Australian Government
Department of Agriculture, Fisheries and Forestry
ABARES

Biochar: implications for agricultural productivity

Jessica Sparkes and Peter Stoutjesdijk

Research by the Australian Bureau of Agricultural and Resource Economics and Sciences

TECHNICAL REPORT 11.06
December 2011

© Commonwealth of Australia

Ownership of intellectual property rights

Unless otherwise noted, copyright (and any other intellectual property rights, if any) in this publication is owned by the Commonwealth of Australia (referred to as the Commonwealth).

Creative Commons licence

All material in this publication is licensed under a Creative Commons Attribution 3.0 Australia Licence, save for content supplied by third parties, logos and the Commonwealth Coat of Arms.

Creative Commons Attribution 3.0 Australia Licence is a standard form licence agreement that allows you to copy, distribute, transmit and adapt this publication provided you attribute the work. A summary of the licence terms is available from creativecommons.org/licenses/by/3.0/au/deed.en. The full licence terms are available from creativecommons.org/licenses/by/3.0/au/legalcode.

This publication (and any material sourced from it) should be attributed as: Sparkes, J & Stoutjesdijk, P 2011, *Biochar: implications for agricultural productivity*, ABARES technical report 11.6. CC BY 3.0.

Cataloguing data

Sparkes, J & Stoutjesdijk, P 2011, *Biochar: implications for agricultural productivity*, ABARES technical report 11.6, Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra.

ISSN 189-3128 (online)
ISBN 978-1-74323-002-2 (online)
ABARES project 43070

Internet

Biochar: implications for agricultural productivity is available at: daff.gov.au/abares/publications.

Contact

Department of Agriculture, Fisheries and Forestry

Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES)

Postal address	GPO Box 1563 Canberra ACT 2601
Switchboard	+61 2 6272 2010
Facsimile	+61 2 6272 2001
Email	info.abares@daff.gov.au
Web	daff.gov.au/abares

Inquiries regarding the licence and any use of this document should be sent to: copyright@daff.gov.au.

The Australian Government acting through the Department of Agriculture, Fisheries and Forestry has exercised due care and skill in the preparation and compilation of the information and data in this publication. Notwithstanding, the Department of Agriculture, Fisheries and Forestry, its employees and advisers disclaim all liability, including liability for negligence, for any loss, damage, injury, expense or cost incurred by any person as a result of accessing, using or relying upon any of the information or data in this publication to the maximum extent permitted by law.

Acknowledgements

The authors wish to acknowledge Dr Evelyn Krull for providing review comments.

Front cover image courtesy of Black is Green Pty Ltd.

Contents

Tables

Figures

Boxes

Preface

This report presents findings of a desktop review into biochar, covering potential applications, benefits, costs and risks, and future research required to realise the agricultural productivity improvement and environmental sustainability potential of biochar. This report focuses on production and application of biochar to soils to improve soil function and the ancillary benefits that may arise. Use of biochar as a way to abate greenhouse gases and sequester carbon is discussed in only general terms.

Biochar production options are discussed to highlight feedstock biomass sources and production conditions that maximise biochar production for agricultural purposes. The report describes biochar characteristics required to maximise agricultural productivity, followed by a detailed description of the potential benefits of biochar additions to plant and animal productivity. The potential of biochar for carbon sequestration and waste management is also discussed briefly. Finally, potential risks, barriers and limitations to biochar application are discussed and knowledge gaps for future research identified.

A cautionary note

No standards exist that prescribe the composition or preparation of biochar to distinguish it from charcoal produced as a fuel source. Within this report, biochar is defined as a carbonaceous material produced for application to agricultural land as part of agronomic or environmental management; while the terms char and charcoal are used to describe a carbonaceous material for no specific end use. To ensure production of safe biochar products that are sustainably generated (carbon negative), minimum quality standards need to be developed to minimise the risks to agricultural productivity and the environment of inappropriate use of biochar.

Summary

Biochar is a stable, carbon-rich form of charcoal that can be applied to agricultural land as part of agronomic or environmental management. It can be produced by pyrolysis; where biomass such as crop stubble, wood chips, manure and municipal waste is heated with little or no oxygen.

The main focus of this report is on agricultural productivity benefits of biochar. Specifically, information about the effects of biochar on the productivity of agricultural soils to which it is added has been analysed and documented. This report's focus is on Australian agricultural systems and draws heavily from international and Australian research; it does not examine in detail, the use of biochar as a carbon sequestration mechanism.

Increased agricultural productivity and environmental sustainability are policy objectives for many governments and this report seeks to provide decision makers with information about these objectives in the context of biochar. Before any decisions can be made about using biochar as a soil conditioner and a climate change mitigation tool, agricultural policy makers need to understand the potential benefits and risks of its use in agricultural soils.

This report gives policy makers information about the:

- processes and feedstocks available for biochar production
- physical and chemical characteristics of biochar
- effects of biochar application to agricultural soils
- economic considerations of biochar production and use
- risks associated with using biochar in agricultural systems
- barriers to using biochar in agriculture.

Biochar feedstocks and production conditions can significantly influence the quality of biochar. Further, due to biochar's heterogeneous nature, its production and assessment is complex, prohibiting a simple classification or generalisation of the end product. This means production conditions need to be optimised for each feedstock used to ensure the resultant product is fit for purpose and it will deliver the intended effects when added to agricultural soils. Incorrect production could result in a product that is detrimental to agricultural production and the environment.

There are significant potential productivity and other benefits from adding appropriate biochars to Australian agricultural soils. These include improvements in physical and chemical soil characteristics, nutrient use efficiency and reductions in greenhouse gas emissions derived from nitrogenous fertilisers. Generally, biochar has been found to improve infertile and degraded soils. However, not all crops behave the same way and not all soils show broad improvements with biochar application; even when the biochar appears fit for purpose. Within farming systems, biochar may also bind and reduce the efficacy of some agricultural chemicals.

Recently, researchers have focused on the potential of biochar to mitigate climate change by storing carbon in soils in an inert and stable form. However, to do this in agricultural soils, the addition of biochar should also benefit agricultural production as there are no viable methods to separate biochar from soils once it is added. If biochar has negative or even neutral effects on agricultural soils and systems, there may be no argument for its use. If it is beneficial to agricultural production, its use must also be of economic benefit.

Current knowledge about the effects of adding biochar to Australian agricultural soils is not sufficient to support recommending its use. However, international and Australian research will aid decisions about its use when results become available. Australian research funded by the Australian Government through the Climate Change Research Program and through research and development corporations, will help answer questions around feedstock choice and production conditions for manufacture of beneficial biochars, as well as its impact in different Australian farming systems. The current state of Australian research has been highlighted in factsheets and brochures, produced as a result of the Climate Change Research Program (see www.daff.gov.au/climatechange/australias-farming-future/climate-change-and-productivity-research).

Despite the uncertainty surrounding its production and use, some farmers are producing their own biochar. This may result in a biochar product that has negative effects on agricultural production, as well as falling short of its climate change mitigation potential. An environmental sustainability analysis, including a life cycle analysis, will give an indication of the overall impact of biochar use in agricultural situations. Development of a classification and governance system should then be used to promote the benefits from biochar use while limiting the potential negative environmental effects from its production.

More research is needed before confident predictions can be made about biochar's suitability for use in Australian agricultural systems. To that end, the Australian Government and research and development corporations are funding biochar research. The Australian Government recently announced more funding for biochar research under the Carbon Farming Initiative. The Biochar Capacity Building Program will fund research that investigates mitigation of greenhouse gas emissions, projects that demonstrate biochar use on farms and projects that facilitate development of offset methodologies so biochar users can access both domestic and international carbon markets. Once more research results become available, it may be possible to start investigating the economics of biochar production and use in Australia.

1 Introduction

According to the Food and Agriculture Organization,

> [development and implementation of] productivity-increasing farming technologies … that are truly sustainable in the sense that they do not themselves inflict damage on the soil, water and ecological resources as well as on the atmospheric conditions on which future food output depends [is essential to maintaining food security and productivity] (FAO 2009).

For technologies to be effective, food security actions must be coupled with adaptation and mitigation measures that relate to climate change and sustainable management of natural resources (G8 2009). Biochar, a product of the thermo-chemical pyrolysis of biomass, may be one such emerging technology to improve agricultural productivity and food security, while potentially reducing greenhouse gas emissions.

As Johannes Lehmann, a leading researcher in the field, said 'biochar can be used to address some of the most urgent environmental problems of our time—soil degradation, food insecurity, water pollution from agrichemicals and climate change' (Renner 2007). Such statements within the media have given rise to the idea of biochar as a potential option to increase food security. However, others remain sceptical about the potential of biochar to secure food supplies and mitigate climate change (Ho 2010; Powlson et al. 2011). Production and application of biochar in a global context may emerge as a win-win strategy for agricultural productivity, environmental sustainability and climate change mitigation, but further research is needed to address concerns.

The modern concept of biochar for soil amendment originated from soils particular to the Amazonian Basin, where charcoal from incompletely combusted biomass, such as wood from household fires and in-field burning of crop stubble has, over thousands of years, produced highly fertile *terra preta* (literally 'black earth') soils. These soils have been found to contain high levels of organic matter and nutrients when compared with adjacent soils and are now used to produce fruit crops (Krull 2009). More recently, biochar is used extensively in Japan to accelerate snow melt to extend the growing season (Sohi et al. 2010).

Terra preta soils have received widespread media coverage in recent times due to the positive effects on crop growth and this has led to the belief that biochar was the important ingredient. However, on closer examination, *terra preta* soils contain residues from human and animal waste, food scraps and other nutritious waste material that were not charred (Krull pers. com. 2011). As a result of media coverage, scientific interest in emulating *terra preta* soils in modern agriculture is increasing. The addition of biochar to soils for enhanced soil fertility and agricultural productivity is one such area that appears promising. Research has illustrated the potential of biochar to improve soil health and fertility, soil structure and nutrient availability. Furthermore, biochar may become a viable method for long-term carbon storage in soils, while providing other greenhouse gas emission benefits. However, extensive life cycle assessments need to be undertaken before widescale biochar application to ensure net benefits in both agricultural productivity and greenhouse gas mitigation are realised.

2 Biochar production and characteristics

Production technologies and systems

Pyrolysis

Biochar is most commonly produced through an energy conversion process known as pyrolysis; the heating of organic materials (such as crop stubble, wood chips, manure and municipal waste) in the complete or near absence of oxygen (Schahczenski 2010). Pyrolysis converts easily broken down organic matter into a highly stable form of carbon, which is mainly used as a soil additive to improve nutrient retention and carbon storage (Krull 2009). In some instances, biochar can remain stable in soil for hundreds to thousands of years (Sohi et al. 2009). Worldwide, 41 million tonnes of biochar is produced annually (McHenry 2009). Other products of pyrolysis may include synthetic or synthesis gas (syngas) and pyrolysis liquor (bio-oil).

Syngas and bio-oil

If syngas and bio-oil are captured, they can be used as a renewable energy source or as feedstock for producing other chemicals, such as food additives and pharmaceuticals. Syngas consists of a variety of gases, such as carbon monoxide, hydrogen and methane and can be burned to provide heat to the pyrolysis system, or to generate electricity for external use. Bio-oil can also be used to provide heat to the pyrolysis system, or used for fuelling heaters, furnaces and boilers to generate heat and electrical energy (Maraseni 2010). Syngas can be further refined to bio-diesel, while bio-oil can be used as a feedstock for producing chemicals (Maraseni 2010).

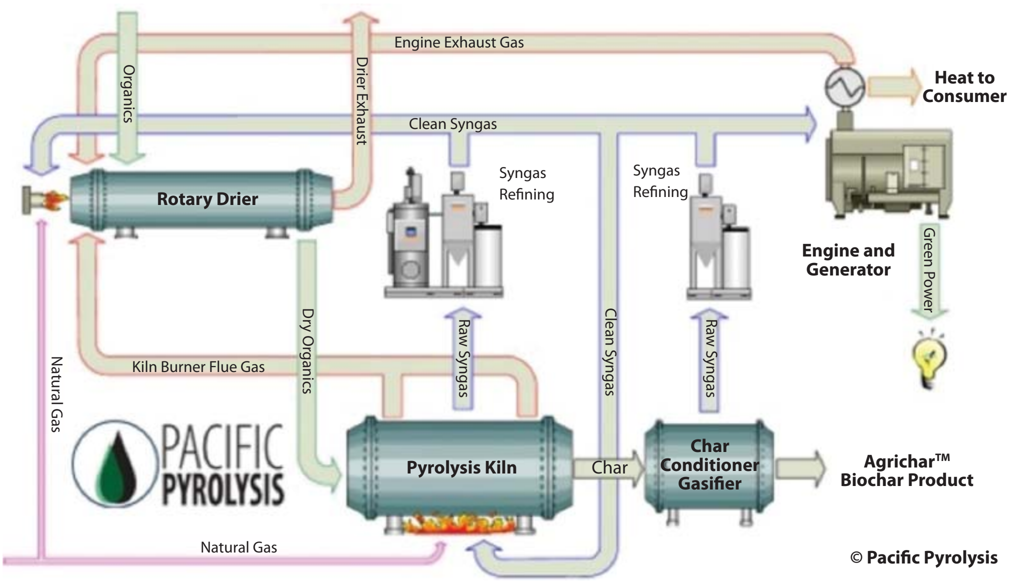
Production methods

Pyrolysis can occur on many different scales; from simple, low-input traditional kilns to large, highly efficient industrial plants. Humans have used temporary pits and kilns constructed from earth, stones and wood for char production for thousands of years (Pratt & Moran 2010). Traditional pit kilns and mound kilns are a low cost method of producing char; particularly in developing countries. Simple kilns are designed for batch pyrolysis, thereby losing the potential to use the heat, syngas and bio-oil produced in the process for other applications (Brown 2009).

Although simple kilns are easy to use and incur low capital costs, they are highly polluting. Further, efficiency of the system can be as low as 8 per cent due to air entering the kilns, gasifying biochar to carbon monoxide and carbon dioxide (Brown 2009) and producing excess heat in the process. Modification of stoves and kilns used in rural areas of developing nations offers a cost-effective way to produce biochar, which is more efficient, emits less pollution and improves the health of users (Pratt & Moran 2010). For example, bricks, concrete and metal have recently been used to improve traditional kilns. Although these pyrolysis systems can produce biochar, other benefits such as production of energy from syngas and bio-oil remain unavailable.

In contrast to kilns and pits, modern pyrolysis plants incur high capital costs and are expensive to run, but may offer the greatest returns in terms of efficiencies and greenhouse gas abatement potential (Pratt & Moran 2010). Most modern pyrolysis plants operate a continuous process where pollution control is possible (Brown 2009). A simplified diagram of a continuous-flow pyrolysis system is given in figure 1.

1 A pyrolysis reactor



Note: In this system, biomass (organics) is fed into the reactor where it is heated in an oxygen free environment. This causes breakdown of the biomass into smaller and more volatile compounds, which are cooled and collected as syngas, bio-oil and biochar.
Source: Pacific Pyrolysis Pty Ltd

Small-scale pyrolysis plants that can be used on-farm or by small industries are available, with feedstock inputs of 50 to 1000 kilograms per hour (figure 2). At a regional level, pyrolysis units can be operated by cooperatives or larger industries, such as sugarcane growers, and can process up to 8000 kilograms of feedstock per hour (figure 3) (Talberg 2009). Pyrolysis plants offer the advantage of capturing syngas and bio-oil to heat incoming feedstock or to be used as a renewable energy source in other applications, such as generating electrical or mechanical energy.

2 Portable on-farm BiGchar pyrolysis system

Photo courtesy of Black is Green Pty Ltd, Queensland

3 Large capacity slow pyrolysis industrial system

Photo courtesy of Pacific Pyrolysis Pty Ltd.

Two main pyrolysis systems are in use for processing biomass: fast pyrolysis and slow pyrolysis. Both result in production of the three co-products—biochar, syngas and bio-oil—where the relative amounts and characteristics of each are controlled by the processing conditions (Roberts et al. 2010). Gasification systems—where feedstock biomass is combusted in a directly-heated reaction vessel with limited introduced air—also produce biochar but at lower proportions than either fast or slow pyrolysis.

The composition of the feedstock, temperature and heating rates can be altered to provide different amounts of each product (that is, syngas, biochar and bio-oil) and their inherent properties (table 1). It is important to note that maximising biochar yields will always be at the expense of bio-oil and syngas production, which could affect the economics of production. In particular, it should be noted that production of biochar for agricultural purposes will probably never be energy self sufficient. Ideally, systems would have some degree of flexibility with respect to the proportions of biochar, syngas and bio-oil produced, so operators could respond to seasonal fluctuations in demand for these products.

1 Fate of biomass feedstock for different pyrolysis conditions

approach	conditions	liquid (bio-oil) %	solid (biochar) %	gas (syngas) %
Slow	Moderate temperature ~500°C Long vapour residence time ~5–30 minutes	30	35	35
Moderate	Moderate temperature ~500°C Vapour residence time ~10–20 seconds	50	20	30
Fast	Moderate temperature ~500°C Short vapour residence time ~1 second	75	12	13
Gasification	High temperature >750°C Vapour residence time ~10–20 seconds	5	10	85

Source: Brown 2009

The terms fast and slow pyrolysis are indicative of the time in which vapours are driven off the biomass in the reaction vessel. Fast pyrolysis occurs at moderate temperatures, with very short vapour residence times and produces more bio-oil and less biochar than slow pyrolysis. Slow pyrolysis produces maximum yields of biochar due to the generally lower operational temperatures and heating rates (Kwapinski et al. 2010). Slow pyrolysis best describes the process in less complex biochar kilns and pits.

The particle size and moisture content of the feedstock are also important considerations when developing an efficient pyrolysis system as they will affect biochar characteristics and quality. Wet feedstocks with large particle sizes will require greater amounts of energy to bring the biomass to the desired temperature, decreasing the efficiency of the system (Kwapinski et al. 2010). In a study using wastes from corn, olives and tea, Demirbas (2004) demonstrated the effect of a number of variables on biochar yield. First, lower reactor temperatures favour higher yields of biochar with a temperature of 177°C producing the most biochar. Second, larger particles (sizes tested were 0.5, 1.0, 1.5 and 2.3 millimetres) yielded more biochar and third, feedstocks with a higher lignin content provided maximum biochar yields. The observations of Demirbas (2004) regarding particle size confirm earlier work of Suuberg et al. (1996) where it was found that increasing particle dimensions of cellulose pieces increased biochar yield from approximately 2 to 8 per cent at a heating rate of 60°C per minute to 750°C.

Controlling operating conditions to improve process efficiency and optimise biochar production has not been explored extensively due to competing priorities from bioenergy production (Brown 2009). More research is needed to better understand the mechanisms of biochar formation to ensure development of energy efficient pyrolysis plants that target production of desired products and provide a degree of flexibility with respect to the relative amount of products produced. This may be achieved through modifying heating rates, temperatures and pressures, or developing a flexible reactor design and considering the supply and type of feedstocks available.

Potential feedstocks for biochar production

Researchers are increasingly aware that biomass and organic wastes are valuable feedstocks for pyrolysis that can produce biochar, syngas and bio-oil (Kwapinski et al. 2010). However, due to the large effect a feedstock source has on the physico-chemical properties of biochar (such as particle size, composition and pore sizes) careful consideration must be given to choosing the correct feedstock for the intended end use.

Cellulose, hemicellulose and lignin are the major components of fibrous biomass (such as wood, crop stubble and bioenergy crops). However, the relative amounts of these components can vary considerably between different species of plants, as well as within the same species; due to variations in soil type, time of harvest and climatic conditions (table 2) (Brown 2009).

2 Typical components of fibrous biomass for use in pyrolysis and gasification

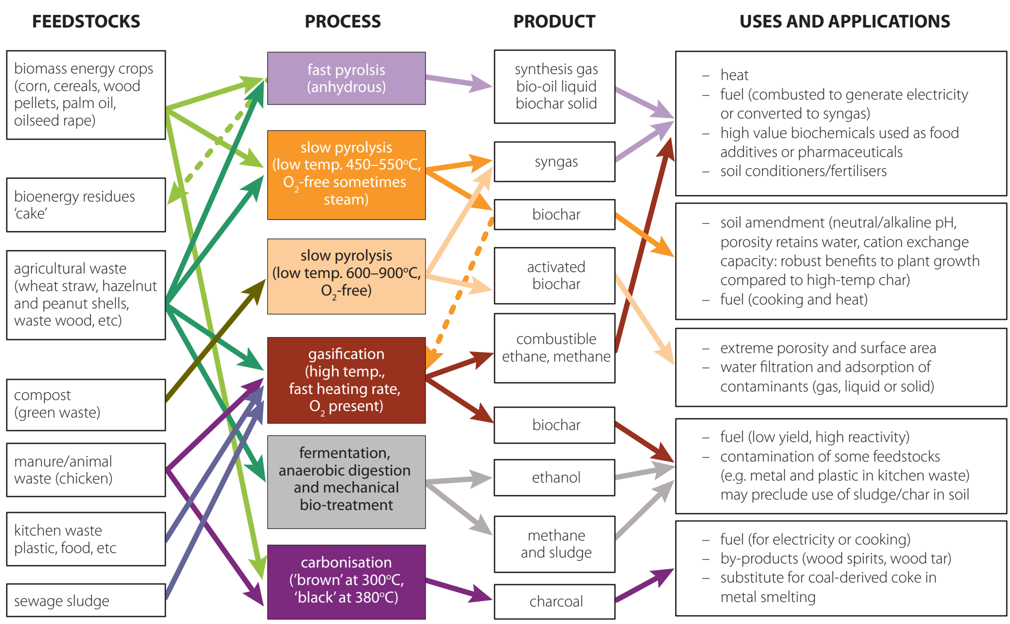
feedstock	cellulose % a	hemicellulose % a	lignin % a	extractives % a	ash % a
Hybrid poplar	45	19	26	7	1.7
Willow	43	21	26	–	1
Switchgrass	32	25	18	17	6
Miscanthus	38	24	25	5	2
Maize stover	39	19	15	–	4.6
Wheat straw	38	25	14	–	10
Bagasse b	50	30	20	–	–

a Per cent of total weight on a dry matter basis.
Source: Brown, 2009; b Mousavioun & Doherty, 2010

Further, due to structural differences, each component of the biomass breaks down at different rates when exposed to high temperatures. For example, cellulose is more resistant to thermal decomposition than hemicellulose, while lignin is more difficult to break down than cellulose and hemicellulose. Greater proportions of residual biochar are therefore produced with increasing proportions of lignin. As such, the most suitable materials to maximise biochar yields are woody types, with a high lignin content such as nutshells, residues from sawmills and forest wastes (Demirbas 2004).

Figure 4 identifies various potential feedstocks, their ideal processing conditions and their end-use applications to maximise potential benefits. For example, switchgrass (a bioenergy crop) may be used in both slow pyrolysis (450–550°C, oxygen free environment, long biomass and gas vapour residence times) and fast pyrolysis (450–500°C, short biomass and gas vapour residence times) to produce syngas, bio-oil and biochar for use as a soil amendment or as an energy source for fuel production and heating, respectively (Brown 2009; Roberts et al. 2010; Sohi et al. 2009). However, when considering a potential feedstock for biochar production, biomass availability and moisture content must also be considered to ensure continual operation of the processing plant, with minimal energy input requirements.

4 Potential biomass feedstocks for various pyrolysis conditions



Note: The figure also identifies specific end-uses and applications for products to maximise the benefits from the biochar produced.
Source: Sohi et al. 2009

Australia has an extensive range of biomass suitable for pyrolysis, including broadacre grain trash/stubble, agricultural processing residues (macadamia nut shells, olive pips, bagasse from sugar cane production and husks from cereals or rice), forestry residues (wood blocks, wood chips and tree bark) and grass residues (both improved pastures and native grasses) (Bridgewater & Peacocke 2000; Lehmann et al. 2006; O'Connell & Haritos 2010).

Mallee eucalypt trees could potentially be grown on arid and semi-arid lands in Australia for both salinity control and as a biofuel feedstock (Abdullah et al. 2010; Garnaut 2008). Planting mallee trees can help restore areas affected by dryland salinity and the leaves and upper branches can be harvested perennially as a biofuel feedstock. Despite the potential of mallee trees for both ecosystem restoration and biochar/bioenergy production, a number of processing and harvesting issues (such as developing integrated cropping strategies in extensive production systems and the ability to attract private sector investment) need to be resolved before it has the potential to become commercially viable as a biochar production industry (Bell 2005; McHenry 2009). Nevertheless, use of biochars produced from mallee trees for application to soils to improve agricultural productivity is being investigated.

Biochar can also be produced from manures and other animal wastes, including bone. For instance, dairy shed waste and chicken litter have been used to produce biochar (Cao & Harris 2010; Joseph et al. 2010; McHenry 2009). Many types of manure are anaerobically digested to produce biogas (a mixture of methane and carbon dioxide) and it is possible that the remaining solid by-products could be used in pyrolysis reactions to produce biochar.

Pyrolysis of these types of waste may produce both energy and a biochar product with relatively high levels of plant nutrients, such as phosphorous, potassium, nitrogen, magnesium and calcium. Containment and use of nutrient-rich manures and animal products for production of biochar may also have positive environmental effects including reduced nutrient run-off and corresponding reductions in greenhouse gas emissions, such as methane and nitrous oxide (He et al. 2000). Although manure and municipal waste may be used in pyrolysis, the high risk of contamination from toxic chemicals and heavy metals may limit its use on agricultural soils.

The mineral content of potential biomass feedstocks must also be considered. Nik-Azar et al. (1997) found that impregnating woody biomass with sodium, potassium and calcium increased biochar yields by up to 15 per cent. These findings are in agreement with other studies, where addition of inorganic salts (magnesium chloride, sodium chloride, iron sulphate and zinc chloride) increased production of char from 5 per cent (control feedstock; no addition of salts) to 8, 14, 17 and 28 per cent respectively (Varhegyi et al. 1988). However, addition of any minerals to feedstocks to increase biochar yield would, from an agricultural productivity perspective, have to be weighed against the effect of those minerals on soil structure, soil fertility and plant growth, and the cost of supplying these nutrients through other means. See 'Nutrient content of biochars' below for information on the natural nutrient content of biochars.

Not all agricultural waste materials are suitable for biochar production for agricultural purposes (Lehmann et al. 2006; McHenry 2009). Some production conditions and feedstock types can cause the resulting biochar to be ineffective in retaining nutrients and susceptible to microbial decay (McHenry 2009). Depending on the biomass source, some biochar products, such as municipal waste, may contain high levels of toxic substances (heavy metals and organic pollutants) which must also be considered in the context of adding biochar to agricultural soils (Lehmann et al. 2006).

Biomass availability

Availability of large quantities of biomass feedstock and the transportation distance to a pyrolysis plant are essential considerations for an efficient and economically viable biochar production system (Roberts et al. 2010). Lehmann et al. (2006) indicated that nut shells, bagasse and olive and tobacco waste are all highly suitable feedstocks due to the location of farms, and their existing processing facilities, and because of the large biomass quantities produced. For example, bagasse production in Queensland produces approximately 12 million tonnes annually (Krull 2009).

It is possible to co-locate pyrolysis plants with biomass processing operations (for example, in the sugar cane industry) to minimise handling costs and provide a waste management solution. Production of biochar has the potential to be scaled to any level of production based on location and feedstock quantities and quality. As such, pyrolysis systems can be developed for on-farm production or at a regional or state level.

Biochar quality

As biochar can be produced from any biomass feedstock, it is essential to develop quality standards to ensure non-toxic biochar is produced sustainably. Kwapinski et al. (2010) support the idea that feedstocks should be ranked according to their suitability for biochar production for agricultural soil application and that guidelines should be developed to ensure adequate planning of feedstock use.

Both feedstock type and pyrolysis conditions affect the physico-chemical characteristics of biochar. Due to the range of biomass options and pyrolysis systems available, the variability in biochars that can be produced is high. This variability has significant implications for nutrient content of the biochar and nutrient availability to plants when biochar is applied to soil (Downie et al. 2009).

Generally, lower maximum temperatures, slower heating rates and higher pressures in the pyrolysis system, and greater proportions of lignin in the biomass feedstock produce larger biochar yields at the expense of syngas and bio-oil production (Demirbas 2004; Downie et al. 2009). Apart from affecting the quantity of biochar produced, pyrolysis conditions also have an effect on the quality of the biochar produced. For example, Downie et al. (2009) indicate that at temperatures above 120°C, chemically bound moisture is released, while at 200–260°C hemicellulose and cellulose begins to decompose (table 3). This has important implications for the porosity and carbon content of the resultant biochar.

3 Typical thermal decomposition temperatures for common feedstock component

feedstock component	decomposition temperature (°C)
Water	>120
Hemicellulose	200–260
Cellulose	240–350
Lignin	280–500

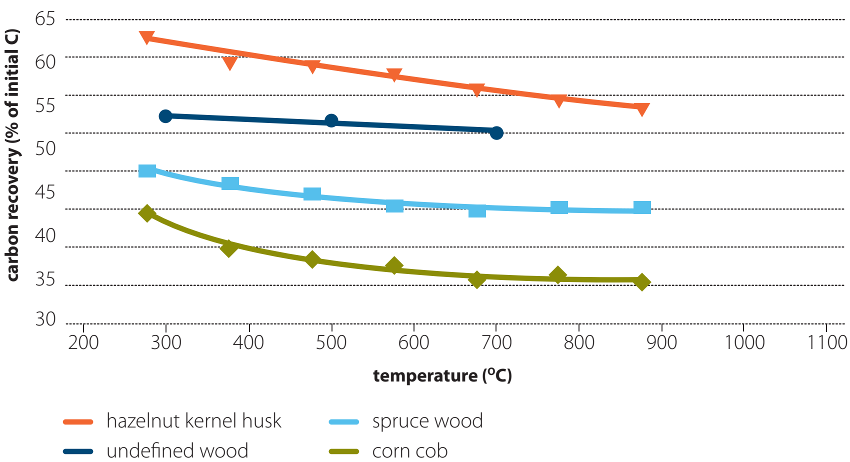
Data adapted from Downie et al. 2009.

Carbon content

When producing biochar for long-term carbon sequestration in soils, carbon content is almost the sole consideration, but when producing biochars to improve agricultural productivity, the carbon content of the biochar is not the main focus. Other factors of greater importance include structural characteristics and ion exchange capabilities (see 'Structural characteristics' and 'Ion exchange capacities' below).

The carbon content of different biochars is variable and is dependent on both the feedstock used and the pyrolysis conditions (figure 5). Generally, carbon concentrations increase with higher temperatures, with a coinciding decrease in biochar yield (Lehmann et al. 2006; Sohi et al. 2009). One study demonstrated a decrease in biochar yield from 67 to 26 per cent, with a corresponding increase in carbon content from 56 to 93 per cent at temperatures of between 300 and 800°C (Sohi et al. 2009). Baldock and Smernik (2002) found a similar trend in char yield; where the char mass of *Pinus resinosa* sapwood decreased from 97 to 19 per cent when the temperature increased from 150 to 300°C. This relationship becomes less pronounced beyond a certain temperature threshold, where an increase in temperature does not affect carbon content (figure 5). This can be seen in Baldock and Smernik's (2002) work where temperatures above 350°C did not result in a significant decrease in char yield.

5 Carbon recovery of different feedstocks with increasing temperatures



Note: The thresholds where an increase in temperature does not increase carbon content.
Source: : Lehmann et al. 2006

Due to its aromatic structure, biochar carbon is also chemically and biologically more stable than carbon in the original biomass. This has important implications for carbon sequestration and is the reason there is so much interest in biochar as a climate change mitigation tool. Lehmann et al. (2006) found that through conversion of biomass to biochar, about 50 per cent of the initial carbon was retained, compared with the low amounts retained after burning (3 per cent) and natural decomposition (less than 10 to 20 per cent after 5 to 20 years), depending on the type of biomass used (see also chapter 4).

Ash content

The ash content of biochar includes the inorganic constituents (calcium, magnesium and inorganic carbonates) after all the organic elements (carbon, hydrogen and nitrogen) have been volatilised (Joseph et al. 2009). The feedstock source and pyrolysis conditions have been shown to affect the inorganic ash content of biochar, which in turn could affect potential end uses (Kookana et al. 2011). Woody feedstocks generally produce char with low ash content (less than 1 per cent), while some grasses and straws are high in silica and produce up to 24 per cent ash in the char (Joseph et al. 2009). However, under certain processing conditions and when the feedstock has high silica content, the resultant biochar has the potential to cause silicosis in humans; appropriate precautions (such as face masks) should therefore be used (Krull pers. comm. 2011; Shackley & Sohi 2010).

4 Mean ash content of biochars produced from various feedstocks using slow pyrolysis at 550°C and 700°C with steam activation

feedstock used	ash content (g/kg)	
	550°C	700°C
Eucalyptus saligna wood	42 ± 4	37 ± 2
Eucalyptus saligna leaves	99 ± 1	40 ± 1
Paper sludge	654 ± 5	475 ± 6
Poultry litter	459 ± 2	444 ± 1
Cow manure	762 ± 6	757 ± 5

Source: Singh et al. 2010a

Bagreev et al. (2001) reported ash content increasing from 61.7 per cent to 76.8 per cent when sewage sludge was heated at 400°C and 800°C, respectively. In contrast, Singh et al. (2010a) found that increasing the pyrolysis temperature caused ash content of various biochars to decrease (table 4). This trend was most pronounced when paper sludge was used as the feedstock. As such, if ash content is found to be a favourable trait, further research may be needed to identify the effects of temperature on ash content to ensure optimal levels are applied to soils.

Structural characteristics

The structure of biochar can influence some of its quality characteristics. The porosity and surface area of biochar are particularly important and have a large role in determining its potential end use. The initial macrostructure of a feedstock is similar to that of the resulting biochar and this is particularly the case for plant materials that are high in cellulose (Sohi et al. 2010). As pyrolysis removes mainly volatile compounds, the macrostructure of the biomass is to a large extent retained in the biochar. However, structural stress causes cracks in the macrostructure, and escape of volatilised gases causes smaller pores and openings in the material (Downie et al. 2009).

The surface area and porosity of biochar under different pyrolysis temperatures has potentially significant effects on water holding capacity, adsorption capacity (ability of particles to stick to the surface of biochar) and nutrient retention ability (Downie et al. 2009; Sohi et al. 2010). Bagreev et al. (2001) illustrated that the increase in porosity and hence surface area of biochar is related to the temperature of pyrolysis. Boateng (2007) found that the surface area of biochar produced from switchgrass was low; ranging from 7.7 to 7.9 square metres per gram. Another study reported similar initial results, but then showed that biochar surface area increased by a factor of three as the pyrolysis temperature increased from 400 to 950°C (41 to 99 square metres per gram, respectively) (Bagreev et al. 2001). These results and those of Keiluweit et al. (2010) demonstrate a general trend of increasing surface area of biochars with increasing pyrolysis temperatures. Keiluweit et al. (2010) also illustrated that increasing porosity (and hence surface area) is coupled with reductions in total carbon and volatile matter.

While the mechanisms of increased water holding capacity of soils amended with biochar are not well understood, it is well known that the surface area of soil particles strongly influences its water holding capacity; sand holds little water and clay holds a lot. Adding biochar to soils to increase surface area may have an impact on water holding capacity. While it is generally accepted that biochar tends to increase water adsorption capacity and infiltration rates of some soils, some researchers have reported that some biochars produced at low temperatures (400°C) may be hydrophobic, which could limit their effectiveness to store water (Day et al. 2005).

Low temperature pyrolysis conditions may also produce biochars suitable for use as a nitrogen fertiliser substitute (Day et al. 2005), while biochars created at high temperatures would be best suited to adsorption activities such as reducing heavy metal contamination in soils (Sohi et al. 2010). In contrast, Boateng (2007) indicated that biochars produced at 480°C had poor adsorption characteristics without further activation. Furthermore, it has been found that biochar produced at low temperatures are brittle and prone to abrasion (Day et al. 2005). As such, the porosity and surface area of biochar may not affect the quality of the product over the long term.

Ion exchange capacities

The nutrient retention capacities of biochars (and soils) depend on their cation exchange capacity and their anion exchange capacity (Chan & Xu 2009). Cations (positively charged ions) and anions (negatively charged ions) are attracted to the opposite charge. Plant mineral nutrients such as calcium, phosphorus, potassium and nitrogen are present in soil water (soil solution); predominantly as cations and in some cases anions. In soils, small particles, such as those of humus and clay, carry negative charges and therefore attract cations, while anions are relatively free to move in the soil solution and are both freely available for uptake by plants and for leaching. Cation exchange capacity determines the soil's ability to hold cations and, as a general rule, the higher the cation exchange capacity the more fertile the soil.

Biochar has an appreciable anion exchange capacity and can therefore adsorb anion nutrients (such as nitrate and phosphate) and when they are incorporated into simple organic molecules. Researchers have shown that biochars produced at low temperatures have a high cation exchange capacity, while those produced at high temperatures (greater than 600°C) have limited or no cation exchange capacity (Chan et al. 2007; Lehmann 2007a; Navia & Crowley 2010). This finding would suggest that biochars for soil amendment should not be produced at high temperatures. Additionally, freshly produced biochars have little cation exchange capacity, while their anion exchange capacity is substantial. As biochar ages or matures in the soil, its cation exchange capacity increases.

High cation exchange capacity biochars have the ability to adsorb heavy metals and organic contaminants such as pesticides and herbicides from the environment (Navia & Crowley 2010). Use of biochars for environmental remediation is discussed in the scientific literature, but is beyond the scope of this report. However, addition of biochar to agricultural soils as a soil ameliorant is predicted to adversely affect the efficacy of agrochemicals, such as herbicides and pesticides (Jones et al. 2011a; Kookana 2010; Smernik 2009). These effects will need to be understood before widespread application of biochar to agricultural soils occurs.

Nutrient content of biochars

In general, the nutrient content of biochar reflects the nutrient content of the feedstock. Biochar derived from manure or bone is relatively high in nutrients, especially phosphorous. Of the biochars produced from plant material, those produced from wood generally have low nutrient levels and those produced from leaves and food processing waste have higher nutrient levels. Pyrolysis conditions also affect nutrient content and availability.

High pyrolysis temperatures may decrease nitrogen content and availability. Total nitrogen content was found to decrease from 3.8 to 1.6 per cent when the pyrolysis temperature was increased from 400 to 800°C, respectively (Bagreev et al. 2001). Another study reported a similar effect on the nitrogen content in both woody and herbaceous char: nitrogen was gradually released from the char samples, beginning at 400°C and continuing through to 750°C, at which time slightly more than half the initial nitrogen remained (Lang et al. 2005). In addition to partial loss of nitrogen, a reduction in availability of the remaining nitrogen to plants was also found (Bagreev et al. 2001). An explanation for this proposes that the remaining nitrogen becomes incorporated into the carbon matrix, limiting the availability of nitrogen in the biochar produced (Bagreev et al. 2001; Chan & Xu 2009; Macias & Arbestain 2010).

pH

Biochars used to improve soils are usually alkaline and, as will be discussed later, may have the effect of raising the pH of soils to which they are added. However, not all biochars are alkaline. The pH of biochars can range from 4 to 12 depending on the feedstock used and the pyrolysis conditions (Bagreev et al. 2001; Lehmann 2007b). Further, it has been observed that increasing the pyrolysis temperature can increase the pH of some biochars. It has been found that increasing the pyrolysis temperature from 310 to 850°C, biochar produced from bagasse increased in pH from 7.6 to 9.7 (Sohi et al. 2010). Although high pH biochars can be produced, they may not have a big impact on the pH of soils to which they are added; this effect is related to biochar’s acid neutralising capacity.

3 Biochar applications in agriculture

Biochar production and use is not a new phenomenon. Throughout the Amazon Basin, there are areas of *terra preta*—highly fertile dark-coloured soils—up to 2 metres deep, covering areas of up to 2 hectares (Talberg 2009). These soils were created by pre-Columbian indigenous farmers who covered their fields with burnt remains of domestic and agricultural trash (Casselman 2007). The high fertility of *terra preta* soils has been attributed to high levels of organic matter from the addition of materials such as charcoal, residues from human and animal waste, food scraps and other nutritious waste material that were not charred (pers. comm. Krull 2011). *Terra preta* soils have a carbon content of up to 150 grams per kilogram of soil, compared with 20 to 30 grams per kilogram in adjacent un-amended soils (Novotny et al. 2009). Further, the carbon is mainly in the form of black carbon, which is up to six times more stable than that in adjacent, un-amended soils (Novotny et al. 2009).

In addition to increased carbon content, *terra preta* soils are characterised by higher pH, calcium, magnesium and phosphorous levels, higher cation exchange capacities and higher base saturation levels, compared with adjacent un-amended soils (table 5) (Novotny et al. 2009). This has important implications for the soil's physical, chemical and biological properties (discussed later in this chapter). Due to these characteristics, *terra preta* soils are now used to produce crops such as mangoes and papaya, which reportedly grow three times faster than in the surrounding unimproved soils (Sohi et al. 2010).

5 Chemical attributes of *terra preta* and adjacent (un-amended) soils in the Amazon Basin

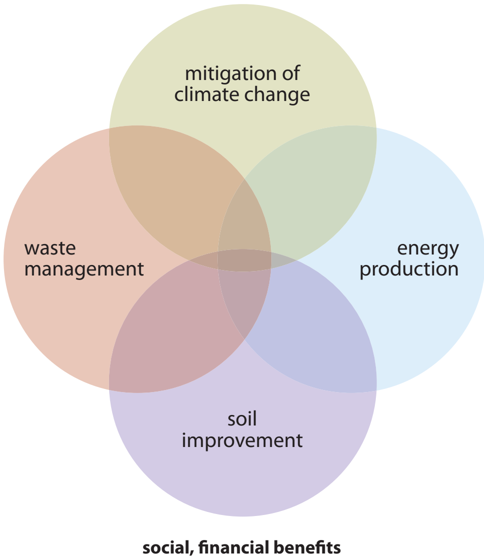
Soil	pH	Ca + Mg (a)	CEC	P (b)	base saturation (c)
		(cmol$_c$ kg^{-1})		(mg kg^{-1})	%
Control	4.4	1.3	9.5	5	21
Terra preta	5.4	6.8	17.3	300	55

a Exchangeable. **b** Mehlich. **c** Base saturation = (Ca + Mg + Potassium) / CEC.
Note: CEC = cation exchange capacity.
Source: Novotny et al. 2009

Recently, biochar has been manufactured with four complementary and generally synergistic objectives in mind: soil amelioration to improve agricultural productivity, waste management, climate change mitigation and energy production (Roberts et al. 2010). Figure 6 identifies the interactions between the differing objectives and motives for biochar production and application. These competing priorities may pose issues for future large-scale biochar production, where one will come to dominate at the cost of others (Pratt & Moran 2010). As the primary focus of this report is use of biochar for agricultural productivity and soil carbon storage, it will only briefly discuss the other objectives.

Researchers have been conducting biochar field trials on varying soil types and within different parts of the world since 1980 (Talberg 2009). These trials have focused mostly on tropical or semi-tropical regions in South America and South-East Asia (Blackwell et al. 2009; Talberg 2009; Verheijen et al. 2009). Research is currently underway to determine the effects of biochar in an Australian context through, for example, the Climate Change Research Program (DAFF 2011) and projects within the Grains Research and Development Corporation (GRDC 2011). However, the long-term effects of biochar application are still unknown, with available information generally only relating to the first few years after application (Verheijen et al. 2009). As well, information on the effect of biochar on pastures, fodder shrubs and trees, and within dry and temperate climates is limited (Blackwell et al. 2009). Research to identify the long-term effect of biochar additions on specific soil types and climatic areas is needed to further understand the effects of biochar within an Australian context.

6 Objectives and motivations for applying biochar to soils



Source: Lehmann & Joseph 2009a

Application of biochar

Owing to the variability of biochar types and potential applications, limited information is available to farmers on how best to apply it (Casselman 2007; IBI 2011). However, with current research and the potential of biochar use to become widespread, it is possible that application guidelines and specific machinery will be developed for its application.

There are a number of options for applying biochar and include deep banding with manures or composts, applying through liquid slurries and spreading by hand or machine; however, most have not been extensively researched. Field trials to date have spread biochar and incorporated it into the soil through some form of tillage (Blackwell et al. 2009). This method of application minimises biochar movement though soil erosion, but may pose challenges for pasture application and no-tillage farming (Blackwell et al. 2009; Sohi et al. 2009).

In addition, strategies on timing and location of biochar application need to be developed. Due to the relatively small amounts of biochar produced compared with the initial biomass feedstock volume and the land harvesting area, it may not be feasible to apply the biochar back to the entire harvested area. Rather, biochar may be sequentially and annually applied to the feedstock harvest area on a hectare-by-hectare basis, where farmers have access to a small-scale, on-site pyrolysis plant.

Biochar for soil improvement

Application of biochar as a soil amendment may be a valuable tool to enhance infertile and/or degraded lands. When applied to soil, biochar may improve nutrient supply to plants, as well as the physical and biological properties of the soil. However, due to the irreversibility of biochar application, researchers need to conduct long-term studies to achieve a high level of certainty that adding biochar to agricultural soils, for whatever reason, will not negatively affect soil health and productivity.

Soil bulk density and water holding capacity

Most researchers agree that adding biochar to infertile soils decreases its bulk density and increases its water holding capacity. Adding biochar to infertile soil increases porosity, by the nature of its particle size and shape, and because of biochar's particularly porous internal structure. In addition, increased soil porosity increases the surface area of soil so water is better able to penetrate.

Ion exchange capacity

Soil with a high cation exchange capacity has the ability to hold or bind cationic plant nutrients on the surface of biochar particles, humus and clay, so nutrients are available for uptake by plants. A high cation exchange capacity means applied nutrients are held in soils rather than leached in times of high rainfall. High soil cation exchange capacity translates to a soil with high buffering capacity; meaning that addition of acidic or basic components has a smaller effect on soil pH (until a certain point). For example, a high-cation exchange capacity soil will take a longer time to develop into an acidic soil compared with a lower-cation exchange capacity soil. Conversely an acidic soil with a high cation exchange capacity will need application of more lime to correct the soil pH compared with an acidic soil with a lower cation exchange capacity.

A number of studies have illustrated that biochar can increase the cation exchange capacity of the soil. Once fresh biochar is exposed to oxygen and water in the soil environment, spontaneous oxidation reactions occur, resulting in an increase in the net negative charge and hence an increase in cation exchange capacity (Joseph et al. 2009). As such, aged biochar particles are associated with high concentrations of negative charge, potentially promoting soil aggregation and increasing nutrient availability to plants (Liang et al. 2006; Major et al. 2010a). However, Granatstein et al. (2009) found that cation exchange capacity did not change significantly as a result of biochar application, although there was a trend of increasing cation exchange capacity when added to soils with a low initial cation exchange capacity.

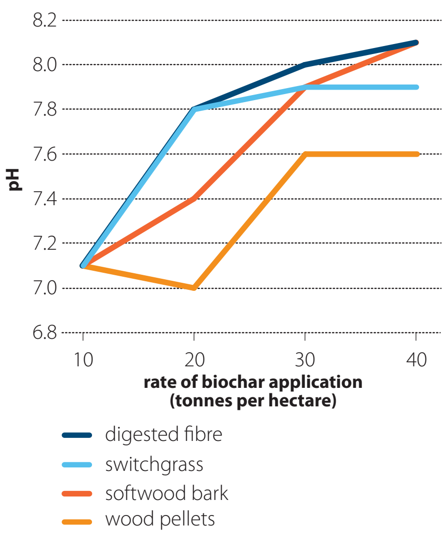
Inyang et al. (2010) also measured the anion exchange capacity in bagasse biochars and suggest that the addition of biochar would significantly enhance the exchange capacities (cation and anion) of soils and improve their nutrient holding capacities.

Soil pH

pH is a measure of the acidity or alkalinity of a solution and is an important characteristic of soils in terms of plant growth. Most plants have a preferred pH range where maximum growth and production can be attained. However, most of Australia's crop species need only slightly acidic to neutral soils. Due to the differential uptake and distribution of positively and negatively charged ions, plant growth, fertiliser application and crop harvesting acidifies soils. It is usual practice to amend acidic soils by adding agricultural lime to raise the pH, which allows plants to grow at their maximum potential (when other requirements such as water and nutrient availability are met).

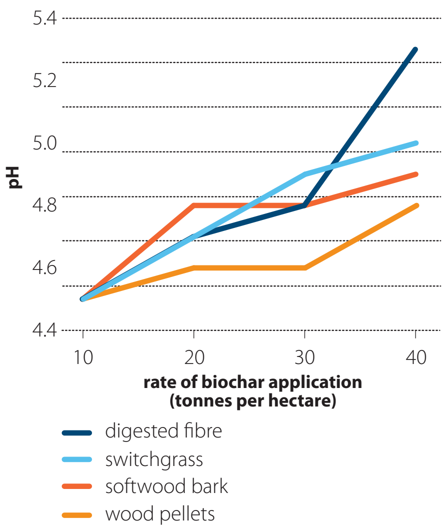
A recent study found varying pH effects when different types of biochar were added to the soil (Granatstein et al. 2009). This study noted that soil pH increased from 7.1 to 8.1 when 39 tonnes per hectare of herbaceous feedstock derived biochar was added to a sandy soil. The increase in pH was less pronounced for biochars from woody feedstocks (figure 7). A smaller overall pH increment was observed when all types of biochar were applied to silt loam soils at rates up to 39 tonnes per hectare (figure 8). Notably, pH increases in the sandy soil reached a plateau at a biochar application rate of around 20 tonnes per hectare. In loamy soil types, a similar plateau effect at 20 tonnes per hectare was observed, but showed additional increases at the rate of 39 tonnes per hectare. The authors suggested that the smaller pH increases in loam soils was due to the high initial cation exchange capacity (and hence, a high buffering capacity) of the loams.

7 Change in soil pH with increasing biochar application rates to sandy soils



Source: Granatstein et al. 2009

8 Change in soil pH with increasing biochar application rates to silt loam soils



Source: Granatstein et al. 2009

Note: The range of pH values is different in each figure.

Nutrient content

The pyrolysis operating conditions and biomass feedstock affect both the composition and structure of biochar, resulting in significant differences in nutrient content. Moreover, the variation in the physico-chemical nature of biochars causes variability in the availability of nutrients within each biochar to plants. Biochars derived from manure and animal-product feedstocks are relatively rich in nutrients when compared with those derived from plant materials and especially those derived from wood. However, biochars in general are probably more important for use as a soil amendment and driver of nutrient transformation and less so as a primary source of nutrients (DeLuca et al. 2009).

Biochar effects on soil biological activity

Soils can be viewed as complex communities of organisms which are continually changing in response to soil characteristics and climatic and management factors, especially the addition of organic matter (Thies & Rillig 2009). However, addition of biochars to soils is likely to have different effects on soil biota (all organisms living within the soil) compared with addition of fresh organic matter (biomass). The differences arise because of the relative stability of biochar and the general lack of energy and biologically useable carbon in comparison with fresh organic matter.

Nevertheless, addition of biochar to soils affects the abundance, activity and diversity of soil biotic communities. Biochar addition to soils can stimulate microorganism activity in the soil, potentially affecting the soil microbiological properties (Hammes & Schmidt 2009). Rather than supplying microorganisms with a primary source of nutrients, biochar is thought to improve the physical and chemical environment in soils, providing microbes with a more favourable habitat (Krull et al. 2010).

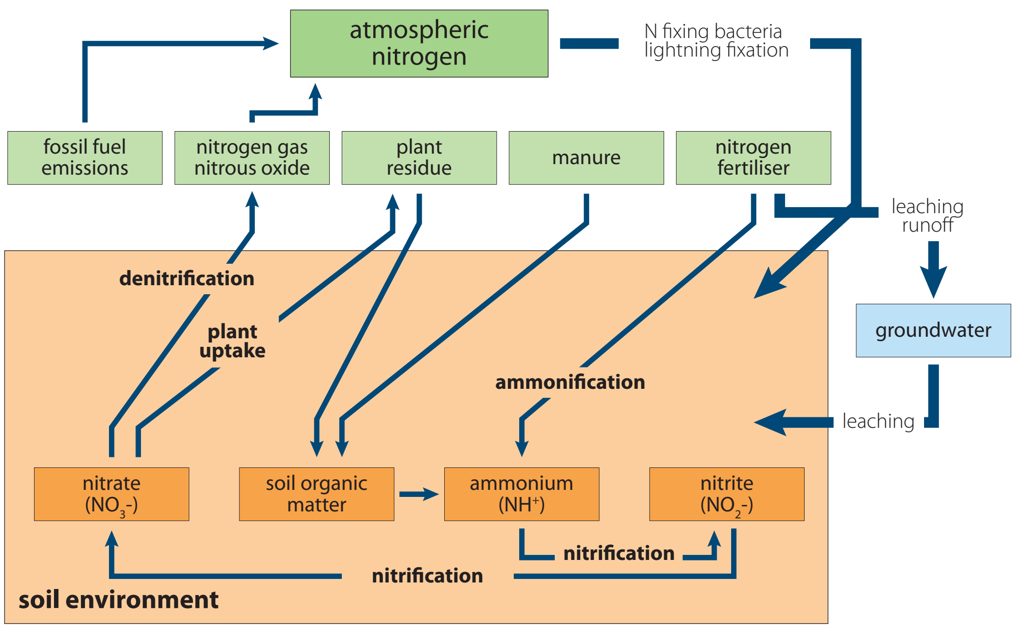
Biochar, because of its porous nature, high surface area and its ability to adsorb soluble organic matter and inorganic nutrients, provides a highly suitable habitat for microbes. This is true for bacteria, actinomycete and arbuscular mycorrhizal fungi from which some types may preferentially colonise biochars depending on its physio-chemical properties. Biochar pores may act as a refuge for some microbes, protecting them from competition and predation. Microbial abundance, diversity and activity are strongly influenced by pH. The buffering capacity (that is, the ability of the soil solution to resist changes in pH) imparted by biochar cation exchange capacity may help maintain appropriate pH conditions and minimise pH fluctuations in the microhabitats within biochar particles.

Biochar is relatively stable and has long soil residence times, which suggests that biochar is not a good substrate (food) for soil biota. However, biochars freshly added to soils may contain suitable substrates to support microbial growth. Depending on feedstock type and production conditions, some biochars may contain bio-oils or recondensed organic compounds which could support the growth and reproduction of certain microbial groups over others. The implications of this are that microbial communities in biochar will change over time once it has been added to the soil. In addition, there could be a concomitant change in the range of ecological roles filled and services provided by successive communities. It may be that ecosystem services which are beneficial for agriculture, such as nutrient cycling or mineralisation of organic matter, develop over time.

Nutrient transformation

Nitrogen is a very important plant nutrient. Application of biochar to soils may aid transformation of nitrogen, potentially improving its availability to plants. Soil biota is responsible for biotic fixation of atmospheric nitrogen and for nitrogen mineralisation. Nitrogen mineralisation refers to transformation of nitrogen held in organic forms (such as humus and decaying plant and animal matter) to forms available for uptake by plant roots; namely ammonium and nitrate. Mineralisation consists of two major transformations that are catalysed by different groups of biota. Firstly, organic nitrogen is ammonified to ammonium and then nitrified to nitrate (figure 9).

9 Nitrogen cycle



Note: Nitrogen applied through fertiliser application or animal manure is converted to ammonium (ammonification). Ammonium is oxidised to nitrite, which is converted to nitrate (nitrification) which is reduced to nitrous oxide or nitrogen gas (denitrification). Nitrates are also taken up by plants and are converted to proteins (both plant and animal).

Biochar has been found to increase nitrification rates in natural forest soils that have very low natural nitrification rates. However, in agricultural soils, which already have appreciable rates of nitrification, the effect of biochar on nitrification was found to be minimal. In some cases, biochar additions to agricultural soils also decreased apparent ammonification rates (that is, the breakdown of organic forms of nitrogen to ammonium) (DeLuca et al. 2009). Similarly, Granatstein et al. (2009) found that addition of biochar to soils led to a decrease in soil nitrate production (nitrification) and a decrease in the amount of nitrogen available to plants.

DeLuca et al. (2009) also documents different experiments which show biochar decreases nitrogen availability in tropical agricultural soils and that biochar increases nitrogen uptake by plants. Biochar is thought to be able to bind ammonium ions from the soil solution, thereby reducing their concentrations in the soil solution (availability) and increasing their concentration in biochar particles. Immobilisation of nitrogen on biochar should reduce nitrogen losses from soil through leaching.

Nitrogen can also be lost from the soil through volatilisation of ammonia and through denitrification in which nitrate is converted to nitrogen gas or the intermediates nitric oxide and nitrous oxide. Biochar is thought to reduce the potential for ammonia volatilisation, because it decreases available ammonium in the soil solution and moderately raises the pH of soils; both conditions which do not favour ammonia formation and volatilisation. Also, biochar is thought to be able to catalyse the reduction of nitrous oxide to nitrogen gas, thus completing denitrification and reducing the amount of nitrous oxide—an important greenhouse gas—entering the atmosphere (box 1) (DeLuca et al. 2009; Van Zwieten et al. 2009).

Some biochars may also enhance biological nitrogen fixation by bacterial root nodules of plants. Biological nitrogen fixation is very important in low input systems where nitrogen fertiliser inputs are minimal, such as in developing countries. Biological nitrogen fixation is also important in terms of Australian crop rotations, where green manure crops (such as legume crops) are used, and in the functioning of improved pastures. Rondon et al. (2007) found that biochar additions significantly increased biological nitrogen fixation by rhizobia at all application rates (30, 60 and 90 grams per kilogram). They also noted that the improvements in biological nitrogen fixation and biomass productivity were significantly greater compared with normal productivity achieved by conventional fertiliser application (in the absence of biochar). Rondon et al. (2007) therefore recommended that in-depth field studies be conducted to investigate this significant improvement in productivity. Free living nitrogen gas fixing bacteria are ubiquitous in soils, but no studies show biochar application having a direct effect on nitrogen assimilation by this group of nitrogen-fixing organisms.

Phosphorus is another important plant nutrient. Microbial turnover and organic matter decomposition regulate phosphorus mineralisation and hence its availability to plants. Several studies have demonstrated enhanced phosphorus uptake by plants in the presence of biochar, but little work has been done on the underlying mechanism for this enhanced uptake. The mechanisms are likely to include biochar as a:

- direct nutrient source of phosphorus
- store of phosphorus bound to surface sites through its anion exchange capacity
- modifier of soil pH, thereby modifying the pH-dependent solubility characteristics of phosphorus compounds
- promoter of microbial activity and phosphorus mineralisation (DeLuca et al. 2009).

Researchers suggest that biochar also improves the bioavailability of sulphur; an important nutrient that depends on mineralisation of organic forms of sulphur to cycle through soils (DeLuca et al. 2009).

The overall nutrient impact of biochar additions to soils appears to increase the ability of the soil to store or hold nutrients, rather than directly increasing nutrient content. This in turn is expected to reduce the amount of nutrient loss through leaching.

Effects of biochar on plant growth

With the modification to soil characteristics described above, the effect of biochar additions to soil on plant productivity is the most important outcome for its use in Australian agriculture.

Evidence gathered from both glasshouse and field trials indicates that biochar additions to acidic and nutrient poor soils, combined with fertiliser application, can produce yields greater than either fertiliser or biochar alone. However, the effect of biochar on crop growth depends on application rates and the soil type to which it is applied.

A key feature of biochar addition to soils is increased nitrogen use efficiency by plants. The evidence suggests that significant reductions in nitrogen fertiliser application can be achieved while maintaining similar yields, with the addition of biochar to soils. Alternatively, yields may increase significantly with the addition of biochar to soils and little change in established nitrogen fertiliser regimes.

Glasshouse trials

Chan et al. (2007) conducted a glasshouse pot test using radish grown in Australian soils and found that adding herbaceous biochar (pH 9.4) at the rate of 100 tonnes per hectare significantly increased soil pH from 4.77 to 5.99, without affecting plant growth. However, addition of both biochar and nitrogen fertiliser significantly affected soil pH and plant growth. At 100 tonnes per hectare application rate of biochar and nitrogen fertiliser, dry matter production was 266 per cent of the 100 tonnes per hectare biochar-without-nitrogen treatment. When compared with untreated soil (no biochar and no fertiliser), dry matter production was 4.5 times greater when biochar and nitrogen were added. Despite this biochar-induced increase in nitrogen use efficiency by plants at 100 tonnes per hectare biochar, a yield depression at the rate of 10 tonnes per hectare biochar in both the nitrogen-amended and no fertiliser treatments was evident.

In glasshouse trials using Australian soils Van Zwieten et al. (2010a) found an increase in nitrogen use efficiency when wheat was grown with biochar and nitrogen fertilisation. In this case, wheat yield was 30 per cent more with 2.2 per cent biochar application at the top fertiliser application rate, when compared with the same fertiliser rate and no biochar addition. Radishes also showed improvements in nitrogen use efficiency, particularly at the lower fertiliser application rates. For instance, radish biomass production at 17 kilograms nitrogen per hectare and 2.2 per cent biochar was equivalent to biomass production at 88 kilograms nitrogen per hectare alone.

In other glasshouse experiments, Van Zwieten et al. (2010b) found positive effects of biochar and nitrogen fertilisation on the growth of wheat, soybean and radish in an initially acidic, nutrient-poor Australian ferrosol. Indeed, wheat growth was 2.5 times the no-biochar no-fertiliser control. However, when the same species were grown in a pH neutral and relatively fertile soil, biochar in combination with added fertiliser caused a significant decrease in growth for wheat and radish and had no effect on soybean growth. Only radishes increased growth rates when biochar alone was added to this pH-neutral and fertile soil. These results suggest the positive impacts of biochar would probably be greatest in acidic and nutrient poor soils. Biochar additions to calcareous soils in southern Australia have recently produced positive results (Krull pers. comm. 2011).

Field trials

Field trials with biochar application have also shown increased yields of many plants; especially where they are added with mineral fertilisers or with organic fertilisers, such as manure (Blackwell et al. 2009). In tropical soils, above-ground biomass was shown to increase by 189 per cent when 23 tonnes per hectare biochar was added to Columbian soils (Major et al. 2010a). Plant growth was differentially stimulated; with legume biomass increasing almost 20 fold (1916 per cent yield increase), while forb (herbaceous) and grass biomass increased to a lesser extent (292 and 93 per cent yield increase, respectively), compared with no biochar addition.

In adjacent field trials, the maize yield over the four years following biochar application was higher in all but the year of application. In that year biochar addition showed no effect (Major et al. 2010b). In the second, third and fourth years after 20 tonnes per hectare biochar application, maize yield increased by 28, 30 and 140 per cent respectively. At an application rate of 8 tonnes per hectare, maize yields also increased in these years by 19, 15 and 71 per cent respectively. Japanese researchers also reported biochar-induced yield increases in the field for sugarcane, rice and maize production in Japan, Laos and Indonesia (Asai et al. 2009; Chen et al. 2010; Ogawa & Okimori 2010).

In the Australian context, several longer-term field trials are underway (Van Zwieten pers. comm. 2010). Solaiman et al. (2010) reported encouraging results from biochar application to acidic soils with low cation exchange capacity in Western Australia. When using soluble fertilisers at half the recommended rate (30 kilograms per hectare), addition of biochar at 6 tonnes per hectare resulted in a yield increase of 18 per cent. This treatment yielded 500 kilograms per hectare more wheat than when using soluble fertiliser at the recommended rate of 55 kilograms per hectare and biochar at 6 tonnes per hectare (Solaiman et al. 2010).

In an experiment with different planting densities and mineral fertiliser application, biochar applications at 1.5, 3 and 6 tonnes per hectare resulted in significantly greater yields than when biochar was not added (Solaiman et al. 2010). The yield increases in all biochar treatments was approximately 45 per cent compared with the control.

Van Zwieten et al. (2010c) reported extended benefits of biochar application over three seasons in a maize-legume rotation in northern New South Wales. Papermill biochar applied at 10 tonnes per hectare provided yields of 125 per cent in maize in 2007–08, 185 per cent in faba beans in 2008 and 140 per cent in maize in 2008–09, when compared with the control. With respect to corn yields, paper mill biochar was more effective than poultry litter biochar, lime or compost applications. Conversely, for faba beans, both biochars provided similar benefits which were lower than the yield increases with lime or compost addition. Table 6 summarises the effects of biochar application on plant yield for a number of glasshouse and field trials.

6 Summary of selected glasshouse and field trials

Location/soil type	Crop grown	Treatment	Yield effect	Reference
Glasshouse trial on yellow orthic tenosol soil	Wheat (*Triticum aestivum* L.) and radish (*Raphanus sativus* L.)	Biochar: 0, 5, 10, 20, 50 t ha^{-1} (whole tree residue) and Nitrogen: 0, 17, 44, 88, 177 kg ha^{-1}	Wheat: biomass increased with increasing nitrogen application rates, up to 20 tonnes per hectare biochar addition Wheat: negative yield response with biochar application rates greater than 10 t ha^{-1} and 177 kg nitrogen Wheat: ~215% yield increase with the application of 177 kg nitrogen and 10 t ha^{-1} biochar Radish: under all biochar rates, radish biomass increased with increasing nitrogen	Van Zwieten et al. 2010a
Glasshouse trial on clay loam soil	Maize (*Zea mays* L)	Biochar: 0, 1 and 5% of total soil mass (miscanthus, willow, pine) produced at either 500°C for 10 min, 400°C for 10 min or 600°C for 60 min	Biochar (400°C for 10 minutes): ~23% yield reduction Biochar (600°C for 60 minutes): 165% yield increase at 5% inclusion rate Biochar (500°C for 10 min): up to 437% yield increase at 5% inclusion rate	Kwapinski et al. 2010
Glasshouse trial on Ferrosol soil from New South Wales, Australia	Radish (*Raphanus sativus*), wheat (*Triticum aestivum*) and soybean (*Sorghum bicolour*)	Biochar: 0, 10 t ha^{-1} (papermill waste) and ± fertiliser (1.25 g controlled release fertiliser)	Wheat: biochar + fertiliser = 250% Wheat: biochar = no difference in plant growth Soybean: biochar = no difference in plant growth Radish: biochar = ~150% yield increase Radish: biochar + fertiliser = ~170% yield increase	Van Zwieten et al. 2010b

continued...

6 Summary of selected glasshouse and field trials continued

Location/soil type	Crop grown	Treatment	Yield effect	Reference
Glasshouse trial on loamy calcarosol soil from Victoria, Australia	Radish (*Raphanus sativus*), wheat (*Triticum aestivum*) and soybean (*Sorghum bicolour*)	Biochar: 0, 10 t ha^{-1} (papermill waste) and ± fertiliser (1.25 g controlled release fertiliser)	Wheat: biochar = ~50% yield reduction Wheat: biochar + fertiliser = ~45% yield reduction Soybean: biochar = no difference in plant growth Radish: biochar = ~325% yield increase Radish biochar + fertiliser = ~60% yield reduction	Van Zwieten et al. 2010b
Colombian savanna Oxisol soil	Grasses, forbs and legumes	Biochar: 0, 23.2 t ha^{-1} (prunings of old mango trees)	189% yield increase (2.4-4.5 t ha^{-1} additional dry biomass)	Major et al. 2010a
Colombian savanna Oxisol soil	Maize (*Zea mays L.*)	Biochar: 0, 20 t ha^{-1} (wood biochar)	First year: no significant effect Second year: 28% yield increase Third year: 30% yield increase Fourth year: 140% yield increase	Major et al. 2010b
Shimajiri maji, heavy clay soil, Japan	Sugarcane	Biochar: 0, 3% (bagasse)	106% yield increase (56 kg ha^{-1} additional crop)	Chen et al. 2010

continued...

6 Summary of selected glasshouse and field trials
continued

Location/soil type	Crop grown	Treatment	Yield effect	Reference
Shimajiri maji, heavy clay soil, Japan	Sugarcane	Biochar: 0, 1% (biosolids from agricultural sewerage)	120% yield increase (189 kg ha^{-1} additional crop)	Chen et al. 2010
Sandy clay loam soil, Western Australia	Wheat (*Triticum aestivum* L. var. Bonnie rock)	Biochar: 0, 1.5, 3.0 and 6 t ha^{-1} (oil mallee) and nitrogen: 0, 30, 55, 100 kg ha^{-1}	Biochar (6 t ha^{-1}) +fertiliser (30 kg ha^{-1}): 18% yield increase (340 kg ha^{-1} more wheat)	Solaiman et al. 2010
Chromosol soil, New South Wales, Australia	Radish (*Raphanus sativus* var. Long Scarlet)	Biochar: 0, 10, 50 and 100 t ha^{-1} (green waste including grass clippings, cotton trash and plant prunings) and nitrogen: 0, 100 kg ha^{-1}	Biochar alone: no effect on yield at any inclusion rate Biochar + fertiliser: higher yield increases with increasing rates of biochar Biochar (10 t ha^{-1}) ±fertiliser: reduced dry matter production	Chan et al. 2007
Ferrosol soil, New South Wales, Australia	Sweet corn	Biochar: 0, 10 t ha^{-1} (poultry litter)	Corn: 120% yield increase	Van Zwieten et al. 2010c
Ferrosol soil, New South Wales, Australia	Sweet corn	Biochar: 0, 10 t ha^{-1} (papermill waste)	Corn: 140% yield increase	Van Zwieten et al. 2010c

Improving livestock productivity

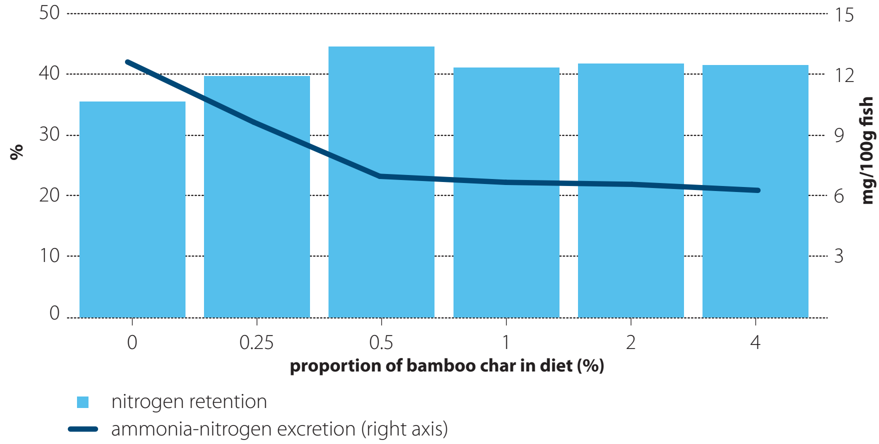
In addition to the potential of biochar for soil amelioration and crop productivity, it may also have the potential to improve livestock growth rates, while decreasing nitrogen outputs. Through limited studies conducted to date, the addition of char to the diets of economically significant livestock species has been shown to improve production parameters. Further research is needed to identify whether use of char as a feed additive would improve animal productivity parameters, while potentially reducing emissions.

Feed is one of the most important costs of livestock production for producers; particularly within the intensive livestock industries such as feedlots and aquaculture. As such, researchers and producers are continuously searching for ways of minimising feed costs while maximising productivity. Recently, addition of char to livestock feeds has been identified as a way to improve production efficiencies.

Van et al. (2006) compared the growth rates of goats fed a control diet of a tannin-rich Acacia species fodder with diets comprising differing amounts of char (0.5, 1.0 and 1.5 grams bamboo char per kilogram body weight) over a 12-week period. They found that adding char to the diets of growing goats significantly increased average daily weight gains compared with the control (53 versus 44 grams per day, respectively). Similar results have been demonstrated in flounder, ducks and broiler chickens where adding char to diets improved growth performance (Kana et al. 2010; Ruttanvut et al. 2009; Thu et al. 2010). However, Kana et al. (2010) indicated an upper tolerance limit of 0.6 per cent char of the total diet. Inclusion levels above 0.6 per cent of the diet was shown to depress weight gain. Further research should therefore be conducted to identify the optimal char inclusion levels in feed to maximise feed efficiency.

In addition to potential productivity gains, adding char to livestock diets has the potential to minimise nitrogen excretion and improve the carbon sequestration potential of manure. Researchers have found that inclusion of char up to 4 per cent of the total diet decreases ammonia nitrogen excretion from Japanese flounder (Thu et al. 2010) (figure 10). This has the potential to reduce the amount of nitrogenous waste excreted into the environment, with potential flow-on effects for both nitrification and denitrification; however, current research in this area is limited. A coordinated research approach that incorporates productivity improvements with mitigation and adaptation goals (such as incorporating char in livestock diets) may provide a cost-effective way to realise both productivity improvements and emissions reduction targets.

10 Carcass nitrogen retention at the end of a 50-day feeding trial and cumulative ammonia nitrogen excretion for 12 hours after adding bamboo char to the diets of Japanese flounder (*Paralichthys olivaceus*)



Source: Thu et al. 2010

Agricultural impacts summary

Although researchers have shown great interest in using biochar as a soil ameliorant, its current use remains minimal. This is predominantly due to uncertainty surrounding biochar, caused by the relatively short time it has been the subject of research and the high cost of production. Scientists are beginning to document the potential benefits of biochar and are examining some of the risks (see also chapter 9). In particular, the benefits of biochar have not proven to be universal, with some biochars resulting in negative effects on plant growth; especially in already fertile soils. Another factor that needs clarification is the long-term effects of biochar on soil fertility. There is little doubt that biochar can improve the characteristics of some soils and enhance nitrogen use efficiency in these soils, at least in the short term. Further research is needed to ensure that addition of biochar will not reduce soil fertility in the longer term.

Including biochar into livestock diets may also have the potential to improve animal growth rates, while providing an opportunity to reduce greenhouse gas emissions. However, due to the infancy of this research, a deeper understanding of the cause-and-effect relationship of biochar and growth rates is needed. As such, further studies should be undertaken to ensure real net benefits are obtained when incorporating biochar into the diets of agricultural production animals.

4 Biochar as a carbon store

Soils play an important role in the global carbon cycle, both as sources and sinks of carbon. Carbon exists in two forms within soils; organic (referred to as soil organic carbon) and inorganic. Most soil organic carbon originates from decay of organic matter, such as plants, animals and microbes; inorganic carbon includes sources such as calcite and dolomite.

Inorganic carbon is relatively stable within the soil profile and is not strongly influenced by land management practices (other than liming). Soil organic carbon is the organic fraction of carbon found in soil organic matter and is better able to be manipulated as a carbon store compared with the inorganic fraction (Bruce et al. 2010). Soil organic matter comprises leaf litter, plant roots, branches, soil organisms and manure; its chemical, physical and biological properties influence soil quality and function. Soil organic matter further decays into more stable constituents, such as humus and particulate organic matter.

The ability of soils to store additional carbon depends on a number of factors, including existing levels of carbon, soil type, temperature, rainfall, carbon form and how the land is managed (Bruce et al. 2010). Bruce et al. (2010) identified two major strategies for improving carbon sequestration within the soil profile; changing land management practices to achieve 'attainable' carbon levels and enhancing carbon sequestration to achieve 'potential' levels.

Attainable carbon storage levels

The attainable carbon level is determined by soil type, plant growth rates and rates of mineralisation or soil carbon respiration. Researchers have estimated that organic carbon in the top 30 centimeters of Australian soils commonly ranges from 5 to 250 tonnes carbon per hectare; with attainable carbon levels generally limited by rainfall, temperature and plant nutrition in some regions (Bruce et al. 2010). Degraded soils have the greatest potential to store carbon as there is a large difference between current levels and attainable levels of soil organic carbon.

Changing management practices that increase the return of biomass to soil or slows its decomposition is a means by which to reach attainable carbon sequestration levels. Traditional methods to improve soil carbon storage and therefore soil condition include moving to no-till practices, retaining stubble and converting marginal cropping lands into forested areas.

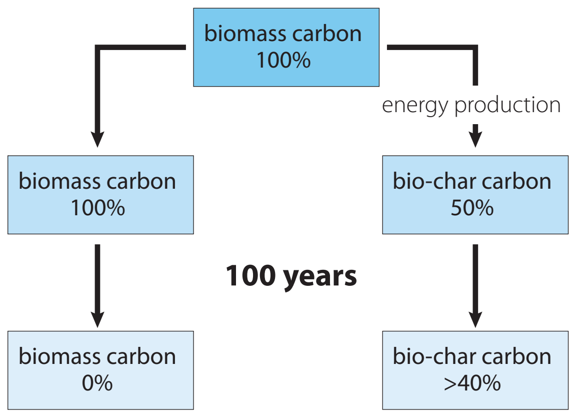
However, increasing soil organic carbon through conventional management is slow and significant uncertainty surrounds the actual relationship between management practices and carbon fluxes to soil. For example, no-till practices may only increase soil carbon in certain agro-ecological regions (dependent on factors such as annual rainfall and average temperature) where soil carbon is below attainable levels (Gaunt & Cowie 2009). In addition, these methods of storing carbon have associated risks in that stored carbon can be released through forest fires and reversion to conventional tillage practices (Lehmann 2007a).

Potential carbon storage levels

The potential carbon storage level is determined by soil type and largely cannot be influenced by management practices. Practices that overcome climatic limitations to increase potential carbon sequestration include applying carbon to soils from external sources, such as manure and biochar. However, no comprehensive estimates of the potential level of carbon sequestration have been published for Australia.

Biochar has received much attention recently as a means of sequestering carbon due to its high chemical stability, high carbon content and its potential to reside in soils over a long period. These physico-chemical properties mean that biochar application to soils may provide a greater sequestration potential, with a lower risk profile than would be the case with increasing organic matter through conventional management practices such as no-tillage farming (Kwapinski et al. 2010). Specifically, conversion of biomass carbon to biochar carbon leads to sequestration of approximately 50 per cent of the initial carbon (Lehmann et al. 2006), but this is highly dependent on the feedstock used and the pyrolysis conditions (figure 5). Soil carbon residence times are also greatly increased when biochar is added to soils compared with direct biomass application to soils (figure 11).

11 Comparison of traditional biomass and biochar applications to soils on soil carbon retention over 100 years



Source: Lehmann et al. 2006

Due to biochar's inherent stability, it is hypothesised that application of biochar to soils results in greater soil carbon sequestration potential than would result from application of biomass of similar carbon content (Kwapinski et al. 2010). It is estimated that if producers move from a 'slash and burn' system to 'slash and char', approximately 12 per cent of all emissions may be offset annually from a change in land use (Maraseni 2010). Further, researchers have estimated that total emissions reductions of approximately 3 tonnes carbon dioxide equivalents per tonne of biochar can be achieved when using yard or garden waste as a feedstock (Roberts et al. 2010). However, this value depends on feedstock used, its conventional management practice, fossil fuel substitution and cropland to which the biochar is applied (Roberts et al. 2010).

A comparison of international findings with an Australian perspective would be beneficial; however, no Australian journal publications are available.

5 Biochar effects on greenhouse gas emissions

Production and use of biochar as a soil amendment, in conjunction with bioenergy production may provide a means to decrease greenhouse gas emissions and provide net environmental benefits. However, careful consideration must be given to the potential negative effects of biochar application to soils such as the potential to increase soil organic matter degradation and a potential increase in erosion from removal of stubble as a feedstock. More research is needed to explore these potentially negative effects before the uptake and use of biochar as a direct method to reduce greenhouse gas emissions from agricultural soil.

An environmental sustainability analysis, including a life cycle analysis, will give an indication of the overall impact of biochar use in agricultural situations. The following chapters outline potential impacts that will need to be considered in any future sustainability analysis.

Non–carbon dioxide greenhouse gas reduction potential with biochar application

In addition to the potential of biochar to sequester carbon, it also has the potential to decrease non-carbon dioxide greenhouse gas emissions; including methane and nitrous oxide. However, according to Sohi et al. (2010), no peer-reviewed studies documenting suppression of nitrous oxide emissions in field experiments have been reported. There are, however, conference proceedings and laboratory-based peer-reviewed studies reporting reductions in nitrous oxide emissions (Clough & Condron 2010). Rondon et al. (2005) found that adding biochar significantly reduced net methane and nitrous oxide emissions when infertile Colombian savannah soils were amended with biochar at a rate of up to 30 grams per kilogram of soil. Researchers found that nitrous oxide and methane emissions were reduced by up to 50 and 100 per cent respectively, at an optimal application rate of 20 grams of biochar per kilogram of soil (Rondon et al. 2005). Similarly, Spokas et al. (2009) found suppression of both methane and nitrous oxide at levels up to 60 per cent inclusion rates in laboratory trials (corresponding to 720 tonnes biochar per hectare).

Yanai et al. (2007) also found that addition of biochar up to 10 per cent reduced nitrous oxide emissions by 89 per cent, but only when the soil was rehydrated with 73 to 78 per cent water-filled pore space. However, biochar added to soils rehydrated at 83 per cent water-filled pore space significantly stimulated nitrous oxide emissions compared with the control (Yanai et al. 2007). This illustrates the complex interactions between soil properties and the biochar applied.

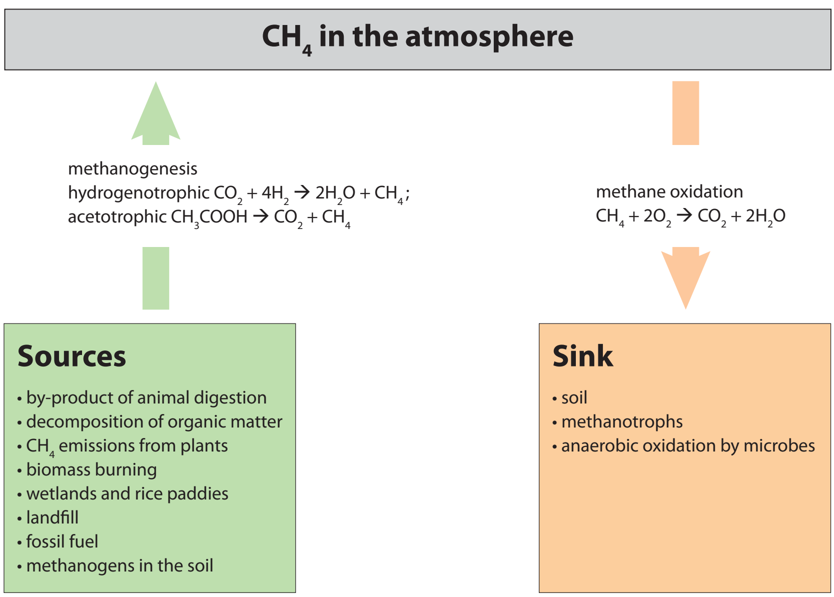
box 1 **Methane emissions**

Methane is a greenhouse gas that is 25 times more effective in trapping heat in the atmosphere than carbon dioxide over a 100-year timescale (Solomon et al. 2007). It is emitted from various natural and human sources, including wetlands, landfill and agricultural practices. Acetate, formate, carbon dioxide and hydrogen gas are all substrates for methane production by methanogenic bacteria, when organic matter is decomposed in the soil environment (Van Zwieten et al. 2009).

Aerobic, well drained soils are commonly a sink for methane due to high oxidation rates by methanotrophic organisms (figure 12). However, the methane uptake capacity of a soil is dependent on a number of factors including land use, management practices, temperature and soil conditions (Van Zwieten et al. 2009). Conversely, methanogenesis (production of methane by methanogens) is greatest in regions with warmer climates and where anaerobic conditions prevail (including landfill, wetlands and rice fields). Both methanogens and methanotrophs are ubiquitous in soil and may occur in close proximity to one another (Van Zwieten et al. 2009).

Oxygen concentration in the soil environment is the main limiting factor for oxidation of methane by methanotrophs. As such, increasing oxygen concentrations in soil through decreasing soil density and increasing porosity through biochar application appears to be a viable option. Evidence that biochar increases methane oxidation in soils is extremely limited (see 'Non–carbon dioxide greenhouse gas reduction potential with biochar application').

12 Sources and sinks for methane production (methanogenesis) and oxidation (methane uptake) relevant to the agriculture sector



box 2 Nitrous oxide emissions

Over recent years, researchers have paid great attention to the sequestration of atmospheric carbon dioxide to mitigate climate change. Nitrous oxide is also a significant contributor to global warming (it contributes approximately 8 per cent to global greenhouse gas emissions) but relatively little research has been undertaken to investigate mitigation methods for this gas. Nitrous oxide is a soil-derived greenhouse gas and is produced through biological processes such as nitrification and denitrification (figure 9). A number of soil properties influence these biological processes, including available nitrogen and carbon, soil pH and water-filled pore space (Clough et al. 2010; Singh et al. 2010b).

The rate of nitrification increases as soil moisture increases, up to 0.6 water-filled pore space, but is increasingly inhibited by low oxygen concentrations beyond 0.8 water-filled pore space (Singh et al. 2010b). Further, as a result of irrigation and rainfall events, soil moisture conditions fluctuate between wet and dry periods. This fluctuation increases the availability of dissolved organic carbon and nitrogen, therefore increasing nitrous oxide emissions from the soil (Singh et al. 2010b).

Nitrogen fertilisers, biological nitrogen fixation by soil biota, soil organic matter content and animal manure and urine are all sources of nitrogen that can lead to nitrous oxide emissions from the soil (Van Zwieten et al. 2009). Specifically, nitrogen fertiliser application rates, crop type, fertiliser type, soil organic carbon content, soil pH and soil texture are factors that significantly influence nitrous oxide emissions from the agricultural and forestry sectors. For example, in New Zealand broadacre grazing systems, urine patches from livestock are the major source of nitrous oxide emissions, as a result of the high rate of nitrogen application to these patches surpassing the pasture's ability to use the deposited urinary nitrogen (Clough et al. 2010). As such, it is important to understand the biological processes in formation of nitrous oxide to ensure optimal management of biochar additions to soil, while minimising nitrate leaching.

However, little is known about the mechanisms through which biochar affects fluxes of nitrous oxide and methane emissions (Singh et al. 2010b). Since the global warming potential of nitrous oxide and methane, on a timescale of 100 years, is 298 and 25 times greater than that of carbon dioxide, respectively (Solomon et al. 2007), it is essential to understand these mechanisms to determine the potential role of biochar to decrease non–carbon dioxide greenhouse gas emissions. Further, it is essential to gain an understanding of the potential negative environmental consequences of applying biochar to soils. These research gaps are being addressed through current research programs (see chapter 12).

Soil organic matter and carbon dioxide emissions

Biochar has the potential to sequester carbon for decades and up to millennia, but a number of studies have found that biochar additions to soil increases soil organic matter mineralisation and consequently carbon dioxide emission rates (Major et al. 2010a; Pietikainen et al. 2000; Spokas et al. 2009). Spokas et al. (2009) found that adding biochar and moisture to a silt loam soil increased overall production of carbon dioxide. The authors attributed this increase to reactions involving water and oxygen in the closed space above the biochar and soil. It is also possible that the carbon dioxide was produced by labile or reactive components adsorbed to the biochar (Spokas et al. 2009). Further, Major et al. (2010a) found that cumulatively, 41 and 18 per cent more carbon dioxide was emitted when biochar was applied to soils, compared with the non-amended soil in the first and second year, respectively. However, these results appeared to be a transient increase in carbon dioxide emissions, with an expected net reduction in emissions over the longer term.

Recent research has shown that instead of biochar stimulating the mineralisation of soil organic matter, it represses it (at least over the short term) (Jones et al. 2011b). While short-term increases in carbon dioxide emissions from soils were detected, the source of the carbon dioxide was from both the biotic (living organisms) and abiotic (non-living chemical and physical factors) release of carbon from the biochar. The amount of carbon dioxide released from the biochar only amounted to 0.1 per cent of the carbon contained in the biochar (Jones et al. 2011b). This research may affect the potential of biochar to reduce carbon dioxide emissions, but further analyses must be undertaken to identify the effects of biochar additions on soil organic matter, carbon dioxide emissions and carbon storage potential.

Ancillary benefits of biochar application

Biochar applications to soils may also reduce the need for nitrogen fertiliser. Due to the potential beneficial effect of biochar application to increase the soil's nutrient retention capacity, biochar may increase the efficiency of nitrogen fertiliser. As such nitrous oxide emissions may be reduced by decreasing producers' reliance on nitrogen fertilisers, therefore reducing production of these fertilisers (Sohi et al. 2009).

When biochar is applied, soil bulk density decreases and porosity increases. These altered soil characteristics from the application of biochar to agricultural land may help decrease tractor effort when ploughing (for example, when sowing crops), which may result in decreased fuel consumption. This will have positive flow-on effects for minimising greenhouse gas emissions from on-farm machinery. As well, the decrease in soil density may result in lower requirements for tillage, reduced labour and machinery hours and reducing overall soil compaction. However, further investigation into the role biochar application has in changing land management practices needs to be undertaken.

Avoided emissions from waste streams

Emissions may also be avoided when using organic wastes and crop residues by preventing its natural decomposition in soil; reducing composting and avoiding landfill (Sohi et al. 2009). It has been estimated that where waste would otherwise be transported, on-site pyrolysis reduces mass by 20 to 30 per cent of the wet waste mass; minimising transportation costs and wastes to landfill (McHenry 2009). However, for biochar to reduce transportation and landfill emissions, pyrolysis plants must be located in close proximity to both the source of the feedstock and the site of biochar application. If the facilities are not within close proximity, transport emissions may negate the benefits of the emission reductions (Krull 2009).

6 Biochar for waste management

Another benefit of biochar production is the potential to minimise waste to landfill, minimise nitrogen runoff from traditional manure application and to mitigate emissions from waste products. Through pyrolysis, the weight and volume of initial biomass feedstock is reduced. As such, the quantity of waste to landfill will decrease, limiting reliance on large-scale landfill sites. In addition, there is the potential to avoid greenhouse gas emissions such as methane and carbon dioxide that are generated from traditional waste disposal, processing and recycling operations (Woolf et al. 2010) (see chapter 5).

Left to accumulate, animal and crop waste can contaminate both ground and surface waters through nitrogen runoff (Talberg 2009). Traditional waste management practices aimed at minimising these effects may become costly in the long term (McHenry 2009). Biochar production and application to agricultural soils may be a way to alleviate nitrogen runoff, while maintaining the supply of nitrogen to crops. Higher phosphorous content has also been found in biochars produced from waste feedstocks such as sewage sludge and poultry litter, potentially increasing the availability of this nutrient to plants (Lehmann & Joseph 2009a).

As well as possible fertiliser benefits, production of biochar above 350°C removes potential pathogens which may otherwise be problematic if waste products were directly applied to soils (Talberg 2009). Although use of waste feedstocks has the potential to provide considerable benefits, it must be noted that household, municipal and industrial wastes may contain heavy metals and organic pollutants, potentially contaminating soils if applied to farm land (Lehmann et al. 2006; Maraseni 2010). To ensure production of safe biochar products, minimum quality standards need to be developed that outline safe and suitable biomass feedstocks.

7 Renewable energy generation

In addition to the potential of biochar to sequester carbon, pyrolysis can also produce bio-oil and syngas which can be used as renewable biofuel or bioenergy sources. For example, biofuels produced may be used to create electricity or heat to run the pyrolysis process. By using the biofuels produced as the energy source for the system, limited or perhaps no external power may be needed (Talberg 2009). This has the potential to greatly reduce both energy inputs and costs associated with pyrolysis.

Capture and use of biofuels not only decreases production costs of the system, but may also provide an effective way to reduce greenhouse gas emissions. One study found that through optimising pyrolysis for energy production, net greenhouse gas emissions were reduced by 68 to 79 per cent (2002 to 3736 kilograms of carbon dioxide per hectare per year) when crop wastes were used. However, the need for energy generation may preclude development of small-scale pyrolysis systems. Further, although biofuels represent an efficient and effective way to run pyrolysis, there may be instances where initial investment of externally-derived energy is needed to activate the system (Sanderson pers. comm. at Bioenergy Australia meeting, 21 September 2010).

While the global potential for biofuel production is large, selection of suitable feedstocks is essential to ensuring the process is greenhouse gas neutral or negative. In particular, full life cycle analyses must be conducted to ensure net greenhouse gas reductions. For example, Roberts et al. (2010) found that purpose-grown energy crops for biochar production may actually be a net greenhouse gas emitter (+36 kilograms carbon dioxide equivalents per tonne biomass); due to indirect land-use change emissions in other locations to maintain food production. Careful consideration must therefore be given to feedstock selection to ensure a net reduction in greenhouse gas emissions. Such issues should not be ignored when considering co-production of biochar and biofuels, as this may affect the profitability and net benefit of the system.

It is not yet clear whether a pyrolysis system producing biochar suitable as an agricultural soil ameliorant will be energy self-sufficient. There is little doubt that a pyrolysis system can be energy self-sufficient, but the physical conditions needed for this may mean the resultant biochar has little effect on plant production and may not be suitable for use on agricultural land.

8 Economic considerations in biochar production

While biochar has the potential to deliver a number of benefits to the agriculture sector, its economic viability must also be considered to ensure significant development within this emerging industry. The economic viability of the pyrolysis system for producing biochar is highly dependent on a number of factors, including feedstock costs, the process itself and the value of end products.

No published work in Australia reflects the potential economic viability of different biochar production facilities. Although reports from the United States are referenced here, it must be noted that Australian conditions will vary significantly from conditions in the United States. In particular, due to wide dispersal of potential feedstock locations in Australia, transportation costs would be significantly higher in Australia. In addition, maize production systems in the United States produce about seven times more biomass on a unit area basis, compared with Australian wheat production systems. These differences mean results from US studies cannot be directly related to the Australian situation. However, the underlying economic trends may be considered in the Australian context. Further research is needed to understand the economic potential of a biochar industry in Australia.

When choosing a feedstock to produce biochar, it is essential to undertake a full life-cycle assessment to estimate the economic costs of a particular system. For example, when considering crop stubble as a potential feedstock, the harvest, transportation and opportunity costs of using the crop stubble for a different purpose (such as preventing soil erosion and supplying nutrients to future crops through soil organic matter) must be examined. By considering these factors it has been estimated that the potential farm-gate price of maize residue for producing biochar is US$27.59 per tonne (table 7) (McCarl et al. 2009).

7 Economic analysis of fast and slow pyrolysis for biochar production using crop stubble in the United States

	fast pyrolysis (US$ per tonne of feedstock)	slow pyrolysis (US$ per tonne of feedstock)
Farm-gate cost	–27.59	–27.59
Transportation cost a	–6.86	–6.86
Storage of seasonal crops b	–25.00	–25.00
Value of energy created	100.00	25.00
Biochar value	2.00	15.75
Biochar transportation cost	–0.39	–3.07
Fixed cost of pyrolysis facility	–34.13	–21.28
Facility operating costs	–55.95	–31.58
Greenhouse gas offset value c	3.29	4.55
Total value of production	**–44.63**	**–70.08**

a Assuming average transportation of 14.8 km. **b** Storage of seasonal crops will ensure a continual supply of feedstock for the pyrolysis process. **c** Includes offsets for displaced fossil fuels and potential of biochar to sequester carbon.
Source: Data adapted from McCarl et al. 2009

Production of biochar from yard waste (such as grass, leaves and other wastes from lawns for composting) and manures may also prove beneficial as it may reduce waste disposal costs and minimise greenhouse gas emissions from the normal breakdown of these waste feedstocks. Roberts et al. (2010) found biomass sources that need waste management have the highest potential to become commercially profitable. This is primarily due to the avoided costs of waste management, as well as the potential to avoid greenhouse gas emissions (methane and nitrous oxide). However, the volume of feedstock produced and the moisture content of the biomass must be carefully examined. If the feedstock has high moisture content, any additional energy needed to dry the biomass and initiate pyrolysis may reduce the financial benefit of the system.

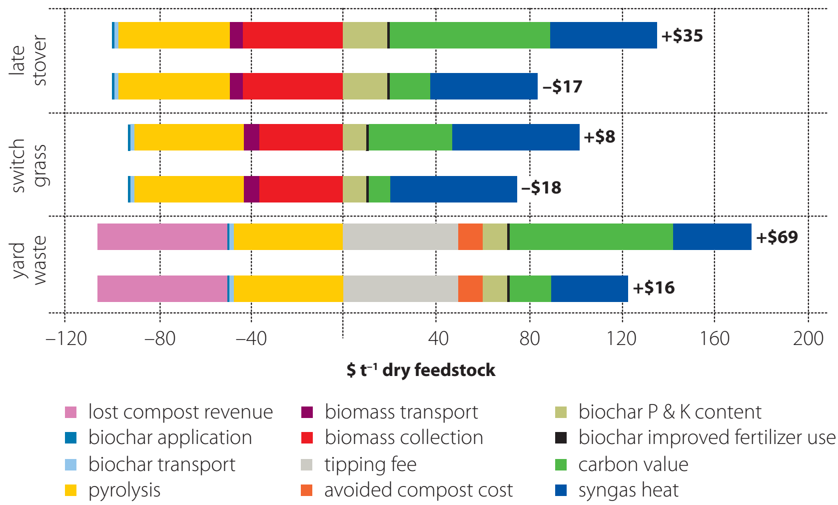
Biochar production systems vary greatly in location and size; both factors have major impacts on the profitability of the system. Generally, two processing options are available to producers: the pyrolysis plant can be located either on-farm with biomass processed on-site or at a communal site with biomass transported to the plant (Lehmann & Joseph 2009b). Generally, a centralised plant will be large and capable of high throughputs, but will also require large capital investment. In contrast, the small, generally mobile pyrolysis plants require less capital investment, but labour costs are typically high and little to no potential excess bioenergy from pyrolysis is used (Granatstein et al. 2009). One study found that only large-scale stationary pyrolysis plants were viable, where biochar was produced in conjunction with bio-oil (Granatstein et al. 2009). The cost of biochar production was estimated at US$87 per tonne of biochar using a large-scale fast pyrolysis plant.

Transportation distance of feedstocks may also decrease profitability of the system (O'Connell & Haritos 2010). Lehmann and Joseph (2009b) identified that 20 per cent of feedstock cost was attributable to transportation and that the cost would significantly decrease if the processing plant was located close to the biomass feedstock. Transportation distance not only has an effect on net profitability of a processing system, but will also affect other potential benefits such as net renewable energy production and net reductions in greenhouse gases as a result of the production of biochar and bio-fuels.

The financial benefits of biochar production comes from a number of potential sources depending on the type of pyrolysis used and includes energy production, biochar production and as a carbon offset in future emissions trading schemes. As shown in table 7, both fast and slow pyrolysis plants are unprofitable under current United States conditions (McCarl et al. 2009). However, if the value of biochar increased from US$47 per tonne to more than US$246 per tonne, slow pyrolysis would be viable for the biochar producer. In Australia, anecdotal reports indicate a cost of $5000 per tonne to purchase biochar from processing companies.

Figure 13 illustrates the potential for both high and low income scenarios when a greenhouse gas offset is considered ($80 per tonne versus $20 per tonne). Although income is received through the sale of biochar and bioenergy, the overall profitability of the process is minimised by the costs of production, even when carbon offsets are valued at US$80 per tonne carbon dioxide equivalents (Roberts et al. 2010).

13 Analysis of the costs of biochar production and potential attainable revenue per tonne dry feedstock for late harvest corn stover, switchgrass and yard waste



Note: The top bar in each feedstock type represents the high greenhouse gas revenue scenario and the bottom bar in each feedstock type represents the low revenue scenario. The value at the end of each bar represents net profit/loss for each scenario.
Source: Adapted from Roberts et al. 2010

The financial justification for developing a biochar pyrolysis system would depend on the price received for biochar and bioenergy products, and any value of avoided carbon dioxide equivalent emissions, the cost of feedstocks used and the cost of pyrolysis itself. Development and commercial viability of a biochar industry would be highly reliant on proven benefits to ensure demand for specific biochar products. Feasibility studies are scarce in this emerging industry and as such, the commercial viability of biochar production remains unclear; especially in the Australian context. Further research is needed to ensure the viability of pyrolysis plants and confirm the potential benefits of biochar application to soils.

The Australian Government's Carbon Farming Initiative may also influence uptake of biochar use in agricultural systems. The Carbon Farming Initiative is a carbon offset scheme for crediting emission reductions and sequestration in land-based sectors. These offset credits will be able to be sold on domestic and international carbon markets. Application of biochar to soils has been placed on the draft Carbon Farming Initiative Positive List, meaning this activity is likely to be eligible for crediting. However, all eligible activities need an approved methodology to enable quantification of emission reductions or sequestration. There are currently no approved methodologies for biochar; further research may be needed before a methodology can be found to meet the integrity standards of the Carbon Farming Initiative. To fast track this process the Australian Government is providing additional funding under the Carbon Farming Initiative for the Biochar Capacity Building Program. This program will help provide practical mitigation options for land holders by assessing the greenhouse gas mitigation potential of biochar. These options may then be considered for generation of offset credits under the Carbon Farming Initiative.

9 Risks associated with biochar production and use

Despite widespread interest in producing biochar for soil amelioration and potential climate change mitigation, substantial uncertainties remain about the impact, capacity and environmental sustainability of biochar production and application. Due to the irreversibility of biochar application to soils, any potential risks should be thoroughly examined before widespread use of biochar is adopted.

Application rates

Of particular concern is the lack of research about the appropriate level of biochar application for different soil types (McHenry 2009); however, current Australian research is attempting to address this knowledge gap (see chapter 12). Due to the limited number of studies and the small range of climatic, crop and soil types examined, caution must be exercised when extrapolating results (Verheijen et al. 2009). This is essential, considering that some biochars have been found to adversely affect plant growth and not all soils respond to biochar application in the same manner (Krull 2010; Kwapinski et al. 2010; Sohi et al. 2010; Verheijen et al. 2009). For example, Kwapinski et al. (2010) reported suppression of plant growth when a miscanthus-derived biochar was applied to soils. It is therefore important to develop in-depth knowledge of appropriate application rates and biochar types that should be applied to different soil types under different climatic conditions to ensure agricultural production is not compromised.

Effect on agrochemicals

The efficacy and bioavailability of agrochemicals when applied to biochar amended soils is also of some concern. The physico-chemical properties of biochar have two potential effects on agrochemicals. First, biochar can bind organic chemicals, such as herbicides, which can reduce the amount of the chemical available to kill target species (Jones et al. 2011a). Second, adding biochar to some soils inhibits microbial degradation of organic compounds (Kookana 2010). While reduced degradation may be related to the binding of chemicals to biochar particles, it is not yet proven that this is always the case.

Researchers have found that adding 1 per cent wheat biochar results in up to 80 times higher herbicide soil sorption (binding) rates and, in turn, decreases its ability to kill target weeds (Yang et al. 2006). For example, Yang et al. (2006) have illustrated that weed survival rates increased with increasing biochar content at potentially damaging application rates of a soil-incorporated herbicide. These results may have important implications for the efficacy of herbicides and other agrochemicals particularly those applied to, or incorporated into, soils. The potential costs of applying additional agrochemicals to gain the same outcomes must also be factored into any risk assessment. However, researchers have suggested that biochar in soil could prevent leaching of some foliar-applied agrochemicals resulting in fewer negative offsite environmental effects from these types of applications.

Biochar's ability to inhibit microbial degradation of some organic molecules could also affect the longevity of chemicals in soil. Most agrochemicals are degraded by various mechanisms including natural microbial systems. Those degraded by microbes may remain in the environment for longer when biochar is present and could have an effect on off-site and non-target impacts associated with using the chemical.

Biomass availability

While the global potential for biochar and bioenergy production is large, there is only a finite area of land available without compromising food production (Moreira 2006). As the market for these products expands, land use and other resources may be affected. To minimise production and transportation costs, an extensive life-cycle analysis must be conducted before widescale biochar application is considered. This will ensure net benefits in agricultural productivity and carbon sequestration are realised, while minimising effects on global food security.

As biomass density in Australia is lower when compared with more productive landscapes in continental America and Europe, biomass transportation costs may affect the viability of a biochar industry within Australia. It may also be difficult to source adequate quantities of biomass throughout the year, with transportation costs expected to be higher. As such, full cost–benefit analyses should be conducted to ensure biochar production is viable in Australia.

Soil albedo

Due to the ability of biochar to darken the colour of soil, especially in soils already low in organic matter, biochar application to soil increases solar energy absorption and decreases soil albedo. Soil albedo is a measure of the reflectivity of a surface and plays an important role in climate change. Depending on the soil water content and plant coverage, biochar addition may also increase soil temperatures (Krull et al. 2004; Sohi et al. 2010). One study found that charcoal incorporated into the soil decreased surface albedo by 37 per cent and increased soil surface temperatures by an average of 4°C compared with unamended soils (Oguntunde et al. 2008).

The increase in soil temperature and decrease in soil albedo could potentially accelerate cycling of nutrients and extend growing seasons in temperate climates (Sohi et al. 2010). However, with large-scale application of biochar, it also has the potential to decrease the albedo of the Earth's surface, potentially contributing to further climate change. The decrease in soil albedo will have the greatest impact when biochar is applied to light-coloured soils with spring cropping regimes, or applied to orchards or vineyards that experience large periods of time with little ground cover (Verheijen et al. 2009).

Soil residence times

The amount of time that biochar remains in soils (soil residence times) is another area of risk and will depend on the type and quality of the buiochar added. While some authors calculate a biochar half life (the amount of time it takes for half of the biochar mass to decompose) in soil of several hundred to thousands of years, limited field trials have assessed soil residence times over a range of conditions and biochar types. The limited field studies completed have found that finely ground biochar slowly disappears from the soil, provided it is not transported from the site through erosion. In this study, Major et al. (2010a) estimated that less than 3 per cent of biochar is lost through mineralisation (conversion to carbon dioxide) over a 2-year period. The authors also found that biochar had a mean residence time of around 600 years in tropical areas, and much longer in temperate regions (3264 years at 10°C). They also noted a slow migration rate of biochar to the subsoil and significant loss of fine biochar through erosion during high rainfall events. Other aging processes (such as abrasion through tillage and natural soil movements) are expected to reduce the half life of biochar (ANZBRN 2008).

Soil organic matter

With the addition of biochar to soils, some researchers are concerned that it may lead to accelerated decomposition of plant derived soil organic matter (Verheijen et al. 2009). Preliminary and inconclusive evidence suggests that adding biochar increases soil organic matter decomposition rates, and may lead to decreased crop productivity in the long-term (Verheijen et al. 2009). In contrast, Kimetu and Lehmann (2010) found that adding organic matter and biochar together did not result in faster organic matter mineralisation rates. It is clear that further research on this topic is needed. Some commentators suggest that increased rates of loss of soil organic matter caused by biochar addition would be more than compensated by increases in production of biomass both above and below ground, leading to no net change, or perhaps increased accumulation of soil organic matter (Major et al. 2010a). Researchers have observed net increases in soil organic matter upon biochar application.

Although current interest in biochar is high, the extensive risk analyses needed to manage the risks and uncertainties have not been undertaken. If further research can reduce the uncertainty around potential climate change effects and productivity gains, biochar demand may increase, reducing investment risk. This would increase biochar's potential as a valuable income source for producers.

10 Limitations and barriers to implementation

Aside from the risks and uncertainties discussed in chapter 9, limitations and barriers also hinder production of biochar and adoption by the agriculture sector. Due to the heterogeneous nature of biochar, the cost of production and the limited pyrolysis facilities, particularly in Australia, biochar application to soils remains limited. Agreed national policy and industry guidelines on biochar production, quality and use could help increase use of biochar in Australian agriculture.

Each biochar produced has a unique set of properties, based on production conditions and the feedstock used. Also, soils may respond differently based on variables such as the type of biochar used, soil type, climatic zone and land use. However, the heterogeneity of available biochar feedstocks and types provides an opportunity to purpose-produce biochars well suited for particular situations and objectives. It is possible that specific biochar types can be created for different soils and land-use applications to ensure sustained, net benefits are achieved (Macias & Arbestain 2010).

However, due to an incomplete understanding of the processes that occur when biochar is added to soils, it is difficult to predict the agronomic effects in different situations (ANZBRN 2008). Well-designed laboratory and field studies are underway at scales sufficient to enable assessment of agricultural and environmental benefits and risks of using biochar. The experience and evidence gained from these studies will provide further information for developing an accurate predictive model for applying biochar to different soil ecosystems.

Due to the infancy of the biochar–bioenergy industry, supply of biochar from commercial pyrolysis plants is limited and localised in Australia (Sohi et al. 2009). Consequently, appropriate biochars are expensive, with current biochar research activities predominantly restricted to laboratory trials. If field trials are undertaken, they may be expensive and hence restricted in size and/or scope. The cost of biochar for research and for application by farmers is likely to remain a constraint until commercial-scale pyrolysis facilities are established. Unfortunately, the uncertainty around the net greenhouse gas, agronomic and environmental benefits may be deterring the very investments that would pave the way to reducing the cost of research; and hence, the uncertainty.

For example, Queensland has no regulated production and application of biochar because production capacity is not available, materials are not centrally located and supply chains have not been established (Krull 2009). However, biochar companies (such as Black is Green Pty Ltd) are starting to emerge in Queensland. Although it is intended to use biochar for soil amelioration benefits, it is probably too soon to fully embark on major industry development as considerable scientific uncertainty remains.

Lack of regulation within the biochar–bioenergy industry is also affecting the quality of biochar products. For example, some farmers are producing their own biochar in uncontrolled conditions (Sohi et al. 2010). Through unregulated production of biochar, unnecessary emissions of greenhouse gases may occur; with the resultant biochar being unsuitable (unstable) for both carbon sequestration and soil amelioration. In addition, there is neither control on the feedstock source, nor an indication as to whether an accumulation of toxic substances in the final product will occur (Sohi et al. 2010). As such, production parameters and quality control standards need to be developed and implemented to ensure net benefits are realised. As well, a classification system for biochar products is essential to ensuring targeted biochar production for application to specific soil types.

More data is needed before firm predictions can be made about biochar's effect on soil performance across a wide range of soil types, climatic zones and land management practices (Verheijen et al. 2009). Predictions about performance will need to consider the feedstock and production characteristics employed in producing biochar. Development of a classification and governance system will be essential to maximising the net benefits of biochar production, while limiting the potential negative environmental effects.

11 Current research

National funding initiatives are underway to reduce the research gaps and to develop knowledge on the effects of biochar application on greenhouse gas emissions and agricultural productivity benefits. With funding from Australia's Farming Future, the Climate Change Research Program was developed, under which researchers are investigating the:

- characteristics and properties of different types of biochar
- stability of biochar under different soil conditions
- impact of production conditions and biomass source material on biochar properties
- potential risks of using biochar
- potential of biochar to reduce greenhouse gas emissions (DAFF 2011).

Preliminary results of this work have been documented in factsheets and brochures, published by the Department of Agriculture, Fisheries and Forestry, under the Climate Change Research Program (see www.daff.gov.au/climatechange/australias-farming-future/climate-change-and-productivity-research).

A number of other biochar projects are underway throughout Australia and are listed on the Australia and New Zealand Biochar Researchers Network (ANZBRN 2011). Through these initiatives, the knowledge gaps are likely to diminish. Once knowledge of the biological processes involved is enhanced, a coordinated government approach will be needed to develop standards and regulations for the industry to safeguard against contamination of agricultural soils, and to integrate this technology into an accredited emissions trading scheme.

12 Research needs

This report identifies a number of key future research areas. This chapter highlights some of these issues to illustrate the knowledge gaps remaining for the biochar industry. Further research should be undertaken in this field before widescale application of biochar to agricultural soils commences. Further research will be vital to ensuring biochar is produced in an environmentally sustainable manner, with net benefits achieved over the long term.

Limited predictive capacity for determining the performance of different biochar products is limiting its widescale application. Due to the effects of feedstock choice (crop stubble, manure, wood chips) and pyrolysis conditions on the physico-chemical properties of biochar, further research is needed on different biochar products. Once a deeper understanding of the effects of biochar type on different performance parameters has been developed, it will be essential to devise a rapid screening technique to determine biochar quality. This will allow for predictive analyses to be undertaken to best match particular biochar characteristics with intended performance outcomes.

Great uncertainty also surrounds the effect of biochar application on agricultural productivity. To date, limited research has been published to determine the effects of biochar application on agricultural productivity parameters (such as the cation exchange capacity, water holding capacity, the effect of biochar on soil microbial populations, pesticide efficacy and nutrient availability); with many researchers reporting contradictory results. In particular, a maximum application rate needs to be identified to ensure biochar additions to soils do not degrade land. Both short and long-term field trials need to be undertaken to ensure laboratory trials can be extrapolated to the field environment and that productivity will be maintained over the long term.

Although studies have identified biochar's ability to remain stable in the soil for decades (up to millennia), limited field trials have been conducted. Of the trials conducted, researchers have found that biochar rapidly disappears from the soil, particularly through erosion (Major et al. 2010a). Long-term monitoring of biochar field applications is needed to assess the fate and long-term stability of biochar in soils. This may enable biochar applications to be traded under the Carbon Farming Initiative, while ensuring transport and contamination to the surrounding ecosystem does not occur.

Finally, the economic and societal factors of biochar have yet to be assessed in any detail, particularly in Australia. As such, robust figures for the costs and benefits of combined biochar and biofuel production are absent. Detailed integrated studies of biochar and bioenergy production systems that take into account potential leakage will need to be undertaken before any widescale production and application. Such research will identify production limits and optimal ratios (bioenergy versus biochar) for the industry to maximise net economic benefits.

13 Conclusions

Application of biochar to agricultural land for soil amelioration and agricultural productivity improvements is not a new phenomenon. *Terra preta* soils in the Amazonian Basin are characterised by highly fertile dark soils created from burning crop stubble and other household wastes over thousands of years. More recently, biochar production from agricultural waste products has been assessed in an attempt to replicate these fertile soils.

A number of benefits have been identified within the literature; biochar has been found to improve agriculturally significant soil parameters such as soil pH, cation exchange capacity and soil water holding capacity. Researchers have found the increase in these performance parameters has improved nitrogen use efficiency and therefore crop productivity in limited field trials. Further, biochar has the potential to reduce greenhouse gas emissions through carbon sequestration, as well as potentially decreasing methane and nitrous oxide emissions from the soil.

Although much research to date has been promising, knowledge gaps remain. Through current government investment in large biochar projects, such as the Climate Change Research Program, researchers have amassed an impressive amount of data and information, which will form the ideal base to further research. With this information, the net benefits in both plant productivity improvements and greenhouse gas reductions from using biochar may be assessed before widescale application. However, further research is needed to identify optimal application rates, biochar quality parameters and effects of biochar on chemical efficacy. Once further research is undertaken and the knowledge gaps closed, biochar may play a role in improving productivity and environmental sustainability issues in Australian agriculture.

References

Abdullah, H, Mediaswanti, KU & Wu, H 2010, 'Biochar as a fuel: 2. Significant differences in fuel quality and ash properties of biochars from various biomass components of Mallee trees', *Energy Fuels* 24: 1972–79.

ANZBRN 2008, *What are the likely benefits of biochar*?, Australia and New Zealand Biochar Researchers Network, available at www.anzbiochar.org/biocharbasics.html.

ANZBRN 2011, 'Projects', Australia and New Zealand Biochar Researchers Network, available at www.anzbiochar.org/projects.html.

Asai, H, Samson, BK, Stephan, HM, Songyikhangsuthor, K, Homma, K, Kiyono, Y, Inoue, Y, Shiraiwa, T & Horie, T 2009, 'Biochar amendment techniques for upland rice production in Northern Laos 1. Soil physical properties, leaf SPAD and grain yield', *Field Crops Research* 111(1–2): 81–84.

Bagreev, A, Bandosz, TJ & Locke, DC 2001, 'Pore structure and surface chemistry of adsorbents obtained by pyrolysis of sewage sludge-derived fertilizer', *Carbon* 39: 1971–79.

Baldock, JA & Smernik, RJ 2002, 'Chemical composition and bioavailability of thermally altered *Pinus resinosa* (Red pine) wood', *Organic Chemistry* 33: 1093–1109.

Bell, S 2005, 'Constructing sustainable rural landscapes: oil mallees and the Western Australian Wheatbelt', *Geographical Research* 43: 194–208.

Blackwell, P, Riethmuller, G & Collins, M 2009, 'Biochar application to soil', in Lehmann, J & Joseph, S, *Biochar for environmental management: science and technolog*y, Earthscan, United Kingdom: 207–26.

Boateng, AA 2007, 'Characterization and thermal conversion of charcoal derived from fluidized-bed fast pyrolysis oil production of switchgrass', *Industrial Engineering and Chemical Research* 46: 8857–62.

Bridgewater, AV & Peacocke, GVC 2000, 'Fast pyrolysis processes for biomass', Renewable and Sustainable Energy Reviews 4: 1–73.

Brown, R 2009, 'Biochar production technology', in Lehmann, J & Joseph, S, *Biochar for environmental management: science and technology*, Earthscan, United Kingdom: 127–46.

Bruce, S, Sims, J, Walcott, J, White, S, Baldock, J, Grace, P & Wicks, S 2010, *Soil carbon management and carbon trading,* Science for Decision Makers, Department of Agriculture, Fisheries and Forestry, Canberra.

Cao, XD & Harris, W 2010, 'Properties of dairy-manure-derived biochar pertinent to its potential use in remediation', *Bioresource Technology* 101(14): 5222–28.

Casselman, A 2007, 'Special report: inspired by Ancient Amazonians, a plan to convert trash into environmental treasure', *Scientific American*, available at www.scientificamerican.com/article.cfm?id=pyrolyisis-terra-preta-could-eliminate-garbage-generate-oil-carbon-sequestration.

Chan, KY & Xu, Z 2009, 'Biochar: nutrient properties and their enhancement', in Lehmann, J & Joseph, S, *Biochar for environmental management: science and technology,* Earthscan, United Kingdom: 67–84.

Chan, KY, Van Zwieten, L, Meszaros, I, Downie, A & Joseph, S 2007, 'Agronomic values of greenwaste biochar as a soil amendment', *Australian Journal of Soil Research* 45: 629–34.

Chen, Y, Shinogi, Y & Taira, M 2010, 'Influence of biochar use on sugarcane growth, soil parameters, and groundwater quality', *Australian Journal of Soil Research* 48(6–7): 526–30.

Clough, TJ & Condron, LM 2010, 'Biochar and the nitrogen cycle: introduction', *Journal of Environmental Quality* 39: 1218–23.

Clough, TJ, Bertram, JE, Ray, JL, Condron, LM, O'Callaghan, M, Sherlock, RR & Wells, NS 2010, 'Unweathered wood biochar impact on nitrous oxide emissions from a bovine-urine-amended pasture soil', *Soil Science Society of America Journal 7*4(3): 852–60.

DAFF 2011, *Climate Change Research Program: Emissions reduction*, Department of Agriculture, Fisheries and Forestry, Canberra, available at www.daff.gov.au/climatechange/australias-farming-future/climate-change-and-productivity-research/emissions_reduction2.

Day, D, Evans, RJ, Lee, JW & Reicosky, D 2005, 'Economical CO_2, SO_x and NO_x capture from fossil-fuel utilization with combined renewable hydrogen production and large-scale carbon sequestration', *Energy 30*(14): 2558–79.

DeLuca, TH, MacKenzie, MD & Gundale, MJ 2009, 'Biochar effects on soil nutrient transformations', in Lehmann, J & Joseph, S, *Biochar for environmental management: science and technology, Earthscan*, United Kingdom: 251–70.

Demirbas, A 2004, 'Effects of temperature and particle size on bio-char yield from pyrolysis of agricultural residues', *Journal of Analytical and Applied Pyrolysis* 72: 243–48.

Downie, A, Crosky, A & Munroe, P 2009, 'Physical properties of biochar', in Lehmann, J & Joseph, S, *Biochar for environmental management: science and technology*, Earthscan, United Kingdom: 13–32.

FAO 2009, *Feeding the World, Eradicating Hunger,* Food and Agriculture Organization of the United Nations, Rome, available at www.fao.org/fileadmin/templates/wsfs/Summit/WSFS_Issues_papers/WSFS_Background_paper_Feeding_the_world.pdf.

G8 2009, *L'Aquila: Joint Statement on Global Food Security,* The Group of Eight Nations.

Garnaut, R 2008, *The Garnaut Climate Change Review: Final Report*, Cambridge University Press, Port Melbourne, chapter 22.

Gaunt, J & Cowie, A 2009, 'Biochar, greenhouse gas accounting and emissions trading', in Lehmann, J & Joseph, S, *Biochar for environmental management: science and technology*, Earthscan, United Kingdom: 317–40.

Granatstein, D, Kruger, CE, Collins, H, Galinato, S, Garcia-Perez & M, Yoder, J 2009, *Use of biochar from the pyrolysis of waste organic material as a soil amendment: final project report*, Centre for Sustaining Agriculture and Natural Resources, Washington State University, Wenatchee, WA.

GRDC 2011, *A fundamental understanding of biochar: implications and opportunities for the grains industry*, Grains Research and Development Corporation, Canberra, available at www.grdc.com.au/CSO00041.

Hammes, K & Schmidt, WI 2009, 'Changes of biochar in soil', in Lehmann, J & Joseph, S, *Biochar for environmental management: science and technology*, Earthscan, United Kingdom: 169–82.

He, BJ, Zhang, Y, Funk, TL, Riskowski, GL & Yin, Y 2000, 'Thermochemical conversion of swine manure: an alternative process for waste treatment and renewable energy production', *American Society of Agricultural Engineers* 43: 1827–33.

Ho, MW 2010, *Beware the Biochar Initiative*, available at http://permaculture.org.au/2010/11/18/beware-the-biochar-initiative/.

IBI 2011, '*Frequently asked questions about biochar*', International Biochar Initiative, available at www.biochar-international.org/biochar/faqs#ex5.

Inyang, M, Gao, B, Pullammanappallil, P, Ding, WC & Zimmerman, AR 2010, 'Biochar from anaerobically digested sugarcane bagasse', *Bioresource Technology* 101(22): 8868–72.

Jones, DL, Edward-Jones, G & Murphy, DV 2011a, 'Biochar mediated alterations in herbicide breakdown and leaching in soil', *Soil biology and Biochemistry* 43: 804–13.

Jones, DL, Murphy, DV, Khalid, M, Ahmad, W, Edwards-Jones, G & DeLuca, TH 2011b, 'Short-term biochar-induced increase in soil CO_2 release is both biotically and abiotically mediated', *Soil Biology and Biochemistry* 43(8): 1723–31.

Joseph, S, Peacocke, C, Lehmann, J & Munroe, P 2009, 'Developing a biochar classification and test methods', in Lehmann, J & Joseph, S, *Biochar for environmental management: science and technology*, Earthscan, United Kingdom: 107–26.

Joseph, SD, Camps-Arbestain, M, Lin, Y, Munroe, P, Chia, CH, Hook, J, van Zwieten, L, Kimber, S, Cowie, A, Singh, BP, Lehmann, J, Foidl, N, Smernik, RJ & Amonette, JE 2010, 'An investigation into the reactions of biochar in soil', *Australian Journal of Soil Research* 48(6–7): 501–15.

Kana, JR, Teguia, A, Mungfu, BM, Tchoumboue, J 2010, 'Growth performance and carcass characteristics of broiler chickens fed diets supplemented with graded levels of charcoal from maize cob or seed of Canarium schweinfurthii Engl', *Tropical Animal Health and Production* 43(1): 51–56.

Keiluweit, M, Nico, PS, Johnson, MG & Kleber, M 2010, 'Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar)', *Environmental Science & Technology* 44(4): 1247–53.

Kimetu, JM & Lehmann, J 2010, 'Stability and stabilisation of biochar and green manure in soil with different organic carbon contents', *Australian Journal of Soil Research* 48(6–7): 577–85.

Kookana, RS 2010, 'The role of biochar in modifying the environmental fate, bioavailability, and efficacy of pesticides in soils: a review', *Australian Journal of Soil Research* 48: 627–37.

Kookana, RS, Sarmah, AK, Van Zwieten, L, Krull, E & Singh, B 2011, 'Biochar application to soil: agronomic and environmental benefits and unintended consequences', *Advances in Agronomy* 112: 103–43.

Krull, E 2009, 'Stabilisation of organic carbon in soil through biochar production' in *An analysis of greenhouse gas mitigation and carbon sequestration opportunities from rural land use*, CSIRO National Research Flagships: Sustainable Agriculture, available at www.csiro.au/files/files/prdz.pdf.

Krull, E 2010, 'From source to sink: a national initiative for biochar research', *Nineteenth World Congress of Soil Science, Soil Solutions for a Changing World*, Brisbane, Australia, 1–6 August 2010.

Krull, E, Singh, B & Joseph, S 2010, 'Preface to special issue: proceedings from the First Asia-Pacific Biochar Conference, 2009, Gold Coast, Australia', *Australian Journal of Soil Research* 48(6–7): i–iv.

Krull, ES, Skjemstad, JO & Baldock, JA 2004, *Functions of soil organic matter and the effect on soil properties*, Grains Research and Development Corporation, Canberra.

Kwapinski, W, Byrne, CMP, Kryachko, E, Wolfram, P, Adley, C, Leahy, JJ, Novotny, EH & Hayes, MHB 2010, 'Biochar from biomass and waste', *Waste Biomass Valor* 1: 177–89.

Lang, T, Jensen, AD & Jensen, PA 2005, 'Retention of organic elements during solid fuel pyrolysis with emphasis on the peculiar behavior of nitrogen', *Energy and Fuels* 19: 1631–43.

Lehmann, J & Joseph, S 2009a, 'Biochar for environmental management: an introduction', in Lehmann, J & Joseph, S, *Biochar for environmental management: science and technology*, Earthscan, United Kingdom: 1–12.

Lehmann, J & Joseph, S 2009b, 'Biochar systems', in Lehmann, J & Joseph, S, *Biochar for environmental management: science and technology*, Earthscan, United Kingdom: 147–68.

Lehmann, J 2007a, 'A handful of carbon', *Nature* 447: 143–44.

Lehmann, J 2007b, 'Bio-energy in the black', *Frontiers in Ecology and the Environment* 5(7): 381–87.

Lehmann, J, Gaunt, J & Rondon, M 2006, 'Bio-char sequestration in terrestrial ecosystems: a review', *Mitigation and Adaptation Strategies for Global Change* 11: 403–27.

Liang, B, Lehmann, J, Solomon, D, Kinyangi, J, Grossman, J, O'Neill, B, Skjemstad, JO, Thies, JE, Luizao, FJ, Petersen, J & Neves, EG 2006, 'Black carbon increases cation exchange capacity in soils', *Soil Science Society of America Journal* 70: 1719–30.

Macias, F & Arbestain, MC 2010, 'Soil carbon sequestration in a changing global environment', *Mitigation and Adaptation Strategies for Global Change* 15: 511–29.

Major, J, Lehmann, J, Rondon, M & Goodale, C 2010a, 'Fate of soil-applied black carbon: downward migration, leaching and soil respiration', *Global Change Biology* 16(4): 1366–79.

Major, J, Rondon, M, Molina, D, Riha, SJ & Lehmann, J 2010b, 'Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol', *Plant and Soil* 333(1): 117–28.

Maraseni, TN 2010, 'Biochar: maximising the benefits', *International Journal of Environmental Studies* 67(3): 319–27.

McCarl, BA, Peacocke, C, Chrisman, R, Kung, CC & Sands, RD 2009, 'Economics of biochar production, utilization and greenhouse gas offsets', in Lehmann, J & Joseph, S, *Biochar for environmental management: science and technology*, Earthscan, United Kingdom: 341–58.

McHenry, MP 2009, 'Agricultural bio-char production, renewable energy generation and farm carbon sequestration in Western Australia: Certainty, uncertainty and risk', *Agriculture, Ecosystems and Environment* 129: 1–7.

Moreira, J 2006, 'Global biomass energy potential', *Mitigation and Adaption Strategies for Global Change* 11: 313.

Mousavioun, P & Doherty, WOS 2010, 'Chemical and thermal properties of fractionated bagasse soda lignin', *Industrial Crops and Products* 31(1): 52–58.

Navia, R & Crowley, DE 2010, 'Closing the loop on organic waste management: biochar for agricultural land application and climate change mitigation', *Waste Management and Research* 28(6): 479–80.

Nik-Azar, M, Hajaligol, MR, Sohrabi, M & Dabir, B 1997, 'Mineral matter effects in rapid pyrolysis of beech wood', *Fuel Processing Technology* 51: 7–17.

Novotny, EH, Hayes, MHB, Madari, BE, Bonagamba, TJ, deAzevedo, ER, de Souza, AA, Song, G, Nogueira, CM & Mangrich, AS 2009, 'Lessons from the Terra Preta de Indios of the Amazon Region for the utilisation of charcoal for soil amendment', *Journal of the Brazilian Chemical Society* 20(6): 1003–10.

O'Connell, D & Haritos, VS 2010, 'Conceptual investment framework for biofuels and biorefineries research and development', *Biofuels* 1(1):201–16.

Ogawa, M & Okimori, Y 2010, 'Pioneering works in biochar research, Japan', *Australian Journal of Soil Research* 48(6–7): 489–500.

Oguntunde, PG, Abiodun, BJ, Ajaji, AE & van de Giesen, N 2008, 'Effects of charcoal production on soil physical properties in Ghana', *Journal of Plant Nutrition and Soil Science* 171: 591–96.

Pietikainen, J, Kiikkila, O & Fritze, H 2000, 'Charcoal as a habitat for microbes and its effect on the microbial community of the underlying humus', *OIKOS* 89: 231–42.

Powlson, DS, Gregory, PJ, Whalley, WR, Quinton, JN, Hopkins, DW, Whitmore, AP, Hirsch, PR & Goulding, KWT 2011, 'Soil management in relation to sustainable agriculture and ecosystem services', *Food Policy* 36: S72–87.

Pratt, K & Moran, D 2010, 'Evaluating the cost-effectiveness of global biochar mitigation potential', *Biomass and Bioenergy* 34: 1149–58.

Renner, R 2007, 'Rethinking biochar', *Environmental Science and Technology* 41(17): 5932–33.

Roberts, KG, Gloy, BA, Joseph, S, Scott, NR & Lehmann, J 2010, 'Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential', *Environmental Science and Technology* 44: 827–33.

Rondon, M, Ramirez, JA & Lehmann, J 2005, 'Greenhouse gas emissions decrease with charcoal additions to tropical soils', in Proceedings of the Third USDA Symposium on Greenhouse Gases and Carbon Sequestration, Baltimore, Soil Carbon Centre, Kansas State University, United States Department of Agriculture.

Rondon, MA, Lehmann, J, Ramírez, J & Hurtado, M 2007, 'Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with bio-char additions', *Biology and Fertility of Soils* 43(6): 699–708.

Ruttanavut, J, Yamauchi, K, Goto, H & Erikawa, T 2009, 'Effects of dietary bamboo charcoal powder including vinegar liquid on growth performance and histological intestinal change in aigamo ducks', *International Journal of Poultry Science* 8(3): 229–36.

Schahczenski, J 2010, *Biochar and Sustainable Agriculture,* ATTRA National Sustainable Agriculture Information Service, available at https://attra.ncat.org/attra-pub/summaries/summary.php?pub=322.

Shackley, SJ & Sohi, SP (eds) 2010, *An assessment of the benefits and issues associated with the application of biochar to soil*, Department for Environment, Food and Rural Affairs, London, UK.

Singh, B, Singh, BP & Cowie, AL 2010a, 'Characterisation and evaluation of biochars for their application as a soil amendment', *Australian Journal of Soil Research* 48: 516–25.

Singh, BP, Hatton, BJ, Singh, B, Cowie, AL & Kathuria, A 2010b, 'Influence of biochars on nitrous oxide emission and nitrogen leaching from two contrasting soils', *Journal of Environmental Quality* 39: 1224–35.

Smernik, RJ 2009, 'Biochar and sorption of organic compounds', in Lehmann, J & Joseph, S, *Biochar for environmental management: science and technology*, Earthscan, United Kingdom: 289–300.

Sohi, S, Lopez-Capel, E, Krull, E & Bol, R 2009, *Biochar, climate change and soil: A review to guide future research*, CSIRO Land and Water Science Report 05/09.

Sohi, SP, Krull, E, Lopez-Capel, E & Bol, R 2010, 'Chapter 2–A review of biochar and its use and function in soil', *Advances in Agronomy* 105: 47–82.

Solaiman, ZM, Blackwell, P, Abbott, LK & Storer, P 2010, 'Direct and residual effect of biochar application on mycorrhizal root colonisation, growth and nutrition of wheat', *Australian Journal of Soil Research* 48: 546–54.

Solomon, S, Qin, D, Manning, M, Chen, Z, Marquis, M, Averyt, KB, Tignor, M & Miller, HL (eds) 2007, *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007*, Cambridge University Press, Cambridge, United Kingdom and New York.

Spokas, KA, Koskinen, WC, Baker, JM & Reicosky, DC 2009, 'Impacts of woodchip biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil', *Chemosphere* 77: 574–81.

Suuberg, EM, Milosavljevic, I & Oja, V 1996, 'Two-regime global kinetics of cellulose pyrolysis: the role of tar evaporation', Twenty-sixth Symposium (International) on Combustion, Combustion Institute, 1515–21.

Talberg, A 2009, *Background note: The basics of biochar,* available at www.aph.gov.au/library/pubs/bn/sci/Biochar.htm.

Thies, JE & Rillig, MC 2009, 'Characteristics of Biochar: Biological Properties', in Lehmann, J & Joseph, S, *Biochar for environmental management: science and technology*, Earthscan, United Kingdom, 85–105.

Thu, M, Koshio, S, Ishikawa, M & Yokoyama, S 2010 'Effects of supplementation of dietary bamboo charcoal on growth performance and body composition of juvenile Japanese Flounder, Paralichthys olivaceus', *Journal of the World Aquaculture Society* 41(S2): 255–62.

Van Zwieten, L, Kimber, S, Downie, A, Morris, S, Petty, S, Rust, J & Chan, KY 2010a, 'A glasshouse study on the interaction of low mineral ash biochar with nitrogen in a sandy soil', *Australian Journal of Soil Research* 48(6–7): 569–76.

Van Zwieten, L, Kimber, S, Downie, A, Orr, L, Walker, T, Sinclair, K, Morris, S, Joseph, S, Petty, S, Rust, J & Chan, KY 2010c, 'Agro-economic valuation of biochar using field-derived data', 3rd International Biochar Conference, Rio de Janeiro, Brazil, 12–15 September 2010.

Van Zwieten, L, Kimber, S, Morris, S, Chan, KY, Downie, A, Rust, J, Joseph, S & Cowie, A 2010b, 'Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility', *Plant and Soil* 327(1–2): 235–46.

Van Zwieten, L, Singh, B, Joseph, S, Kimber, S, Cowie, A & Chan, KY 2009, 'Biochar and emissions of non-CO_2 greenhouse gases from soil', in Lehmann, J & Joseph, S, *Biochar for environmental management: science and technology*, Earthscan, United Kingdom: 227–50.

Van, DTT, Mui, NT & Ledin, I 2006, 'Effect of method of processing foliage of Acacia mangium and inclusion of bamboo charcoal in the diet on performance of growing goats', *Animal Feed Science and Technology* 130: 242–56.

Varhegyi, G, Antal, MJ, Szekely, T, Till, F & Jakab, E 1988, 'Simultaneous thermogravimetric-mass spectrometric studies of the thermal decomposition of biopolymers: 1. Avicel cellulose in the presence and absence of catalysts', *Energy and Fuels* 2: 267–72.

Verheijen, F, Jeffery, S, Bastos, AC, Van Der Velde, M & Diafas, I 2009, *Biochar application to soil; a critical scientific review of effects on soil properties, processes and functions*, EUR 24099 EN, Office for the Official Publications of the European Communities, Luxembourg.

Woolf, D, Amonette, JE, Street-Perrott, A, Lehmann, J & Joseph, S 2010, 'Sustainable biochar to mitigate global climate change', *Nature Communications* 1:56 doi: 10.1038/ncomms1053.

Yanai, Y, Toyota, K & Okazaki, M 2007, 'Effects of charcoal addition on N_2O emissions from soil resulting from rewetting air-dried soil in short term laboratory experiments', *Soil Science and Plant Nutrition* 53: 181–88.

Yang, Y, Sheng, G & Huang, M 2006, 'Bioavailability of diuron in soil containing wheat-straw-derived char', *Science of the Total Environment* 354(2–3): 170–78.

The ‘Biosphere’ Graphic Element

The biosphere depicts an application of biochar

Also in this brochure series

- TR11.1 Fisheries & climate change: potential challenges & opportunities for Commonwealth fisheries
- TR11.2 Scientific information for making decisions about nrm - a report on the value, status and availability of key ABARES datasets
- TR11.3 Target and path: Maximum Economic Yield in fisheries management
- TR11.4 Scientific Working Group: Australian sea lion management strategy, additional analyses
- TR11.5 Community involvement in recreational fisheries data collection: opportunities and challenges

Department of Agriculture, Fisheries and Forestry

Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES)

Postal address GPO Box 1563 Canberra ACT 2601

Switchboard +61 2 6272 2010

Facsimile +61 2 6272 2001

daff.gov.au/abares