Biochar can enhance soil fertility and reduce greenhouse gas emissions

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Abstract
Biochar has the potential to make a major contribution to climate change mitigation and enhancement of soil fertility. It has been found to stimulate plant growth by up to 100% in some situations, but before the use of biochar is broadly adopted in agricultural systems, we need better understanding of properties of biochar and how biochar interacts with soil, plants and microorganisms to enhance soil fertility and reduce greenhouse gas (GHG) emissions. Current research by Rural Climate Solutions (NSW Department of Primary Industries (DPI) and University of New England) aims to fill some of these gaps. Our research shows that biochar is a stable carbon form with very slow decomposition; that biochar properties are dependent on the biomass feedstock and the production process; and that biochar can stimulate plant growth and reduce nitrous oxide emissions from soil. Evidence is emerging that biochar can stabilise native carbon in soils containing reactive clay minerals. Life cycle assessment of biochar systems shows that the major contributions to climate change mitigation arise from organic matter stabilisation, avoided nitrous oxide and methane emissions, and displacement of fossil fuels. The total abatement value of biochar production and application processes can be greater than the CO_2 sequestered in biomass. Current research is improving understanding of biological, chemical and physical processes contributing to the beneficial (and sometimes adverse) impacts of biochars on soil fertility and crop productivity. Further effort is needed to develop reliable and efficient methods to identify beneficial biochars, and match them to specific soil constraints to maximise crop productivity and reduce GHG emissions.

Introduction
Biochar is the term given to the solid charcoal-like material produced by heating biomass in a low-oxygen environment, when this material is applied as a soil amendment. Use of biochar is not a new concept: the highly fertile terra preta soils in the Amazon have apparently resulted when Amerindians in pre-Columbian times buried charcoal and wastes in the naturally infertile Oxisols (Ferrosols). Research into the properties and impacts of biochar has flourished in recent years. DPI has undertaken some of the earliest trials with “modern biochar”, manufactured using a process known as slow pyrolysis, in an engineered facility where process conditions and emissions are well-controlled. Slow pyrolysis produces both bioenergy, in the form of combustible syngas, and biochar (Downie and Van Zwieten 2012). NSW DPIs research has focussed on the agronomic impacts of biochar, the properties of different biochars, especially with respect to the stability of biochar C in soil, its influence on nitrous oxide emissions from soil, and the life cycle GHG impacts of biochar systems. This paper reviews recent published and unpublished results from DPIs research.

Biochars vary
A wide range of biomass materials can be used for biochar, including wood waste, manures, and urban green waste. The properties of biochar vary widely depending on the feedstock and pyrolysis conditions. Biochar is often alkaline, so can have a liming value. Biochars from materials such as manures and papermill sludge have a high content of minerals (Singh et al. 2010a), which can be a valuable nutrient source.

Biochar is a stable carbon form
Due to its predominantly condensed aromatic structure (McBeath and Smernik 2009) biochar is resistant to chemical and microbial decomposition. DPI research shows that mean residence time of biochars ranges from hundreds to thousands of years, depending on feedstock and pyrolysis conditions (Singh and Cowie 2010; Fig. 1). Manure biochars produced at lower temperatures decompose faster than those made from woody biomass, and at higher temperatures. Figure 1 shows the relationship between biochar carbon stability, pyrolysis conditions and feedstock, for a range of C3 biochars incubated in a clay soil containing C4 organic matter under ideal and controlled environmental conditions in the laboratory (Singh et al., unpublished). Biochar carbon decomposition rate was high initially, but stabilised rapidly with time, suggesting that biochars contain a small amount of labile carbon, but a large recalcitrant carbon fraction.

Proceedings of the 16th ASA Conference, 14-18 October 2012, Armidale, Australia. Web site www.agronomy.org.au

Biochar can stabilise native soil carbon

It has been suggested that biochar may stimulate decomposition of native soil organic matter, known as a "positive priming" effect, which could potentially offset climate change mitigation benefits of biochar (Wardle et al. 2008). Some subsequent studies support this claim, though others do not. Research by DPI and University of Sydney collaborators, using laboratory incubation and field-based studies, has found that although biochar may stimulate native soil organic carbon mineralisation in the short term, an effect related to labile C content in biochar, biochar presence leads to stabilisation of native soil organic carbon in the longer term (Keith et al. 2011; Singh and Cowie, unpublished; Slavich, unpublished). The magnitude of biochar-induced loss of native soil organic carbon appears to be small in comparison with the carbon fixed in the recalcitrant portion of the biochar. Stabilisation of native soil organic carbon may only occur in clay soils (Singh et al. unpublished; Fang et al. unpublished). Further research is under way using biochars with different decomposition rates and soluble organic matter contents to examine the timing, direction and persistence of the priming effect of biochar in soils of contrasting mineralogy and carbon levels.

Biochar can reduce nitrous oxide emissions from soil

DPI research has shown that, in laboratory conditions, biochars can substantially reduce N_2O emissions from soil (Singh et al. 2010b; Van Zwieten et al. 2010a), particularly when conditions are favourable for denitrification . However, field measurements have shown inconsistent results, with reductions of up to 20% in some situations, but small increases in others (Van Zwieten, unpublished). The reduction in N_2O emissions in the presence of biochar, where it occurs, could result from: a) reduced bioavailability of labile organic carbon and nitrogen due to their sorption on aged biochar surfaces and their subsequent stabilisation through interaction with soil, (b) increased soil pH through addition of alkalinity in biochars, and/or (c) increased soil porosity due to reduction in soil bulk density. Current research, including use of CT scanning to quantify porosity (Fig. 2), is focused on identifying which of these explanations are most likely.

Biochar can enhance plant growth and/or reduce fertiliser requirements

Although both positive and negative impacts on crop productivity have been recorded a meta-analysis of published responses to biochar application showed that, on average, yields were increased by 10% (Jeffery et al. 2011), while some studies have found stimulation of plant growth by up to 100% or more (Waters et al. 2011). DPI research has demonstrated that at rates of around 10-20 t/ha, a typical application rate for organic amendments, some biochars can enhance crop yields and/or reduce fertiliser requirements by more than 50% (Chan and Xu 2009). Response is dependent on biochar, soil type, and target crop. Positive responses have been observed with biochars from manures, which have high levels of available nutrients; biochar from papermill sludge (which has high liming potential) when applied to acid soil (Van Zwieten et al. 2010b); and greenwaste biochar when applied in combination with nutrients (Chan et al. 2007). Beneficial effects may result from the impacts of biochars on soil properties, which include reduced acidity, increased cation exchange capacity, increased water holding capacity, reduced soil strength, and enhanced activity of beneficial microbes (Singh and Cowie 2008; Chan and Xu 2009; Van Zwieten et al. 2010b). Biochar develops reactive surfaces during aging in soil (Joseph et al. 2010) that can adsorb nutrients, reducing leaching (Singh et al. 2010b) and thus contributing to increased fertiliser use efficiency.

Biochar can contribute to climate change mitigation

Pyrolysis of biomass to produce biochar can offer multiple benefits in terms of mitigation of GHG emissions: delayed CO_2 emissions from biomass decomposition, stabilisation of native soil organic carbon, decreased N_2O emissions from soil, reduced manufacture of GHG-intensive nitrogen fertiliser. Furthermore, the pyrolysis process can produce syngas which may be used for heat or electricity avoiding emissions from fossil fuels. Additionally, if the feedstock is a biomass material that would otherwise have released methane or N_2O, for example from manure handling, production of biochar can avoid these emissions. An assessment of the theoretical potential mitigation from biochar applications estimated that global implementation of biochar systems could offset about 12% of global GHG emissions, with 50% of the reduction from C sequestration, 30% from replacement of fossil fuels and 20% from avoided emissions of methane and N_2O (Woolf et al. 2010). DPI research (Gaunt and Cowie 2009; Cowie et al. unpublished) has applied life cycle assessment (LCA) to quantify the climate change impacts of biochar production and use as a soil amendment. The net impact of biochar is determined by comparing the biochar life cycle with the applicable reference system, representing the conventional soil amendment and use of the biomass, and, where the biochar production process produces an energy co-product, the conventional energy source. LCA studies have estimated net emissions reduction for different biochar scenarios of -1.1 to 3.2 t CO_2e per t (dry) feedstock where waste material and residues are utilised for biochar production. The wide variation in these assessments results from differences in the biochar scenarios (feedstock type and its alternative fate; design and scale of pyrolysis plant; displaced fossil energy source) and differences in assumed impacts of biochar. Uncertainty is high, particularly for the impacts of biochar on plant growth, fertilizer requirements and nitrous oxide emissions. The major contribution to abatement arises from carbon storage in biochar, while the contribution of avoided nitrous oxide emissions from soil, avoided methane emissions from landfill, displacement of fossil fuel emissions and organic matter stabilization varies between alternative scenarios, and is highly dependent on the assumptions employed. The total abatement value can be greater than the CO_2 sequestered in biomass, and can be greater than if the biomass was used solely for bioenergy.

Limitations of biochar

The greatest factor limiting the potential of biochar is the limited availability of biomass feedstock. While there are some biomass sources that could be readily diverted to biochar production (wastes that are otherwise landfilled or incinerated), utilisation of other biomass sources could have negative impacts: for example, harvest of crop stubble for biochar production could lead to soil erosion and reduction in soil carbon; cultivation of purpose-grown biomass crops could displace food production and result in indirect land use change. There are various hazards to be managed, and risks to be avoided in biochar production and use (Downie et al. 2012; Cowie et al. 2012). In particular, it is critical that the particulate and GHG emissions from biochar production are controlled, and that feedstock quality is managed to avoid air pollution and land contamination (Downie et al. 2012). While agronomic impacts of biochar are generally positive or neutral, negative effects have occasionally been recorded; clearly it is critical that these negative responses are understood so that they can be avoided or mitigated. The sorptive capacity of biochar can also produce negative effects: Kookana et al. (2011) observed that biochar application in pot trials reduced the efficacy of pre-emergent herbicides, while also reducing their biodegradability, which suggests that greater rates of herbicides may be required where biochar is applied, and that these substances will be more persistent in the environment. Further research is required to evaluate long-term impacts of biochar on herbicide efficacy under field conditions.

Conclusion

Biochar shows great promise as a technology that can contribute significantly to mitigation of climate change whilst assisting in the reduction of land degradation and promoting agricultural productivity. Further research is needed to develop reliable and efficient methods to identify beneficial biochars, and match them to specific soil constraints. Future research should focus on elucidating underlying processes, to allow extrapolation to different biochars, soil types and regions. Process-level knowledge should be used to define sustainable applications and develop good practice guidelines, to minimise risks, and facilitate uptake of beneficial biochar applications.

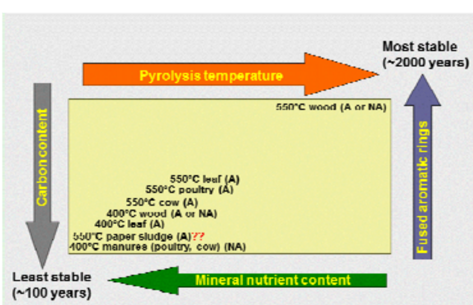

Figure 1 Factors influencing biochar carbon stability. Feedstocks as indicated; A=steam activated; NA = non-activated. BP Singh, E. Krull

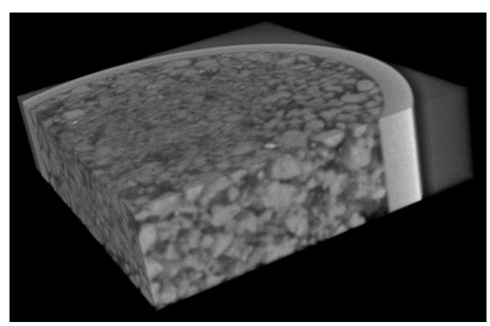

Figure 2 X-ray CT image stack showing oil mallee biochar (5%) in Vertosol.

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