GLOBAL SYMPOSIUM ON SOIL ORGANIC CARBON, Rome, Italy, 21-23 March 2017

Biochar as a strategy for sustainable land management and climate change mitigation

Annette Cowie[1], Lukas Van Zwieten[2], Bhupinder Pal Singh[2], Ruy Anaya de la Rosa[3]*

[1]University of New England, Armidale, NSW Australia; UNCCD Science Policy Interface; annette.cowie@gmail.com
[2]NSW Department of Primary Industries, NSW Australia.
[3]Starfish Initiatives, Armidale, NSW Australia

Abstract

Biochar could play a role in sustainable intensification and climate smart agriculture, through its capacity to enhance land productivity, build soil carbon, contribute to climate change mitigation via multiple mechanisms, and strengthen resilience of agricultural systems. Biochar is produced by pyrolysis, in which biomass is heated under oxygen limitation. Biochar properties depend on the biomass source, pyrolysis conditions and post-production treatments. Biochar is most beneficial in rehabilitating degraded lands and improving low-fertility soils with defined constraints to production. While carbon stabilisation is certain, other impacts of biochar vary widely and benefits are not universally observed. Biochars should be engineered to address specific soil/crop constraints in each target application. Enriched biochar, produced by adding minerals during pyrolysis and/or reacting the biochar with organic matter and minerals, has been shown as an effective fertiliser. Limitations to up-scaling biochar systems include constrained biomass availability particularly in drylands, high capital costs, lack of large-scale production facilities, and lack of awareness of the potential benefits and best methods for biochar utilisation. Risks associated with biochar include production in unsafe, polluting facilities; unsustainable harvest of biomass; and poor quality control. These risks can be managed through certification of biochar products, training and development of knowledge-sharing platforms to communicate best practice in production and use of biochar.

Keywords: Carbon sequestration; resilience; climate smart agriculture; life cycle assessment; greenhouse gas emission, soil health.

Introduction

Feeding the world’s growing population, expected to reach 9 billion by 2050, will be a major challenge, particularly under the influence of climate change and escalating land degradation. In addition, there is increasing competition for land for productive purposes (animal feed, fibre, timber), for urban expansion, transport infrastructure and mining, and for biodiversity protection and recreation.

Increasing food production while per capita resources are decreasing will require increased intensity of production, which may have undesirable environmental consequences if achieved through increased use of chemical fertilizers, agricultural chemicals and irrigation. It is critical that sustainable intensification practices are employed, focusing on efficient use of water, nutrients and land; protection of soil resources; and minimizing off-site impacts on natural and human systems.

Biochar could make an important contribution to sustainable intensification, while improving soil health. Furthermore, biochar offers benefits for climate change mitigation and adaptation. This paper summarises recent findings on the benefits and limitations of biochar in sustainable land management.

Role of biochar in climate change mitigation

Biochar is organic matter that is carbonized by heating in an oxygen-limited environment, and used as a soil amendment. Biochar can be produced from a wide range of organic sources including crop and forest residues, food processing waste, urban green waste, bio-solids, algae and animal manures.

The carbonization process stabilizes the carbon (C) in the biomass. Thus, biochars are relatively resistant to decomposition and therefore provide a long-term C store. Biochars have different properties depending on the feedstock, the conditions of production and post-production treatment: biochars produced at higher temperature, and from woody material tend to have greater stability than those produced at lower temperature, and from manures (Singh et al., 2012). Biochar stability is influenced by soil properties at the site of application, being further stabilized by interaction with clay minerals and native soil organic matter (Fang et al., 2015). Biochar stability has been estimated to range from decades to thousands of years, for different biochars in different applications (Weng et al., 2015; Singh et al., 2015).

Application of biochar may further enhance soil carbon stocks through "negative priming", in which plant-derived carbon is stabilized through sorption of labile C on biochar, and formation of biochar-organo-mineral complexes (Keith et al., 2011; Weng et al., 2015). Conversely, turnover of native soil carbon may increase ("positive priming") due to enhanced soil microbial activity induced by small amounts of labile C in biochar, but this effect is small and short-lived compared to the stabilization of biochar carbon and negative priming effects in the long-term (Singh and Cowie, 2014). Negative priming has been observed particularly in clay-dominated soils (Weng et al., 2015; Whitman et al., 2015).

Biochar can provide additional climate change mitigation benefits through:

- Lower nitrous oxide (N_2O) emissions from soil: a meta-analysis showed an average decrease in emissions from soil of 54% (Cayuela et al., 2014). Processes involved in this response include decrease in substrate availability for denitrifying organisms, driven by the molar H/C ratio of the biochar (Cayuela et al., 2015). Recent studies have improved understanding of the processes involved, and increased ability to predict the likely impact based on biochar characteristics, soil type and environment. Decrease in N_2O emissions from agricultural soils could be important for intensive broadacre and horticultural cropping systems with high N fertilizer inputs, particularly where irrigated, or for manure feedstocks where emissions from manure processing (Agyarko-Mintah et al., 2016) and application can be reduced.
- Reduced fertilizer requirements: there is substantial evidence that biochar reduces the requirement for fertilizer, due to reduced losses of nutrients through leaching and/or volatilization. This is particularly important for nitrogen (N) fertilizer, the production of which is a greenhouse gas (GHG)-intensive process.
- Avoided emissions from decomposition of organic wastes that are instead used for biochar, such as manure that would otherwise be stockpiled, crop residues that would be burned or processing residues that would be landfilled.

Biochar is a potential "negative emissions" technology: the thermochemical conversion of biomass to biochar slows mineralization of the biomass, delivering long term C storage; gases released during pyrolysis can be combusted for heat or power, displacing fossil energy sources, and could be captured and sequestered if linked with infrastructure for carbon capture and storage (Smith, 2016).

Role of biochar in sustainable land management

Biochar can contribute to sustainable land management through the following documented benefits:

- Increased yields: biochars have variable impacts on yields, depending on the feedstock, properties of receiving soil and the target crop, and negative responses are sometimes seen (Macdonald et al., 2014). Yield benefits are generally greatest in poor soils, especially light-textured acidic or degraded soils. Meta-analyses show that the average yield response is +10% (Jeffrey et al., 2011). Identifying soil constraints and addressing these with appropriate biochar is essential to obtain a positive outcome.

- Improved nutrient use efficiency: biochars can enhance retention of N and availability of phosphorus (P) in soils with high P fixation capacity, potentially reducing fertilizer requirements. Furthermore, biochar produced from nutrient dense feedstocks, such as poultry litter, can substitute chemical fertilizer.
- Management of heavy metals: application of biochar can reduce availability of heavy metals, thus providing an affordable means of remediating contaminated soils, and enabling the continued utilization of such soils for food production.
- Improved water holding capacity: biochar could limit plant water stress in sandy soils by improving the soil's water holding capacity (Basso et al., 2013).

Biochar systems can deliver a range of other co-benefits, such as waste management, destruction of pathogens and weed propagules, avoidance of landfill, improved ease of handling, management of odors, reduction in environmental N pollution, protection of waterways and soil remediation.

Risks and Constraints to biochar up-scaling

The following issues have been identified:

- Limitations of biomass availability: in dryland developing countries, biomass is utilized for fuel, feed and soil protection, and there is rarely surplus that could be used for biochar. Nevertheless, conversion from inefficient fuelwood use to efficient biochar stoves could allow biochar production, while also reducing indoor air pollution.
- Risk of unsustainable harvest of biomass: unless controlled, biomass could be harvested unsustainably, with negative implications for C stocks, biodiversity and local communities. Purpose-grown biomass for biochar production may be a viable land use on marginal or contaminated lands that are not suited for cropping. However, if practiced on productive land, there is a risk of indirect land use change that should be quantified, and policies should be introduced to minimize this risk.
- Risk of polluting production methods: to ensure that biochar production does not contribute to air pollution and methane emissions, it is critical that biochar is produced in a facility that captures or combusts the gases released during pyrolysis. The heat produced through combustion of pyrolysis gases can be used as renewable energy. Biochar production can occur at scales ranging from cookstoves to large engineered industrial plants.

Potential contribution to climate change mitigation

Studies of the life cycle climate change impacts of biochar systems generally show emissions reduction in the range 0.4 -1.2Mg CO2-e Mg^{-1} (dry) feedstock. The proportion of C sequestered and GHG emissions avoided varies widely between biochars, soils and target crops. For example, biochar applied to wheat grown in a sandy soil in a temperate environment could give 32-62% lower abatement than the same biochar applied to maize grown in a clayey soil in a subtropical environment (Cowie and Cowie, 2013).

A global analysis in which sustainability constraints were applied to protect against food insecurity, loss of habitat and land degradation, found that annual net GHG emissions could be reduced by up to 3.7 - 6.6Pg CO_2-e per year (7 to 12% of 2012 anthropogenic GHG emissions), with total net emissions over the course of a century reduced by 240 – 475Pg CO_2-e. (Woolf et al., 2010).

Novel biochar formulations

Much of the research into biochar has utilized high doses – e.g. ≥10 t ha^{-1} – of raw biochar. However, high rates of application may be prohibitively expensive for many land holders. Improved understanding of the chemical reactions occurring at the biochar surface has led to design of enriched biochar, produced through mixing biomass with minerals prior to pyrolysis, or composting biochar with manure and ash. These nutrient-enhanced biochar formulations can be effective in stimulating plant growth and/or immobilizing heavy metals at much lower application rates (Joseph *et al*., 2013).

Conclusions

Application of biochar as a soil amendment has been trialed in a wide range of agricultural systems, on various field crops and pastures around the world. Studies have found that biochar can improve plant yields, enhance soil water holding capacity and reduce fertilizer requirements, though results vary widely between different biochars, soil types, climates and target crops. Biochars should be designed to address specific soil constraints.

There are a range of mechanisms by which biochar can deliver GHG mitigation: the most important, and best understood, are stabilization of C in biomass feedstock (delaying significantly the decomposition of biomass), and displacement of fossil fuels with the combustible gases or bio-oil which are co-products of biochar production. Other mechanisms that can contribute to mitigation include lowered N_2O emissions from soil; reduced fertilizer manufacture; enhanced growth; reduced fossil fuel use in irrigation and cultivation; and avoided emissions from biomass decomposition. Recent evidence indicates that biochar can stabilize C inputs to soil from plants, thus increasing soil C stocks beyond the C applied in biochar.

Biochar is thus a technology that can simultaneously enhance soil productivity, and contribute to climate change mitigation and sustainable development. It is therefore well-suited as a strategy for sustainable land management and climate smart agriculture.

References

Agyarko-Mintah, E., Cowie, A.L, Singh. B-P, et al. 2016 Biochar increases nitrogen retention and lowers greenhouse gas emissions when added to composting poultry litter. Waste Managementhttp://dx.doi.org/10.1016/j.wasman.2016.11.027

Basso, A.S., Miguez, F.E., Laird, D.A., et al.., (2013). Assessing potential of biochar for increasing water-holding capacity of sandy soils. GCB Bioenergy, 5(2), pp.132-143.

Cayuela, M. L., van Zwieten, L., Singh, B. P., et al. (2014). Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis. Agriculture, Ecosystems & Environment, 191, 5-16.

Cayuela, M.L., Jeffery, S, and Van Zwieten L, 2015. The molar H:Corg ratio of biochar is a key factor in mitigating N_2O emissions from soil. Agriculture Ecosystems and Environment 202, 135-138.

Cowie, A. L. and Cowie, A. J. (2013) 'Life cycle assessment of greenhouse gas mitigation benefits of biochar', Report to IEA Bioenergy Task 38
http://www.task38.org/publications/T38_Biochar_case_study.pdf

Keith, A., Singh, B. and Singh, B. P. (2011) 'Interactive priming of biochar and labile organic matter mineralization in a smectite-rich soil', Environmental Science and Technology, vol 45, pp9611-9618

Fang Y, Singh B, Singh BP (2015). Effect of temperature on biochar priming effects and its stability in soils. Soil Biology and Biochemistry. 80, 136–145.

Jeffery, S., Verheijen, F. G. A., Van der Velder, M., & Bastos, A. C. (2011). A quantitative review of the effect of biochar application to soil on crop productivity using meta -analysis. Agriculture, Ecosystem and Environment, 144, 175-187.

Joseph, S., Graber, E. R., Chia, C., et al.. (2013) 'Shifting paradigms: development of high-efficiency biochar fertilizers based on nano-structures and soluble components', Carbon Management, vol 4, pp323-343

Macdonald, L.M., Farrell, M,. Van Zwieten, L., & Krull, E.S. 2014 Plant growth responses to biochar addition: an Australian soils perspective. Biology and Fertility Soils, 7. 1035–1045

Singh, B. P. and Cowie, A. L. (2014) 'Long-term influence of biochar on native organic C mineralisation in a low-C clayey soil', Scientific Reports, vol 4, article 3687

Singh, B. P., Cowie, A. L., & Smernik, R. J. (2012). Biochar Carbon Stability in a Clayey Soil As a Function of Feedstock and Pyrolysis Temperature. Environmental Science Technology, 46(21), 11770–11778.

Singh BP, Fang Y, Boersma M, et al. (2015) In Situ Persistence and Migration of Biochar Carbon and Its Impact on Native Carbon Emission in Contrasting Soils under Managed Temperate Pastures. PLoS ONE 10(10): e0141560. doi:10.1371/journal.pone.0141560

Smith, P., 2016. Soil carbon sequestration and biochar as negative emission technologies. Global change biology, 22(3), pp.1315-1324.

Weng Z, Van Zwieten L, Singh BP, et al. (2015) Plant-biochar interactions drive the negative priming of soil organic carbon in an annual ryegrass field system. Soil Biology and Biochemistry 90: 111–121.

Whitman T, Singh BP, Zimmerman A (2015) Priming Effects in Biochar-Amended Soils: Implications of Biochar-Soil Organic Matter Interactions for Carbon Storage. In: (Eds. Lehmann J, Joseph S), “Biochar for Environmental Management: Science, Technology and Implementation”, 2nd Edition, pp. 455-488, Earthscan from Routledge, USA.

Woolf, D., Amonette, J. E., Street-Perrott, F. A., et al. (2010) 'Sustainable biochar to mitigate global climate change', Nature Communications, vol 1, No56