CSIRO PUBLISHING
Soil Research, 2014, **52**, 739–750
http://dx.doi.org/10.1071/SR14112

Review

Opportunities and constraints for biochar technology in Australian agriculture: looking beyond carbon sequestration

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Abstract. The application of biochar technology for soil amendment is largely based on evidence about soil fertility and crop productivity gains made in the Amazonian Black Earth (*terra preta*). However, the uncertainty of production gains at realistic application rates of biochars and lack of knowledge about other benefits and other concerns may have resulted in poor uptake of biochar technology in Australia so far. In this review, we identify important opportunities as well as challenges in the adoption of biochar technology for broadacre farming and other sectors in Australia. The paper highlights that for biochar technology to be cost-effective and successful, we need to look beyond carbon sequestration and explore other opportunities to value-add to biochar. Therefore, some emerging and novel applications of biochar are identified. We also suggest some priority research areas that need immediate attention in order to realise the full potential of biochar technology in agriculture and other sectors in Australia.

Additional keywords: biochar characterisation, contaminants, herbicide efficacy, heavy metals, nitrous oxide, plant growth media, regulations.

Received 1 May 2014, accepted 25 August 2014, published online 5 November 2014

Introduction

Biochar is a carbon (C)-rich, solid material produced by thermal decomposition of organic material or biomass in the absence, or under limited supply, of oxygen (Lehmann and Joseph 2009). Biochar is generally produced with the intent of long-term C storage in soil and other potential benefits to soils, including their physical, chemical and biological fertility. The concept of biochar application to soil has arisen based on observations made in the Amazonian Black Earth (*terra preta*), which has higher organic C content and better fertility than the surrounding natural (unamended) soils (Sombroek 1966; Zech *et al*. 1990). Sohi (2012) suggested that 'over decades, the use of biochar could create soils that in management and function begin to resemble the fertile terra preta'. However, it has been recently shown that *terra preta* have been produced by unintentional addition of inorganic (e.g. ash, fish bones) and organic (e.g. biomass wastes, manure, excrements, urine, biochar) materials to highly weathered and infertile Ferralsols (Glaser and Birk 2012). Therefore, research observations on C sequestration and plant productivity on *terra preta* may not directly reflect all scenarios of soil biochar application.

Biochar production for soil application was initially advocated for long-term C storage by diverting waste biomass C from a rapid to a slow C-cycling pool in soil

(Lehmann 2007*a*, 2007*b*). Modelling results suggest that, under an ideal scenario, biochar application to soil has the potential to mitigate greenhouse gas emissions of the order of 1.8 Pg CO_2-C on an annual basis, and thus, it can make a substantial contribution to mitigating climate change (Woolf *et al.* 2010).

In addition to the long-term C storage potential of biochar, substantial research has been done in the last decade to understand other potential effects of biochars from their soil applications. For example, biochar may reduce greenhouse gas emissions, enhance agricultural productivity, and improve soil properties and microbial, fungal and mycorrhizal growth (Glaser *et al.* 2002; Lehmann *et al.* 2006; Chan *et al.* 2007; Kim *et al.* 2007; Gaskin *et al.* 2008; Kwapinski *et al.* 2010; Singh *et al.* 2010*b*). The potential of pyrolysis technology for waste management is also noteworthy (Kwapinski *et al.* 2010; Macías and Camps-Arbestain 2010). Despite the multiple potential benefits from the application of biochar to soil, the adoption of biochar technology has been slow. Indeed, a recent report considers the biochar industry in a fledgling state (Jirka and Tomlinson 2014).

The present paper highlights constraints and potential opportunities for the realisation of the potential of biochar technology in the Australian context. These are discussed in the context of biochar composition, its environmental behaviour, its various uses and potential areas of application, as summarised in Fig. 1. The paper has resulted from a synthesis of deliberations during a national workshop, where a range of stakeholders representing industry, academia, and research, policy and regulatory agencies participated.

Challenges and opportunities in the adoption of biochar technology for broadacre farming

Uncertainty of production gains

The emissions avoidance and carbon sequestration benefits of biochar application to soil are relatively straight forward; however, the agronomic and economic benefits of biochar are less clear. Biochar has been shown to increase crop productivity significantly in controlled glasshouse and field environments. However, significant negative and neutral results have also been demonstrated, and our ability to predict the growth outcomes in the broader agricultural context is lacking (Glaser *et al.* 2002; Jeffery *et al.* 2013). This uncertainty over the likely production outcomes hinders adoption across the wider community. The contrasting interpretations within the literature are partly due to the wide range of experimental conditions tested, including soil types, climate conditions, crop system, nutrient availability, and the type, rate and chemical characteristics of the biochar (Chan *et al.* 2007, 2008; Smider and Singh 2014).

For land application, the properties of biochar can be carefully selected to maximise the benefits appropriate for a particular soil (Fig. 1). Some studies recommend individual characterisation of biochar for soil application to optimise benefits and to minimise ecotoxicological risks (Novak *et al.* 2009; Singh *et al.* 2010*b*; Kloss *et al.* 2012). Recent meta-analyses conclude that biochar is more likely to be effective in enhancing plant growth in acidic than alkaline soil types (Atkinson *et al.* 2010; Jeffery *et al.* 2011; Biederman and Harpole 2013; Crane-Droesch *et al.* 2013). However, this is not always the case, as demonstrated in an acidic Tenosol with poor buffering capacity and poor fertility (Macdonald *et al.* 2014). Most biochars are alkaline in nature (Krull *et al.* 2012) and offer some degree of acid-neutralising capacity, which can potentially improve the availability of certain nutrients (phosphorus (P), molybdenum (Mo)) and reduce the availability of others (e.g. iron (Fe), zinc (Zn), boron (B)), and/or potentially alleviating toxicity (e.g. aluminium (Al)). In general, biochars produced from manure, greenhouse waste and grasses are more effective for nutrient provision than wood-based biochars (Atkinson *et al.* 2010; Singh *et al.* 2010*b*; Jeffery *et al.* 2011; Biederman and Harpole 2013; Crane-Droesch *et al.* 2013; Slavich *et al.* 2013; Smider and Singh 2014), and the opposite is true in terms of their C sequestration potential. The classification and certification systems developed by the International Biochar Initiative (IBI 2012) and The European Biochar Research Network (EBC 2012) are useful and could be adopted in assessing the complex properties of biochar produced from different feedstocks for particular soil applications.

Indirect gains from reduced emissions of nitrous oxide

More than two-thirds of the global nitrous oxide (N_2O) emissions originate from soil, and these emissions are closely linked with the use of nitrogen (N) fertilisers in agriculture. From

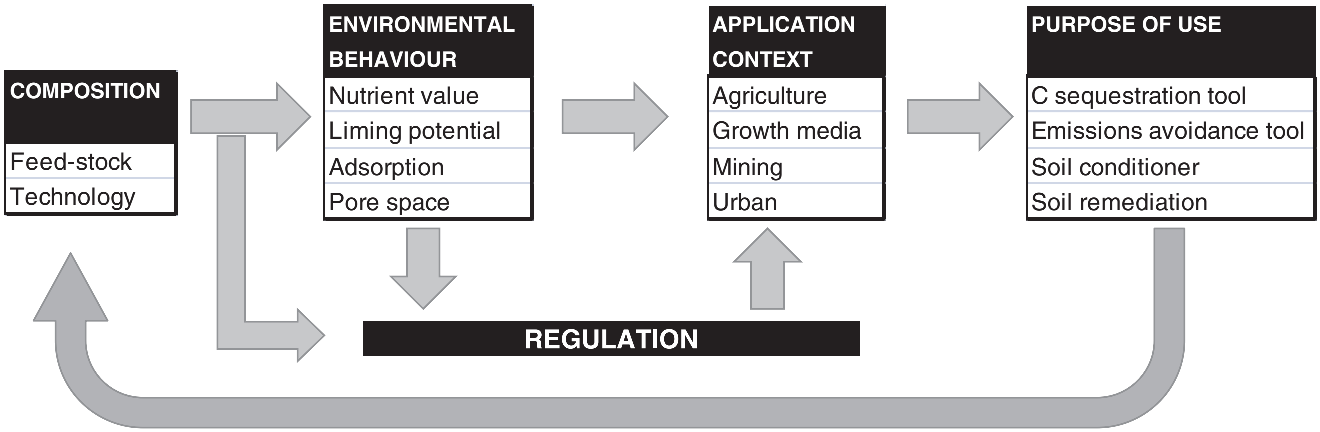

Fig. 1. Interrelationships between biochar composition, behaviour and application in the environment.

the meta-analysis of published literature from 2007 to 2013, Cayuela *et al*. (2014) determined 54% mitigation in N_2O emissions from the overall effect of biochar application to soil. The biochar feedstock, pyrolysis conditions, C/N ratio and application rate were found to be key factors influencing the emission of N_2O. Various mechanisms have been proposed to explain the influence of biochar on emissions of N_2O from soil (Van Zwieten *et al*. 2009). For example, evidence exists that biochar changes soil physical properties (e.g. gas diffusivity, water retention) (Quin *et al*. 2014), soil chemical properties (e.g. pH, Eh, availability of organic and mineral N and dissolved organic C (Singh *et al*. 2010*a*), and soil biological properties (e.g. microbial community structure, microbial biomass and activity, macrofauna activity, N-cycling enzymes) (Cayuela *et al*. 2013; Harter *et al*. 2013; Van Zwieten *et al*. 2014). These changes in soil properties influence N processes and pathways. The challenge is to fully understand the mechanisms by which biochar mitigates N_2O soil emissions across a range of soil moisture conditions under different agricultural systems; this will help to optimise the benefits and mitigate potential risk of the technology failing to achieve targeted improvements (Fig. 1).

Impacts of biochar on herbicide efficacy and options to mitigate such effects

Carbonaceous materials such as biochars are known to have strong affinity for pesticides. Some 40 years ago in Australia, Toth and Milham (1975) reported that some ash-C products caused a significant reduction in diuron phytotoxicity. Markedly reduced efficacy (up to 60%) was also noted for two pre-emergent herbicides, thiobencarb (*S*-4-chlorobenzyl diethyl (thiocarbamate) and molinate (*S*-ethyl azepane-1-carbothioate), when these herbicides were applied over rice stubble ash (Toth *et al*. 1981). Several studies have since confirmed reductions in the efficacy of pesticides in the presence of combustion residues in soil (Yang *et al*. 2006; Xu *et al*. 2008; Nag *et al*. 2011; Graber *et al*. 2012). Yang *et al*. (2006) observed that even doubling the application rate of diuron failed to control weed growth in the presence of 0.5% of wheat char in soil. More recently, Graber *et al*. (2012) noted that although weed control and herbicide efficacy were hindered in the presence of biochars, the effect depended upon the specific surface area (SSA) of biochars, with higher SSA biochar resulting in poorer weed control. The above laboratory studies indicate that there may be agronomic and/or economic implications, in terms of increased input cost of pesticides to the grower, if herbicide application rates need to be adjusted for biochar-amended soils. However, decreased efficacy of pesticides has been observed only with freshly applied biochars in the soil and under laboratory conditions and might not represent what occurs under field conditions. It has been suggested that after application to soil, biochar may rapidly lose its sorption capacity for herbicides (Martin *et al*. 2012). Further research is needed to investigate this aspect thoroughly and assess whether any significant and/or persistent agronomic effect of biochars on pesticide efficacy is likely under field conditions.

In terms of opportunities, even if any adverse effect on weed control is noted after application of biochar in soils under field conditions, options may be available to customise the applications of biochar to mitigate such effects. For example, banded application of biochar may be made at a certain depth in the soil rather than a blanket surface application, to minimise contact with herbicide. Application timing of biochar may be adjusted to minimise detoxification of herbicides by biochars. Biochar may also be conditioned before soil application to add value in terms of enrichment of nutrients, at the same time quenching its sorptive surfaces, which may otherwise detoxify herbicides. Clearly, because of a lack of suitable field study data, ‘the jury is still out’ on the practical impact of biochars on pesticide inputs. Given the potential economic importance of this issue and its possible effect on the acceptance of biochar technology, further research with field experiments is urgently needed.

Biochars: a source or sink of contaminants?

Some concern exists in the literature that the presence of organic or inorganic contaminants in the feedstock used for biochar production may present a long-term soil contamination problem (Kookana *et al*. 2011; Hale *et al*. 2012). For land application of biochar, it is important to know the composition of the feedstock and subsequent quality of the biochar. Commercial biochars in Australia and elsewhere are marketed with only limited (or without any) analytical data for the feedstock and the biochar. Polyaromatic hydrocarbons (PAHs), toxic metals and other organic and inorganic contaminants may occur in biochars. In a comprehensive study involving the analysis of >50 biochars, Hale *et al*. (2012) reported total PAH concentrations of 0.07–3.25 mg kg^{-1} for the slow-pyrolysis biochars, depending on biomass source, pyrolysis temperature and time. Generally, higher PAH concentrations have been found in biochars pyrolysed for shorter times and at lower temperatures (350–500°C) (Hale *et al*. 2012). However, the authors highlighted that even at very high application rates (up to 135 t ha^{-1}), the amounts of PAHs introduced through biochar would not cause a problem in the soil. Similarly, very low PAHs concentrations (<0.5 mg kg^{-1}) were found in 11 biochars produced from five feedstocks in Australia (Singh *et al*. 2010*b*). In another Australian study (Krull *et al*. 2012), a set of 40 different organic compounds, including 16 PAHs, were analysed in the 26 biochar samples. The sum of residues of 16 priority PAHs in the biochar samples was <2.5 mg kg^{-1} in all but two biochars. No guidelines exist for organic contaminants in biochars. The Australian accepted limit is 0.5 mg kg^{-1} for PAHs in soils (NEPM 1999), and mixing biochar in the top 20 cm soil conservatively results in a dilution factor of 200–300. Therefore, the predicted concentration of PAHs in the soil from a biochar application rate of 10 t ha^{-1} is expected to be the range 0.0001–0.01 mg kg^{-1}. These values are 50–5000 times lower than the above guideline value. Biochars are known to adsorb PAHs and other toxic contaminants, and therefore, there is a need to determine which tests give a true indication of the bioavailability and toxicity of PAHs in biochars. These issues need to be resolved so that appropriate guidelines and test procedures can be developed. Regulatory guidelines for

PAHs, dioxins and trace elements must be considered for biochar production and application to soils (Fig. 1).

Biochars offer opportunities to minimise the adverse impact of contaminants in the environment, because the ability of the biochar to bind contaminants can be harnessed for removal of contaminants from soils, sediments and water. In soils contaminated with polychlorinated dibenzo-p-dioxins or dibenzofurans, Chai *et al.* (2012) found that corn-stover ($SSA = 67\,m^2\,g^{-1}$) and pine woodchip ($SSA = 102\,m^2\,g^{-1}$) biochars reduced the bioavailability of 17 congeners of dioxins (measured in terms of toxic equivalent) by 59–62% in two soils. These biochars were found more effective than a coconut-based activated carbon ($SSA = 1320\,m^2\,g^{-1}$), which showed ~48% reduction in bioavailability; other activated C treatments were found to be more effective (80–99%) than biochars. Gomez-Eyles *et al.* (2013) compared the sorption of several persistent organic pollutants (POPs) as well as that of mercury and methyl-mercury from sediments amended with biochars and activated carbons. They found that non-activated biochars had sorption affinity for most POPs that was 1–2 orders of magnitude higher than the natural C in sediment, and resulted in a reduction in POP sediment pore-water concentration by 18–80%. The non-activated biochars were as effective as activated C in reducing the pore-water concentrations of methyl-mercury. Biochars are also known to sorb several toxic elements, including arsenic (As), copper (Cu), cadmium (Cd), nickel (Ni), lead (Pb) and zinc (Zn) (Cao *et al.* 2009; Namgay *et al.* 2010; Uchimiya *et al.* 2010; Beesley *et al.* 2011), possibly by forming surface complexes, which reduce their bioavailability and mobility in soils and sediments.

Potential off-site migration of pesticides used at golf courses has caused community concerns. Bacteria-inoculated biochars have been recommended for *in-situ* bioremediation of herbicide-contaminated golf courses (Takagi and Yoshida 2003). Sand-based golf greens, designed according to US Golf Association standards, usually have peat as one of the main constituents, with only limited ability to attenuate fungicides and herbicides used on golf greens. If carefully selected biochars are incorporated into the design of golf greens to the extent possible (without impinging on drainage and other characteristics of the green), it may help to reduce leaching of contaminants in the drainage water. Biochars may also enhance the attenuation capacity of buffer-strips and riparian zones along the waterways for minimising off-site impacts of contaminants (Hina 2013). The ability of biochars to sorb both organic and inorganic contaminants makes biochar a potentially attractive and cost-effective amendment for the remediation of contaminated soils and water with multiple organic and inorganic contaminants.

Production technology, capacity and costs

Regular supply of a sustainable and consistent feedstock is a challenge in the production of large amounts of biochar for agricultural soils (Downie *et al.* 2012). There are several competing end-users for the waste biomass, which can be used as a feedstock for large-scale biochar production, and small-scale local production using on-farm feedstock materials may be limited by the seasonal biomass production cycle. Although partly depending on the biochar production technology, pre-processing (drying or size reduction) of feedstocks is often required for biochar production. The particle size and moisture content of feedstocks need optimisation for the production of biochars. Unprocessed feedstocks with high water contents and large particle sizes will require greater inputs of energy to achieve the desired pyrolysis temperatures for biochar production, which decreases efficiencies (Kwapinski *et al.* 2010). High application rates of biochars with high content of soluble minerals can cause a salting effect in certain soils and/or plants (Smider and Singh 2014). Feedstocks with high N content may require pre-treatment, such as the addition of a smectitic clay, and then pyrolysis at low temperatures to retain agronomically useful N (Yao *et al.* 2014).

The collection and transportation of feedstock material is likely to form a significant component of the biochar cost, particularly in cases where the biochar production facilities are fixed and the feedstock has to be transported from a distant location. Additionally, there can be safety issues (such as spontaneous combustion) in the transport of large volumes of feedstock, particularly under hot and dry weather conditions. There has been some confusion over the regulatory classification of biochar for transportation, when fresh, dry biochar may present a spontaneous combustion risk and therefore requires classification under the dangerous goods regulations. However, short periods of post-production storage (2 weeks) while ensuring minimum moisture content (e.g. 25%) is considered sufficient to negate the risk, and then biochar products can be classed as a packaged soil amendment for transport regulation.

Cost of the biochar is perhaps the single most important constraint in the uptake of biochar technology. A recent global survey shows that the average price of pure biochar is approximately AU\$3 kg^{-1} (Jirka and Tomlinson 2014), which is agronomically not affordable based on suggested high application rates (5–20 $t\,ha^{-1}$) and the expected benefits in crop yield. Bulk quantities of certain biochars are available at much lower prices in Australia, for example, \$1000 t^{-1} for wheat straw biochar (P. Burgess, Rainbow Bee Eater Pty Ltd, pers. comm.). Biochar produced in much larger plants in China sells for \$300–500 t^{-1} (Joseph *et al.* 2013).

The cost of biochar application to soil can also be significant if specialised equipment is required for this operation. However, as is the case in China, a spreadable fertiliser that can be applied with existing machinery can be produced when biochar is granulated with clay and NPK or with organic amendments such as ash, digested sludge or compost. These products have higher bulk density and they are generally transported to areas within 100 km of the site of manufacture.

A major constraint in many countries is the high cost of many of the existing, small-scale fixed and mobile reactors that have been built to minimise emissions. In some cases, small-scale production has been undertaken with low-cost simple ovens and kilns that have high levels of emissions of unburnt C and oxides of N. This can cause considerable opposition to the production facility from the households nearby and from local government. The cost of gaining approvals from regulatory agencies, local governments and the community can be significant for larger scale pyrolysis plants, especially if waste is being used as a feedstock.

Regulatory issues for biochar application to soil

The regulatory requirements governing the land application of biochar are still in infancy, and the approach used in Australia varies between state jurisdictions. In New South Wales (NSW), for example, biochar is captured by the definition of waste in the Protection of the Environment Operations Act 1997 (www.austlii.edu.au/au/legis/nsw/consol_act/poteoa1997455/). This Act and the Protection of the Environment Operations (Waste) Regulation 2005 (www.legislation.nsw.gov.au/viewtop/inforce/subordleg+497+2005+first+0+N) establish certain requirements for the land application of waste in NSW. In 2008, the NSW Environment Protection Authority (EPA) introduced the Resource Recovery Exemption (RRE) mechanism to facilitate the beneficial reuse of waste for land application as a soil amendment, fertiliser or engineering fill material. Development of RREs follows a robust and transparent process, which should demonstrate that the waste confers a benefit to the soil environment while ensuring minimal risk of harm to the environment or human health.

In addition to the RRE, a second regulatory instrument, the Energy from Waste (EfW) policy also determines suitability of biochars for land application. The EfW policy statement clearly differentiates between wastes that pose a low risk of harm to human health and the environment, and other wastes, such as those from mixed-waste streams, that need to be thermally treated at facilities meeting the requirements of an energy recovery facility. It has been determined by the NSW State Government that biochar produced from facilities using mixed-waste streams will not be considered for land application as a soil amendment in NSW. The NSW EPA is currently developing a general RRE for the use of biochar as a soil amendment that will act in concurrence with the EfW policy. Another key policy objective is that higher value resource recovery outcomes are maximised.

In developing the RRE, the EPA will set conditions defining the acceptable feedstocks, conditions of pyrolysis and characteristics of the biochar produced. Concentration thresholds will be placed on biochar composition, and a sampling and analysis regime will be implemented. An interesting question is whether C sequestration alone is sufficient to claim a beneficial reuse or whether soil amendment benefits must be demonstrated.

Other regulatory issues centre on possible air emissions, a particular concern with smaller mobile units. As discussed above, contaminants in the biochar such as PAHs and dioxins have been investigated before, with some data indicating that concentrations are not of environmental concern. The variability in chemical and physical properties of biochars produced from different feedstocks and pyrolysis processes poses some regulatory uncertainty. Questions remain about whether land application of biochar may have adverse effects on soil and plant growth, and whether, for example, it may result in increased application of pesticides. Communication between researchers, industry stakeholders and regulatory bodies is essential to achieve sustainable outcomes that are protective of the environment.

Emerging opportunities and novel applications of biochars

Use of biochar in growth media

Much of the horticultural industry is currently reliant on peat-based growth media. However, peat is a finite resource that takes centuries to develop. The loss of peat from the natural environment raises concerns relating to contributions to atmospheric CO_2, and loss of natural ecosystem habitats and biodiversity. There is global interest in reducing, or eliminating, the use of peat in the horticultural industry and in finding environmentally and economically sustainable growth media. Biochar has been shown to be a useful replacement for peat (Tian *et al*. 2012) and vermiculite (Headlee *et al*. 2014), in terms of key nutrient availability and total biomass productivity.

Perhaps some of the earliest ‘modern’ uses of biochar (or charcoal) for plant production can be traced back to its function in potting mixes, where it was used for improving physical attributes of potting mixes for growing orchids (Kono 1956). More recently, biochar has been tested in soil-less fertigation medium, where significant improvements in pepper and tomato yields were observed (Graber *et al*. 2010) at rates of 1% and 5% of wood-derived biochar. In a complementary experiment, Harel *et al*. (2012) observed that biochar (1% or 3% biochar-amended potting mixture) suppressed fungal diseases in strawberry plants. Those authors suggest that biochar stimulated a range of general defence pathways, as confirmed by results of a qPCR study of defence-related gene expression.

Biochar from urban waste

About 1.5 Mt of organic waste is generated in Australia every year; this includes food, garden waste and biosolids (Australian Bureau of Statistics 2013). Biochar produced from urban organic waste streams, or urban biochar, has many desirable attributes, chief amongst these the diversion of organic waste from landfill, the potential to avoid greenhouse gas emissions and recycling of nutrients. Biochars have been successfully produced from animal manures (Chan *et al*. 2008; Bird *et al*. 2011), and production from human waste streams such as biosolids is equally valid assuming contaminants (heavy metals in particular) can be minimised or made unavailable through the pyrolysis procedure. In the future, pyrolysis of sewage may be an important source for inorganic P recovery. Inorganic P is concentrated in biochar at temperatures up to 700–800°C (Hossain *et al*. 2011). Commercial-scale pyrolysis plants have been thwarted in the past owing to poor planning but trials have shown agronomically useful nutrient content (Bridle and Pritchard 2004; Wang *et al*. 2012) and that pyrolysis at ~500°C stabilised sewage sludge C in soils (Méndez *et al*. 2012). Zhao *et al*. (2013) compared the chemical properties of wastes from a range of feedstocks including municipal waste pyrolysed at 500°C and suggested that those produced from manures and biosolids have slow P-release characteristics. Large-scale production of biochar from urban waste may be helpful in reducing the cost of biochar production; however, because of the presence of potential contaminants, a proper regulatory framework is required to avoid possible risks of soil contamination. Toxic metal loadings in urban feedstocks may be manipulated through selective removal of ash (Hwang *et al*. 2008). Similarly, biochar from urban greenwaste (lignocellulose) has been evaluated and has shown promising effects on: soil physical properties in glasshouse experiments with radish (Chan *et al*. 2007), reductions in N_2O emissions in field experiments (Felber *et al*. 2014), and chemical properties similar to activated C through slow pyrolysis of a variety of municipal wastes at 480°C (Mitchell *et al*. 2013). A logical extension of this work is to combine mixtures of urban waste streams, in particular biosolids (or manures) and material high in lignocellulose such as greenwaste. Biosolid–greenhouse biochar offers the potential for nutrient enrichment of soil with the favourable effects on soil physical properties often shown in biochar-amended soils.

Composite biochars

Much of the experimental research has been carried out using biochar application rates of $\geq$10 t ha^{-1}; field application of such rates may not be viable except for very high-value crops. Some recent experiments with composite biochars, at much lower application rates, have shown encouraging results. For example, significant increases in yields (20–30%) of rice and vegetable crops were observed with a composite consisting of biochar–mineral–compost at application rates of 500–2500 kg ha^{-1} in field trials in Vietnam (Vinh *et al*. 2014). Similarly, field trials in China with composites made up of biochar, clay and chemical fertiliser have shown consistent increase in yields with reduced N input (Joseph *et al*. 2013; Qian *et al*. 2014). The highest yield increases of 25–30% were achieved with a composite consisting of wheat straw, municipal solid waste and peanut hulls; N_2O and CH_4 emissions were also reduced by 25–50%. In a field experiment with a barley–maize cropping system at the Department of Primary Industries Wollongbar Experimental Station in northern NSW, similar yields were obtained with the recommended inorganic NPK fertiliser (1.054 t ha^{-1}) and a biochar–mineral complex applied at 1.1 and 5.44 t ha^{-1} (Nielsen *et al*. 2014). Further optimisation of biochar composites through addition of minerals and small amounts of organic compounds could lead to additional improvements in crop yield. Coating or intercalating urea (Manikandan and Subramanian 2013) with biochar could provide a major improvement to N efficiency and reduction in N_2O emissions. Although biochar composites have shown promising results at low application rates, the stability of biochar-C in the composites produced at relatively lower temperatures needs to be established.

Biochar for mine site rehabilitation

The soils used in mine rehabilitation are often highly erodible, lacking in physical structure and devoid of nutrients, and contain limited microbial populations (Strohmayer 1999; Ghose and Kundu 2004). These poor soil conditions result from the physical disruption of aggregates in the removal stage, and chemical and biological alterations associated with anoxic conditions in the storage stage during the extraction process (Tacey and Glossop 1980; Moreno-de las Heras *et al*. 2008; Wick *et al*. 2009). Many studies have identified the potential for biochar to improve plant growth on degraded and disturbed soils (Barrow 2012; Mekuria *et al*. 2012; Kumar 2013). Mechanical incorporation of biochar into soils in the stripping, stockpiling or respreading stage has potential to improve mine rehabilitation; however, it requires testing under field conditions.

Small-scale biochar production for better efficiency and converting liability into a resource

For economic and other reasons, it is more efficient and effective to use a biochar from local and regional settings than transporting a biochar over long distances. Technologies are now available for the small-scale production of biochars from various types of feedstocks. There are competing demands for some potential biochar feedstocks, for example manure-based waste materials, which are used as organic amendments or incorporated in growth media for urban horticulture; greenhouse gas benefits from pyrolysing these wastes must be considered in the comparative analysis with other uses (Van Zwieten *et al*. 2013). Biosecurity issues have led to an increased interest in converting manures into biochar and utilisation of the heat for drying or for heating animal pens. Biochar may also be used as an animal feed and bedding material, which can be granulated after use for soil application (Kana *et al*. 2011; Van *et al*. 2006).

For the biochar technology to be cost-effective, the waste (a liability) should be converted into a resource (an asset). Several feedstocks not used for other purposes, such as woody weeds, giant reed and greenwaste from greenhouses, could be used for biochar production. Smider and Singh (2014) suggested that ~133 Mg ha^{-1} year^{-1} of greenwaste (on a fresh-weight basis) from intensive greenhouse tomato production in Australia could be used for biochar production.

Technological advancements in biochar production

Over the last 3 years, new innovative low-emission and low-cost technologies have been developed and are now being commercialised. Innovations that have been developed in Australia relate to production of units with low capital cost, low emissions and multi-fuel capability. Table 1 summarises the types of kilns that have been developed recently, along with their general specifications.

Biochar for multiple benefits

The use of biochar in the agricultural sector is more likely to occur where multiple benefits can be achieved. The key to developing a biochar approach that brings multiple benefits is in understanding the characteristics of biochar and its behaviour in soil and other end-use environments.

The alkaline nature and pH buffering capacity of biochar offers several avenues of potential use. For example, in the Lower Murray region of South Australia, there is a severe risk to water quality due to acid sulfate soils. In some cases, drains into the river are running at pH 2, and carrying in toxic (such as Al) and essential nutrients (such as nitrate). Biochar has been used in this environment with multiple benefits. The whole process is visualised in Fig. 2, and involves the following steps.

1. Native Reeds were established on degraded land at risk of erosion and acid sulfate formation. This also stimulates biodiversity and river resilience.

Table 1. A summary of developments in small- and medium-scale pyrolysis kilns for biochar production in Australia and elsewhere

Type	Feedstock type and quantity of biochar produced	Internal (IF) or external (EF) heating, emissions, highest heating temperature (HHT) of biochar	Production of heat and or power (approx.)	Ease of use	Estimated cost and lifetime
Stoves	Dry wood and agriculture residues 0.5–1 kg during three cooking sessions per day	IF and EF types, emissions high >5000 ppm CO, HHT 350–500°C	Heat 2–10 kW	Easy to operate	$6–50, 1–2 years
Ovens	Dry wood and agriculture residues 10–20 kg per 4-h firing time	IF and EF types Emissions high >10 000 ppm CO/NO_x, HHT 350–700°C	Heat 20–50 kW	Very easy to operate, needs only 1 day of training	$20–100, 1–2 years
Batch kilns, portable or transportable	Both wet and dry wood and agriculture residues 4–24 h for 50–1000 kg	IF and EF types, emissions low–high 100–5000 ppm CO/NO_x, HHT 350–600°C	Heat 50–200 kW	Requires some skill	$2000–85 000, 2–5 years
Batch kilns, fixed	Both wet and dry wood and agriculture residues 100 kg per 8 h	IF and EF types, emissions low–high 100–5000 ppm CO/NO_x, HHT 350–700°C	Heat 50–200 kW	Difficult to load and unload, requires skilled operator	$2000–25 000, 3–10 years
Continuous kilns, portable or transportable	Both wet and dry wood and agriculture residues 100–300 kg per h	IF and EF types, emissions low–high 100–1000 ppm CO/NO_x, HHT 350–600°C	Heat 200–500 kW, electricity 20–100 kW	Requires some skill	$30 000–250 000, 3–10 years
Continuous kilns, fixed	Both wet and dry wood and agriculture residues, 200–1000 kg per h	IF and EF types, emissions low–high 50–1000 ppm CO/NO_x, HHT 350–800°C	Heat 200–2000 kW, electricity 50–100 kW	Requires a high degree of skill	$350 000–4 million, without electricity option

2. The reeds were selectively harvested as a source of biomass for biochar production, and the reeds thrived after harvesting.
3. The biomass was combined with other additives and pyrolysed to make a biochar filter medium designed to suit the circumstances.
4. The acid drains were filtered with the biochar, reducing the acidity and inorganic contaminants in water.
5. The saturated biochar was then applied to high-pH, calcareous cropping soils where the acidity was neutralised, and the toxins either immobilised (e.g. Al) or made available as a nutrient (e.g. NO_3). Biochar additions at low rates seem to provide a fertiliser-use-efficiency response to crops grown on these soils.

Market instruments

Lehmann (2007*b*) suggested the inclusion of biochar technology for energy subsidies and inclusion in the global carbon market. The inclusion of biochar technology in the proposed 'direct action' plan of the Australian Federal Government presents a unique opportunity to benefit from long-term storage of biochar-C. Carbon storage benefits from biochar application to soils can be quantified with a high degree of certainty based on biochar characteristics and environmental conditions. Biochar is a low-risk technology to store C for the long term in soils, compared with other options such as forestry, no-tillage and geological C storage (Lehmann 2007*b*). Additionally, repeated measurements in time may not be required as for the other organic-C sequestration options for increasing soil C.

Opportunities and action items

In order to overcome uncertainties associated with productivity outcomes and ensure that the use of biochar in agriculture and the wider environment leads to sustainable systems without unintended negative consequences, some key actions are required.

Development and adoption of appropriate analytical methods

Limitations of existing laboratory soil and plant methods for biochar or biochar-amended soil analyses have been highlighted in several research studies (Novak *et al*. 2009; Singh *et al*. 2010*b*; Enders and Lehmann 2012; Farrell *et al*. 2013; Kameyama *et al*. 2014; Gomez *et al*. 2014). Researchers need to address this issue collectively by customising and streamlining the analytical procedures for the analysis of biochars.

Field assessment of impact on herbicide efficacy

Given the potential economic impact of biochar in terms of poor weed control, possible extension of plant-back periods and a need for increasing input of herbicides, the results from the laboratory trials available so far need to be tested under field conditions. More importantly, improved methods of customisation and applications of biochars to minimise cost and maximise benefits need to be explored.

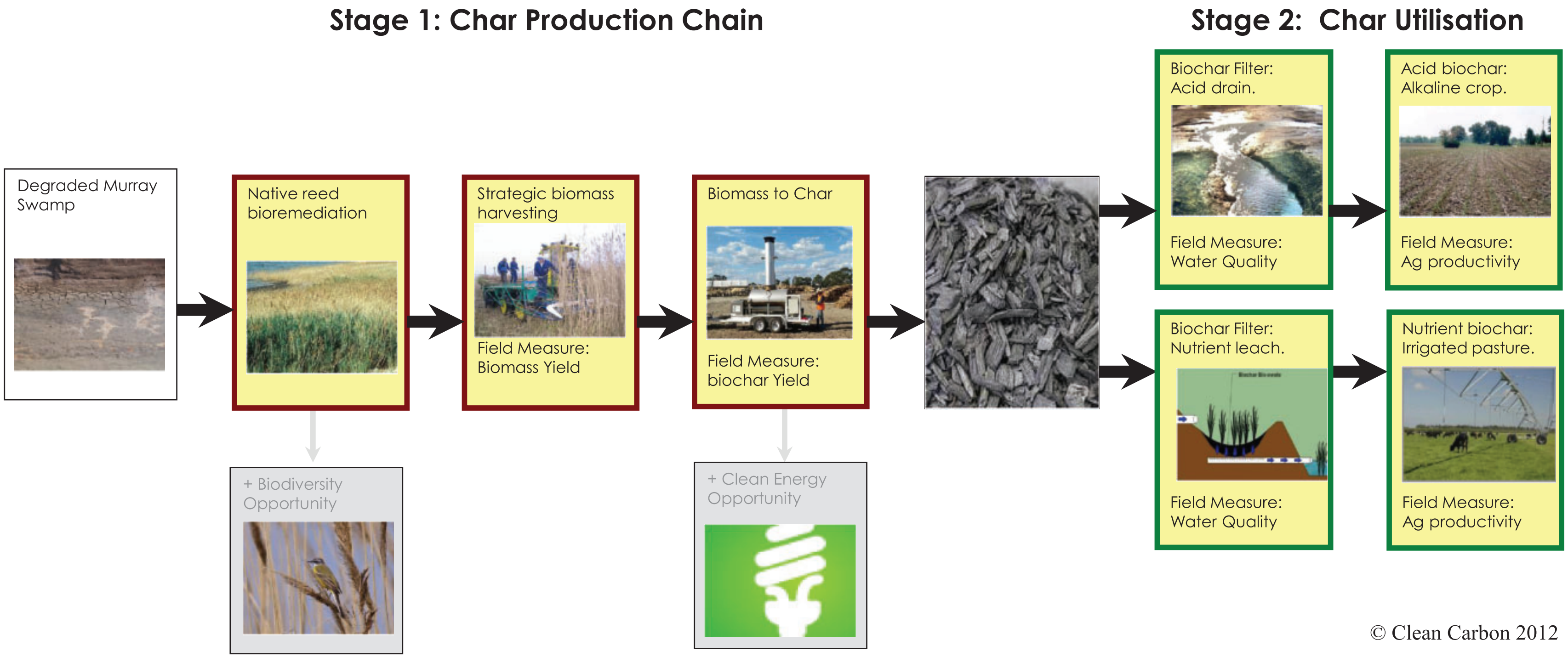

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Fig. 2. Biochar application for multiple benefits: an example from the Lower Murray region of South Australia where biochar is produced from strategic harvesting of native reed and is then used for neutralising acidity and capturing nutrients from acid drains; finally, nutrient-enriched biochar is added to soils.

Security of long-term biochar field trials

For long-term evaluation of biochar effects on soil properties, long-term experimental sites need to be established on different soil types using common biochars. The trials should include different application methods (e.g. surface broadcasting or placement at depth). Such sites on common soil types in Australia should be accessible for inter-disciplinary research into long-term effects of biochar.

Classification and industry standards

Australia has no system for the classification and governance of biochars that are being marketed and sold for land and other applications. It is paramount that a classification system is developed for biochars, or the International Biochar Initiative system be adopted or adapted. This approach will enhance consumer confidence in using biochar for various applications, improve benefits from biochar land application, and limit potential negative environmental effects from biochar application or use.

Unified regulatory policy for biochar in Australia

The environmental agencies of various states and territories should formulate unified regulatory standards for land application of biochars. Similarly, the process for permitting the use of various waste materials as biochar feedstocks should be streamlined with a clearly stated set of standards. The quality protocol approach used for treated sewage sludge, wood, compost and other low-risk materials may provide a starting point for this.

End-user decision support

A decision-support system should be developed to help users to choose a particular biochar, application rate and other parameters to suit a particular requirement. This will help to address the ambiguities about possible benefits from biochar application to agricultural soils.

Communication of research outcomes

There has been substantial research on biochar application to soil for C sequestration and agronomic benefits in Australia. However, the research outcomes are not readily available to users, and there is an immediate need to collate existing data on biochar research on a centralised website. This research should be readily available to potential users of biochars, in the form that is easy to understand. This will help the user to make an informed decision in terms of adopting biochar technology in agricultural production systems.

Conclusions

In the last decade, significant research has been done on the potential of biochar for long-term C storage in soil, and agronomic and environmental benefits. The role of biochar in long-term C storage in soil has been well accepted; however, there is ample ambiguity about the agronomic benefits of biochar application in different soil types. Better characterisation and categorisation of biochars to match soil types and other uses are urgently required in choosing the ‘fit for purpose’ biochar. Better understanding of the role of biochar in the mitigation of N_2O emission and its other soil benefits is required for its application in agricultural systems. Long-term field experiments at sites with different cropping systems, soil types and climatic conditions are needed for this. Biochars strongly sorb various organic and inorganic molecules and elements, which offers many potential benefits (e.g. reduced availability of toxic metals) and present some challenges, such as the reduced efficacy of herbicides. Field experiments are required to evaluate the effects of biochars in agricultural and environmental systems.

Several new applications of biochar have emerged in recent years. Production of biochar from urban and other wastes (greenhouse waste) offers environmental and economic benefits. Technologies are emerging to produce composite biochars that are nutrient enriched and have potential as substitutes for inorganic fertilisers because of controlled nutrient supply and other benefits. The use of biochars for growth media, restoration of mined sites, bedding material in animal houses and restoration of acid sulfate soils are some other examples of potential applications. However, to realise the full benefits of existing and emerging applications of biochar, we urgently need to address some issues. The existing research must be consolidated and the research data should be easily accessible and available so that users can make an informed decision. There is an urgent need to develop a national system to control the quality of biochars available in the market. Analytical techniques need to be streamlined for biochar characterisation and there should be minimal requirements for all biochars produced and marketed in Australia. National regulatory policy should be developed to help the industry and users in the production and use of biochar from various feedstocks.

Acknowledgements

We thank the participants of the ‘National Biochar Workshop: Recent Advances and Future research Directions’, which was held in Sydney in December 2013, for their contribution in the discussions. We acknowledge the financial support for National Biochar Initiative I and II from the Australian Government under its Climate Change Research Program and the University of Sydney for hosting the workshop.

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