climate forcing must be considered. These include the effects of soot and trace gases that are emitted into the atmosphere during combustion. Airborne transport and deposition of soot has been implicated in the acceleration of polar ice melt, but conversely in facilitating cloud formation and 'global dimming' (McConnell et al., 2007; Ramanathan et al., 2008). Currently biomass burning accounts for 10% of global CH_4 emissions and 1% of N_2O (Crutzen et al., 1990). Although current charcoal production activity could account for a component of these emissions (Woolf, 2008), a general shift to pyrolysis-based systems would decrease, if not eliminate, them. However, the net result with great expansion of alternative bioenergy systems have not been assessed. As is apparent in the loam soil, the addition of biochar can dramatically darken the colour of soil, especially in soils that are low in organic matter. A relationship between soil colour and low temperature fire occurrence has been demonstrated (Ketterings et al., 2000). Oguntunde (2008) found soil at charcoal manufacturing sites to have 8% greater hue, and 20% higher value and chroma. Since dark soils absorb more solar energy they may, depending on water content and plant cover, display higher soil temperatures (Krull et al., 2004). This will affect rate processes, enhancing the cycling of nutrients and potentially extending the growing season in seasonal climates. In Japan it is a traditional farming practice to apply charcoal to accelerate snow melt. Anecdotal evidence suggests more rapid crop establishment in temperate soils enriched in char, but to date no quantitative relationships between biochar application rate and these parameters have been reported. The study of Oguntunde (2008) showed a one-third reduction in soil albedo in soils enriched in char. On a large spatial scale, the application of biochar could affect the albedo of the Earth's surface. Increasing surface albedo has been proposed as a possible mitigation measure for climate forcing (Crutzen, 2006). The frequency with which potentially toxic compounds materialize in biochar and their concentration is inadequately researched. Two classes of compounds are of generic concern, since they can potentially from in the pyrolysis of any feedstock: polycyclic aromatic hydrocarbons (PAH) and dioxins.

Soil fertility

Expectation of increased soil fertility benefits arise from studies of the *Terra Preta* that contains high proportions of black carbon (Haumaier et al., 1995; Glaser et al., 2002; Lehmann et al., 2003; Lehmann and Rondon, 2006). The evident fertility of the *Terra Preta* is generally attributed to high soil organic matter content – organic matter assists in the retention of water, soil solution and cations – and the retentive capacity of aged biochar itself for nutrients and water. The black carbon present in *Terra Preta* is thought to originate from partially-combusted biomass residues derived from a range of anthropogenic activities, including kitchen fires and field burning. A particularly striking characteristic is a stronger relationship between soil carbon content and soil CEC in these soils relative to adjacent land, indicating that biochar comprises a greater proportion of soil carbon (Liang et al., 2006). Since CEC is indicative of the capacity to retain key nutrient cations in the soil in plant-available form and minimize leaching losses, this is cited as a key factor where differences in crop productivity are observed. High rates of biochar addition in the tropical environment have been associated with increased plant uptake of P, K, Ca, Zn and Cu (Lehmann and Rondon., 2006). In contrast to mainstream chemical fertilizer, biochar also contains bioavailable elements such as selenium that have potential to assist in enhancing crop growth. There has been much speculation concerning the potential effects of biochar on microbial activity in soil, which in the context of *Terra Preta* has been reviewed in detail by Steiner et al. (2003). Assuming that plant inputs and hence microbial substrate remain unchanged, enhanced microbial activity alone would diminish soil organic matter. However, this is contrary to the observation in *Terra Preta*, where soil organic matter is generally higher than in similar surrounding soil (Liang, 2006). However, a change in the balance of microbial activity between different functional groups could benefit crop nutrition, specifically enhancement of mycorrhizal fungi (Ishii et al., 1994), and this could feed back into higher net primary productivity and carbon input. There is relatively extensive literature documenting stimulation of indigenous arbuscular mycorrhizal fungi by biochar, and this has been reflected in plant growth e.g. Rondon (2007), Nishio (1996). This literature has been reviewed in some detail by Warnock (2007), who proposed four mechanistic explanations, of which a combined nutrient, water and CEC effect was considered most probable.

Crop yield

The majority of currently published studies assessing the effect of biochar on crop yield is generally small scale, almost all short term, and sometimes conducted in pots where environmental fluctuation is removed. These limitations are compounded by a lack of methodological consistency in nutrient management and pH control, biochar type and origin. Studies in a wide range of climates, soils and crops have been conducted. It is not therefore possible at this stage to draw any quantitative conclusion, certainly not to project or compare the impact of a particular one-time addition of biochar on long-term crop yield. Nonetheless, evidence suggests that at least for some crop and soil combinations, moderate additions of biochar are usually beneficial, and in very few cases negative. Glaser (2001) reviewed a number of early studies conducted during the 1980s and 1990s. These tended to show marked impacts of low charcoal additions (0.5 t ha^{-1}) on various plant species. Higher rates seemed to inhibit plant growth. In later experiments, combination of higher biochar application rates alongside NPK fertilizer increased crop yield on tropical Amazonian soils (Steiner et al., 2007) and semi-arid soils in Australia (Ogawa, 2006). Due to the year to year variation in climate and its impact on short-term dynamics, results from a number of field experiments recently set up are, whilst generating data, not yet published. The nature and mechanistic basis for interactions between crop, soil type, biochar feedstock, and production method and application rate will have to be understood to gain predictive capacity for the performance of biochar in soil, and open the possibility for large scale deployment.

Priorities and future challenges

Based on the results of this review, the following research priorities have been identified:

1) Determine a predictive relationship for properties and qualities of biochar and its manufacture such that it can be optimized for use in soil.

2) Examine how the possibility of adverse impacts on the soil and atmosphere can be eliminated with certainty.

3) Model the impact of alternate bioenergy systems on the carbon cycle at the global scale, and in the context of national targets, in order to support policy decisions and devise suitable market instruments.

Since the underlying context for biochar-based strategies is that of global climate change, research needs to provide answers that are applicable under diverse combinations of climate, agriculture and energy production systems. This requires a fundamental, mechanistic understanding of how biochar provides its unique functional characteristics, probably embodied in models, and would include its interactions with other living and nonliving components of soil.

Globally coordinated research activity across a range of countries and climates is necessary if the global applicability of knowledge gained is to be rigorously assessed.