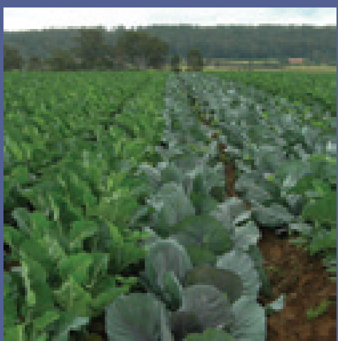
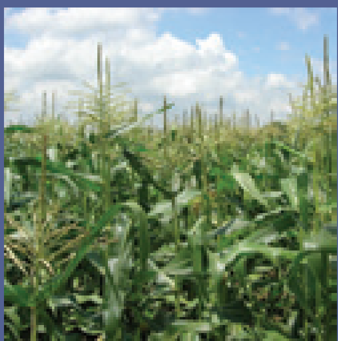
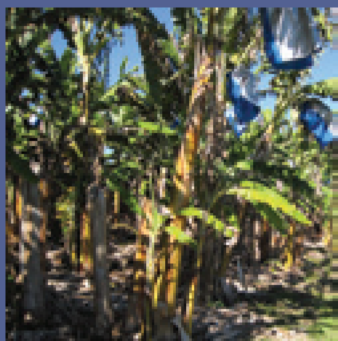
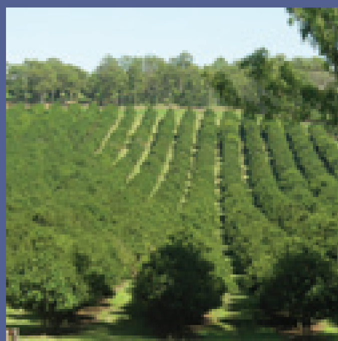
Biochar in horticulture









Prospects for the use of biochar in Australian horticulture

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NSW GOVERNMENT
Department of Primary Industries

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Foreword

Horticulture Australia Ltd has commissioned this review to help Australian horticultural industries understand the general role of carbon amendments in horticulture, and current knowledge of biochar production, effect on soil and horticultural yields, and potential for carbon trading.

Australia's horticultural production is the country's third largest agricultural sector by value and the fastest growing. It encompasses fruit, nuts, vegetables, mushrooms, nursery, turf and cut flowers, most of which are grown in soil with inputs and amendments to create a sustainable production system.

Carbon-rich soil amendments such as mulch, compost and biochar offer horticulture the benefit of improved soil condition and potential for carbon trading for the most stable forms. As the scope of this book was to review carbon amendments in terms of long term carbon storage and potential for involvement in carbon trading, amendments that decompose readily over time, although contributing greatly to soil health, are not described in detail. There are many published reviews of the benefits of compost, mulches etc in horticultural production but the requested focus was a review of the soil amendments with high, stable and very long term carbon >100 years, ie biochar. Biochar, a type of charcoal, is attracting particular interest around the world for its potential to improve soil health, crop productivity and sequester carbon over the long term. However, many questions remain about its use in agriculture due to the early stage of scientific interest and adoption.

The authors of this review include some of Australia's pioneer biochar researchers, who have collaborated to compile information of specific interest to horticulturists, including an introduction to soil carbon and the effect of different organic amendments on soils (Chapter 1), and a brief overview of biochar production methods and their effect on biochar characteristics (Chapter 2).

Biochar production involves high temperatures and production of flammable gases. The end product is potentially dusty and is also classified as a dangerous good. Therefore appropriate risk management for producers and users is mandatory (Chapter 3).

There is an extensive literature review of scientific research into the impacts of different types of biochar on soil properties (Chapter 4), agricultural field trials (Chapter 5), and some preliminary analyses of biochar's potential economic benefit in horticultural crops based on current information (Chapter 6).

Biochar's potential to sequester carbon has relevance to Australian government policy, including the Carbon Farming Initiative and research funding support (Chapter 7).

Many growers have questions about biochar's relevance for their enterprise, and the book has anticipated and answered some of the most commonly asked questions (Chapter 8).

This review has highlighted the pace of recent biochar research and findings, and the considerable uncertainty that still surrounds the use of biochar in farming systems given the range of production processes, the types of biochar, and the variety of soil types in horticulture.

This means that this review is a snapshot in time of the biochar carbon story, and that horticultural industries will need to engage with research and stay up to date on developments in this rapidly growing field.

Justine Cox
Editor

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Summary

Horticulture Australia Limited has commissioned NSW Department of Primary Industries to review current knowledge of high carbon soil amendments such as biochar and the prospects for biochar use in Australian horticultural systems. Biochar is the carbon-rich solid product resulting from the heating of biomass in an oxygen-limited environment. It is chemically and biologically more stable than the biomass from which it was made. It is attracting interest around the world for its potential to improve soil health and mitigate carbon emissions, but there is little known about its potential in Australian horticulture.

Biochar can be produced in various ways, ranging from pits in the ground through to sophisticated industrial pyrolysis kilns. Australia's commercial biochar industry is in its infancy with only a handful of companies producing semi-commercial quantities for sale.

Risk management is crucial in biochar production due to the high temperatures and flammable gases involved, and the potential for emissions of carbon monoxide, smoke, particulates, and greenhouse gases if controls are inadequate. Several state and federal regulations are in place to minimise these risks. Any end users of biochar should request product information that shows production methods and compliance with environmental and safety laws.

Biochar characteristics are determined by the feedstock, the maximum production temperature, heating rate, oxygen level, pressure and residence time in a reactor. Studies have shown that considerable differences in biochar properties arise from variations in these factors.

It is difficult to generalise the impact of biochar on soil properties due to this range of biochar production variables and biochar's complex interactions with soil organisms, chemical elements and physical structure.

The literature suggests that biochar application to soil has been shown to alter chemical functionality such as soil CEC, pH and nutrient availability. Biochar application can increase soil carbon immediately, but biochar carbon may last for centuries to millennia due to its high stability in soil. Biochars from manure sources have a higher mineral content than biochars from woody sources, so can supply more nutrients to soil, possibly in a slow-release form. Some biochars can provide a liming effect, particularly those made from papermill residues and manures at higher temperatures, so their use can be targeted to address constraints associated with low soil pH.

Biochar may improve the physical properties of the soil, particularly aggregation, water retention, water use efficiency, and reduce tensile strength in hard setting soils. Australian research in this area is very limited.

Biochar application has also been demonstrated to modify the biological functionality by providing a habitat for microorganisms due to its highly porous nature or by altering substrate availability and enzyme activities on or around biochar particles. Biochar application has suppressed some soil-borne diseases in some studies.

Research into the use of biochar in horticulture is limited, therefore inferences to improvements in crop productivity, soil properties etc have to be made from all agricultural crops studied. Our review of the research from a wide range of crop types and agro-climatic regions has shown that biochar increased yield in many cases. Fertiliser application with biochar often substantially increased the effect on yield compared with biochar or fertiliser on their own. A published meta-analysis of the effects of biochar showed an average yield increase of 10%, irrespective of soil type, crop type, rate and fertilisation.

Current methods of biochar incorporation use surface application, then mechanical incorporation into the topsoil, a method suitable for most annual and semi-permanent orchard crops. Alternative incorporation methods need to be developed to introduce biochar into permanent perennial horticultural crops without damaging existing root systems. Possible methods include coring using modified turf aerators, and combining biochar with a mulch material for surface application.

Further research and demonstration is needed in Australian horticultural systems if the benefits of biochar are to be fully realised. Development of biochars that allow reduced mineral fertilisation, improve water use efficiency and possibly contribute to disease-suppression will be critical to address horticulture's current economic and environmental priorities.

The adoption of biochar for use in horticulture will depend on the extent to which reliable increases in crop yield can be achieved. Currently, there is a high level of uncertainty. A model vegetable production system used to highlight different scenarios showed that potential reductions in applied nitrogen fertiliser costs are likely to only have a minor effect on the Net Present Value of crop production using applied biochar. More information about nutrient availability from biochars is needed before the interaction between biochar use, fertiliser inputs and crop yields can be evaluated. At current prices for carbon, the value of carbon offsets to primary producers may not be a significant incentive alone for biochar application in horticulture.

Biochar use in soils is an eligible activity in the Australian Carbon Farming Initiative (CFI), and state and local governments are interested in biochar production as a waste management option. For example, in June 2012 Ballina Council received $4.3 million from the Regional Development Australia Fund to build an $8.5 million pyrolysis plant to divert 29,000 tonnes of organic waste.

There are still issues to be resolved; including the development of a CFI methodology to gain carbon offset credits from production and application of biochar to soil, the adaptation of an international standard or guidelines for Australian use, and the eventual retail price of biochar to growers. These and other aspects about biochar use in Australia are currently being considered by scientists, engineers, agronomists, growers, entrepreneurs, agricultural suppliers, policy makers, regulators, politicians and waste management operators, to create a way forward.

What is biochar?

Biochar is essentially charcoal that is used to sequester carbon and improve soil fertility. Scientists around the world are investigating properties of biochar, its influence on soil properties, and potential risks associated with its application to soil; they are particularly interested in how to tailor biochar applications to address specific soil constraints. Biochar producers are investigating how to optimise biochar production to produce the best biochar for soil improvement. This dynamic research and investigation phase means there is active debate about what biochar is and what it does in the soil.

In 2011-12 the International Biochar Initiative worked with interested parties around the world to develop a definition of biochar. They agreed on the following definition:

> *Biochar: A solid material obtained from thermochemical conversion of biomass in an oxygen limited environment.*[71]

The Australia and New Zealand Biochar Researchers Network defines biochar thus:

> *Biochar is the carbon-rich solid product resulting from the heating of biomass in an oxygen-limited environment. Due to its highly aromatic structure, biochar is chemically and biologically more stable compared with the organic matter from which it was made.*

These descriptions also describe charcoal, so the International Biochar Initiative has differentiated biochar by describing its production for specific soil use.

Biochar characteristics are those physical or chemical properties of biochar that affect the following uses for biochar: 1) biochar that is added to soils with the intention to improve soil functions; and 2) biochar that is produced in order to reduce emissions from biomass that would otherwise naturally degrade to GHG, by converting a portion of that biomass into a stable carbon fraction that has carbon sequestration value.[71]

There is currently discussion among scientists about the need for a fuller definition which takes into account three sustainability factors: use of sustainable biomass (e.g. organic wastes, sustainably managed forests, forest residues), sustainable production processes (i.e. processes that do not create net increases in greenhouse gas emissions or environmental pollutants), and sustainable end-use (e.g. do not add contaminants to the soil or harm human health). If any of these factors are not ensured, biochar's net benefit to environment and production systems is diminished.

Some scientists believe that to be defined as biochar, biomass needs to be produced in a controlled process that treats all tar and pyrolysis gas by-products to maximise resource recovery and minimise their environmental impacts, and from which char yield and properties can be quantified. Without this level of care (and certification to prove it), the product should be called char rather than biochar.

The IBI has developed standardised product definition and product testing guidelines for biochar that is to be used in the soil, to enable potential users to assess the properties of the final product and whether it is fit for purpose. The IBI is also considering guidelines for development and testing of pyrolysis plants, and a sustainability protocol to ensure that biochar use avoids short- and long-term detrimental effects to the wider environment, and adverse impacts on human and animal health.

The IBI definitions and guidelines are dynamic and likely to be updated as biochar research develops. They are also voluntary and designed to be used in the development of national and regional standards around the world. This means that debate about the definition and application of biochar is likely to continue for some time.

Chapter One • The role of carbon in the soil

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NSW DPI

Key messages

1. Soil organic carbon is part of soil organic matter (usually over 50% by weight).
2. Soil organic carbon is vital for maintaining physical, chemical and biological properties of soil.
3. Soil organic carbon has different fractions that decompose at different rates. The active fraction decomposes quickly, the humus (or slow) fraction decomposes slowly, and the recalcitrant fraction takes centuries to decompose.
4. Soil organic carbon can be increased with addition of organic amendments.
5. Organic amendments vary in their contribution to each soil carbon fraction.
6. Organic amendments differ in their effects on soil properties, so need to be selected carefully for use on horticultural soils.

Biochar is a form of carbon. To assess its potential for use in horticultural soils it is important to understand the role of carbon in the soil, and how different soil carbon amendments, including biochar, affect soil health, plant growth and yield. This chapter provides a guide to the different types of soil carbon and the performance of soil carbon amendments.

Carbon

Carbon (C) is one of the most abundant chemical elements on earth. The cycling of carbon plays a vital role in governing the cycling and availability of plant nutrients and the functioning of the soil system. Soil carbon is the largest component of the terrestrial (land) pool of the global carbon cycle.

The soil carbon cycle

Plants capture carbon from the atmosphere through photosynthesis. Using the energy of the sun they produce carbon-rich vegetation (also known as biomass or organic matter). When this biomass dies it is decomposed by soil organisms which eat the carbon-rich biomass material and breathe out most of the carbon they consume as carbon dioxide. A small amount of the biomass carbon converts to other forms of carbon within the soil organisms themselves. When the organisms die and decompose, this carbon is released.

Through each step of decomposition some soil organic carbon is released as carbon dioxide and some is converted into other forms of organic carbon (Figure 1.1). There may be several phases of decomposition before stable forms of carbon, relatively resistant to further decomposition, are produced. Humus is considered to be produced through this process. Organic carbon may also be stabilised in the soil through organo-mineral associations and other processes that physically disconnect soil organic matter from decomposers and their enzymes. These processes are governed by clay content and type, and pore structure in the soil. Charcoal is considered to be an even more stable form of carbon and is produced through burning of plant biomass at elevated temperatures in open air such as during wildfire.

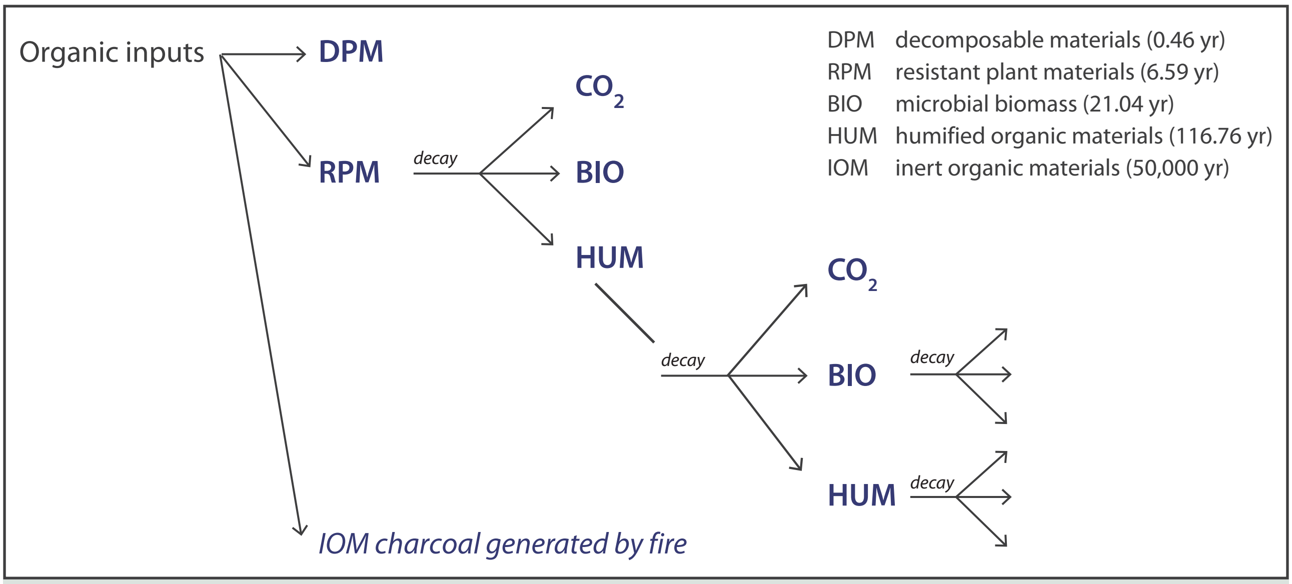

FIGURE 1.1: This diagram shows how organic matter decomposes over time. Some materials decompose quickly and return to carbon dioxide; others take years, decades and even millennia to break down.[12]

Soil organic matter and carbon

The terms soil carbon, soil organic carbon and soil organic matter are often used interchangeably, but have distinct meanings (Figure 1.2). It is important to understand the differences.

Soil organic matter (SOM)

Soil organic matter is the matter found in the soil associated with living things. It includes living organisms, fresh residues, well rotted organic matter, silica-occluded plant carbon (phytoliths), charcoal, nitrogen, sulphur, phosphorus and compounds beneficial to horticultural production and soil health in general, such as plant promotant chemicals. Soil organic matter is not tested in soil analysis, but can be calculated by multiplying the soil organic carbon test result by 1.75.

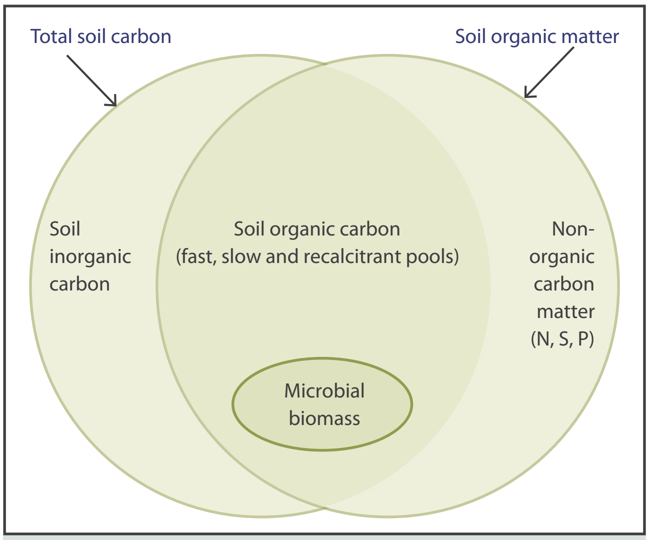

FIGURE 1.2: A conceptual model of carbon in the soil.

Soil carbon

Soil carbon is all the carbon found in the soil from both living things and nonliving sources such as carbonates. It is sometimes referred to as total soil carbon.

Soil organic carbon (SOC)

Soil organic carbon as measured by laboratory analysis is all soil carbon from plant and animal sources at various stages of decomposition. It does not include new plant and animal material as much of this decomposes easily, with carbon released quickly to the atmosphere as carbon dioxide. It is also known as total organic carbon (TOC) and organic carbon. Soil organic carbon is around 58% of soil organic matter.[66]

Soil inorganic carbon

Soil inorganic carbon is mineral carbon in the soil such as carbonates (e.g. calcium carbonate in limestone) not associated with recently living plant and animal matter.

Microbial biomass carbon (MBC)

Microbial biomass carbon is the carbon in soil microorganisms, predominantly bacteria and fungi. Microbial biomass carbon is usually between 1-4% of soil organic carbon.

Benefits of soil organic carbon

Soil organic carbon benefits the soil biologically, chemically and physically (Figure 1.3). It is thought that biochar will also benefit the soil, but exactly how it will do this is the subject of recent and ongoing research, and is discussed in subsequent chapters.

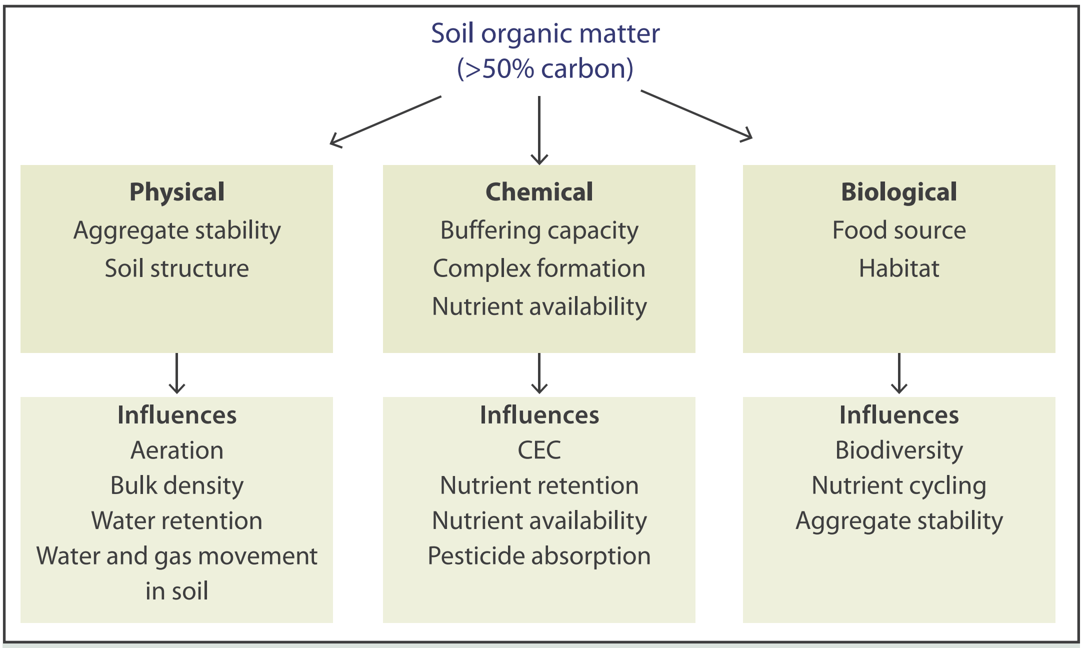

FIGURE 1.3: Benefits of SOM in the soil.[44]

Carbon fractions in the soil

Soil organic carbon comprises several fractions, also known as pools, distinguished by their rate of decomposition in the soil (Table 1.1). The size of the fractions fluctuates seasonally, and with climate, soil type and topography. Each of these fractions plays an important role in creating healthy resilient soils.

TABLE 1.1: Soil organic carbon fractions.[12]

Fraction name	Decomposition rate	Function	Examples
Active living	None, as they are living, but once dead will enter the fast pool	Decomposition Nutrient cycling Soil pore structure	Fungi, bacteroa, protozoa, arthropods, earthworms
Active non-living (also known as labile or fast pool) – dissolved	Hours to days	Food and energy source for soil organisms	Sugars, proteins
Active non-living – particulate	Weeks to years	Micro aggregate stability Nutrient cycling	Small pieces of organic matter
Slow pool (also known as humus)	Decades to centuries	Nutrient supply Cation exchange capacity Water holding capacity Soil structure stability	Fats, lignins, humic substances
Stable (also known as resistant, recalcitrant, inert or inactive pool)	Centuries to millennia	Cation exchange capacity pH buffering Soil temperature modulation	Charcoal, phytolith, biochar

The importance of biological stability of carbon in soils and its role in partitioning soil carbon into pools has been recognised by the expert panel on monitoring soil condition across Australia.[108] The panel points out that 'measuring total carbon is inadequate for understanding the role of carbon in many soil processes' and recommends partitioning soil carbon into three pools, active, slow and inert.

1. Active pool

The labile or active carbon pool is readily used by micro organisms as an energy source and is very sensitive to changes in both land management and weather. The active pool also includes microbial biomass carbon (MBC) which makes up about 5% of SOC.[43]

2. Slow pool (moderately to highly resistant humified organic matter)

The slow pool (also known as humus) is carbon that is more resistant to decomposition due to its location and/or its chemical nature. Some slow pool carbon is contained in very complex molecules that have been through various stages of decomposition to form very stable carbon compounds (chemically, highly aromatic forms), that resist further breakdown. Other carbon in this pool is more resistant to decomposition due to its location in the soil, either adsorbed onto clay particles in the soil or 'hidden' within soil aggregates or micropores and thus inaccessible by decomposer organisms. This pool makes up between 30–60% of TOC.[1] It is usually the largest pool and most difficult to increase.

3. Inert pool (highly protected organic matter)

The inert pool, also known as stable, resistant or passive pool, consists mostly of charcoal and can comprise up to 30% of TOC in some Australian soils such as Vertosols.[12] There may also be some organo-mineral-metal complexed SOC in this pool (carbon linked to metal elements and minerals). Biochar and phytolith carbon is part of this pool.

In the soil, carbon moves between the different pools and over time, the carbon in all pools decomposes and is released into the atmosphere, so organic matter needs to be constantly added to soil to maintain soil organic carbon levels.

Where is carbon in the soil?

Most soil organic carbon is found near the soil surface because that is where biomass grows and decomposes, and where most soil organisms live because they need food, oxygen and moisture to survive. This means that soil organic carbon decreases with depth (see Figure 1.4). Changes in soil organic carbon due to land management generally occur in the top 10–30 cm of the soil profile. Soil organic carbon levels at depth (>30cm) are often more stable over time because carbon is more 'protected' from microbial decomposition here.

The top 0–10 cm, sometimes 0–15 cm, is the standard soil sampling depth for most agronomic diagnostic soil tests, including soil organic carbon. Where soils are cultivated, considerable mixing of soil layers occurs to the depth of the implement used. If the cultivation depth is greater than 10 cm this must be taken into account when sampling soils to assess soil organic carbon levels.[132] For carbon accounting purposes protocols require sampling to be carried out to a depth of 30cm.

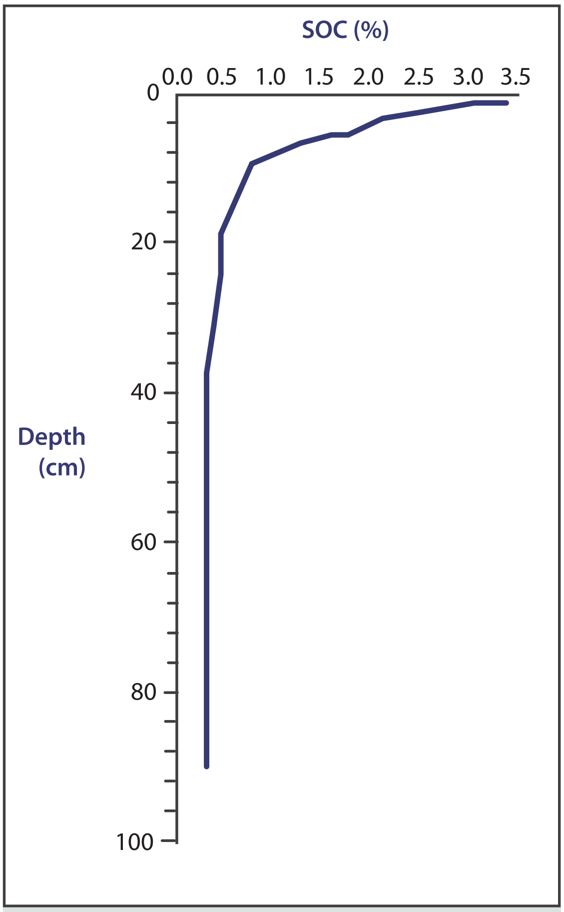

FIGURE 1.4: Soil carbon decreases with depth.[31]

Building organic carbon in the soil

The organic carbon content of soil is defined by the balance between inputs of carbon-rich material (plant growth and additional material) and losses through decomposition, erosion and product removal (Figure 1.5). Where inputs are greater than losses, soil organic carbon increases.

Land management affects carbon inputs and losses, so soil organic carbon increased through one practice may be lost under another practice. For instance, soil organic carbon built up through growing pasture is lost quickly when the soil is cultivated for a crop. Management practices will not increase the different carbon pools uniformly. Activities that enhance nutrient cycling and resilience will not add recalcitrant carbon required for carbon sequestration. Green manuring adds to the active/fast pool, while biochar will build the stable pool.

Inputs

- Net primary productivity
- Addition of organic matter from off-site

Losses

- Conversion of organic C to CO_2 during decomposition
- Erosion
- Removal of agricultural produce

FIGURE 1.5: Input and losses determine SOC.[11]

Most organic carbon added to the soil is cycled quickly by soil organisms and released into the atmosphere as carbon dioxide. This fast-cycling active pool is vital for microbial activity and facilitating the release of nutrients into the soil for use by plant roots. Only 5-15% of carbon added to the soil becomes soil organic carbon.[31]

The table below summarises management practices that increase soil organic carbon by providing carbon inputs or decreasing carbon losses from the soil. The first seven management activities listed in Table 1.2 are appropriate and feasible for horticultural systems.

TABLE 1.2: Management practices to increase soil organic carbon[29]

Activity	Provides C inputs	Reduces C losses
1. Increase plant (biomass) production by applying sufficient nutrient and water	✓	
2. Retain stubble/crop residue	✓	✓
3. Reduce fallow periods	✓	✓
4. Include opportunity crop/rotations/ green manure crops	✓	✓
5. Apply high carbon amendments such as compost, biochar, some manures	✓	
6. Reduce erosion		✓
7. Reduce cultivation		✓
8. Introduce farm forestry	✓	
9. Improve pasture management	✓	✓

Using organic amendments in horticulture

Adding carbon-rich amendments to soils is becoming increasingly common in horticulture, but is only really effective when the amendments are selected for a purpose. Growers need to be clear whether they are addressing a specific soil constraint (e.g. lack of nutrients), or want to build soil organic carbon. Organic amendments unsuited to a particular soil, site or production type may have detrimental effects on the soil or environment.

Carbon content

The carbon content of organic amendments ranges from more than 50% in some biochars, down to under 1% in seaweed extracts.[122] There is still uncertainty about the way in which plant biomass contributes to the various carbon pools and whether this source is 'long term' soil organic carbon required for carbon sequestration. Recycled organics, which include biosolids, composts, biochar, manures and mulches, can be important sources of organic carbon because they often contain more stable carbon than fresh plant material.[29] European experiments have shown that soils treated with organic amendments over the long term have 20-100% more soil organic carbon than those treated with inorganic fertilisers.[91] It is possible to calculate how much additional carbon an organic amendment can add to the soil (see box below).

Products sold as humic acid and fulvic acids to promote soil carbon vary widely in their characteristics. The very existence of these substances as fractions of the greater slow pool of humus is currently a topic of much debate. A very recent review[16] indicates that separation of humus on the basis of solubility may be nothing more than an artefact of laboratory analysis and these substances may not, in fact, even exist in the soil. In research these terms are no longer recognised as valid terms when describing fractions of organic matter despite their use in the organic amendment market place.

Nutrient content

Some growers prefer organic amendments to synthetic fertilisers as a source of nutrients because they may release nutrients more slowly, lose less nitrogen via leaching or may reduce net greenhouse gas emissions.[15] It has been argued that the value of a soil amendment is not derived solely from its own carbon content particularly if it promotes greater plant growth. The nutrient value of biochars depends on the nutrient content of the original biomass, and is the subject of current research as discussed in Chapter 4.

How much carbon does biochar add to the soil?

It is possible to determine the increase in soil carbon content after application of biochar if the following information is available.

1. Rate of application (tonnes dry weight of amendment per ha)
2. Carbon content of the biochar (% C)
3. Depth of incorporation (m)
4. Bulk density of the soil (g/cm^3)

Increase in % soil C due to biochar (B) =

$$\frac{\text{rate (t/ha)} \times \text{\% C in biochar}}{[\{10{,}000 \times \text{depth incorporation (m)}\} \times \text{bulk density}] + \text{amount of biochar (t/ha)}}$$

Predicted soil C concentration in the biochar-amended zone = existing C concentration + B.

Example:

A farmer decides to apply 15 tonnes of dry biochar per ha.
The biochar has been tested at 60% organic carbon.
The farmer decides to rotary hoe to a depth of 0.08m (80mm).
The farmer's soil has a bulk density of 1.1.
The original soil carbon level is 2.10%.

$$\frac{15 \times 60}{[\{10{,}000 \times 0.08\} \times 1.1] + 15}$$

= 1.01 increase in % soil carbon

Predicted soil C concentration in the amended zone =
2.1 + 1.01
= 3.11%

FIGURE 1.6: Woodchip mulch used on blueberry orchards in NSW reduced daily temperature fluctuations, protected plants from weeds and increased organic matter to the soil. Photo: Justine Cox

Carbon:nitrogen ratio

The carbon to nitrogen ratio (C:N) describes the proportion of carbon to nitrogen in an organic material. It is important to know the ratio when considering amendments because if the nitrogen level is low in relation to the carbon level, decomposing organisms will draw on nitrogen (e.g. woodchip, Figure 1.6) in the soil to survive, and this can affect plant growth. The ideal C:N ratio for decomposition to avoid nitrogen immobilisation by microbes is around 25-30 parts carbon to one part nitrogen. Nitrogen drawdown does not occur with biochar amendments because biochar carbon is stable and not available for decomposition by organisms. Some of the more agronomically attractive biochars made from animal manures may have a C:N ratio as low as 10 while others have a C:N ratio over 100 without causing the temporary loss of plant available nitrogen.

Carbon sequestration

There is little research into the long term carbon sequestration value of organic amendments, with the exception of manures[29] and biosolids.[81, 82] A recent Australian review[15] assumes that 45% of the carbon applied in compost is retained over a 20 year period, 35% over 50 years, dropping to 10% over a 100 year period. The actual sequestration value is determined by the amount of amendment added and the frequency of addition[29] and is ultimately governed by the climate and soil type. Despite the paucity of Australian research, the review[15] argues that compost may benefit greenhouse gas emission mitigation by reducing emissions, increasing capture of atmospheric carbon, and avoiding emissions.

Production of carbon-rich soil amendments often requires carbon sources from one area to be harvested, processed into an amendment, and applied in another area. This means that the first area suffers a loss of soil organic carbon so there is now increasing interest in life cycle assessment to determine the net benefit of the application of any carbon-rich ameliorant due to this 'redistribution' of carbon across the landscape.[29] Amendments produced from organic waste materials are attracting much interest because they deliver carbon and nutrients while diverting materials from waste disposal sites where they have potential to produce greenhouse gas emissions.

How do carbon-rich amendments compare?

Table 1.3 summarises the main sources of carbon-rich amendments available for horticultural use, and their impacts and risks, to enable a comparison of the different amendments, including biochar. Organic amendments vary in quality and characteristics, and Australian Standards are available for composts, mulches and soil conditioners[6] and potting mixes.[7] The International Biochar Initiative[72] has developed an optional standard for biochar to enable users to compare biochar content. Biochar characteristics vary widely because they are determined by the biomass material and the production conditions. Detailed explanations about biochar production and the effects of production methods on biochar characteristics can be found in Chapter 2.

Table 1.3: Soil carbon amendments.[122, 133]

Amendment / product	Residence time in soil	Claimed benefit	Examples of use	Risks*	Feedstock / raw ingredients / source
Commercial products containing humic or fulvic acids, or humin (now considered outdated descriptions of organic carbon)	Days to weeks	May stimulate soil microbial activity Increases penetration and retention of calcium in soil Increases CEC Improves soil pH buffering Improves soil structure (especially coal derived) Increases water holding capacity Stimulates root growth Stimulates hormonal response in plants to promote growth May improve micronutrient availability	Soil drench, foliar application, solid spread or incorporated	Highly variable product quality	Composted organic matter, vermicompost, coal (e.g. leonardite), peat
Mulch (organic, not synthetic)	Weeks to months, can be selected for specific timeframe	Reduces erosion risk Reduces soil temperature fluctuations Reduces evaporation May improve infiltration and water storage	Surface application usually >5 cm thick	Short-term nitrogen drawdown Harbour for pathogens or insect pests and weed seeds Offsite transport by water/ wind	Any carbon-rich organic material that remains on the soil surface for the time required. (e.g. bark chips, nutshells, woodchips, straw)
Vermicast (worm casts)	Weeks to months	May stimulate microbial activity to release plant nutrients Supplies small quantities of plant nutrients Adds some organic matter Some control of plant pests and disease	Applied as a spray or solids	Weed inhibiting compounds may negatively affect crop plants Highly variable product	Municipal wastes, organic wastes including manures Industrial wastes
Manure	Weeks to months	Increases microbial activity Adds plant nutrients Improves CEC Adds organic matter and improves organic carbon content Improves soil structural stability Reduces disease incidence	Surface application and incorporation Compost	Disease, weeds, pathogens and toxic compounds if not composted Water contamination from erosion of manured soils Variable quality	Bulk manure from chicken sheds, pig farms, cattle feedlots, horse stables
Seaweed and fish extracts	Weeks to months	Can promote plant growth thorough plant promotant compounds and microbial activity Adds plant nutrients Improves soil structure through increased microbial activity Improves control and resistance to plant pests and diseases	Foliar application and soil drench		By-products and wastes from fish processing industries and/or feral fish control

Amendment / product	Residence time in soil	Claimed benefit	Examples of use	Risks*	Feedstock / raw ingredients / source
Compost (made from decomposition of any organic matter)	Months to years	Increases microbial activity Increases earthworm biomass Increases release of plant nutrients due to microbial activity and biomass Adds plant nutrients Improves cation change capacity Increases water holding capacity Improves soil structure Enhances plant disease suppression May reduce pathogen attack Increases organic carbon level	Surface spread and incorporation (rates vary from 1-30t/ha in broadacre crops, and 5-100t/ha in horticulture	Some risk of soil contamination depending on feedstock Heavy metals from some feedstocks Weed and pathogens from manures Highly variable product Immature compost can cause nitrogen drawdown and harbour weeds, pests and diseases Excess application can result in leaching losses of nutrients and water contamination particularly on sandy soil	Any organic material e.g. manures, crop residues, municipal wastes
Biosolids (dried and composted sewage)	Months to years	Increases biological activity Adds plant nutrients May have a liming effects Increases organic matter	Surface application and incorporation	Heavy metals from some feedstocks Retain human pathogens if not composted May contain organic pollutants	Solid municipal sewage waste
Lignite (brown coal)	1000+ years	High carbon content High moisture content Increases plant available phosphorus in acid soil		May have high sulphur levels	Brown coal from Latrobe Valley, Victoria
Coal byproducts (e.g. leonardite)	1000+ years	Can improve water holding capacity High in humic acids (leonardite) but yield increases only in some crops	Surface spread	Contains heavy metals May have toxic levels of some trace elements May lock up soil phosphorus	
Biochar	100+ years	Stores stable carbon in the soil and sequesters carbon as recalcitrant carbon Other claimed benefits are currently the subject of research. See Chapter 4 for more details.	Surface application Incorporation Banded / slotted next to young trees	Feedstock may contain contaminants including heavy metals and toxic compounds Production processes may produce toxic compounds Reduced pesticide efficacy See Chapters 3 and 4 for more details	Any biomass such as woodchips, municipal green waste, papermill waste, animal processing waste, crop wastes See Chapter 2 for more details

* The use of organic amendments is governed by regulations in each state and territory which mitigate some of the risks outlined in the table. It is the responsibility of users and landholders to comply with these regulations, and important to remember that regulations do not safeguard against all risks involved in use of organic amendments.

FIGURE 1.7: Wood chip and greenwaste pyrolysed at 550°C is completely charred but there is still some evidence of the original feedstock (here the larger pieces represent woodchip) Photo: Elspeth Berger

Chapter Two • Biochar production

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Key messages

1. There are several methods of producing carbon products such as biochar, ranging from soil pits to sophisticated industrial plants.
2. Australia's commercial biochar industry is in its infancy with only a handful of companies producing commercial quantities for sale.
3. Production processes vary temperature, heating rate, oxygen, pressure and residence time to produce biochar with differing characteristics.
4. Biochar characteristics are also determined by the feedstock.
5. Biochar production plants need to be sited near sources of large quantities of feedstock.
6. Engineered pyrolysis processes can produce both energy and biochar, and can be optimised to favour one or the other.

Biochar is produced by heating biomass (feedstock). The feedstock undergoes thermal decomposition and is reduced to a carbon-rich residue, a process known as carbonisation (Figure 2.1). The heat required to carbonise the biomass comes from outside the chamber in which the biomass sits or within the chamber via an inert heat carrier such as sand or gas. Some systems move feedstock through a chamber, e.g. drum pyrolysers, rotary kilns and screw pyrolysers.

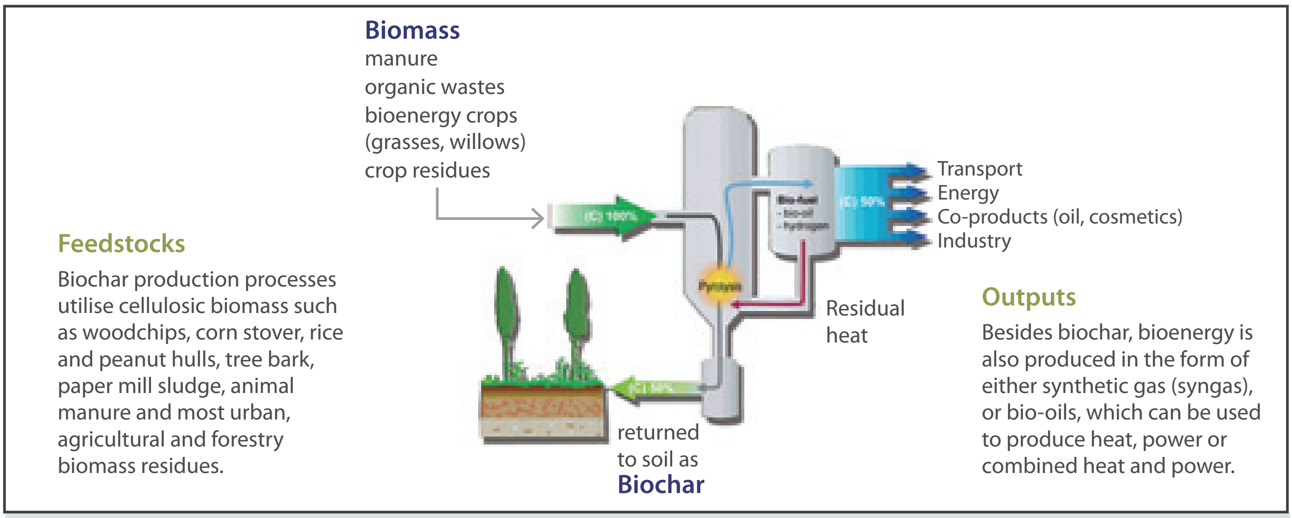

FIGURE 2.1: A conceptual model of biochar production.[71]

This chapter provides an overview of some biochar production systems, and the effect of different production factors on biochar characteristics. It is not intended to drive decisions for selection of a specific production system. More detailed information about each system can be found in the cited references.

FIGURE 2.2: These bamboo lengths are combusting on the surface before collapsing into a zone of pyrolysis below.
Photo: Lukas Van Zwieten

Biochar production processes

A range of thermal conversion processes can be used to produce carbon products which include biochar. Torrefaction, pyrolysis, gasification, hydrothermal carbonisation, and combinations of these[2] may all be used in char production (e.g. Figure 2.2) but pyrolysis is the process optimised for biochar production where the main aim is to produce an agronomically useful char product with no adverse environmental outcomes. The carbonisation process occurs along a continuum from torrefaction (low temperature, low oxygen, see Figure 2.3) through pyrolysis (low oxygen) to gasification (high temperature, higher oxygen). Most carbonisation procedures include all these processes in varying degrees. Different heating conditions produce different products (see Table 2.1), including biochar, bio-oil, syngas (a mix of methane, carbon monoxide, carbon dioxide and hydrogen), heat, ash and sometimes wood vinegar (from the exhaust cooling processes).

FIGURE 2.3: Torrefied material can closely resemble the parent feedstock, with some charring evident.
Photo: Lukas Van Zwieten

Torrefaction

Torrefaction heats feedstock slowly (from minutes to days) to 200°C-300°C in low oxygen conditions to produce biochar.[2] The word is derived from the Latin *'torrere'*, to parch, roast or scorch.

Pyrolysis

Pyrolysis heats feedstock at slow or fast rates to high temperatures (>300°C) in the absence of oxygen. In the process it irreversibly changes the chemical and physical characteristics of the biomass. The word 'pyrolysis' is derived from the Greek *'pyr'* (fire), and *'lysis'* (separating).

Fast pyrolysis heats feedstock in a matter of seconds to produce bio-oils, currently being developed for potential use as fuels. This process often results in a higher percentage of feedstock being converted to bio-oil and a lower recovery of biochar.

Slow pyrolysis heats feedstock from minutes to days to produce biochar, bio-oil and syngas. Modern slow pyrolysis can be optimised to produce biochar and syngas as the main products, with very little oil.[49]

Gasification

Gasification heats feedstock in the presence of limited oxygen to produce syngas with some biochar and ash as byproducts. In very efficient gasification systems, ash and syngas are the principal products. Gasification tends to focus more on energy production and export with a much lower biochar yield than other technologies.

Hydrothermal carbonisation

Hydrothermal carbonisation, also known as wet pyrolysis, heats biomass and water for hours to days to 180-220°C in a sealed vessel under pressure to produce a lignite-like material.[109] These materials tend to be best suited for energy purposes (e.g. co-firing in coal fired power station).

Activation

The process of activation subjects pyrolised material to partial gasification at high temperatures greater than 700°C with steam, carbon dioxide or a mixture of the two to produce material that can have a more porous structure and increased surface area.[50]

TABLE 2.1: Biochar yields obtained from different production processes.[25, 49, 109]

Process type	Process temperature range (°C)	Residence time	Bio-oil (%)	Syngas (%)	Biochar (%)
Torrefaction	~290	10–60 minutes	0-5	20	80
Traditional low pyrolysis	~400	minutes to days	30	35	35
Fast pyrolysis	~500	~1 second	75	13	12
Gasification	~750–900	~10–20 seconds	5	85	10
Modern slow pyrolysis	>400	30–90 minutes	0	~70	~30

Biochar production technology

The technology used in biochar production ranges from simple soil pits to sophisticated industrial plants. Simple systems are easy to build, but yields of biochar are low, and pollution from particulates and gases can be high. Modern technologies aim to yield more biochar from feedstock by regulating temperature, pressure and residence times and capturing emissions. For this reason, slow pyrolysis reactors are favoured for the production of biochar.[109] It is important to recognise that biochar production is an inherently hazardous process, with risks to both human health and the environment. Therefore it should not be entered into without sound specialist engineering advice. For a full discussion of risks see Chapter 3.

Australian commercial biochar production

Australia's commercial biochar industry is in its infancy, with most activity still in the research phase. One of the first modern biochar plants in Australia is Pacific Pyrolysis' 1/10th commercial scale pilot at Somersby NSW which has supplied researchers in Australia, New Zealand and internationally with characterised feedstocks under known process conditions (Figure 2.4). It is now raising capital to build a commercial biochar plant in Melbourne to turn municipal organic and wood waste into electricity and biochar.[105]

In June 2012 Ballina Shire Council received $4.3 million from the Regional Development Australia Fund to build an $8.5 million slow pyrolysis plant to divert 29,000 tonnes of organic waste from the region's landfill and convert it into electricity and biochar.[37]

Other identified operations include Mackay-based Black is Green Pty Ltd[19] which specialises in mobile and modular fast pyrolysis production systems to char agricultural biomass and also produces biochar in bulk quantities (Figure 2.5). Black Earth Products[18] north of Brisbane produces biochar-based soil conditioners from agricultural biomass for garden and bulk use and is developing simple open source biochar production equipment. Biochar-Energy Systems[17] is associated with Victoria's Northern Poultry Cluster to manage poultry waste (Figure 2.6), while Real Power Systems (Figure 2.7) has developed a portable gasification module.[46]

FIGURE 2.4: Pilot commercial pyrolysis unit based at Somersby, NSW, owned and operated by Pacific Pyrolysis. Photo: Adriana Downie

FIGURE 2.5: BiGchar 1800 equipment set up for mobile in field processing of sugar cane trash.
Photo: James Joyce

FIGURE 2.6: Biochar-Energy Systems' single module continuous slow pyrolysis unit.
Photo: Russell Burnett

FIGURE 2.7: Portable 200kg/hr biomass gasification module for biochar and clean fuel gas production.
Photo: Peter Davies, Real Power Systems P/L

Production factors and biochar characteristics

The characteristics of any biochar depend on a number of production factors (see Figure 2.8) including:

- type of feedstock (discussed in detail in Chapter 4)
- preparation of the feedstock for biochar production
- production temperature
- production residence time
- heating rate (fast or slow)
- oxygen level during production

Type of feedstock

Nut shells, sugar cane bagasse, coconut husk, and olive and tobacco waste are particularly suitable for pyrolysis, but other suitable biomass materials from agriculture include broadacre grain trash/stubble, wood chips and tree bark, grass residues, animal bedding, livestock manure and chicken litter. Mallee eucalypt trees are also being investigated for their feedstock potential, but processing and harvesting issues need to be resolved before they have potential to become commercially viable as a biochar production industry.[139] Municipal waste has great potential given the constant supply, but in industrial areas may contain high levels of toxic substances which will make the biochar unsuitable for agricultural soils.[139] The viability of biochar production depends on having large quantities of feedstock close by to minimise transport costs. This means the larger pyrolysis plants need to be located in areas near to large quantities of biomass feedstock.

Feedstock preparation

Feedstock particle size, moisture content, and contaminant levels all affect biochar quality. The size of feedstock pieces affects the rate of heat transfer into, and the rate of gas transfer out of, each piece.[50] In large particle feedstock the transfer of heat into the particles is slower and transfer of volatiles out is also slower, so feedstocks may need to be broken into small pieces to facilitate pyrolysis. Fast pyrolysis production systems require all feedstocks to be pre-processed to allow the high temperatures to penetrate all particles very quickly.

Production temperature

Woody biochars produced at temperatures above 600°C are generally more likely to be stable and have greater porosity and adsorptive capabilities than biochars produced at lower temperatures. The improved porosity is due to the volatilisation of tars and impurities that clog the biochar's finer pores and reduce pore connectivity.[50] As a general rule, an increase in highest temperature attained during pyrolysis (HTT) leads to an increase in the surface area of biochar which makes it more adsorptive for chemical reactions.[50] However, when high HTT is combined with a feedstock that has an inorganic component with a melting point lower than the HTT, the biochar pores fill with inorganic compounds and reduces the surface area of the biochar.[50] At lower temperatures (300–400°C) carbonisation is only partially achieved and biochar will have smaller pores and lower surface area.[2]

H:Corg ratio

The more energy used in the production system (a combination of temperature, residence time and heating rate), generally the lower the molar hydrogen : organic carbon ratio (H:Corg), because hydrogen is lost in the process and the carbon becomes aromatic and more stable. In general terms, the lower the ratio, the more stable the biochar is likely to be. The IBI has suggested a minimum molar H:Corg ratio of 0.7 for a material to be classified as biochar.

Residence time

In biochar production the term residence time refers to the time a feedstock is held within a constant temperature range and a given carbonisation process.[72] The combination of high temperature and longer residence times allows carbonisation reactions to be completed, resulting in biochars that have lower H:C ratios (which tend to be more stable), and are likely to have larger surface area.

Heating rate

Heating rates and pressures are important factors determining properties of biochars.[50] The faster the heating rate, the smaller the particle size needed to ensure that heat passes all the way through the particle. Thus fast pyrolysis completed in a few seconds needs powdered feedstock particles. Slow pyrolysis is used for larger feedstock particles to ensure they carbonise completely. Fast pyrolysis encourages formation of bio-oil, and slow pyrolysis is more commonly used for biochar.

Oxygen level

Biochar production requires low levels of oxygen to ensure that biomass converts to solid carbon rather than combusting to produce carbon monoxide, carbon dioxide and ash. High oxygen levels move production systems towards more complete combustion, so are used to produce gas and energy (and some ash) rather than biochar.

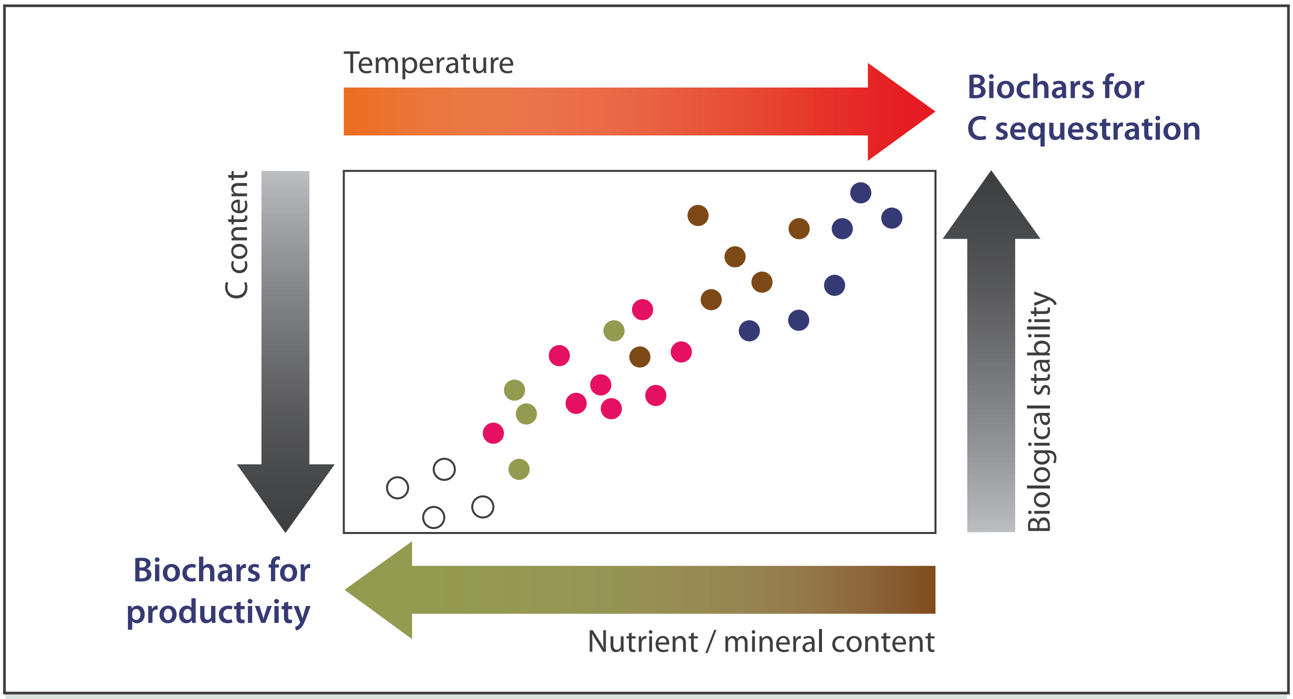

FIGURE 2.8: Biochars produced from different feedstock at different temperatures vary in their properties.[39]

Biochar standard characteristics

Biochars vary considerably according to their feedstock and production, so may vary in their suitability for use in soil. The International Biochar Initiative's new guidelines[72] *'Standardised product definition and product testing guidelines for biochar'* that is used in soil define the characteristics that should be declared by biochar producers to enable users to assess the suitability of the product for use in soil. Mandatory characteristics include particle size, moisture level, levels of elemental hydrogen, carbon, nitrogen, proportion of ash, electrical conductivity, pH/liming ability, organic carbon content, and carbon stability. A mandatory toxicity assessment includes levels of metals, polychlorinated biphenyls, polycyclic aromatic hydrocarbons, and dioxins. Optional assessments of biochar characteristics for soil enhancement include nitrogen, phosphorus, potassium, volatile material, and surface area.

This chapter has outlined the main production systems and factors that determine the characteristics of biochar. Chapters 4 and 5 look in more detail at the chemical and physical characteristics of biochars with potential benefits for soils and crop yield in horticulture.

Chapter Three • Risk

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Pacific Pyrolysis Pty Ltd

Key messages

1. Production and application of biochar present many opportunities as well as potential risks.
2. There are several existing regulations that affect production and use of biochar.
3. Production hazards include high temperatures, flammable gases, carbon monoxide, smoke and particulates.
4. Application hazards include dust, soil contamination, and exacerbation of existing soil constraints.
5. Plant productivity hazards include water repellence, alkalinity and reduction in pesticide efficacy.

There are many potential benefits that can be achieved by using biochar in horticultural production. These benefits can be optimised if the potential hazards and risks associated with biochar production and use can be identified and effectively managed.

It is especially important for early adopters to use caution, to be aware of the risks involved, and actively manage them so that no adverse effects to themselves or the environment result from their actions. If biochar use becomes more widely adopted, and it moves from being a niche product to an agricultural commodity (Figure 3.1), then it can be expected that this will move the requirement to manage risks from the users to regulators, producers and suppliers.

Standards for biochar products have been put forward by the International Biochar Initiative and are being drafted by the Commission of the European Union. There are however currently no mandatory regulations in Australia that define different biochar products and qualify their suitability for use.

This chapter has been compiled to raise awareness of the potential risks associated with biochar products so that early adopters can take action to avoid potential negative impacts on their:

- environment
- health and safety
- finances (productivity).

It should be noted however that not all the risks associated with biochar production and use will be identified here and no responsibility will be taken by the authors if harm results from biochar production and use that adheres to these suggestions.

There are several steps involved in the life cycle of biochar production and use, and there are risks associated with each step that need to be considered:

- biomass sourced for feedstock
- production system
- quality of biochar product produced
- application method of biochar
- impact of biochar once applied
- long-term fate of biochar once applied.

FIGURE 3.1: Biochar trial establishment at a coffee plantation, northern NSW. Photo: Josh Rust

The discussion about risks also needs to be put in the context of the objectives of the biochar use. Some risks will pose a threat to meeting some objectives, but not others.

Reasons for biochar use are likely to be one or more, but not necessarily all, of the following:

- reducing requirements for other inputs, such as conventional fertilisers
- sequestering carbon and hence reducing atmospheric greenhouse gas concentrations
- increasing crop yields by addressing a constraint to growth (e.g. poor soil structure, low pH etc)
- increasing the quality of the crop by addressing a constraint (e.g. poor nutrient uptake resulting in low protein content)
- remediation of contaminated soils
- improving the physical properties or aesthetic of the soil or growing media (e.g. making it dark in colour, decreasing bulk density for transport etc.)

If a user is applying biochar with the only objective being to decrease input requirements, then its carbon sequestration potential may be of no interest, and vice versa. Therefore the risks to carbon sequestration are not important to that user.

Regulations

There are a number of regulations that govern several of the steps in biochar production and use. Some examples of these have been included in Table 3.1.

TABLE 3.1: Examples of regulations that cover biochar production and use.

Aspect of biochar production and use	Examples of regulations that may apply
Feedstocks	Feedstocks that are classified as wastes. Biomass that is covered by planning laws. Biomass that is preserved under conservation legislation.
Production	Planning and environmental consents. For example, processes that produce smoke are not permissible in some jurisdictions. Workplace health and safety regulations must be followed. These will dictate the safety controls required, such as the maximum temperature of kiln surfaces, personal protective equipment to be worn, and mechanical safety systems to be employed, such as flares, pressure relief values, and monitoring equipment (e.g. CO monitors).
Application	Carbon offsetting with biochar may require some ownership of the land where it is applied. Regulations for soil amendments (such as those that govern the application of biosolids). Regulations for land application of materials that were classified as wastes. Organic certification may be required if produce is to meet organic labelling certification requirements.
Biochar plant operation	Workplace health and safety regulations in some jurisdictions require specific training for operators of specific equipment, especially those that operate at high temperatures and/or pressures.
Greenhouse gas emissions mitigation	Using biochar to generate carbon offsets or decrease a carbon liability under a mandated or voluntary scheme will require accreditation and verification.

Regulations depend on the specific application and jurisdiction so it is recommended that producers and users consult with their local authorities, including government departments of agriculture or primary industries, environmental protection agencies, and local government to ensure that regulations are being followed. Users who are planning on applying biochar to rented, leased or mortgaged land also may have a responsibility to inform the land owner or mortgagee.

Biochar production risks

The pyrolysis of biomass for the production of biochar requires high temperatures and results in both gas and liquid by-products. All three of these products have been shown to be dangerous under some circumstances to human health and hence appropriate procedures need to put in place to ensure potential adverse effects are prevented.[51]

Flammable gases

Gases evolved during the pyrolysis process are flammable and potentially explosive, presenting a burn and asphyxiation risk to operators. To manage this hazard, producers should use production systems that are equipped with appropriate after-burners and pressure relief devices, and ensure ignition sources are well separated. Operational procedures should maintain a safe distance between operators, potential flames and hot surfaces. Flame detection devices should be employed appropriately to provide warning of the release of flammable gases to the local environment.

Carbon monoxide

One of the major gas species in pyrolysis off-gases (otherwise known as syngas) is carbon monoxide (CO), inhalation of which causes poisoning. Due to carbon monoxide being an odourless, colourless and tasteless hazard it is advisable that operators of biochar production systems wear CO detection devices to ensure they are not exposed to toxic levels of this gas. Producers should ensure that the technology used effectively captures and manages the pyrolysis gases before they are released to the atmosphere. Pyrolysis production systems should be operated in well ventilated areas.

Smoke and particulates

Smoke and particulate release reduces air quality and puts respiratory health at risk. Smoke and particulates can also pose an irritation risk to eyes. If larger particulates are released from the system they can be very hot and/or on fire and cause serious burns if they come in contact with skin, and pose a serious fire hazard. Producers should use production technology that does not result in the release of smoke and particulate emissions (above regulation limits) during any stage of the production process. It is certainly not ideal if large particles or cinders are released from the system, however systems employed to manage smoke and small particulates will also manage these so they should not be an issue for well-designed production systems. Personal protective equipment, such as respirators, should be worn by those exposed to smoke or pyrolysis off-gases.

Examples of production hazards

Biochar producers should ensure that the manufacturing technology they use is produced by a suitably qualified and reputable supplier who has complied with Australian engineering and construction standards and has performed a comprehensive HAZOP (hazard and operability study). Inappropriate production technologies can pose serious hazards as shown in the examples below.

1. Pyrolysis reactors made from metals that have not been specified to withstand the very high, localised temperatures within the kiln are likely to melt and fail. This results in a rapid, unexpected release of a projectile of flammable/flaming gas that could cause serious injury or death to an operator or bystander.
2. The gas in the after-burner may not sustain a flame due to incorrect equipment sizing and/or too much moisture in the gas. This results in pyrolysis gas being released directly to the local environment. If no flame detector is installed and operators are not wearing CO monitors to provide warnings, operators will suffer from carbon monoxide poisoning which may include minor symptoms such as headache or vertigo, or major symptoms such as damage to the central nervous system or even death.
3. If standards for insulating or guarding hot surfaces have not been followed and an operator trips and puts a hand on a hot metal surface that is 500°C (or more) this would result in severe burns and permanent disfigurement.

Operations standards

Operations manuals including emergency procedures should be included with the supply of the equipment along with some warranty. Customers buying biochar production technology may also wish to check that the supplier holds an appropriate level of insurance to cover any damage to property or health resulting from its use. Operators should be appropriately trained in the operation of the production technology and hold the necessary qualifications according to the local regulations.

Transport, storage and application risks

Biochar users should read and follow the safety precautions outlined on the materials safety data sheet provided with the product. Biochars are often classified as Class 4 dangerous goods, so transport and storage needs to comply with international standards for these products.

Dust

Biochars can be dusty. The inhalation of small particles of biochar is a respiratory health hazard and should be prevented. Biochars become less dusty if they are damp, or compacted into pellets or prills. Users should wear a dust mask when handling and applying biochar to prevent inhalation (Figure 3.2). Biochar particles are irritants if they get in the eyes. Users should wear eye protection to prevent this.

FIGURE 3.2: Safety equipment needs to be used when working with biochar. Photo: Justine Cox

Environmental risks

One of the great benefits of biochar, from a long-term carbon sequestration perspective, is that once it is applied to soil there is no practical way to remove it again. This also presents an alarming challenge and a critical onus on ensuring that the product is suitable for use before it is applied, because once it is applied the damage done may be irreversible.

The main risk factors that may result in a biochar not being suitable for use are

- contamination, such as heavy metals,[157] poly-aromatic hydrocarbons (PAH),[24] bulk metals, glass, ceramics, dioxins etc
- characteristics that amplify existing constraints (e.g. applying a high pH biochar to an already high pH soil making the issue of alkalinity worse, or a hydrophobic biochar to soils limited by lack of water penetration).

Biochar products should be tested to ensure levels of contaminants are below background levels and/or meet local environmental regulations. Contaminants can result both from operational conditions (e.g. PAH, dioxins and furans can be generated as a result of the thermal processing), and the feedstock (e.g. heavy metals in treated timbers).

Risks to greenhouse gas mitigation potential

One of the attractions of using biochar is its potential to actively sequester carbon in a long-term terrestrial sink, and hence reduce the concentration of atmospheric greenhouse gases (GHG) that are resulting in global warming.

The amount of sequestration achieved is put at risk by emissions leakage or GHG emissions during biochar production and application. The net GHG emissions mitigation benefit of applied biochar considers not only the amount of carbon that is stabilised and sequestered but all of the activities associated with its production and application that may have resulted in GHG emissions. This is known as life cycle assessment.

The alternative fate of the biomass feedstocks, if not used in biochar, also needs to be considered as it may be replaced with another product that is more or less emission-intensive which would impact on the overall GHG emissions balance of the system

Methods to maximise GHG mitigation benefit of biochar

1. Use biomass feedstocks that would have been returned relatively quickly to the atmosphere.[126]
2. Use efficient systems that do not use a lot of fossil fuel inputs to harvest and transport biomass, and produce and transport biochar.[34]
3. Use production systems that do not directly release particulates or gases with higher global warming potentials than carbon dioxide (i.e. have effective after-burners and particulate emissions controls in place).
4. Use production systems that achieve a high recovery rate of carbon in highly aromatic (stable) chemical structures.
5. Ensure that once biochar is applied it does not need more fertiliser or irrigation and hence produce more greenhouse gases.

If one or more of these is not achieved then the GHG emissions mitigation benefit of the biochar is put at risk. It is possible for biochar to result in a net increase of GHG concentration in the atmosphere if one or more of the listed factors above results in a greater release of GHG than the equivalent quantity of carbon stored in the biochar.

If biochar is to be accredited for GHG emissions mitigation benefits in a carbon trading scheme, such as the Carbon Farming Initiative, then the overall GHG emissions balance will need to be measured, monitored and verified (Figure 3.3). If one of the objectives for users is to achieve a net sequestration of carbon then it is advisable that biochar products are:

- sourced from producers that have capability to verify the emissions associated with production
- accredited under some regulated scheme.

FIGURE 3.3: Greenhouse gas chambers measure carbon dioxide, nitrous oxide and methane continuously in the field.
Photo: Lukas Van Zwieten

Risks to productivity and financial viability

There is a risk that biochar may result in a decrease in production capacity of the soil system, or not result in productivity increases that warrant the cost of the product plus application.

Soil constraints

To reduce this risk it is essential to target the biochar use to address or rectify a specific constraint in the cropping system. For example, if the growth of a crop is limited by water logging and the biochar used has been shown to improve the hydrology of heavy soils, there is a good chance there will be a productivity benefit from the application. If there is not a constraint present that biochar application improves, then no productivity benefit can be expected. Biochar's effectiveness to deal with various soil constraints cost effectively should be considered in respect to other soil amendments that may also deal with the same constraint.

Pesticide efficacy

Biochars have been shown to decrease the efficacy of some herbicides and pesticides[87]. This is due to the biochar binding the active ingredients and hence making them less available and active on their target species.

Water repellence

If biochar becomes dry it can be hydrophobic and repel water. Dry biochar will float on water. This hydrophobicity may pose a risk to the hydrology of the soil and prevent water getting to the root zone of plants if dry biochar is applied as a thick blanket over the surface. However, in time biochar will absorb water into its pores and eventually sink in water. Its ability to hold water has been shown to keep some soils moist longer than without biochar.

Productivity

Biochar application may dimish productivity if:

- contaminants in the biochar cause a toxic effect to germination or growth
- changed soil characteristics are not ideal for plant growth (e.g. soil becomes too alkaline)
- application exacerbates an existing problem
- water is repelled
- herbicides and pesticides are less effective.

Conclusion

This brief overview shows that there are a number of possible risks associated with the production and use of biochar products, some of which have severe consequences to the environment and human health if not managed effectively.

Chapter Four • Biochar effects on soil properties

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Key messages

1. Biochar can provide an immediate increase in soil carbon, and has been shown to last for between centuries to millennia.
2. Biochars from manure sources have a higher mineral content than biochars from woody sources, so supply more nutrients to soil. Some nutrients in biochar are unlikely to become plant available.
3. Nutrients from biochar may not be immediately plant available; some biochars act as 'slow release' fertiliser.
4. Some biochars can provide a liming effect, particularly those made from papermill residues and manures at higher temperatures.
5. Fertilisers added after biochar application may be more effective than fertilisers applied on their own.
6. Biochar may improve the physical structure of the soil, particularly aggregation, water retention, water use efficiency, and reduce tensile strength in hard setting soils.
7. Biochar can provide a habitat for microorganisms in soil, and changes to microbial populations following amendment have been shown. What this means to productivity is still largely unknown.
8. Biochar application has potential to suppress soil-borne diseases in some cases.
9. Impacts of biochar on earthworms depend on soil-biochar interactions.
10. Organic chemicals in biochar may benefit seedling germination and plant establishment while other organic chemicals may be toxic in soil. These organic chemicals depend on the feedstock and processing conditions.

Scientists and policy makers are recognising that biochar is a novel soil amendment with a potential role in sequestering carbon, reducing greenhouse gas emissions, providing renewable energy and managing waste.[87] In this chapter, we evaluate the potential role of biochar in horticultural soils, with particular emphasis on soil constraints that may be addressed by managed applications of biochar. Biochar is produced from a wide range of waste organic materials under a variety of processing conditions, resulting in different characteristics for individual biochars. These characteristics influence the soil's chemical, physical and biological properties. As we develop our understanding of biochar-soil interactions it may be possible to develop biochars to address specific soil constraints.

Influence of biochar on soil carbon

Biochars are recalcitrant organic materials, which means they are highly resistant to biological and chemical decomposition.[106, 170] The rate and extent of biochar decomposition in soil depends on type of feedstock and pyrolysis conditions,[135, 170] soil organic matter levels,[79,100] soil type[100] and environmental conditions.[113, 114] The mean residence time (MRT) of biochars in soil has been estimated to range from several decades (usually >100 years) to millennia as determined mainly through laboratory incubation studies.[89, 135, 170] This high stability is an important factor in biochar's potential to mitigate greenhouse gas emissions from soil.[136,163]

Biochar has been shown to both stimulate (positive priming) and suppress (negative priming) the breakdown of existing soil organic carbon, which can negate or enhance the carbon sequestration benefits of biochar application to soil.[159, 171] A study[100] has recently shown that biochar application can stimulate the decomposition rate of native soil organic carbon due to increases in biological activity following biochar application; however, this loss of native soil organic carbon occurs only directly following application of the biochar and is not likely to be a long-term effect.

Some studies have observed suppression of soil organic carbon turnover in the presence of biochars. This effect varies with soil type, organic carbon and nutrient levels in soil and biochar ageing.[38, 79, 89, 97, 171] There is no doubt that adding biochar leads to increases in soil carbon, but this effect needs to be carefully quantified to enable future use of biochar as a carbon offset.

Soil-biochar chemical interactions

This section describes some of the key impacts of biochar on soil chemical fertility and fertiliser use efficiency.

Impacts on plant germination and establishment

Biochar can contain organic compounds that may impact plant germination and growth.[128] These include nitrogen-heterocyclics, substituted furans, phenols and substituted phenols, benzene and substituted benzene, carboxylics and aliphatics.[2] The compounds vary according to production conditions and feedstock materials, both of which may influence potential phytotoxicity. For example a study[90] showed the growth of maize seedlings was inhibited with biochar from *Miscanthus* (a type of giant grass) made at 400°C, but stimulated by *Miscanthus* biochar made at 600°C. Extracts from biochars produced by gasification contained compounds that suppressed seedling growth.[128] However, extracts from biochars produced from the same feedstocks through pyrolysis (ca. 500°C) did not impact on either germination or seedling growth.

They[128] suggested that ageing of the biochars in soil would result in removal of phytotoxic effects. Different researchers[80] undertook an experiment to test the impacts of tar-enriched biochar (fast pyrolysis at 600°C) on phytotoxicity. The authors noted that even with tar-enriched biochar amendment up to 10% by weight in soil, germination and seedling growth of lettuce increased. Another group[57] tested the impact of feedstocks (biosolids, corn stover, eucalyptus, fresh pine and willow) on biochar properties (all pyrolysed at 550°C). No effect on seedling germination was observed when these were applied at rates up to 10t/ha into soil.

The presence of small quantities of toxic components in biochar may induce a hormeotic response,[64] which is a positive influence of low levels of chemical on seedling germination or plant growth. The authors provided evidence that following biochar amendment, microbial populations in the growing matrix shifted towards beneficial plant growth promoting rhizobacteria or fungi. Extracts from the biochar contained phytotoxic or biocidal chemicals that stimulated plant growth at low doses. The presence of organic acids and substituted phenolics[166] in wood or bamboo vinegar, a by-product of charcoal/ biochar manufacture, have been shown to inhibit plant germination at high application rates, but provide positive responses at lower application rates.[110] The impacts of these components of biochar may have a higher relevance to vegetable production systems, but are less likely to be important in established perennial horticulture.

Nutrient and liming values of biochar

The plant nutrient values of biochar depend on how much biochar is added to soil, the properties of the nutrient within the biochar, and the interaction of the biochar with the soil.

Nutrients are present in biochar, but their availability to plants depends on the type of nutrient and type of biochar.[47, 165] For example, phosphorus is found mainly in the mineral fraction of biochar and only a small component is likely to be associated within the organic structure of biochar. Its solubilisation is pH-dependent.[47] Potassium in biochar is generally readily available to plants.[2]

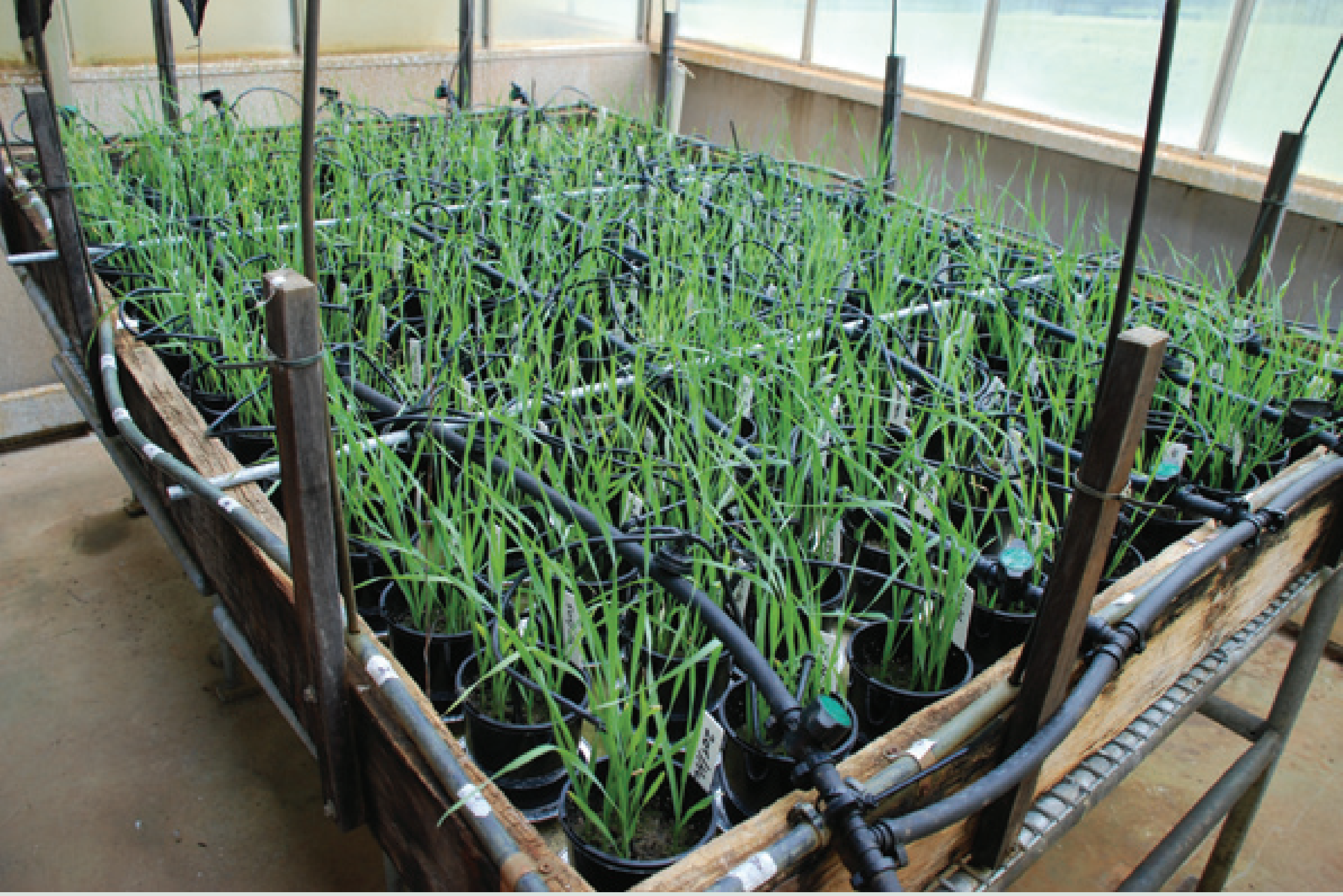


FIGURE 4.1: Biochar pot trials with various application rate, sown with wheat. Photo: Josh Rust

Nitrogen availability from biochars has been shown to vary widely depending on final temperature of pyrolysis, heating rate, time of holding at final temperature, and type of feedstock.[2,77] Nitrogen can occur in many forms within biochar, including heterocyclic nitrogen (N included within the carbon structure of biochar),[85], an organic form of nitrogen which would only become plant available as it mineralised (broken down) in soil by microorganisms. New South Wales researchers[30] observed that poultry litter biochar had a significant concentration of nitrate that was readily leachable, but other biochars did not have this property.

Table 4.1 provides a list of selected biochars and their properties as influenced by feedstock and processing conditions. What should be noted here is that feedstocks with some animal origin (e.g. poultry litter, biosolids etc) have far greater concentrations of some nutrients, particularly phosphorus, than plant-only feedstocks.

TABLE 4.1: Properties of selected biochars

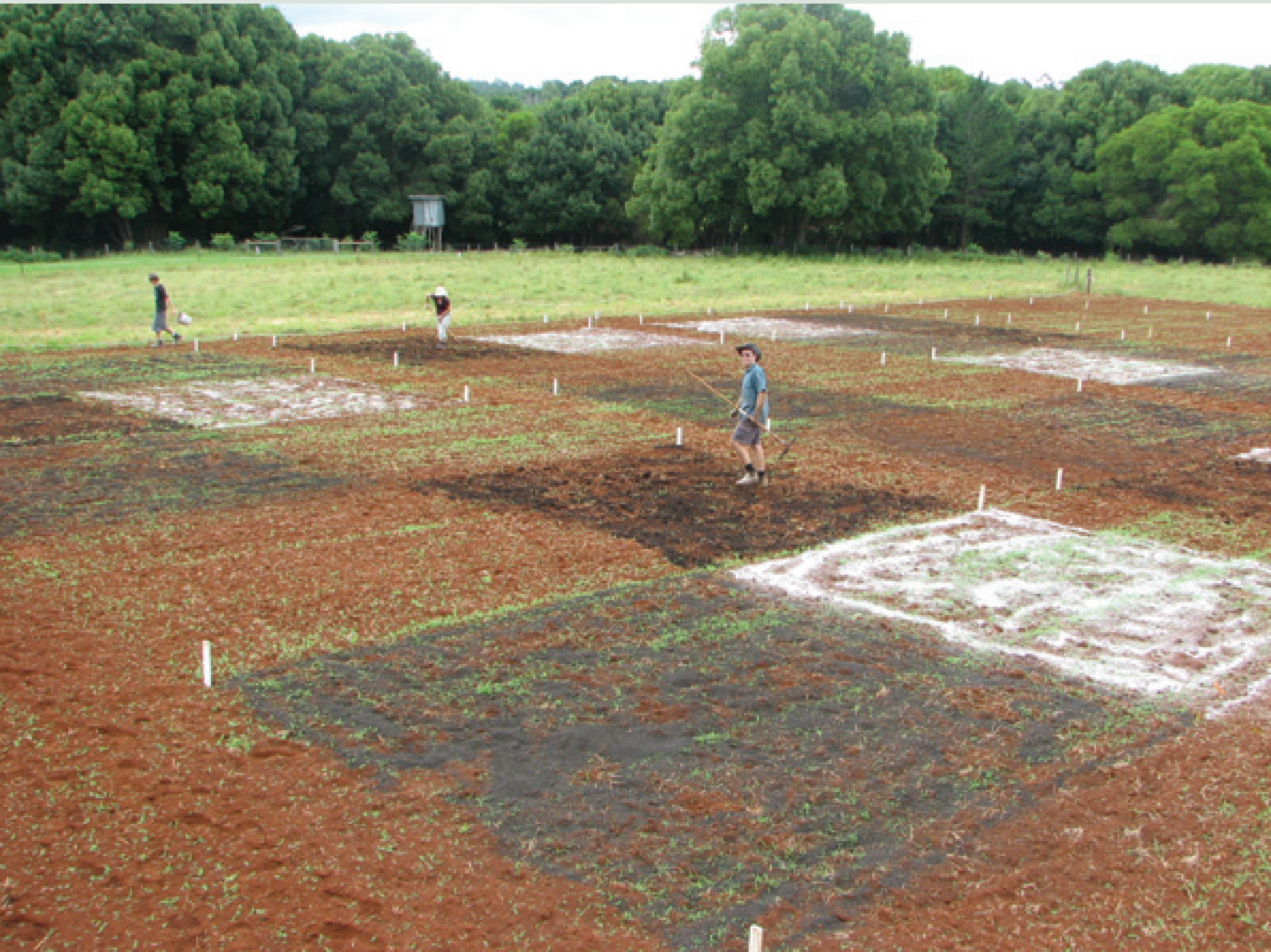
Biochar source	N%^	P%^	K%^	Ca%	CEC cmol/kg	C%	pH water	C:N	EC ds/m	Production temp °C*	Reference
Plant only											
Green wastes	0.18	0.07	0.82	<0.01	24	36	9.4a	200	3.2	450	Chan et al. 2007[28]
Green waste	0.21	0.056	0.098	0.23	-	62	4.9 a	295	-	350	Van Zwieten et al. 2010a[153]
Green waste	0.24	0.037	0.063	0.12	-	75	7.3 a	312	-	550	Van Zwieten et al. 2010a[153]
Green waste	0.14	0.01	0.06	0.14	3.2	78	7.5 a	557	0.13	600	Van Zwieten et al. 2010b[154]
Sugarcane trash	1.2	0.25	2.0	-	39.6	68	9.6	57	4.8	550	Quirk et al. 2010[123]
Sugarcane bagasse	1.1	0.22	0.25	-	3.5	65	8.4	59	0.18	550	Quirk et al. 2010[123]
Sugarcane millmud	1.4	3.4	0.35	-	21.5	24	9.2	17	0.5	550	Quirk et al. 2010[123]
Acacia mangium bark	1.04	-	-	-	37.14	40	7.4	38	-	Not defined	Yamato et al. 2006[164]
Paper mill sludge and wood (1:1)	0.48	-	0.22	6.2	9.0	50	9.4 a	104	-	550	Van Zwieten et al. 2010c[155]
Paper mill sludge and wood (1:2)	0.31	-	1.0	11.0	18.0	52	8.2 a	168	-	550	Van Zwieten et al. 2010c[155]
Soybean cake	7.82	-	-	-	-	59	-	7.5	-	550	Uzun et al. 2006[149]
Pinus ponderosa bark	<0.01	<0.01	-	-	34.5	72	4.81	<1000	1.12	350	Gundale & De Luca 2007[68]
Pinus taeda chips	0.255	0.015	0.145	0.171	7.27	74	7.55	290	-	400	Gaskin et al. 2008[59]
Pinus taeda chips	0.223	0.014	0.145	0.185	5.03	82	8.3	366	-	500	Gaskin et al. 2008[59]
Eucalyptus deglupta wood	0.57	0.06	-	-	4.7	82	7.00	144	-	350	Rondon et al. 2007[129]
Eucalyptus saligna wood	0.22	0.03	0.27	0.98	-	85	9.4	387	-	400-500	Kimetu et al. 2008[84]
Eucalyptus saligna leaves	1.7	0.27	1.49	2.05	12.8	72	9.88	42.3	-	550	Singh et al. 2010[134]
Tectona Grandis, Pterocarpus macrocarpus	0.3	-	3.1	4.4	10.7	87	7.5	290	-	Earth mound	Asai et al. 2009[3]
Macadamia shell	0.49	0.02	0.18	0.099	7.7	90	8.5	183	1.2	Unknown	Produced using top lit updraft (TLUD), Van Zwieten unpublished
Camphor laurel	0.13	0.02	0.37	0.29	6.6	78	8.6	600	0.17	Unknown	Produced using TLUD; Van Zwieten unpublished
Bamboo	1.2	0.55	0.36	0.41	8.9	77	8.6	64	0.62	Unknown	Produced using TLUD; Van Zwieten unpublished
Animal only											
Cow manure/ *Pinus* spp. (3:1)	1.2	0.3	1.9	1.0	-	73	9.4	61	-	500	Kolb et al. 2009[86]
Poultry litter	3.5	3.01	5.1	4.27	61.1	39	10.1	11	-	400	Gaskin et al. 2008[59]
Poultry litter	2	2.5	-	-	-	38	9.9 a	19	5.6	450	Chan, et al. 2008b[30]
Poultry litter	3.1	3.59	5.9	5.04	38.3	39	9.74	13	-	500	Gaskin et al. 2008[59]
Poultry litter	2.6	2.4	2.8	4.0	-	42	8.9 a	16	-	550	Van Zwieten et al. 2010a[153]
Paunch waste (abattoir)	0.69	0.51	0.50	1.5	100	47	11	68	16	~550	Continuous feed semi- commercial. Van Zwieten unpublished
Human origin											
Biosolids	2.2	5.7	0.19	5.5	-	21	7.9 a	9.5	-	550	Van Zwieten et al. 2010a[153]

Note: pH measured in 1:5 soil/0.01M $CaCl_2$ extract
* highest temperature of production reported
^ total N, P or K (%) may not reflect plant available portion of that nutrient

Many biochars have a neutral to alkaline pH (see Table 4.1) so can provide some benefit in neutralising acidic soils. However this alkalinity may be detrimental when applied to soils with neutral or alkaline pH values, as reductions in plant productivity have been demonstrated when alkaline biochars are added to a Calcarosol.[155] In this paper, authors reported liming values of 33% and 29% for two papermill waste biochars (compared with carbonate), with the alkalinity due to the presence of oxides and hydroxides in the biochar. As a general trend, researchers[134] found that the calcium carbonate ($CaCO_3$) equivalence of biochars increased with increasing pyrolysis temperature. Although oxidation of biochar surfaces generates acidity,[113] this acidifying effect could be buffered by the dissolution of cations such as potassium and calcium from the biochar.[77]

Cautious authors[87] have suggested that unintentional consequences of biochar application such as nutrient tie-up, increased leaching of some nutrients and increased electrical conductivity (EC), need to be considered before adding biochar to soil. Adding biochars high in ash (mineral) content may raise soil EC to unfavourable levels. In particular, the presence of sodium and potassium in the biochar-soil matrix has been shown to influence EC.[93, 117]

FIGURE 4.2: A NSW pasture trial with biochars, lime and control plots, before incorporation. Photo: Lukas Van Zwieten



Biochar influences on nutrient availability in soil

Nitrogen

There is mounting evidence that biochars of plant origin with generally low nutrient value can improve nitrogen use efficiency when amended into soil.[28, 142, 153] In most applications of nitrogen fertiliser, less than 50% of the nitrogen is taken up by the crop.[13] Biochar application may benefit farm returns and the environment through improving nitrogen use efficiency, by processes such as reducing off-farm loss of nitrogen-based fertiliser.

The changes in nitrogen dynamics, including emissions of nitrous oxide, following biochar application are still under investigation.[35, 92, 134] Biochar may bind inorganic nitrogen, which would reduce the rate of nitrogen cycling, including N_2O emissions, e.g. via nitrification and denitrification. Weathering of biochar in soil may also immobilise nitrogen.[134, 165] Biochar can reduce leaching of ammonium in soil,[93, 134] depending on the properties of the biochar and the characteristics of the soil. This occurs through development of exchange sites of biochar surfaces,[77, 99, 134] which in turn is influenced by the ageing and interaction of biochar with soil constituents. Biochar application may increase the rate of nitrification (conversion of ammonia to nitrate) in Ferrosols,[45,152] possibly due to increased soil pH and more favourable conditions for nitrifying organisms.

Soil type

Biochar's effect on soil nutrient status depends on both the soil and the biochar. In one trial, NSW researchers[136] noted long-term increases in plant available phosphorus in acidic Ferrosols following amendment with animal manure biochar, but no increase after amendment with a greenwaste biochar on the same soil (both biochars produced at 550ºC). These biochars had contrasting properties, especially nutrient content. A complimentary study[158] shows that phosphorus from high-ash biochars, such as those originating from manure feedstocks, and having a high total phosphorus concentration, are potential phosphorus sources with high-agronomic efficiency. Conversely, high rates of greenwaste biochar (4.4% and 11%, w/w) applied to a Tenosol used for commercial vegetable production in NSW resulted in a small reduction in plant available phosphorus.[155]

FIGURE 4.3: Biochar trial growing beans in a rotation, northern NSW. Photo: Lukas Van Zwieten

Cation exchange capacity

Biochars may influence nutrient sorption and desorption through altering the cation exchange capacity (CEC) and/or anion exchange capacity (AEC).[77] CEC is a measure of the ability of a substrate to retain positively charged ions (e.g. Ca^{++}, K^{+}) through electrostatic forces,[23] while AEC refers to the retention of negatively charged ions (e.g. NO_3^-). Biochar has been associated with CEC enhancement in some soils,[62, 155] thereby increasing the availability and retention of plant nutrients and potentially increasing nutrient use efficiency. It has been suggested that the CEC is likely to increase over time as biochar ages in soil, due to oxidation of biochar surfaces,[32, 33, 96] while AEC is likely to reduce.[77]

While the effect of biochar on soil nutrients can vary widely, an understanding is developing within biochar literature on characteristics of biochars and how these may influence key soil nutrient processes, although the range of biochars studied, the influence of soil type and climatic zone is still limited.

Influence of biochar on soil biology

Research on biochar interactions with soil biology is less developed than our understanding of soil chemistry. Biochar particles have been described as acting in a similar manner to soil aggregates. For example, they provide continuous soil pores, aeration, root penetration and water infiltration, and provide microsites and reactive surfaces for complex biochemical interactions and retention of nutrients.[94] The large variation in properties between biochars, such as pH, sorptivity, surface area, intrinsic mineral matter and labile organic matter, contribute to the complexity with which biochar influences soil biota and biochemical functions.

Beneficial organisms

Biochar addition may increase soil microbial biomass (population size), and affect microbial community structure (species present) and enzyme activities.[8, 10, 75, 83, 94] Australian researchers[30] observed an increase in microbial biomass in the presence of poultry litter biochar in a hard-setting soil growing radishes. While increased microbial biomass has been observed, it has often been accompanied by a reduction in microbial activity,[142, 75] most probably due to sorption of labile organics, nutrients, and enzymes on the biochar.[94]

Biochar application has been shown to increase the rate of mycorrhizal fungal colonisation in roots, although it depends on the biochar, soil type and plant species.[22, 119, 137, 160] A much cited review of published studies on this topic attempted to determine the causes for the increased colonisation and concluded that there were four possible mechanisms.

1. Biochar favourably alters the physical and chemical properties of the soil, especially availability of nutrients,
2. It may affect other microbial populations and indirectly encourage mycorrhizae.
3. It can influence the signalling chemicals between plants and fungi.
4. It may provide habitat that protects fungi from fungal grazers.

Biochar addition can alter the presence and abundance of microbial species.[75, 146] Biochar particles contain tiny pores that protect microorganisms from predation,[121, 146, 160] possibly benefiting bacterial and fungal communities over larger organisms. Several biochar studies report reduced microbial diversity and a significant change in microbial communities.[56, 83] For instance, adding wood biochar to a nursery mix in a pot trial of capsicums and tomatoes increased the mass of fungi and *Pseudomonas* bacteria.[64] Furthermore, root-associated yeast species and *Trichoderma* species were present in biochar-amended potting mix but not in non-amended control pots.[64]

Pathogens

There is growing evidence that biochar addition can reduce disease severity for several crop species.[94,108] A glasshouse study that monitored two fungal pathogens and a pest mite in capsicum and tomato plants showed that citrus wood biochar reduced *Botrytis cinerea* (gray mould) by 181%, *Leveillula aurica* (powdery mildew) by 58%, and mite damage by 50-60%.[53] The suppression of these diseases and mite infestation was caused by the plants' defence systems being activated, possibly in response to moderate stress levels, or through increased populations of microorganisms known to induce resistance, e.g. *Trichoderma*.[64]

Some studies have shown significant disease control of *Fusarium* in asparagus,[54, 55] and bacterial wilt in tomatoes.[112] The mechanism of disease suppression was attributed to the presence of calcium precipitates in the biochars, as well as improvements in the physical, chemical and biological characteristics of the soil. However, preliminary results using a green waste biochar from an Australian study have shown minimal disease suppression of *Rhizoctonia solani* (damping-off) in radishes.[67] Clearly, the disease-suppressive ability of biochars needs to be tested for a range of combinations of diseases, biochars and soil types before generalising this impact of biochar.

Soil fauna

There is little information currently available on the impact of biochar on soil faunal groups. Earthworms are the most studied soil fauna, possibly because they ingest soil (and biochar) and show greater sensitivity to changes in soil conditions than other soil faunal groups. Results to date are inconclusive: earthworms have avoided,[98] preferred[154] and shown no preference to soil amended with biochar.[30] A recent review concluded that there were some short term negative impacts, but in the longer term earthworm population density and size were not affected by biochar.[162] Negative impacts occurred because the biochar was too dry, too alkaline or affected feeding behaviour.[95, 162] These variable impacts of biochar on earthworms highlight the need for further research to underpin biochar use in horticultural systems, to ensure that it enhances beneficial organisms and, consequently, productivity. An earthworm avoidance assay has been included in guidelines developed by the International Biochar Initiative to minimise any potential impacts of biochars on soil fauna.[72]

FIGURE 4.4: Roots penetrating rice husk biochar in a coffee plantation, northern NSW. Photo: Justine Cox

Roots

Biochar addition has been shown to enhance root biomass, length and diameter,[94, 137, 116, 127] possibly due to its ability to reduce soil compaction, improve soil aeration and water relations and increase aggregation (see the next section), all of which assist fine root growth.[94]

Influence of biochar on soil physical conditions

An early study in 1948[147] using charcoal amendment to soil showed significant increases in retention of water in sandy soils, and reduced retention of water in clay soils. This varied response highlights the importance of understanding the specific soil constraint, and the ability of biochar to address the constraint. Researchers[63] reported an 18% increase in field capacity for high black carbon Anthroposols (soils formed by human activity) compared with surrounding low black carbon soils, and attributed this to the increased surface area and porous structure of the char particles. It should be noted however that these Anthroposols had a high level of charcoal addition over many years (amounting to up to hundreds of tonnes per hectare). Biochar was reported to enhance saturated hydraulic conductivity and water-holding capacity in upland rice production in Northern Laos.[3] In a study on upland sandy soils, a study[150] found that application of biochar increased the available water by 97%, saturated water content by 56%, and reduced hydraulic conductivity with increasing moisture content when compared with unamended sand.

FIGURE 4.5: Scanning electron microscope image of wood waste biochar. Note the original internal structure. Photo: Adriana Downie

However, improvements in water holding capacity depend on the biochar and the soil,[143] with the physical structure of the biochar having the greatest influence. This evidence suggests that biochars possess the potential to improve water use efficiency and productivity in water-limited conditions.

Increases in soil organic matter have been shown to enhance soil aggregate stability.[27, 36] It could be argued that biochar amendment is not the best form of organic matter to achieve increased soil aggregation, but its stable nature is likely to contribute to aggregation over the long term.[26]

Biochar may contribute to the physical stabilisation of other soil organic matter which could further enhance structure. Australian reseachers[28] reported significant reduction in soil tensile strength following application of high rates of greenwaste biochar in a hardsetting soil (which could enhance seedling emergence, root growth and water infiltration, and reduce fuel use in cultivation), but further data on impacts on tensile strength are lacking. Biochar tends to be a low density product,[50] so its application to soil would be expected to reduce bulk density. This has been reported for some field studies,[167] but application rates of below 30t/ha and incorporation to 100mm depth may not result in an easily measurable difference in bulk density in the field.

Chapter Five • Use of biochar in crop production systems

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Key messages

1. There is not enough research on biochar effects targetted to horticultural crops to provide targetted information, however other crop types provide valid comparisons.
2. Biochar application increased agricultural crop yields in the majority of field trials reviewed.
3. Fertiliser application with biochar often substantially increased the effect on yield.
4. Current methods of biochar incorporation into topsoil are suitable for most annual and semi-permanent orchard crops.
5. Alternative incorporation methods may need to be adapted for permanent perennial horticultural crops.

Biochars have been applied in many agricultural field trials around the world to assess their impact on productivity, soil process, carbon sequestration, greenhouse gas emission, and to provide a more realistic assessment environment than the laboratory or greenhouse. This chapter reviews 33 papers relating to these field trials to assess the potential for biochar use in Australia. The review includes research in extensive agricultural crops (e.g. grains, rice), broadacre field crops, pastures as well as horticultural crops. It is necessary to include all of these agricultural crops as there is too little research in horticultural crops to synthesise the information effectively. Trial crops included wheat, rice, maize, bananas, sorghum, pastures (e.g. forage peanut, rye grass), native grasses, soybean, cassava, peanut, water spinach, faba beans and cashews. All trials were conducted with appropriate controls, adequate replication, statistical analysis of the results and peer review before publication, providing confidence that the results are valid and without bias.

Effects of biochar on horticultural crops

Of the 33 total papers, the horticultural crops included eight studies on corn (maize), with single papers on water spinach (a green leafy vegetable), cassava (root crop), banana and cashews. This limited data set makes it very difficult to draw any conclusions on biochar effectiveness in horticulture. The research on corn was undertaken in many climactic zones and soil types, with different biochar feedstocks. Not surprisingly a variety of results were observed, with some biochars showing no difference in crop yields or quality, while other biochars increased yields and improved soil quality measures. It is therefore of more value to combine crop types to try to improve the data set, given that the issues are the same for most plant/soil systems.

Effects of biochar on field crop yield

Most of the agricultural field trials observed beneficial effects of biochar on crop yield: 58% recorded a yield increase with biochar use and 37% recorded no differences. There were two cases of yield decline within trials that showed overall yield increases: one showed a decline in the first year of the trial followed by a yield increase in the next year; the other had contrasting results for different varieties of rice. It is not clear why these biochars reduced yield. A recent review and statistical meta-analysis of biochar results worldwide reported a significant positive effect on yield of 10%.[74] The authors combined many data sets of high quality and complete studies to analyse the overall effects of biochar, and effects of important contributing factors such as soil pH, soil type, fertiliser addition, biochar feedstock, application rate and crop species.

Feedstocks

Biochars used in the 33 trials varied from burnt local timber in Brazil,[140, 142] to high grade material from a commercial pyrolysis unit.[136] They were made from a variety of plant and animal residues, and pyrolysed at different temperatures, which makes direct comparisons difficult and predictions premature. Despite this, most manure-based biochars showed higher yields than plant-based biochars in comparison trials.[73, 136, 144, 156]

Application methods

All biochars were incorporated into the soil to 10 or 15 cm depth, often with machinery, at the beginning of trials. There has been no major research effort to evaluate banding biochar for row crops, except for studies on wheat in Western Australia, where researchers have deep banded biochar 5-15 cm below the soil surface.[20, 22] There are no published studies that have compared incorporation of biochar into soil (ensuring high interaction of soil and biochar particles) with any alternative methods such as banding or coring.

Use of fertilisers

The presence or absence of fertiliser with biochar application appears to affect yield response (Figure 5.1). Many studies found that the addition of fertiliser (inorganic or organic) to soil with bark, mallee, forest and wheat straw biochar increased the yield response.[20, 140, 137, 164, 168] For example, authors[140] found that forest wood biochar by itself had no effect on rice and sorghum yield (at 11t/ha rate), yet biochar with fertiliser increased yield by 73, 820, 50 and 100% over four harvests, compared with fertiliser alone. On the other hand, research in China[168] found similar maize yield increases with and without fertiliser (at both 20 and 40t/ha), while trials in USA[148] found no effect of biochar (feedstock not described) with or without fertiliser (at 4.5 and 18 t/ha). Studies that assessed biochar on fertilised plots found yield increases of between 7-820%, e.g. farm manure biochar produced at 300°C[73] cattle dung (at 330°C) and coconut shell biochar (at 280°C)[144] and wheat straw biochar (at 550°C).[169] As Australian commercial horticultural practice usually includes fertilisation, these results are relevant to Australian horticultural systems. Several studies attributed increased yields with forest trees and mallee biochar plus fertilisers to increased fertiliser use efficiency.[22, 142]

Combination amendments

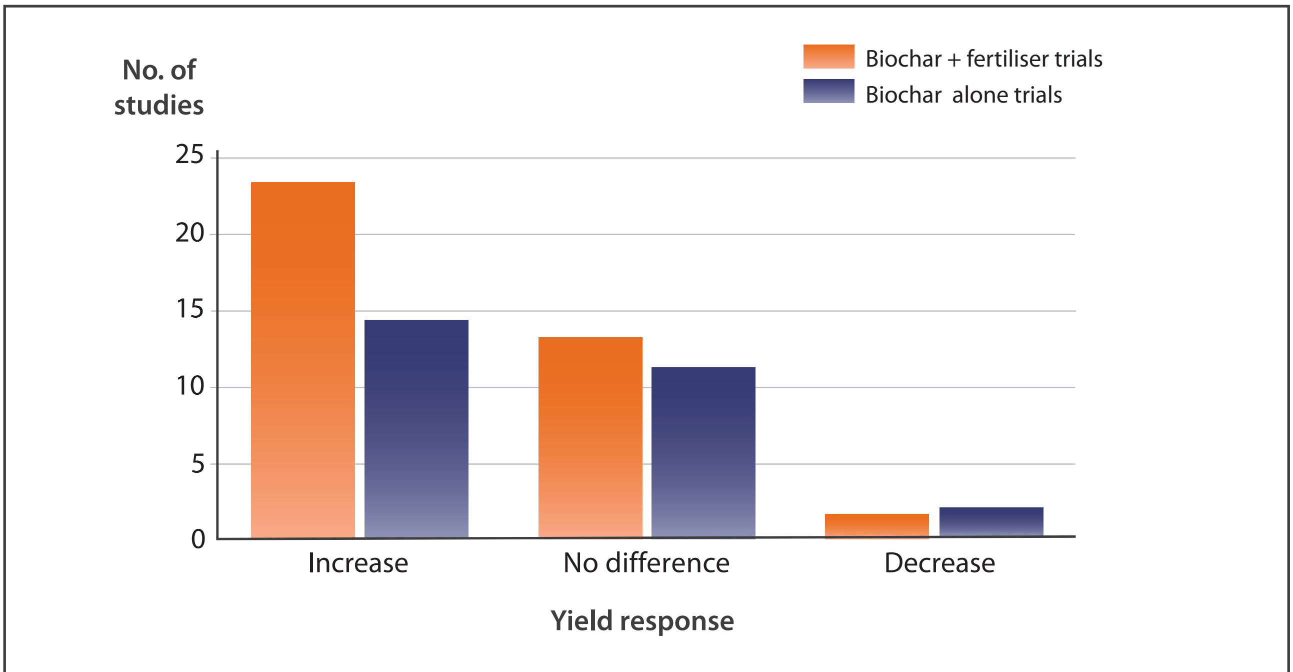

FIGURE 5.1: This graph shows the number of of biochar trials that have shown increased yields, decreased yields and the same yields as appropriate controls.

Several studies discovered increased yields with a combination of biochar, fertiliser or another amendment such as compost or crop residues. Researchers in Brazil[140] observed that while forest wood biochar with fertiliser had no effect on sorghum yield, biochar with fertiliser and compost increased yield by 250%. Research in Italy[14] also found no difference in maize yield with wood biochar plus fertiliser, but a 24% increase if crop residues were added. A PhD study[111] discovered that forest wood biochar and fertiliser had no effect on rice yield, but if half the biochar was substituted with compost, then grain yield increased by 282%. An ACAIR study[78] found that in Vietnam, peanut yield increased with rice husk biochar, fertiliser and manure by 33, 25, 48 and 16% over four harvests. It has become evident that biochar in combination with other soil amendments can be more effective in increasing yield than on its own.

Application rates

Biochar application rates in the trials varied from 0.20-10 t/ha in wheat, 4-40 t/ha in rice, 4.5-50 t/ha in maize, and 12 -116 t/ha in native grasses. Some trials showed increased yields with increased rates,[60, 76, 103, 151, 169] while others showed maximum yield at an intermediate rate.[3, 20, 168] A meta-analysis[74] using a range of biochars, soil types and crops found no influence of application rate on crop productivity. This is unsurprising given the range of rates, soil types and crops the review included. Grower decisions on application rates will depend on expected yield, cost, and carbon sequestration value. Rates in the region of 10-40 t/ha may be useful to include in future trials with new crops, with higher and lower rates also considered. As more trials are published on more crops and in more soil types, recommendations on effective application rates can be developed.

FIGURE 5.2: Biochar rate trial growing corn in rotation in northern NSW. Photo: Lukas Van Zwieten

Longevity of biochar effects

Long term trials are vital to assess the longevity of biochar effects and its fate in the environment. The common term for field trials in the literature is around six months. The longest field trial published (in Colombia) showed biochar had no effect on maize yield in the first year, but subsequent yearly harvest increases were measured at 28, 30 and 140% at 20t/ha.[103] There are several examples where crop yields have continued or started to increase two to three years after the initial biochar application.[73, 76, 136, 140]

Factors contributing to biochar response

The meta analysis[74] evaluated a range of likely factors in variable plant responses to biochar. Overall there was a significant contribution from soil pH (acidic soil responded positively), soil texture (sandy soil responded positively), fertiliser addition (nitrogen fertilisers improved crop response), crop species (some species responded more than others) and biochar feedstock (manure-based biochar was more effective than wood-based biochar) with no effect from application rate. Some of these conclusions were supported in field trials reviewed in this chapter: acidic soils showed improved yields,[22, 138, 156] fertiliser additions increased yields,[20, 168] and maize and peanut yields increased while cowpea did not.[164] Biochar feedstock has also influenced yield with most manure-based biochars more effective than plant-based biochars in the same experiment.[73, 136, 144, 156]

Conclusions

The key message from the meta-analysis[74] and this chapter review is that biochar can increase yield, especially when it is applied with fertiliser. The best results were obtained when biochar was applied to light-textured and acidic soil, low in fertility, with some crop species responding better than others. For these reasons, the outlook is promising for many horticultural crops. The next step is to determine the most beneficial feedstocks and production processes for different horticultural soils and crops. Current lack of data for non-grain crops, perennial horticulture and long term studies means these areas should be priorities for future horticultural research into biochar.

Biochar application in annual crops

Annual horticultural crops such as vegetables and some cut flowers have a short growing period, and may benefit from the current understanding of biochar application in agricultural cropping systems. Spreading biochar on the soil surface is a risky operation because biochar is light, easily blown away and losses can be high.[101] Wetting biochar before application has reduced dust in several research trials in Australia (L Van Zwieten pers. comm. 2011). Ideally, biochar should be incorporated to at least 10-15cm depth. Incorporation machinery used in field trials has included rotary hoes and power harrows; these mixed the biochar into the topsoil to ensure maximum soil-biochar contact and to enable even access by plant roots over time. Almost all pot and field trials have evaluated incorporated biochar.

Another application method, subsurface banding, has been successfully used to deliver biochar to the wheat root zone in a sandy soil in Western Australia.[22] A subsurface strip 50 or 100mm wide was placed at 50-150 mm depth by a modified pneumatic seeding machine. This type of incorporation was required due to high wind erosion and a goal of precision placement in the root zone.

There are no published studies comparing different application methods in the field. As most research has focused on incorporated biochar, there may be different effects on soil properties with surface-applied biochar. One study that compared the effects of incorporated and surface-applied biochar on soil chemistry in PVC columns found that soil pH and ammonium leachate increased with surface application but not incorporation.107 There was, however, no difference in levels of major nutrients in soil treated with incorporated and surface-applied biochar.

Opportunities for biochar use

Broad scale application and incorporation of biochar before planting is suitable for some horticultural crops, especially species with large root zones. It is also ideal for other row crops such as soybean and corn. For enterprises that have moved towards permanent beds or raised beds, biochar could be incorporated during bed formation. Incorporating biochar in bands/rows before planting may be another alternative. This method concentrates biochar in a particular area (e.g. future root zone) and may be a method to reduce costs. Equipment would have to be sourced or modified to deliver biochar to the required areas.

Biochar application in perennial crops

There has been very little research on biochar in perennial systems. In some established orchards trenching has delivered biochar to the root zone of established plants. Soil near shrubs and trees was removed from around each tree[78] or in radial strips from the tree trunk.[102] The trench was filled with biochar and either incorporated into the soil surface with surrounding soil or covered with soil. In Vietnam a circular trench was dug around each cashew tree inside the tree's circular flood irrigation bund.[78]

A biochar text[21] describes combining biochar with other usual orchard inputs such as compost, fertiliser and manures. In this way, biochars have been applied to orchards using current machinery, e.g. side delivery spreaders and spinning discs. This mixture approach could reduce the dust hazard of biochar spreading while not requiring any new equipment. Biochar has also been applied into each planting hole in bananas.[141]

A few longer term studies have detected that biochar has moved down the soil profile over time but have also acknowledged that biochar was lost via surface runoff and erosion.[104,125,130] Research is needed to address the fate of biochar in horticultural production systems, especially in those that include tillage.

Opportunities for biochar use

When establishing new orchards, biochar could be applied and incorporated by several methods. These include surface spreading and incorporating biochar over the entire area; applying it in bands in the crop row and incorporating before planting; and adding to planting holes.

In established orchards, especially those with large trees, extensive biochar incorporation may not be an option due to potential root damage, so banding and coring may be more appropriate. Cores can be removed around trees and filled with biochar or, preferably, a biochar-soil mixture to increase biochar-soil contact. At this stage, depth and volume recommendations are unknown, but would be related to root distribution and canopy size. Biochar could also be surface applied in the tree row and then covered with mulch material for protection, but it would take time, water and animal action for biochar to reach the soil layers and be active in the root zone. This may not provide the benefits seen in trials using incorporated biochar. Biochar-compost mixtures could be applied easily to the surface of orchard rows using current compost-spreading machinery.

A mechanised lawn aerator with hollow tynes could inject biochar into orchard soils to deliver the biochar to the roots of the plants and maximise biochar/soil interactions. Ideally the soil would then be covered with mulch to protect the soil surface. Such machinery is used on golf courses, lawns and racetracks to deliver sand to aerated turf to improve soil structure (see Figure 5.3).

FIGURE 5.3: Sand injected into cores in golf course turf.
Photo: Tim Miller www.dryject.com.au

Current horticultural biochar field trials in Australia

FIGURE 5.4: Application of biochar to an apple orchard trial in the Huon Valley, Tasmania. Photo: Justin Direen

FIGURE 5.5: Four cores around each macadamia tree received a total of 11.3 kg of biochar and were refilled with soil. Photo: Craig Maddox

FIGURE 5.6: Biochar applied in a band next to newly planted coffee trees. Photo: Josh Rust

Apple orchard, Tasmania

A replicated field trial funded by Horticulture Australia Limited was established by the University of Tasmania and the Tasmanian Institute of Agriculture in November 2009 in a new planting of Fuji apple trees established on a replant site in the Huon Valley, Tasmania (Figure 5.4). The trial is investigating the effects of biochar and compost on soil physical and chemical properties, soil functioning, tree growth and fruit quality. Biochar, compost and a combination of biochar plus compost are being compared with an untreated control. Parameters studied include tree growth measurements as well as changes in soil physical and chemical properties and in soil fauna, and fruit yield and quality. Data collected during the first two years of the project indicate that biochar is beneficial in reducing soil compaction and improving tree growth.

Macadamia orchard, Alstonville NSW

NSW Department of Primary Industries has established a small trial to investigate biochar cores in an established macadamia orchard at Alstonville (Figure 5.5). Soil from four cores (300mm diameter, 500mm depth) around each macadamia tree was removed and biochar added to the base of each hole. The remaining soil was used to refill the core space.

Coffee plantation, northern NSW

A current trial (established in 2008) undertaken by NSW DPI and Richmond Landcare has banded two contrasting biochars on the soil surface next to young coffee trees (Figure 5.6), spread the biochar across the row, and then covered it with woodchip mulch (Figure 5.7). Coffee trees started producing in 2012 and yield measurements are currently being undertaken.

FIGURE 5.7: Woodchip mulch protects the biochar from wind and water erosion. Photo: Josh Rust

Vegetable rotation trial, Gatton Qld

In November 2011 the University of Queensland established a biochar trial to compare green waste and sugar cane trash biochar, created with different technologies, which also included compost and compost+biochar treatments. At UQ Gatton a tomato crop (*Lycopersicon esculentu*m Mill. cv. Rebel) was grown for four months and the trial terminated in early March 2012 (Figure 5.8).

Blueberry orchard, northern NSW

In October 2011 the University of Queensland and NSW DPI established a biochar and compost trial funded by Horticulture Australia in a commercial blueberry orchard. A trench was created down the middle of each newly created mound with a hoe, biochar applied and then incorporated into the top 10cm manually with a hoe (Figure 5.9), creating a flat wide mounded soil surface. Plants were then established on the mounds and covered with woodchip mulch. The trial is comparing green waste and sugar cane trash biochar, compost, and biochar + compost combination.

Macadamia trial, northern NSW

In a NSW DPI/Richmond Landcare trial on a new commercial orchard block, two contrasting biochars were applied to a 3m diameter zone before planting. The biochars were incorporated to 10cm depth with a hand held rotary hoe (Figure 5.10). A planting hole was created with a machine driven screw auger, each tree was inserted and the soil was repacked into the hole (Figure 5.11).

FIGURE 5.8: Mature fruits harvested weekly for five weeks and fruit from each plot were collected and analysed separately. Shown is the third harvest. Photo: Jitka Kochanek

FIGURE 5.9: Incorporating biochar into blueberry mound soil (top 10cm) by hoe. Photo: Justine Cox

FIGURE 5.10: Hand-driven rotary hoe for biochar incorporation. Photo: Josh Rust

FIGURE 5.11: Macadamia tree planted in biochar-soil mix. Photo: Josh Rust

Application in other industries

Turf

Turf suppliers have the option of incorporating or banding biochar at establishment or during the growing season. Surface application of biochar to established turf, such as with a lime, manure or sand spreader may be possible due to its penetration into a protective thatch,[102] but losses may occur through wind and/or water erosion, and losses would occur with product removal, so regular re-application would be necessary.

Nursery and soil-less media

While there are only few studies focussing on potting mix or soilless media systems, biochar may be a viable component, given appropriate attention to the potential risks of each biochar (for example high CEC). A study of biochar-peat combinations found that the optimal proportion for a container mix was 75% peat and 25% biochar pellets.[52] The biochar portion was half biochar and half finely ground pinewood compressed into pellets 4.8 mm in diameter. Starch binders were also included to maintain pellet integrity. The best combination improved water movement, retained the desired air filled porosity, offset peat shrinkage, increased the carbon:nitrogen ratio and decreased CEC.[52]

Another nursery study highlighted Canadian experiments to assess biochar created from coir, wheat straw and wood shavings for growing greenhouse cucumbers hydroponically.[115] There is great potential for biochar to be a component of growing media due to its many positive observed benefits, including disease suppression, increased nitrogen use efficiency, and improved water holding capacity.

FIGURE 5.12: A biochar trial assessing pasture growth by NSW DPI. These application techniques could be adapted for the turf industry. Photo Josh Rust

The few studies using plant growth media in greenhouses have demonstrated enhanced yield, increased plant growth-promoting microbes due to citrus wood biochar addition,[64] and significant disease suppression with both citrus wood and greenhouse plant waste biochar.[69] These two studies both measured induced systemic resistance (or an immune response) after biochar addition, against fungal pathogens and also mites. As the range of pathogens acted via different pathways, this stimulation of a general defence mechanism to reduce many diseases and insect predation is very valuable. These responses may be biochar specific however. Both studies found increased effectiveness to suppress disease infestation at 3% biochar application rate but not at the 1% rate.

Biochar as an inoculant carrier

There is a possibility that biochar could be added to or replace peat and other carriers of microorganisms in the future. There is mixed evidence of success in trials using biochar-like substances with both *Rhizobia* and mycorrhizal fungi inoculations. Some studies have shown superior inoculation success with biochar compared with peat and other carriers, while others show the reverse.[94] Experiments over 20 years in Japan have yielded success for both *Rhizobia* and mycorrhizae inoculation together with biochar, with the results only recently becoming accessible in English.[146]

Future application options

It is possible that biochar may be further modified to improve its application to soil. Several scenarios can be envisaged, depending on need and costs. One scenario has biochar combined with compost and added to soil. Several studies in Australia have been established to evaluate this combination. Biochar could be added to other moist soil amendments to reduce its dustiness, and could be added during the composting process, which could influence many chemical and biological processes[21] and consequently the quality of the composts. Biochar could be pelletised to improve handling, although one trial with pellets has shown a yield decline.[60] The economics of pelletising will determine whether this is an acceptable product. There are currently thousands of tonnes of biochar being pelletised or granulated together with either NPK fertilisers or composts in China (Stephen Joseph, pers. comm. 2012). It may be possible to slurry biochar with water or liquid manure if subsurface injection is considered an appropriate method.

Research gaps

The authors continue to urge caution in the use of biochar as a soil amendment and emphasise the need for a scientific approach to evaluate potential benefits. While the literature on biochar has expanded significantly in the last few years, there are still many knowledge gaps that need to be filled before a sustainable, economically viable and agronomically reliable biochar industry is established. Table 5.1 summarises some of the gaps in knowledge identified in recent biochar literature that would be relevant to horticultural industries.

TABLE 5.1: Biochar research gaps relevant to horticultural industries

Gap in knowledge	Details	Reference
Properties of biochar resulting from production conditions	Properties of biochar are related to production conditions/feedstock, and a sound understanding of this relationship is still lacking.	Kookana et al. 2011[87]
	There is no comprehensive study that addresses the issues of potential contaminants in biochar.	Kookana et al. 2011[87]
	Determination of 'net environmental benefits' from different production systems is lacking.	Waters et al. 2011[161]
Optimisation of biochar properties for the purpose of soil amendment	Further work is needed to determine the optimal properties of biochar, in relation to pyrolysis conditions and feedstock, as a soil amendment.	Kookana et al. 2011[87]
	Knowledge gaps exist in the understanding of nutrient retention and interactions with soil constituents such as native organic matter and minerals in a range of soil type, vegetation systems and climatic conditions.	Waters et al. 2011[161]
	Further work on potential ecotoxicological impacts of biochar on plants, microorganisms, earthworms etc, as general indicators of soil health is required.	Kookana et al. 2011[87]
	Little is known about the impacts of biochar on quality of produce.	Kookana et al. 2011[87]
	More research is required on the potential benefits of biochar in reducing emissions of greenhouse gases such as nitrous oxide from soil.	Waters et al. 2011[161]
	Further studies on impacts of biochar on N dynamics in soils are warranted.	Clough et al. 2010[35]
Impacts of changing properties of biochar in soil (ageing and organo-mineral interactions)	Most studies on biochar have been short term and did not consider the aspect of biochar ageing. This is particularly relevant for consequences for pesticide efficacy, nutrient availability, native organic matter stabilisation, and chemical and microbiological interactions.	Kookana et al. 2011[87], Waters et al. 2011[161]
	There is a need for an elucidation of mechanisms, differentiated by environmental and management factors, and studies over longer time frames, particularly on effects of soil tillage/cultivation on carbon turnover in biochar-amended soils.	Jeffrey et al. 2011[74]
	A standard method for determining CEC of biochars needs to be developed.	Singh et al. 2010[134]
	Efficacy of some soil applied pesticides (herbicides, insecticides) may be compromised in the presence of biochars in soils. It is important to establish how these effects are going to change with ageing of biochars in soils.	Kookana 2011[87]
Agro-climatic zones and potential benefits	Most reported studies are limited to subtropical regions. Other regions encompassing a range of soil types and environmental conditions need to be studied.	Jeffrey et al. 2011[74]
Biochar and biological processes	No studies have examined the impact of biochar on mycorrhizal fungal assemblages, and not just abundance.	Warnock et al. 2007[160]
	Both culture-based and molecular tools (e.g. PCR) will be required to assess the impact of biochars on microbes.	Ennis et al. 2011[56]
	Biochar research needs manipulative experiments that unambiguously identify the interactions between biochar and soil biota.	Lehmann et al. 2011[94]
	There is an identified gap in knowledge of impacts of biochar on biological N_2 fixation at field scale.	Rondon et al. 2007[129]
	There is a paucity of published data on the effects of biochar on soil-borne pathogens.	Downie et al. 2012[51]

Research gaps for Australian horticulture

There are many research gaps in this new and emerging industry, but there are some critical questions to be asked about biochar for Australian horticulture. As most global trials have been established under annual production systems, there needs to be attention paid to perennial systems, where shrubs and trees are grown in permanent rows. There are likely to be differences in potential application methods, rates used, and length of time considered for benefits to be realised.

There is a need for trials to evaluate different mechanised application methods (especially important for perennial orchards). Methods must be devised to deliver biochar into the soil without damaging surface roots.

Some semi-permanent row crops may also need an alternative to broad scale application. A range of viable options should be trialled to compare incorporation and surface application, banding, coring and co-delivery with other amendments.

There is a great need to further evaluate the water holding effects of biochar in different soil types. Improvements in water retention and release will be critical in rain-limited systems and also for increased water use efficiency in irrigated systems.

There is a need to clarify the relationship of biochar with fertilisers, especially nitrogen and phosphorus. Trials are required to compare different biochar types with and without fertilisers using a range of crop types.

A potential goal may be to distinguish the best biochar for different crops, while also assessing whether less fertilisers can be used with no impact on yields. A related question would ask does reduced nitrogenous fertilisers lead to a reduction in nitrous oxide emissions?

There is a gap in our knowledge encompassing the potential disease-suppressive actions of biochars. Trials to evaluate the level of diseases suppression for a range of biochar types, diseases and crops are a research priority.

Research into biochar use in potting medium and soilless media is warranted due to the range of potential benefits to plant growth. The best biochar types for this industry should be determined by screening different biochar feedstocks, with different properties.

As biochar is an emerging soil amendment, potential risks need to be considered. Examples of risk studies include bioassays, effects on soil biota, losses due to erosion and long term fate of applied biochar.

It is important that biochar research addresses soil or growing system constraints and contributes to the understanding of biochar action by answering relevant, specific questions. Applying biochar to just measure the effects, is no longer an adequate line of enquiry.

It is critical that long term experiments are established to evaluate the processes that occur on a longer time scale than the current 1–3 year project average. Do the effects of biochar change over time, and how long do they influence the soil and crop?

If biochar emerges as a Carbon Farming Initiative (CFI) approved methodology, then research into quantifying the additional soil carbon is vital for this industry to gain credits.

Chapter Six • Profitability of biochar in horticulture

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Key messages

1. The adoption of biochar for use in horticulture will depend on the extent to which reliable increases in crop yield can be achieved. Currently, there is a high level of uncertainty.
2. To fully assess the profitability and the economic value of biochar in horticulture, a greater understanding of biochar impacts on soil carbon sequestration and crop productivity is required over the shorter and longer terms.
3. Potential reductions in applied nitrogen fertiliser costs are likely to only have a minor effect on the Net Present Value of crop production using applied biochar.
4. More information about nutrient availability from biochars is needed before the interaction between biochar use, fertiliser inputs and crop yields can be evaluated.
5. The high upfront cost of biochar may be a deterrent to the adoption of biochar.
6. At current prices for carbon, the value of carbon offsets to primary producers may not be a significant incentive alone for biochar application in horticulture.

Interest in the agricultural application of biochar has stemmed from the potential positive effects on crop productivity, soil health and climate change mitigation. This chapter examines the financial returns to farmers from the application of biochar. Central to the analysis is:

- the capacity of horticultural industries to offset the cost of biochar and its application
- the extent of any productivity improvement associated with biochar
- the potential value of any carbon offsets.

An example based on the vegetable industry is used to examine the likely financial implications of biochar use, as well as the reliability of estimates used in the analysis. The estimates that were used reflect current understandings with respect to the relationship between biochar and crop production, but there are many gaps in this knowledge. As such the analysis undertaken is an indication of the potential profitability of biochar as a soil amendment. A series of assumptions are made with respect to the conditions under which biochar is used as well as the extent of change to crop productivity. These assumptions will change as knowledge in this area improves.

Two types of benefits are likely to be associated with the application of biochar to agricultural land:

- crop productivity improvements primarily through improved microbial activity and soil physical and chemical benefits, including more efficient nutrient use or increased soil moisture holding capacity
- emissions avoidance by substituting biochar for synthetic fertilisers and/or lime.

The potential for carbon sequestration benefits from biochar production and for emission avoidance (point 2 above) means biochar may also have financial value as a carbon offset if its use becomes an approved carbon sequestration method. To demonstrate the additional value for farmers should carbon markets become available for this product, a price for carbon offsets has been included in the analysis.

When biochar is intended for agricultural purposes, attributes such as structural characteristics (i.e. surface area and porosity) and interaction with soil nutrients[139] become more relevant. There is some evidence to suggest that biochars with greatest potential for improving crop productivity may have characteristics which make them less effective as a means for removing carbon dioxide from the atmosphere over long timeframes.[139] Understanding the different attributes of biochar products will be vital if the expected benefits from its production (i.e. long term carbon storage) and/or its use in agriculture (crop productivity) are to be realised.

FIGURE 6.1: Rice hull biochar placed underneath woodchip mulch in a coffee trial, northern NSW. Photo: Josh Rust

From a crop productivity perspective, much more needs to be understood about the fertiliser properties of biochar in terms of both nutrient content and nutrient availability over time, and under different site conditions (soil types, climatic zone etc). There may also be interactions between biochar applications and the soil's emission of non-carbon dioxide greenhouse gas emissions.[139] However, there is little information available to define this interaction and so it has not been included in the analysis.

Main assumptions

Potential for crop yield increases and more efficient input use are the main rationales underlying interest in agricultural land as a storage environment for biochar.[51] There is some evidence that yields may increase under particular site conditions and types of biochar, although greater substantiation of this evidence is required, particularly given that some trials have also identified the potential for yield reductions (discussed in Chapter 5). Biochar is thought to attract and hold nutrients, with some suggestion that this may reduce fertiliser costs because nutrients are retained in the soil rather than leached or lost through volatilisation (see Chapter 4). There also appears to be some consensus that biochar has positive effects on soil pH where soils are acidic in nature. However, the amounts needed to achieve an effect in terms of increasing soil pH may make it financially unfeasible for biochar to be applied for this purpose alone.[58]

Given the lack of information available about biochar interactions in horticulture, the following assumptions have been made for the purpose of the financial analysis in this chapter.

1. The biochar assessed is made from manure and produced at low temperatures. The evidence suggests that low temperature biochars may have better attributes for soil health and plant growth and may be less likely to interfere with the efficacy of chemical use for weed, pest and disease control.[139]
2. The soils are sandy loam and slightly acidic.
3. The biochar is assumed to be spread by machine and incorporated into the soil through tillage activities which would have been undertaken as part of usual land preparation.
4. Soil-incorporated chemicals for weed and disease control are assumed not to be affected by the presence of biochar in soils.

Greater confidence in the premise that biochar can be used in agricultural systems with beneficial effects will come from improvements in understanding the relationship between biochar, soils and crop production. From the information that is available to date it is clear that biochar used in agricultural systems will require particular characteristics advantageous to crop plant growth and fertiliser substitution if there is to be any financial benefit for farmers from its application.

Vegetable farm case study

The financial impact of biochar is examined using a vegetable rotation of tomatoes and fresh corn and a discounted cashflow analysis over a 12 year period. As the science remains unclear on precisely how biochar application may affect crop production, a range of variables are tested to demonstrate the potential range of possible financial impacts. The analysis is based on the best estimates of NSW DPI horticulturalists and soil scientists with experience in biochar trials. These estimates will change as knowledge develops. Due to the large number of variables (e.g. biochar feedstock and processing, application rate, soil type, climate, crop) influencing the performance of a biochar product, this analysis is only an indication of the potential financial impacts of biochar application.

The vegetable rotation is assumed to be four years: tomatoes; tomatoes; fresh corn and fallow. The 12 year period of the study reflects three rotation cycles. In field trials, positive yield effects have been observed for some crops on certain soils up to six years following the application of biochar (van Zwieten, pers. comm. 2012). Impacts beyond year six are unknown.

Analysis method

Gross margins were prepared for year 1 and year 2 tomatoes, year 3 corn and year 4 fallow (which is based upon green manure crop of oats with low inputs).

A comparison is made between a baseline scenario where no biochar is applied and a set of scenarios based on biochar application at 10 tonnes per ha with differing estimated effects on crop yields, fertiliser use and lime applications.

A discount rate of 6 per cent is used to calculate the Net Present Value of the flow of benefits and costs over the 12 year period. Sensitivity testing of the discount rate is undertaken at 10 per cent.

Biochar price

The price of biochar used in this analysis is not based on the cost of production. There are two reasons for this. First, there are no large scale biochar production facilities in Australia. Second, biochar is expected to be produced as a co-product to bioenergy production. If the pyrolysis system can generate more energy than it uses, that energy may be sold. Where this can be done cost-effectively, pyrolysis for energy production alone may be viable, with biochar essentially a co-product of the process. With respect to pyrolysis as a means of renewable energy generation, an ABARES review[139] reported that it is not yet clear whether a pyrolysis system producing biochar for agriculture will be energy self-sufficient. Biochar produced from a pyrolysis plant with syngas as the major output may have high ash and low carbon content, and may not be suitable as a soil amendment for agricultural land.

The financial viability of pyrolysis systems for producing biochar to enhance crop production and soil health is not within the scope of this study. However, if the value of the energy product (i.e. electricity) produced is sufficient to offset production costs (including cost and operation of the facility, feedstock and transport costs), the value of biochar is then likely to more closely reflect the value of nutrients contained in the product. It is on this basis that the biochar price in the study has been calculated. It should be noted that if large amounts of nutrient are tied up for long periods, the plant available nutrient value of biochar would be a more relevant basis for pricing the product. For the purposes of this report, the biochar price only reflects total estimated nutrient content and does not take into account nutrient availability to plants.

While there are no large scale production facilities, niche biochar producers do exist. These biochar products appear to be specifically targeting attributes to make a product primarily suited to agriculture. These products are currently marketed around $2,000 per tonne of biochar.[41] To reflect that some biochar production may not be a co-product of energy generation, a value of $2,000 per tonne is used in one scenario.

Value of biochar nutrients

The nutrient value of three different biochars was assessed on the basis of their nutrient compositions (Table 6.1).

TABLE 6.1: Nutrient composition of alternative biochar products[152]

Feedstock	Poultry litter Agrichar ™	Greenwaste Agrichar ™	Papermill Agrichar™
N (%)	2.2%	0.25%	0.44%
P (%)	2.4%	0.049%	0.11%
K (%)	2.1%	0.0072%	0.047%
$CaCO_3$ (%)	14.0%	0.9%	7.5%
Total C (%)	**35.0%**	**66%**	**37%**

FIGURE 6.2: A biochar and compost trial in Gatton Qld, collected over 1.5 tonnes of tomato fruit in total (including unripe fruit, analysed separately) in February 2012. Photo: Chris George

In Table 6.2, the dollar value of key nutrients is based on the cheapest available source of each nutrient. These values are then applied to the nutrient composition of three biochar products shown in Table 6.1. Based on current fertiliser prices the nutrient value of the biochar products is estimated to range from approximately $170 per tonne to $6 per tonne. As would be expected these values will fluctuate according to the market price of fertilisers as well as the nutrient composition and plant availability of nutrients for different biochar products (see Table 4.1, for potential ranges).

TABLE 6.2: Estimated nutrient value of biochar products based on nutrient composition

Nutrient	Nutrient source	Percentage of nutrient (%)	Product price for nutrient source * ($/t)	Value of nutrient component ($/t)	Poultry litter Agrichar ™ ($)	Greenwaste Agrichar ™ ($)	Papermill Agrichar ™ ($)
N	Urea	46%	600	1304	$28.70	$3.26	$5.74
P	Single super	8.8%	375	4261	$102.27	$2.09	$4.69
K	Muriate of potash	50%	817	1634	$34.31	$0.12	$0.77
$CaCO_3$	Agricultural lime	100%	34	34	$4.76	$0.31	$2.55
Estimated value $AU/tonne biochar					**$170.04**	**$5.77**	**$13.74**

* Product prices based on current prices from agricultural input suppliers.
Source: Authors' estimates.

A limitation of this approach is that there is very little documented evidence about plant availability of nutrients in biochar products. For example, the plant availability of nitrogen is thought to be low, despite the nitrogen content of some biochars being high.[4] Should less nutrient be available than indicated in Table 6.1, the nutrient value of biochar will be less than estimated in Table 6.2. The asssment of biochar undertaken is based on biochar produced from a manure feedstock. Reflecting this, a price of $170 per tonne is used for biochar (see Table 6.2).

Reduction in fertiliser costs

The reduction in fertiliser costs used in this analysis is based on a 50 per cent reduction in applied nitrogen fertilisers, with other fertilisers unchanged. The fertiliser inputs used in the gross margin budgets for tomatoes and corn are shown in Table 6.3. These application rates and current fertiliser prices were used to calculate the percentage reduction in total fertiliser costs associated with a 50 per cent reduction in applied nitrogen fertiliser. Due to the uncertainty associated with the potential for biochar to replace applied nutrients, one scenario is also based on no change in fertiliser input costs.

TABLE 6.3: Assumed reduction in nitrogen fertiliser use

Tomatoes - current practice (Baseline)	Input price per unit	Fertiliser application rates (per ha)		Input cost per ha	
		Current Practice	With applied biochar	Current practice	With applied biochar
Starter fertiliser e.g. Single super	$0.38	24 kg per ha	12 kg per ha	$9.00	$4.50
Starter fertiliser e.g. Starterfos MAP	$0.54	46 kg per ha	46 kg per ha	$24.61	$24.61
Side dressing fertiliser e.g. Big N	$0.77	1200 kg per ha	600 kg per ha	$921.60	$460.80
Total fertiliser cost ($/ha) based on a 50 per cent reduction in N fert applications with biochar				$955.21	$489.91
Reduction in total fertiliser costs ($/ha)					**49%**

Fresh corn - current practice	Input price per unit	Fertiliser application rates (per ha)		Input cost per ha	
		Current practice	With applied biochar	Current practice	With applied biochar
Urea	$0.60	200 kg per ha	100 kg per ha	$120.00	$60.00
Sulphate of potash	$0.82	100 kg per ha	100 kg per ha	$81.70	$81.70
Starter fertiliser e.g. Starterfos MAP	$0.54	200 kg per ha	200 kg per ha	$107.00	$107.00
Foliar fertiliser e.g. Liquid Zinc	$8.18	2 L per ha	2 L per ha	$16.36	$16.36
Side dressing fertiliser e.g. urea	$0.60	180 kg per ha	90 kg per ha	$108.00	$54.00
Total fertiliser cost ($/ha) based on a 50 per cent reduction in N fert applications with biochar				$433.06	$319.06
Reduction in total fertiliser costs ($/ha)					**26%**

Source: Authors' estimates based on current fertiliser prices and application rates.

Gross margin budgets

Gross margin budgets for the baseline scenario of no biochar application are shown in Table 6.4. The gross margin budgets are relevant to the crop rotation assumed for the analysis (i.e. tomatoes – 1; tomatoes – 2; sweet corn; fallow (oats). Budget items assumed to change with biochar application are marked by the green shading.

TABLE 6.4: Gross margin budgets (per ha)

	Tomatoes (Year 1)	Tomatoes (Year 2)	Sweet corn	Fallow
Yield (t/ha)	5,000	4,500^	2,150	0
Price ($ per carton*)	$13.50	$13.50	$11.00	0
Total income	**$67,500**	**$60,750**	**$23,650**	**0**
Variable costs ($ per ha)				
Seed / transplants	2,671	2,671	324	77
Fertiliser	960	960	440	
Pest control	743	846	417	
Weed control	57	57	77	8
Irrigation	470	470	626	
Land preparation+	949	833		56
Casual labour	6,852	6,852	2,778	
Harvesting	6,795	6,195	1,260	
Marketing & freight	21,025	19,682	6,333	
Total variable costs	**40,522**	**38,565**	**12,256**	**141**
Gross margin ($ per ha)	**26,978**	**22,185**	**11,394**	**-141**

* Carton size for tomatoes is 10 kg and for corn 16.5kg.

+ Includes plastic mulch. Beds formed are retained for three years. For fallow, this includes cost of incorporating oats.

^ A 10 per cent reduction in yields is factored for the Year 2 tomato crop to account for disease and pest build up (M.Hickey, pers.comm. April, 2012).

Other costs

Other costs are also incurred in this rotation although not on an annual basis. Lime applications are assumed to take place at a rate of 1 tonne per ha every three years. With the application of biochar, it is assumed that the first lime application is no longer needed. Subsequent applications of lime continue then every four years.

With the application of biochar, spreading and transport costs are also incurred. These are included in the analysis with the cost of biochar, as a one off cost in year 0 of the analysis.

Other costs also include the cost of replacing irrigation drippers every fourth year of the crop rotation following the fallow period.

Other data and assumptions

The values used for the other parameters within the analysis are shown in Table 6.5. The potential range in these values as presented in other published studies is shown in Appendix A. Note that in the assessment a manure-based biochar is assumed to be used.

TABLE 6.5: Parameter values used

Parameter estimates	Value
Tonnes of CO_2 (per tonne of biochar)	2
CO_2 Offset price ($ per tonne of CO2-e)	Year 0 $23
Biochar($ per tonne)	$170
Lime price ($ per tonne)	$34
Biochar application rate (tonnes per ha)	10
Biochar transport costs (approx 80km)*	$28/tonne
Lime transport costs (approx 80km)	$14/tonne
Biochar spreading costs ($ per tonne)	$25
Lime spreading costs ($ per tonne)	$16
Yield change	(see Table 6.4 and 6.6)
Fertiliser costs	50% reduction in nitrogen fertilisers
Discount rate (%)	6%
Time period (years)	12 (based on three crop rotations)
Lime application rates (t/ha)	1 (T. Napier, pers. comm. 2012)
Lime applications without biochar	3 over 12 years
Lime applications with biochar	2 over 12 years (L.van Zwieten, pers. comm. 2012)

Transport costs associated with bulk biochar products are not known. The costs will depend on the product's dry matter content and overall bulk density. Low bulk density is associated with increased costs for transportation. To gain the estimate for transport costs used in this study, a comparison of the bulk density between lime and charcoal (powder) was used. Information on bulk densities was obtained from the site http://www.powderhandling.com.au/bulk-density-chart. For this analysis, transport costs have been assumed at twice the cost of lime transport, reflecting the bulk density of lime being approximately twice that of charcoal (powder). To the extent that biochar products could be pelletised, the product's bulk density would increase and this would reduce transport costs.

Biochar scenarios

Reflecting the uncertainty of how biochar will affect crop growth and soil health given current knowledge, five scenarios are considered for changes in key variables.

Scenario A – moderate yield increase

Yields gradually increase at a moderate rate of 2 per cent until Year 6, at which point yields stabilise (at plus 10 per cent) then decline by 2 per cent per year, to Year 11.

Scenario B – larger yield increase

A larger immediate yield increase of 10 per cent for Years 0 to 5 and 5 per cent for Years 6 to 11.

Scenario C – decline in fertiliser costs

Total fertiliser costs for tomatoes and corn are assumed to decline by 50 per cent and 25 per cent respectively, based on calculations in Table 6.3.

Scenario D – moderate yield increase + decline in fertiliser costs

Gradual yield increase as per Scenario A and with a decline in total fertiliser costs for tomatoes and corn of 50 per cent and 25 per cent respectively.

Scenario E – carbon offsets recognised

No yield or fertiliser benefit but with 2 tonnes of CO_2 per tonne of biochar applied recognised by carbon markets.

Scenario F – Scenario D with high biochar price

As per Scenario D but with a biochar price of $2000 per tonne (i.e. estimated cost of production when biochar is not a byproduct of energy generation).

TABLE 6.6: Net Present Value (NPV) scenarios

Key parameters	Baseline	Scenarios with biochar applied					
		A	B	C	D	E	F
Carbon price ($/t carbon)		23	23	23	23	23	23
Tonnes (t carbon/t biochar)		0.0	0.0	0.0	0.0	2	0.0
Cost of biochar ($/t)		170	170	170	170	170	2000
Application rate (t/ha)		10	10	10	10	10	10
Transport & spreading costs ($/t)		53	53	53	53	53	53

Yield (cartons per ha)	Units per ha	Percentage change to baseline					
Year 0 - Tomatoes	5,000	0.00	0.10	0.00	0.00	0.00	0.00
Year 1 - Tomatoes	5,000	0.02	0.10	0.00	0.02	0.00	0.02
Year 2 - Corn	2,150	0.04	0.10	0.00	0.04	0.00	0.04
Year 3 - Fallow	0	0.06	0.10	0.00	0.06	0.00	0.06
Year 4 - Tomatoes	5,000	0.08	0.10	0.00	0.08	0.00	0.08
Year 5 - Tomatoes	5,000	0.10	0.10	0.00	0.10	0.00	0.10
Year 6 - Corn	2,150	0.10	0.05	0.00	0.10	0.00	0.10
Year 7 - Fallow	0	0.08	0.05	0.00	0.08	0.00	0.08
Year 8 - Tomatoes	5,000	0.06	0.05	0.00	0.06	0.00	0.06
Year 9 - Tomatoes	5,000	0.04	0.05	0.00	0.04	0.00	0.04
Year 10 - Corn	2,150	0.02	0.05	0.00	0.02	0.00	0.02
Year 11 - Fallow	0	0.02	0.05	0.00	0.02	0.00	0.02

Fertiliser ($ per ha)	Units per ha	Percentage change to baseline					
Year 0 - Tomatoes	952	0.00	0.00	0.50	0.50	0.00	0.50
Year 1 - Tomatoes	960	0.00	0.00	0.50	0.50	0.00	0.50
Year 2 - Corn	433	0.00	0.00	0.25	0.25	0.00	0.25
Year 3 - Fallow	0	0.00	0.00	0.00	0.00	0.00	0.00
Year 4 - Tomatoes	952	0.00	0.00	0.50	0.50	0.00	0.50
Year 5 - Tomatoes	960	0.00	0.00	0.50	0.50	0.00	0.50
Year 6 - Corn	433	0.00	0.00	0.25	0.25	0.00	0.25
Year 7 - Fallow	0	0.00	0.00	0.00	0.00	0.00	0.00
Year 8 - Tomatoes	952	0.00	0.00	0.50	0.50	0.00	0.50
Year 9 - Tomatoes	960	0.00	0.00	0.50	0.50	0.00	0.50
Year 10 - Corn	433	0.00	0.00	0.25	0.25	0.00	0.25
Year 11 - Fallow	0	0.00	0.00	0.00	0.00	0.00	0.00

* The green shaded cells indicate the parameters that have changed for the 'with biochar' scenarios relative to Scenario A.

Discussion

In Table 6.7 the results of the NPV analysis are shown for the six scenarios. The flow of benefits and costs over time for each scenario are provided in Appendix B. It is important to reiterate that the results are only indications of profitability based on current knowledge and best estimates of the impact of biochar applications on crop production and input costs. As more reliable estimates become available, the analysis will need to be updated, and as such, profitability estimates would be expected to change.

TABLE 6.7: NPV results by scenario

	NPV ($)	% Change to baseline
Baseline - no biochar	139,978	
Scenario A	153,798	9.9%
Scenario B	169,194	20.9%
Scenario C	140,302	0.2%
Scenario D	156,282	11.6%
Scenario E	138,278	-1.2%
Scenario F	137,982	-1.4%

NPV with yield changes

While the analysis is indicative only, the results highlight that reliable increases in yield will be needed over time if the application of biochar is to benefit farmers financially.

Scenario A: Compared with the baseline of no biochar application, assuming moderate incremental increases in yield until Year 5 followed by a gradual decrease in yield, the NPV of biochar use increased from $139,978 to $153,798, a 9.9 per cent increase.

Scenario B: With an increase in yield of 10 per cent for year 0 to 5 and 5 per cent for years 6 to 11, the NPV increased by 20.9 per cent compared to the baseline.

NPV with fertiliser reduction

The potential for biochar applications to reduce chemical fertiliser input costs contributed only to a minor increase in NPV compared to the no biochar baseline.

Scenario C: Fertiliser costs represented less than 4 per cent of the total crop gross margin for tomatoes and sweet corn. Consequently, reductions in fertiliser costs only gave rise to small changes in the NPV for applied biochar of around 0.2 per cent. The NPV of biochar with a 50 per cent reduction in nitrogen fertiliser inputs (equivalent to a reduction of 25 per cent of total fertiliser costs for corn and 50 per cent reduction for tomatoes), was estimated at $140,302 compared to $139,978 for the no biochar baseline. The value of any potential fertiliser input reductions associated with biochar would rise with increases in the market price of fertiliser inputs.

NPV with yield increase and fertiliser reduction

Scenario D: In this scenario the combined effect of biochar applications increasing yield and reducing fertiliser inputs is shown. Based on the moderate yield increases from Scenario A, the NPV from biochar application increased by 11.6 per cent compared to the no biochar baseline.

NPV with carbon credits

Scenario E: In this scenario, it is assumed that carbon credits from the application of biochar are recognised by carbon markets. The current carbon price of $23 per tonne of CO_2-e was used and credits were based upon 2 tonnes of CO_2 per tonne of biochar applied. With application rates of 10 tonnes per ha, the value of carbon credits did not offset the cost of application and NPV declined by 1.2 per cent compared to the baseline of no biochar. This scenario highlights that at current carbon prices, the value of carbon offsets from biochar application alone may not be a significant incentive for biochar application in horticulture. Demonstrated increases in yield will be critical if biochar application is to be financially beneficial for farmers.

NPV with high biochar price (plus yield and fertiliser benefits)

Scenario F: In this scenario the moderate yield increase and fertiliser reduction benefits of Scenario D are replicated. The scenario examined the financial implications of a significantly higher biochar price of $2,000 per tonne. Even with the full yield and fertiliser benefits, rates of $2,000 per tonne would make the farmer worse off financially. NPV declined by 1.4 per cent compared to the no biochar baseline, under these conditions. Confidence in the product's ability to generate improvements in crop yields over the full 12 year period would need to be high before producers would engage in biochar application at this price. The profitability of biochar is driven mainly by the extent to which improvements in crop yield can offset the cost of biochar.

Conclusions

Much is still to be understood about the relationship between crop production, input use and biochar applications under different site conditions and over time. Future research into the potential biochar benefits of soil carbon sequestration and crop productivity is needed before the profitability and the economic value of biochar can be assessed. More reliable estimates for the timeframe over which crop productivity benefits can be expected would also improve the reliability of financial analysis, as would information about nutrient availability for plant growth.

The adoption of biochar for use in horticulture will depend upon the extent to which increases in crop yield can reliably be achieved. At this stage there is little evidence as to the effect of biochar on the yield of horticultural crops or with respect to the changes in yield expected using different biochar types or for the range of key soil types and climatic conditions pertinent to horticultural production. Consequently, the financial benefits of biochar applications to horticultural producers are associated with high levels of uncertainty.

The upfront cost of biochar application is high (estimated at $1530 per ha in this study). While any benefits from the application may persist over several years (in this study 12 years was assumed), this high upfront cost may be a deterrent to the use of biochar on agricultural land. Whether the product could be applied annually at lower rates may be a consideration to lessening the upfront cost. This would affect crop yield response.

Any potential for biochar application to reduce applied nitrogen fertiliser cost is likely to have only a minor effect on the Net Present Value of crop production. In the vegetables example used, this minor effect reflects the small proportion of fertiliser costs as a percentage of the total gross margin for the crops selected.

At current prices for carbon, the value of carbon offsets to primary producers may not be a significant incentive alone for biochar application to proceed in horticulture.

At this stage, any assessment of the financial implications of biochar on particular crops and soils remains indicative of profitability only and should not be used as the basis for deciding whether or not biochar should be used by a horticultural enterprise. The financial analysis can be used to provide insights into key pieces of information which need to be understood before more reliable estimates of the profitability of biochar applications can be prepared. This could be used to help guide further areas of work to improve the reliability of the parameter estimates used in both financial and economic analysis.

Chapter Seven • Biochar in Australia

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Key messages

1. Biochar is one of the eligible activities under the Australian Government's Carbon Farming Initiative.
2. Development of a methodology to enable reliable measurement of stable carbon in biochar is underway but will take time, so use of biochar as a carbon offset is still some way off.
3. State and local governments are interested in biochar as a waste management option.
4. There is strong scientific interest in biochar with several research projects and trials underway in Australia.
5. Biochar guidelines are needed to increase confidence in and use of biochar in Australian agriculture.

Australian scientists have been investigating biochar since 2004, with field trials established from 2006 (Van Zwieten pers. comm.). The Australian Government has provided funding from 2007 for research into the use of biochar in soils as a tool for mitigating greenhouse gas emissions. The Government has also included biochar as an eligible activity to earn carbon credits under the CFI, and commissioned a review of biochar's productivity potential.[139]

State and local government policies are also encouraging interest in biochar. Biochar production may help manage municipal waste and produce income through energy production and a saleable soil ameliorant. Tightening regulations for soil application of composts, biosolids and poultry litter to minimise health and environmental contamination risks make biochar a potential alternative because pyrolysis destroys microbial pathogens.[51]

Carbon Farming Initiative

The Carbon Farming Initiative (CFI) is a government-initiated carbon offsets scheme that enables farmers and land managers to earn carbon credits by storing carbon or reducing greenhouse gas emissions on their land (Figure 7.1). These credits (Australian Carbon Credit Units) can then be sold to people and businesses wishing to offset the emissions they produce.[48]

Application of biochar to soils has been placed on the Carbon Farming Initiative Positive List, which identifies activities that are eligible to earn credits because they are deemed to go beyond common practice in the relevant industry or environment. Application of biochar to soils is listed because it is not a common practice in Australia.

Biochar's long term carbon stability is attracting the interest of farmers who want to earn carbon credits through its use, but CFI-eligible activities need an approved methodology before projects can commence. The methodology must specify the procedure for calculating abatement, and be approved by the Domestic Offsets Integrity Committee to ensure accurate assessment of emissions reductions or sequestration before credits can be traded. At the time of writing there was no methodology for biochar, and development of an approved methodology is likely to take some time.

Some activities, including reforestation and reduction in livestock emissions, count towards Australia's emissions target under the Kyoto Protocol. These so-called 'Kyoto activities' (Figure 7.1) generate credits that can be used to offset emissions of a business with a liability under the Clean Energy Act 2011. A second group of activities that reduce emissions or sequester carbon, but are not counted by Australia towards its Kyoto Protocol target, are known as 'non-Kyoto activities'. Credits generated through these activities can be sold on the voluntary market, and may be purchased by the Australian government through the $250 million Non-Kyoto Carbon Fund.

The Australian Government's $250 million CFI non-Kyoto Carbon Fund will be operational from July 2013 to purchase non-Kyoto ACCUs via competitive tender. The price the Australian Government will pay for non-Kyoto ACCUs will be no higher than the price of Kyoto ACCUs which is currently $23/tCO$_2$-e, rising at 2.5 per cent per year until 2014–15 when the price will be determined by the market. It is likely that the price for non-Kyoto ACCUs will be lower than the price for Kyoto-compliant activities.

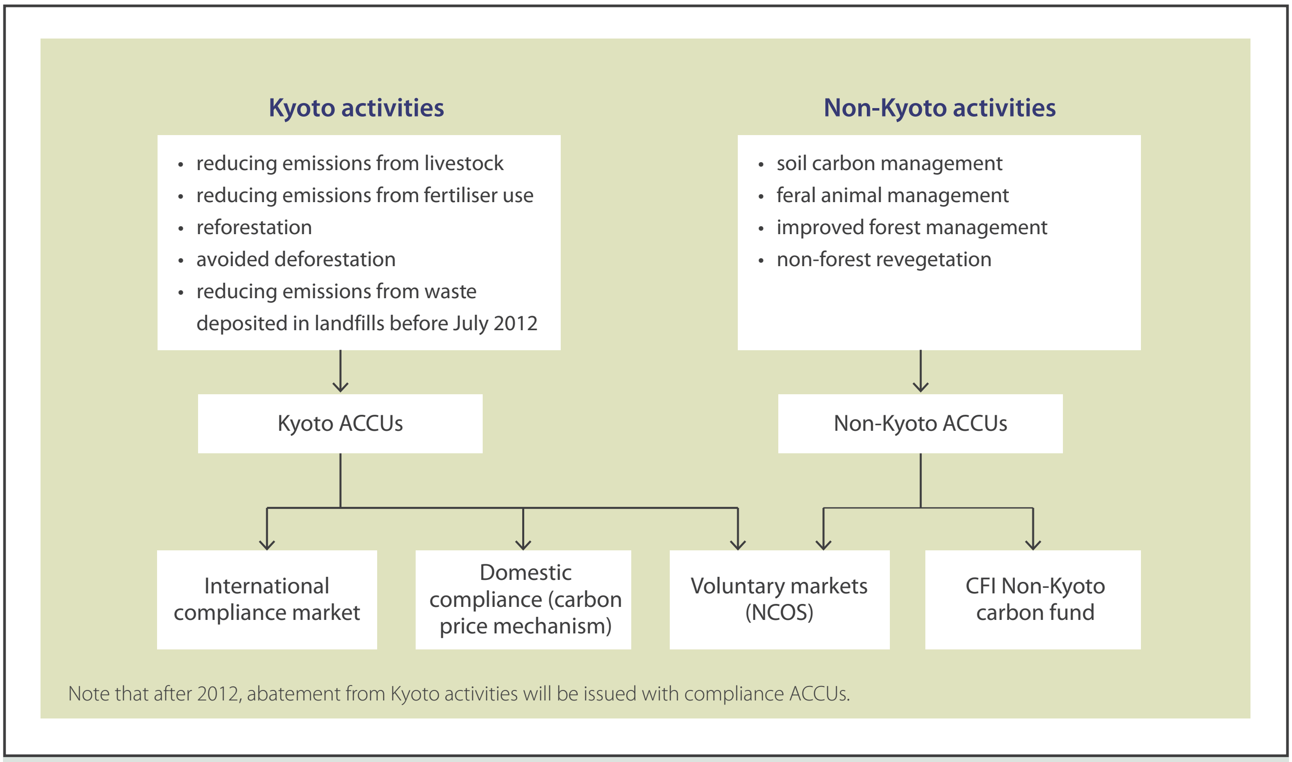

FIGURE 7.1: Carbon Farming Initiative activities, carbon credits and markets.[48]

The CFI requires that carbon sequestration projects retain the carbon sequestered for 100 years. This 'permanence' provision is a major challenge for reforestation and soil carbon management projects, in which the sequestered carbon is vulnerable to loss, such as from fire in the case of reforestation, or drought in the case of soil carbon. Biochar is less vulnerable to loss due to its biological and chemical stability.

More details about the CFI and how it operates can be found in the Carbon Farming Initiative handbook.[48]

Scientific research

In Australia several research projects are underway to develop knowledge on the effects of biochar application on carbon sequestration, greenhouse gas emissions and agricultural productivity, to enable confident predictions about biochar's suitability for use in Australian soils and agriculture.

FIGURE 7.2: PVC tube greenhouse gas chamber inserted into the soil to monitor greenhouse gases. Photo: Josh Rust

National Biochar Initiative 2009-2012

In 2009 the Australia Government provided $1.4 million funding for the National Biochar Initiative under its Climate Change Research Program (2008-2012). Led by CSIRO,[40] this initiative worked with scientific organisations around Australia to:

- categorise biochars according to their properties and suggested usage, including impacts on soil carbon sequestration
- assess the economics of biochar use for both net greenhouse gas emissions and potential profitability to land owners
- undertake a life cycle assessment of biochar from feedstock source to production to substitute applications, including costs, risks, benefits and implications for farmers
- analyse risk factors in terms of rates of applications as well as the potential production of toxic by-products during pyrolysis.

The final report for this project is due in late 2012.

Biochar Capacity Building Program 2012-14

This $2 million program[42] builds on the National Biochar Initiative, and has funded projects to:

- develop a simple methodology to predict the stable carbon content of biochar from common feedstock types
- develop and establish new demonstration sites to demonstrate the applicability of biochar in a broad range of agricultural and land management situations and examine biochar stabilisation processes and effects
- establish willow tree biochar field sites and trials
- demonstrate the potential of biochar and biochar/compost blends to increase soil carbon in native woody bioenergy crops
- use native reed biochar to filter polluting river drains loaded with acid or nutrients and then apply the biochar to local dairy and cropping soils.

Grains Research and Development Corporation biochar project 2009-2012

GRDC provided funds to researchers from CSIRO and the University of Western Australia to evaluate the potential of different biochars to positively affect grain crop productivity and to optimise fertiliser use through the combination of biochar application and conventional fertilisers. Outputs will include:

- a comprehensive datasheet on chemical, physical and biological properties of biochars produced from different feedstocks and under different conditions
- a report on the effects of biochar on grain crop response as a function of soil type, fertiliser application and biochar type and application
- a report on the interactions between biochars and the microbial community
- a web-calculator to assess the effect of biochar on grain crop productivity.

The final report from this project is due in late 2012.[88]

Horticulture Australia Limited biochar projects

Several horticultural industries are interested in investigating the effects of biochar and carbon ameliorants on their crops, including apple and pear, blueberry, vegetables, and nursery and garden. Horticulture Australia Limited has funded this review and is currently funding three studies assessing biochar/green manures:

- Carbon and sustainability – A demonstration on vegetable properties across Australia
- A scoping study on biochar and pyrolysis gas production
- Novel, sustainable and profitable horticultural management systems – soil amendments and carbon sequestration.

Richmond Landcare Inc. biochar projects

Richmond Landcare in conjunction with NSW DPI has managed two Caring for our Country projects and a National Landcare project investigating biochar's usefulness in addressing acidity, soil organic carbon decline and productivity. The projects currently manage 350 field plots that are testing effects of contrasting biochars (feedstock and process temperature) in macadamia, coffee, soybean, sugarcane and mixed cropping. These trials are on three key soil types in the northern rivers region of NSW (Van Zwieten, pers.comm 2012).

Other projects

Biochar has attracted research interest around Australia, and projects are underway in universities and agricultural industries around the country. Many projects are in their infancy and have yet to publish results; some are listed on the projects page of the Australia and New Zealand Biochar Researchers Network.[5]

FIGURE 7.3: Biochar trial assessing Fuji apple response. Photo: Sally Bound

FIGURE 7.4: Maintaining biochar trial plots at two months after sowing tomatoes. Photo: Jitka Kochanek

For example, Griffith University and University of the Sunshine Coast, Queensland have a new project funded through the Collaborative Research Network, to assess the effects of (possibly macadamia shell) biochar on soil properties, tree growth and nut quality in the Sunshine Coast region macadamia orchards.

Standards and guidelines

ABARES' 2011 review[139] concluded that given the heterogeneous nature of biochar, the cost of production and the limited pyrolysis facilities, national policy and industry guidelines on biochar production, quality and use could help increase confidence in the use of biochar in Australian agriculture. A classification system for biochar products is essential to ensure targeted biochar production for application to specific soil types.[139]

The ABARES review also recommends that Australian biochar standards be developed on an environmental sustainability analysis, including life cycle assessment, to indicate the overall impact of biochar use in agricultural situations. This information can then be used to develop standards and regulations that can promote beneficial use of biochar, prevent pollution and soil contamination, and integrate its benefits into an accredited emissions trading scheme.

International guidelines for biochar use in soil

In May 2012 the International Biochar Initiative launched its *'Standardised product definition and product testing guidelines for biochar that is used in soil',*[71] developed in consultation with scientists and industries around the world, including Australian biochar researchers, and freely available on the internet. The intention of the 47 page guidelines is to establish testing and measurement methods for selected biochar properties and labelling guidelines for biochar materials, so that consumers have credible information about biochar quality and properties. The guidelines relate to the physicochemical properties of biochar only, and do not prescribe production methods or specific feedstocks. Nor do they provide limits or terms for defining the sustainability and/or GHG mitigation potential of a biochar material. The guidelines are science-based, voluntary, and able to be used by any local, national or regional body to develop standards, certification, or regulatory processes to advance the commercialisation of biochar.

Feedstock guidelines

As biochar can be produced from any biomass feedstock, guidelines are needed to ensure that biochar is produced sustainably. Some biochar experts[90] 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 sourcing and use for biochar production.[139]

Pyrolysis guidelines

Pyrolysis of biomass creates gas and/or liquid products as well as biochar. There is concern that on-farm pyrolysis systems with limited gas handling technology and limited health and safety management systems may result in injury and release toxic gases as outlined in Chapter 3. Biochar produced on-farm may have properties unsuitable for either carbon sequestration or soil amelioration, and may contain toxic substances. For this reason, production parameters and quality control standards need to be developed and implemented.[139]

Conclusion

Australian scientists have been investigating the use of biochar in agricultural soils since 2004, supported by Australian Government funding since 2007 to investigate biochar's potential in agricultural systems. While biochar has been listed as an eligible activity for carbon offsets in the Australian Government's Carbon Farming Initiative, a methodology has yet to be developed to ensure accurate assessment of biochar's net emissions reduction. Development of national guidelines and standards for the production and use of biochar is also needed to ensure that the production process complies with State and Federal emissions guidelines, worker health and safety, and soil amendment guidelines. Horticultural producers are advised to stay in touch with developments in biochar research and policy through their industries, state agricultural agencies, and the Department of Climate Change and Energy Efficiency's Carbon Farming Initiative website: www.climatechange.gov.au/cfi

Chapter Eight • Frequently asked questions about biochar

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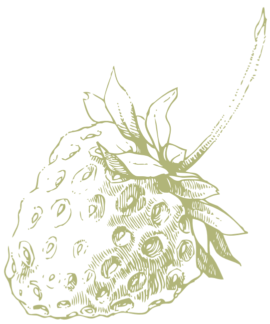

1. What are carbon amendments and how do they improve my soil?

Carbon is one of the fundamental building blocks of soil health. While carbon does not provide direct plant nutrition, it is closely linked with the cycling and availability of plant nutrients, native soil organic matter and the functioning of the soil system which is why carbon ameliorants are so vital to plant production systems involving soil.

Carbon amendments are products added to the soil to increase soil carbon. They include living and non-living plant residues incorporated into the soil, manures, composts and microbes. Biochar, char, and charcoal are stable forms of carbon now being used as soil amendments in horticulture to improve soil fertility. Conversion of plant biomass such as wood to biochar stores carbon that otherwise would have been emitted as CO_2 when the biomass decomposed.

Amendments have other soil benefits besides contributing carbon. Animal manures add nutrients such as nitrogen and phosphorus which play a direct role in plant growth. Lime is commonly used to raise pH levels in acidic soils, making nutrients more available to the plant and therefore indirectly benefits plant growth.

FIGURE 8.1: Coffee plantation owner/manager helping to establish a biochar trial on his property. Photo: Lukas Van Zwieten

2. What are the benefits of biochar?

Studies have suggested that addition of biochar to soils can have many and varied effects. The most dramatic effect is the increase in soil carbon. Under normal circumstances, soil carbon will only increase relatively slowly, usually as a result of applying organic matter such as compost or animal manure. Biochar is a highly stable form of carbon, usually containing 20-70% carbon depending on feedstock and the production system. When added to soils it will increase the stable organic carbon levels in the soil.

Other potential benefits of biochar include enhanced seed germination and plant growth, stabilisation and increase of native soil organic carbon, enhanced nutrient availability and liming effect, increased microbial biomass, and increased root biomass. However it is still early days, and further research is required to validate many of these initial findings.

It is important to note that not all biochar effects are beneficial. Highly alkaline biochars may be detrimental in alkaline or calcareous soils. Some biochars can enhance the turnover rate of native organic carbon in certain soils.

3. Can I make biochar on-farm?

Some Australian farmers are currently testing a variety of commercial and home-made technologies for producing biochar on their own farms. In most situations, biochar production on-farm has been prompted by the need to deal with organic wastes such as prunings, animal manures or forestry wastes, or the desire to obtain a cost-effective soil ameliorant to improve soil carbon and other soil properties.

Some of the simplest technologies are kilns constructed from brick, metal or concrete which produce charcoal-like materials of variable quality, along with greenhouse gas emissions and toxic gases. There are very high risks involved in making biochar on-farm, and these risks must be addressed before contemplating on-farm production of biochar to ensure human health and safety (see Chapter 3). Improved technologies pyrolyse biomass at specific temperatures with minimal emissions and maximum energy efficiency to produce biochar with consistent characteristics. The economics of the different technology scales still need to be assessed. However the industry is moving towards fully automated certified machines which pyrolyse only recommended feedstocks to ensure optimum safety to the operator and quality of the end product.

4. What feedstocks can be used to make biochars?

Feedstock has a major influence on biochar quality and chemical characteristics. Biochars made from animal manure will have more nitrogen, potassium and phosphorous than biochar made from a carbon-rich woody material, although not all of the elements present would necessarily be readily available to plants. Farm feedstocks will largely be determined by the type of farm enterprise, and can include tree prunings, animal manures, hay, and processing by-products such as rice hulls, and nut husks and shells. Forestry prunings, woody weed species and green waste from packing sheds are also possible sources. Wood biochar has lower total plant nutrient content, higher total carbon and lower ash content than manure-based biochars. Feedstock moisture content is also important to consider, because biomass with a high moisture percentage such as vegetable matter requires more energy to convert to biochar than drier biomass such as woodchips. Using small woodchips for feedstock will give a finer grade biochar then larger blocks of wood, but firing at higher temperatures (>500°C) will result in smaller particle size regardless of the size of feedstock, as the biochar becomes brittle and easily fractured.

By weight, biochar is cheaper to transport than feedstock, so locating the kiln or reactor close to the source of the feedstock may be important to keep costs down.

5. What is the best way to incorporate biochar in an orchard?

When establishing an orchard, biochar can be spread over the entire planting area and incorporated, although this may not be economical. A cheaper option is to apply it in a band along the planting line on flat or mounded soil, and incorporate it into the soil before planting. If not incorporated, it is vulnerable to wind and water erosion. Another application option is to incorporate biochar in the planting hole where it will be located in the root zone during the early years of orchard establishment.

In an established orchard, the objective is to deliver biochar to the roots of plants to maximise biochar-soil interactions. This can be done using narrow soil strips parallel to the tree row, or radiating out from the trunk soil strips, or coring. Other options are:

- Apply the biochar on the surface of each strip and cover with mulch.
- Apply the biochar on the surface of each strip and incorporate into the soil.
- Dig trenches along each strip, apply the biochar and refill the trenches (not an option for large trees because of the potential for root damage)
- Core soil around the tree and backfill the holes with biochar or biochar-soil mix.

The depth and volume of soil to be removed under each tree will depend on root distribution and canopy size, and researchers have yet to develop recommendations for this. Existing machinery may need to be adapted for best results.

6. How much does biochar cost?

In mid 2012, biochar was not being produced commercially for large scale agricultural applications in Australia, and therefore a price per tonne of biochar had not been determined. Some commercial biochar products, often mixed with composts or manures, are being marketed to the home gardener at a cost that is still prohibitive for broadacre use. Once commercial plants are established it is likely the market will determine the price based on demand and the capacity for the biochar production units to meet that demand.

The eventual price for biochar will be determined according to a number of factors:

- cost of feedstock collection
- cost of feedstock transport to pyrolysis production unit
- cost of establishment and running of the pyrolysis production unit
- level of revenue generated from co-production outputs used for energy generation such as syngas and biofuel.

At a farm level, the cost of transporting the biochar to the farm, and then spreading it would need to be considered in addition to the cost of purchasing the product. On-farm biochar production would reduce the overall cost, but the labour to produce it would need to be factored in, and the resultant quality of the biochar could be more variable than a product made in a commercial pyrolysis unit. It could also have adverse environmental implications.

Whatever the eventual price for biochar, it needs to be weighed up against the benefits of using biochar on your farm. Those benefits could include:

- increased crop yield
- increased resilience of the crop through better soil health and improved water use efficiency
- improved fertiliser use efficiency due to biochar, resulting in decreased inputs and costs of fertiliser
- additional revenue streams from carbon sequestration in biochar (only if eligible for the Carbon Farming Initiative)
- increased revenue through the production of carbon emission reductions from renewable energy.

See Chapter 6 for more discussion on economic costs and benefits.

FIGURE 8.2: Greenwaste biochar applied at 30 t/ha to mounded soil and incorporated to 10cm depth for blueberry production. Photo: Justine Cox

7. What is the minimum amount of biochar I need per hectare to have a benefit?

Biochar application rates will vary according to nutrient content, presence of other materials such as compost, soil type and crop. Many studies report application rates of 10 tonne/ha, and at these relatively high levels some biochars may contribute significant amounts of nutrients to the soil. In one study, poultry litter biochar produced at 550°C contained 2.4% phosphorus, and when applied at 10 tonnes/ha was equivalent to adding 240kgs of phosphorus to the soil. In contrast, biochar produced from a low nutrient feedstock such as wood would contain much lower nutrient levels.

8. Do I have to keep adding biochar?

The amount of biochar required will vary depending on soil type, crop type and climatic conditions, but generally higher rates may be required under intensively cropped and cultivated situations such as annual vegetable production, compared with permanent pasture or tree crops. A warm moist environment encourages rapid growth and decomposition of organic matter, resulting in rapid carbon cycling. In a cold dry climate growth and decomposition are much slower, which slows the carbon cycle and keeps carbon in soils for much longer. In horticultural soils where irrigation is common, carbon cycling tends to be quicker than dryland systems such as cereal cropping, so organic matter needs to be added to the system more frequently. Only 5-15% of organic matter added to the soil becomes stable soil organic carbon; the remainder, mainly labile carbon, is released back into the atmosphere as carbon dioxide. One of biochar's important properties is its stability and longevity in the soil compared to other sources of carbon. However the relative longevity of different biochars has not been researched extensively, and is therefore difficult to quantify.

9. Will biochar help reduce inputs of fertilisers, composts or manures?

Biochar can contribute nutrients if it comes from a high nutrient feedstock, although nutrient availability is initially low. It can also improve fertiliser use efficiency, reducing costs and improving nutrient release and thereby encouraging soil microbial activity. Some biochars can enhance the cation exchange capacity of some soils, which will increase the availability and retention of plant nutrients, improve fertiliser efficiency, reduce the effects of leaching and volatilisation, and possibly reduce the amount of fertiliser needed. Adding biochar to composts or manures before spreading may lead to more uniform distribution of the biochar, and these organic amendments can provide additional nutrients, particularly for low nutrient biochars. There is some evidence that biochar products with the greatest potential to increase crop productivity, such as poultry manure biochars may be less effective at supplying stable carbon and therefore of less value in carbon sequestration terms.

See Chapter 5 for more detail.

10. In a nutshell, what are the three main reasons for improving levels of soil organic carbon?

1. Maintenance of a healthy soil through increasing the stable carbon fraction of the soil, which in turn will potentially improve factors such as soil microbial function, soil water holding capacity, improved soil pH and suppression of soil borne diseases.
2. Reduction of production system inputs such as fertilisers.
3. Potential for generation of income through carbon sequestration under the Carbon Farming Initiative (CFI).

Glossary

Activated charcoal
Charcoal that has been heated or otherwise treated to increase its adsorptive power.

Anion exchange capacity (AEC)
Measure of the soil's ability to retain negatively charged ions (e.g. Cl^- NO_3^-) through electrostatic forces.

Agrichar
Global brand name and US registered trademark for biochar produced from BEST Energies proprietary slow pyrolysis process.

Ammonia (NH_3)
Water soluble compound of nitrogen and hydrogen.

ANZBRN
Australian and New Zealand Biochar Researchers' Network

Aromaticity
A property of chemicals that describes structural stability. Biochar has a high degree of fused carbon rings that make it chemically and biologically more stable than the biomass carbon from which it was made.

Ash
The inorganic matter or mineral residue that remains when an item is burned or pyrolysed.

Australian Carbon Credit Unit (ACCU)
A credit issued for emissions reduced or removed, usually one tonne of CO_2e.

Biochar
Biochar: A solid material obtained from thermochemical conversion of biomass in an oxygen-limited environment (see Definition of biochar, page vii).

Biochar characteristics
Physical and chemical properties of biochar resulting from type of feedstock and pyrolysis conditions, including temperature, activation and residence time.

Biomass
Material that contains carbon compounds originated from living organisms.

Bio oil
Low viscosity, dark-brown fluid with up to 15 to 20% water, produced by pyrolysis. Also known as pyrolytic oil.

Biorefinery
Facility that processes biomass to produce multiple products (e.g. biochar, energy, bio oil, lignin).

Biosolids
Solid matter recovered from waste water treatment.

Bioturbation
Mixing of soils by living organisms.

Black carbon
Any solid carbonised material found in the soil.

C
Chemical symbol for carbon

Calorific value
Heat produced by the combustion of a unit weight of a fuel.

Carbon
A widely distributed element which can be organic or inorganic.

Carbon credit
Generic term for any credit given in return for reduction or removal of a given quantity of greenhouse gas emissions.

Carbon cycle
See Soil carbon cycle

Carbon dioxide (CO_2)
The principal anthropogenic greenhouse gas that affects the earth's temperature, produced by human, animal and microbial respiration, burning fuels and chemical oxidation of carbonate rocks.

Carbon dioxide equivalent (CO_2e)
The measure used to compare emissions of different greenhouse gases based on their global warming potential (on an equivalent CO_2 level). It is obtained by multiplying the mass and the global warming potential of the gas. For example, the global warming potential for methane over 100 years is 21, i.e. one tonne of methane is equivalent to 21 tonnes of carbon dioxide.

Carbon Farming Initiative (CFI)
Australian legislation that allows farmers and land managers to earn carbon credits by storing carbon or reducing greenhouse gas emissions on their land. These credits can then be sold to businesses wishing to offset their emissions.

Carbon footprint
A measure of direct and indirect CO_2e emissions attributable to an activity or lifestyle.

Carbonisation
Thermal conversion of biomass to char.

Carbon price
The price of the carbon dioxide or equivalent. From 1 July 2012 emitters pay a fixed price of $23 per tonne, before moving to an emissions trading scheme in 2015 where the price will be determined by the market.

Carbon offset
See Carbon credit.

Carbon sequestration
Capture and long-term storage of carbon dioxide. Potential storage options include soil, forests, vegetation, and underground geological formations.

Carbon sink
Anything that absorbs more carbon from the atmosphere than it releases (e.g. growing forest).

Carbon tax
A tax on greenhouse gas emissions. See Carbon price.

Carbon trading
Process by which organisations can buy and sell emissions permits depending on whether their emissions are higher or lower than their permitted emissions.

Cation exchange capacity (CEC)
Measure of the soil's ability to retain positively charged ions (e.g. Ca^{++}, K^{+}) through electrostatic forces. Regarded as an important measure of soil fertility because many soil nutrients are cations.

Char
Solid material that remains after light gases and tar have been released by fire from carbonaceous material.

Charcoal
Porous black solid obtained when biomass is heated in an oxygen-limited environment.

CFI
Carbon Farming Initiative

CO_2
Chemical symbol for carbon dioxide.

CO_2e
Carbon dioxide equivalent.

Compost
Biologically decomposed organic matter. Australian Standard AS4454 (2012) for composts, soil conditioners and mulches defines composts for Australian use.

Contaminant
An undesirable material in feedstock that compromises the quality or usefulness of a soil ameliorant.

EC
Electrical conductivity is a measure of the soil's ability to conduct an electrical current, and is used as a measure of soil salinity.

Feedstock
Biomass that is utilised to produce biochar.

Fulvic acid
Outdated term which was used to describe a type of organic acid derived from chemical fractionation of humus with alkaline and acid compounds in the laboratory, and which cannot be replicated outside the laboratory. More advanced technologies have improved understanding of soil organic matter chemistry.

Gasification
Process that heats organic or fossil based carbonaceous material at high temperatures without combustion, with a controlled amount of oxygen and/or steam to produce a mixture of carbon monoxide, hydrogen and carbon dioxide known as syngas (synthetic gas), and a small amount of biochar.

Global warming potential (GWP)
Index describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to that of carbon dioxide over a given period of time. For example, methane (CH_4) has a GWP of 21 which means it has 21 times the amount of heating capacity of CO_2. Nitrous oxide has a GWP of 310.

Greenhouse effect
Occurs when heat provided by infrared radiation from the sun is prevented from radiating back into space by greenhouse gases in the earth's atmosphere.

Greenhouse gases (GHG)
Atmospheric gas that absorbs and emits radiation within the thermal infrared range. The primary greenhouse gases in the Earth's atmosphere are water vapour, carbon dioxide, methane, nitrous oxide and ozone.

H:Corg ratio
Atomic ratio between elemental hydrogen and organic carbon in biomass or biochar. The lower the ratio (ie the greater the level of organic carbon compared with hydrogen) the more stable the material is likely to be. The H:Corg ratio of biochar varies, with lower ratios found in biochar produced under high temperatures and/or prolonged heating.

Humate
Outdated term describing a type of humic acid.

Humic acid
Outdated term which was used to describe a type of organic acid derived from chemical fractionation of humus with alkaline and acid compounds in the laboratory, and which cannot be replicated outside the laboratory. More advanced technologies have improved understanding of soil organic matter chemistry.

Humus
Outdated term which was used to describe the dark stable substance produced by well-rotted organic matter. Now considered an out of date concept because more advanced technologies have improved understanding of soil organic matter chemistry (see Slow pool).

IBI
International Biochar Initiative

Inorganic carbon
Carbon derived from mineral sources, with no carbon-hydrogen bonds, and not normally found in living things, e.g. calcium carbonate, carbon dioxide.

Ion exchange capacity
Ability of an insoluble material to exchange ions on its surface with ions in the surrounding matrix (e.g. soil or water).

K
Chemical symbol for potassium.

Labile carbon
Short-lived soil carbon pool in which fresh residues such as plant roots and living organisms are readily decomposed within a few years. Derived from the Latin *'labi'* (to slip).

Life cycle assessment
Evaluation of the environmental impacts of a product or service from production through to use and disposal.

Lignite
Younger coal with distinct woody texture. Also known as brown coal.

Methane (CH_4)
Potent greenhouse gas (GWP = 21) emitted during decomposition of biomass from ruminant animals, landfills and compost.

Microbial biomass carbon (MBC)
Soil carbon associated with soil microorganisms, predominantly bacteria and fungi. Microbial carbon is usually between 1–4% of soil organic carbon.

Mulch
Any protective cover placed on soil to retain moisture, reduce erosion, provide nutrients, and suppress weed growth.

Municipal waste
Solid non-hazardous refuse from all residential, industrial, commercial, institutional, demolition, land clearing, and construction sources.

Mycorrhizal fungi
Colonisers of plant roots that help plants obtain additional nutrients and water from the soil.

N
Chemical symbol for nitrogen.

Nitrogen drawdown
Loss of nitrogen from the soil due to soil microorganisms using the nitrogen as an energy source when decomposing low nitrogen organic matter such as woodchips, sawdust and bark mulches.

Nitrous oxide (N_2O)
Potent greenhouse gas (GWP = 310) emitted naturally by microrganisms in soils and oceans. Agriculture is the main source of human-produced nitrous oxide because soil cultivation, nitrogen fertilisers, livestock urine and manure all stimulate N_2O producing microorganisms.

Organic carbon
Carbon-based substances that contain carbon-hydrogen bonds, found in all living things e.g. methane, sugars, cellulose carbohydrates, proteins, lipids and nucleic acids.

P
Chemical symbol for phosphorus.

Particulate matter
All airborne particles, including fly ash.

pH
Logarithmic scale measuring acidity or alkalinity of a solution. The scale ranges from 0 to 14 with 7 being neutral. Above 7 is increasingly alkaline, and below 7 is increasingly acidic.

Priming effect
Impact on existing soil organic carbon due to microbial response to a soil amendment. Negative priming effect reduces the turnover rate of existing organic carbon, causing an increase in soil organic carbon. Positive priming effect increases the turnover rate of native soil organic carbon and may decrease soil carbon levels.

Pyrolysis
Thermochemical decomposition of biomass at elevated temperatures in the absence of oxygen. It involves the simultaneous change of chemical and physical characteristics and is irreversible. The word is coined from the Greed *'pyr'* (fire), and *'lysis'* (separating).

Recalcitrant carbon
Unlikely to decompose for hundreds to thousands of years. Likely to be a significant part of charcoal and biochar.

Residence time
The time anything stays in a particular place, e.g. carbon in the soil, feedstock in a heating kiln.

Slow pool
Stable carbon compounds formed from decomposed organic matter and very slow to break down in soil (formerly known as humus).

Soil carbon
All the carbon found in the soil both from living things (organic), and nonliving (inorganic) sources such as carbonates (limestones etc). Sometimes referred to as total carbon.

Soil carbon ameliorant
A carbon-rich product that can be added to the soil.

Soil carbon cycle
The constant flow of carbon atoms between the atmosphere and soils. Plants capture carbon dioxide from the atmosphere. Plant, soil and animal respiration (including decomposition of dead biomass) returns the carbon to the atmosphere as carbon dioxide or as methane (CH_4) under anaerobic conditions.

Soil carbon fractions
See Soil organic carbon pools.

Soil organic carbon turnover
The rate at which soil organic carbon mineralises to carbon dioxide, influenced by moisture, temperature, land use and management, including biochar application.

Soil inorganic carbon
Mineral carbon in the soil such as carbonates (e.g. limestone) not associated with living plant and animal matter.

Soil organic carbon (SOC)

The measure determined by laboratory analysis of all the soil carbon from plant and animal source at all stages of decomposition. It does not include new plant and animal material as much of this readily decomposes and the carbon is released back to the atmosphere quickly as CO_2. Also known as total organic carbon (TOC) and organic carbon. Comprises around 58% soil organic matter (SOM). To convert SOC to SOM multiply SOC by 1.75.

Soil organic carbon pools

Types of carbon classified according to their stability in the soil: labile (short-lived), slow, and recalcitrant (long-lived). The labile pool includes partly decomposed biomass and microbial biomass, the slow pool includes humus and the recalcitrant pool includes natural charcoal.

Soil organic matter (SOM)

All the living matter found in the soil associated with all living things dead or alive. As well as carbon it includes other elements such as nitrogen, sulphur, and phosphorus. It includes living organisms, fresh residues, decomposition products such as humus, silica-occluded plant C (phytoliths) and inert forms of carbon such as humic substances and char. To convert SOM to SOC, divide SOM by 1.75.

Soil constraint

Limiting factors that affect soil function and productivity, such as salinity, sodicity, compaction, pH, and nutrient availability.

Soot

Nano particles of solid residue originating from incomplete combustion of tar aerosols and hydrocarbons.

Syngas

Synthetic gas produced by gasification or pyrolysis of of biomass, containing carbon monoxide, carbon dioxide, hydrogen and small amounts of higher hydrocarbons.

Torrefaction

Low temperature pyrolysis that removes moisture from biomass to improve its fuel quality for combustion and gasification applications. From the Latin *'torrere'* (parch, roast, scorch).

Wastes

Materials for which there is no further use in their current form.

Wood vinegar

Dark liquid produced when wood is burnt without oxygen during pyrolysis. Also known as pyroligneous acid.

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Appendices

Appendix A: Parameter value ranges and source

Parameter	Value	Source
Tonnes of CO_2 per tonne of biochar)	2.2 to 2.93	Collins 2008 as cited in Galinato et al. (2011)[58]
	3	Robert et al. (2010)[126]
CO_2 Offset price ($ per tonne of CO_2-e)+	Year 0 $23.00 Year 1 $24.15 Year 2 $25.40	Australian Government 2011
Low mineral content biochar price ($ per tonne)*	$100	Van Zwieten (pers. comm., 2012)
High mineral content biochar price ($ per tonne)	$300	Van Zwieten (pers. comm., 2012)
Low mineral content biochar price ($ per tonne)	$170	Authors' estimate (table 6.2)
High mineral content biochar price ($ per tonne)	$6	Authors' estimate (table 6.2)

* Commercial biochar production costs are estimated to range from $1,000 per tonne biochar to $1,500 (Farm Journal 2012). The price of biochar above is based on the nutrient value of biochar, reflecting biochar as a by-product for either electricity generation or greenwaste disposal.

Biochar application rate (tonnes per ha)	10	Hossain et al. 2010[70], Chan et al. 2008[30], Van Zwieten et al. (2009)[152]
	4-20	Chan, et al. 2008[30]
Biochar transport costs ($ per t)	24	Orr 2010[120]
Lime transport costs ($ per t)	14	Current contractor rate
Spreading costs ($ per t)	16	Current contractor rate
Biochar spreading costs ($ per t)	25	Orr 2010[120]
Lime spreading costs ($ per t)	16	Current contractor rate
Yield change(% of base yield – with fertiliser)	20%	Hossain et al. 2010[70]
Yield change (% of base yield)	10%	Jeffery et al. 2011*[74]
	No change	Roberts et al. 2010[126]
Fertiliser costs (% of base fertiliser cost)	Unclear	Collins 2008[58]
	10% reduction	M Hickey (pers comm. 2012), Knudsen 2012[61], Gaunt and Lehmann 2008[85a]
	No change	Hossain, Strezov et al. 2010[70]
Discount rate (%)	6	
Time period (years)	12	Based on three crop rotations.
	At least six years	Van Zwieten (pers. comm. 2012)
	4	Major et al. 2010[103]
	2-3	Sinclair et al. 2009[133], Islami et al. 2011[73], Jones et al. 2012[76]
One unit increase in soil pH (tonnes)	Biochar = 17 t/acre	Collins 2008[58]
	Lime = 0.54 t/acre	
	Biochar = 39 t/ha	Granatstein et al. 2009[65]
Biochar pH	4 to 12	Bagreev et al 2001[9], Lehmann 2007[92]
Lime application rates (t/ha)	1	T. Napier, (pers. comm. 2012)
without biochar (no. of applications)	3 applications over 12 years	M. Hickey, (pers. comm. 2012)
with biochar (no. of applications)	2 applications over 12 years	Van Zwieten, (pers. comm. 2012)

* A quantitative review of 16 biochar studies.

Appendix B: Cashflow of estimated benefits and costs

TABLE B.1: Baseline – no biochar applied

Year	Rotation	Expenses				Income			Cashflow
		Other costs*	Variable costs (except fert.)	Fertiliser costs	Total	Production	Carbon credits	Total	
0	Tomatoes	$83	$39,562	$952	$40,597	$67,500		$67,500	$26,903
1	Tomatoes		$37,605	$960	$38,565	$60,750		$60,750	$22,185
2	Sweetcorn		$11,816	$440	$12,256	$23,650		$23,650	$11,394
3	Fallow		$141		$141			$0	-$141
4	Tomatoes	$83	$39,562	$952	$40,597	$67,500		$67,500	$26,903
5	Tomatoes		$37,605	$960	$38,565	$60,750		$60,750	22,185
6	Sweetcorn		$11,816	$440	$12,256	$23,650		$23,650	$11,394
7	Fallow		$141		$141			$0	-$141
8	Tomatoes	$83	$39,562	$952	$40,597	$67,500		$67,500	$26,903
9	Tomatoes		$37,605	$960	$38,565	$60,750		$60,750	$22,185
10	Sweetcorn	0	$11,816	$440	12,256	$23,650		$23,650	$11,394
11	Fallow	0	$141		141			$0	-$141

NPV @: 6 per cent = $139,978; 10 per cent = $121,193. * Other costs refer to lime and biochar application costs.

TABLE B.2: Scenario A – with biochar applied

Year	Rotation	Expenses				Income			Cashflow
		Other costs*	Variable costs (except fert.)	Fertiliser costs	Total	Production	Carbon credits	Total	
0	Tomatoes	$2,249	$39,562	$952	$42,763	$67,500	$0	$67,500	$24,737
1	Tomatoes		$37,605	$960	$38,565	$61,965		$61,965	$23,400
2	Sweetcorn		$11,816	$440	$12,256	$24,596		$24,596	$12,340
3	Fallow		$141	$0	$141	$0		$0	-$141
4	Tomatoes	$83	$39,562	$952	$40,597	$72,900		$72,900	$32,303
5	Tomatoes		$37,605	$960	$38,565	$66,825		$66,825	$28,260
6	Sweetcorn		$11,816	$440	$12,256	$24,596		$24,596	$12,340
7	Fallow		$141	$0	$141	$0		$0	-$141
8	Tomatoes	$83	$39,562	$952	$40,597	$71,550		$71,550	$30,953
9	Tomatoes		$37,605	$960	$38,565	$63,180		$63,180	$24,615
10	Sweetcorn		$11,816	$440	$12,256	$24,596		$24,596	$12,340
11	Fallow		$141	$0	141	$0		$0	-$141

NPV @: 6 per cent = $153,798; 10 per cent = $132,195. * Other costs refer to lime and biochar application costs.

TABLE B.3: Scenario B – with biochar applied

Year	Rotation	Expenses				Income			Cashflow
		Other costs*	Variable costs (except fert.)	Fertiliser costs	Total	Production	Carbon credits	Total	
0	Tomatoes	$2,249	$39,562	$952	$42,763	$74,250	$0	$74,250	$31,487
1	Tomatoes		$37,605	$960	$38,565	$66,825		$66,825	$28,260
2	Sweetcorn		$11,816	$440	$12,256	$26,015		$26,015	$13,759
3	Fallow		$141	$0	$141	$0		$0	-$141
4	Tomatoes	$83	$39,562	$952	$40,597	$74,250		$74,250	$33,653
5	Tomatoes		$37,605	$960	$38,565	$66,825		$66,825	$28,260
6	Sweetcorn		$11,816	$440	$12,256	$26,015		$26,015	$13,759
7	Fallow		$141	$0	$141	$0		$0	-$141
8	Tomatoes	$83	$39,562	$952	$40,597	$70,875		$70,875	$30,728
9	Tomatoes		$37,605	$960	$38,565	$63,788		$63,788	$25,223
10	Sweetcorn		$11,816	$440	$12,256	$26,015		$26,015	$13,759
11	Fallow		$141	$0	141	$0		$0	-$141

NPV @: 6 per cent = $169,194; 10 per cent = $146,749. * Other costs refer to lime and biochar application costs.

TABLE B.4: Scenario C – with biochar applied

Year	Rotation	Expenses				Income			Cashflow
		Other costs*	Variable costs (except fert.)	Fertiliser costs	Total	Production	Carbon credits	Total	
0	Tomatoes	$2,249	$39,562	$476	$42,287	$67,500	$0	$67,500	$25,213
1	Tomatoes		$37,605	$480	$38,085	$60,750		$60,750	$22,665
2	Sweetcorn		$11,816	$330	$12,146	$23,650		$23,650	$11,504
3	Fallow		$141	$0	$141	$0		$0	-$141
4	Tomatoes	$83	$39,562	$476	$40,121	$67,500		$67,500	$27,379
5	Tomatoes		$37,605	$480	$38,085	$60,750		$60,750	$22,665
6	Sweetcorn		$11,816	$330	$12,146	$23,650		$23,650	$11,504
7	Fallow		$141	$0	$141	$0		$0	-$141
8	Tomatoes	$83	$39,562	$476	$40,121	$67,500		$67,500	$27,379
9	Tomatoes		$37,605	$480	$38,085	$60,750		$60,750	$22,665
10	Sweetcorn		$11,816	$330	$12,146	$23,650		$23,650	$11,504
11	Fallow		$141	$0	141	$0		$0	-$141

NPV @: 6 per cent = $140,302; 10 per cent = $121,187. * Other costs refer to lime and biochar application costs.

TABLE B.5: Scenario D – with biochar applied

Year	Rotation	Expenses				Income			Cashflow
		Other costs*	Variable costs (except fert.)	Fertiliser costs	Total	Production	Carbon credits	Total	
0	Tomatoes	$2,249	$39,562	$476	$42,287	$67,500	$0	$67,500	$25,213
1	Tomatoes		$37,605	$480	$38,085	$61,965		$61,965	$23,880
2	Sweetcorn		$11,816	$330	$12,146	$24,596		$24,596	$12,450
3	Fallow		$141	$0	$141	$0		$0	-$141
4	Tomatoes	$83	$39,562	$476	$40,121	$72,900		$72,900	$32,779
5	Tomatoes		$37,605	$480	$38,085	$66,825		$66,825	$28,740
6	Sweetcorn		$11,816	$330	$12,146	$24,596		$24,596	$12,450
7	Fallow		$141	$0	$141	$0		$0	-$141
8	Tomatoes	$83	$39,562	$476	$40,121	$71,550		$71,550	$31,429
9	Tomatoes		$37,605	$480	$38,085	$63,180		$63,180	$25,095
10	Sweetcorn		$11,816	$330	$12,146	$24,596		$24,596	$12,450
11	Fallow		$141	$0	141	$0		$0	-$141

NPV @: 6 per cent = $156,282; 10 per cent = $134,352. * Other costs refer to lime and biochar application costs.

TABLE B.6: Scenario E – with biochar applied

Year	Rotation	Expenses				Income			Cashflow
		Other costs*	Variable costs (except fert.)	Fertiliser costs	Total	Production	Carbon credits	Total	
0	Tomatoes	$2,249	$39,562	$952	$42,763	$67,500	$460	$67,960	$25,197
1	Tomatoes		$37,605	$960	$38,565	$60,750		$60,750	$22,185
2	Sweetcorn		$11,816	$440	$12,256	$23,650		$23,650	$11,394
3	Fallow		$141	$0	$141	$0		$0	-$141
4	Tomatoes	$83	$39,562	$952	$40,597	$67,500		$67,500	$26,903
5	Tomatoes		$37,605	$960	$38,565	$60,750		$60,750	$22,185
6	Sweetcorn		$11,816	$440	$12,256	$23,650		$23,650	$11,394
7	Fallow		$141	$0	$141	$0		$0	-$141
8	Tomatoes	$83	$39,562	$952	$40,597	$67,500		$67,500	$26,903
9	Tomatoes		$37,605	$960	$38,565	$60,750		$60,750	$22,185
10	Sweetcorn		$11,816	$440	$12,256	$23,650		$23,650	$11,394
11	Fallow		$141	$0	141	$0		$0	-$141

NPV @: 6 per cent = $138,278; 10 per cent = $119,490. * Other costs refer to lime and biochar application costs.

TABLE B.7: Scenario F – with biochar applied

Year	Rotation	Expenses				Income			Cashflow
		Other costs*	Variable costs (except fert.)	Fertiliser costs	Total	Production	Carbon credits	Total	
0	Tomatoes	$20,549	$39,562	$476	$60,587	$67,500	$0	$67,500	$6,913
1	Tomatoes		$37,605	$480	$38,085	$61,965		$61,965	$23,880
2	Sweetcorn		$11,816	$330	$12,146	$24,596		$24,596	$12,450
3	Fallow		$141	$0	$141	$0		$0	-$141
4	Tomatoes	$83	$39,562	$476	$40,121	$72,900		$72,900	$32,779
5	Tomatoes		$37,605	$480	$38,085	$66,825		$66,825	$28,740
6	Sweetcorn		$11,816	$330	$12,146	$24,596		$24,596	$12,450
7	Fallow		$141	$0	$141	$0		$0	-$141
8	Tomatoes	$83	$39,562	$476	$40,121	$71,550		$71,550	$31,429
9	Tomatoes		$37,605	$480	$38,085	$63,180		$63,180	$25,095
10	Sweetcorn		$11,816	$330	$12,146	$24,596		$24,596	$12,450
11	Fallow		$141	$0	141	$0		$0	-$141

NPV @: 6 per cent = $137,982; 10 per cent = $116,052. * Other costs refer to lime and biochar application costs.