Novel, Sustainable and Profitable Horticultural Management Systems: Soil Amendments and Carbon Sequestration

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Soil Amendments, Waste Reuse and Carbon Sequestration

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Purpose of the report: This project explored emerging versus conventional processing technologies for their efficiency and ability to convert city and farm recycled organics into usable products that enhance productivity for horticulture, with attendant benefits of improved environmental health and carbon sequestration. This study has shown that intelligent biochar design promises enhanced plant establishment, long term perennial plant success, enhanced soil quality and carbon sequestration for horticulture.

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Media Summary

This project has explored emerging (biochar from pyrolysis) versus conventional (composting) processing technologies for their efficiency and ability to convert city and farm recycled organics into usable products that enhance productivity for horticulture, with attendant benefits of improved environmental health and carbon sequestration. Uniquely, this study has used a systematic approach whereby test products were made by four commercial technologies - three pyrolysis and one composting - to align with grower and urban waste manager needs. From this study, we now know that biochar promises enhanced plant establishment, long term perennial plant success, enhanced soil quality and carbon sequestration for horticulture. However, intelligent design is needed for consistency in plant and environmental benefits; biochar should be manufactured by trained personnel who understand feedstock quality control and how pyrolysis can create biochars with characteristics for specific market needs.

Compost and biochar production is synergistic, biomass that readily decomposes is ideal for compost production, while woody feedstocks are best for biochar production. Applied together, these products promise to be a winning combination for perennial crop yield, soil quality and carbon sequestration over the long term. Plant establishment, a key for productivity and profitability, most benefited from certain biochar additions. Better seed germination, faster seedling and plant establishment and more robust seedlings and plantlets were observed with certain biochars. However, the interplay of chemical stimulants and inhibitors is likely responsible for species/crop specific plant responses to biochar during establishment. To design biochars with consistent plant promoting results, manufacturers should aim for biochars devoid of inhibitors or leach inhibitors post-pyrolysis.

Once consistent and cost-effective biochars are available, they promise to be most useful as carbon rich matrices that can be dosed with compounds for more controlled release to plants and, in soils and growing medias, provide homes for plant-promoting microbes, physical structure, improved water holding and cation exchange capacities and sequestered carbon. The *Closing the Green City Loop* project will continue to work towards biochar design to ensure consistent, cost-effective batch to batch plant and media promoting products to address needs for individual markets in horticulture.

Technical Summary

Nature of the problem: This project explored emerging (biochar from pyrolysis) versus conventional (composting) processing technologies for their efficiency and ability to convert city and farm recycled organics into usable products that enhance productivity for horticulture, with attendant benefits of improved environmental health and carbon sequestration. Uniquely, this study employed a systematic approach whereby products were made by four commercial technologies - three pyrolysis and one composting - to align with broad stakeholder needs, *viz.* growers and urban waste managers. From this study, we now know that intelligent biochar design promises enhanced plant establishment, long term perennial plant success, enhanced soil quality and carbon sequestration.

Science undertaken: Organic product preparation used one composting and three commercial pyrolysis technologies to make compost and biochars (Section 2). Biochar is a new technology, hence physical and chemical properties were quantified and related to production technologies and plant establishment outcomes (Section 3). To validate the purported agronomic and environmental benefits of organic products, long term field trials with annual vegetable versus perennial fruit crops determined the logistics and practicality of biochar and compost use and quantified in-field crop yield, soil health and carbon sequestration (Section 4). Proof-of-concept focus turned to urban horticulture because plant establishment, a key for productivity and profitability, most benefited from certain biochar additions (Section 3 and 5). The study concluded with a current versus predicted costing of pyrolysis and biochar technologies to aid in economic decisions (Section 6).

Major research findings and industry outcomes:

1) Product preparation and physical and chemical quantification:
- Compost and biochar production are ideally synergistic.
- The carbon in study biochars was highly aromatic, hence useful for sequestration.
- Fertiliser co-application with biochar is required to optimise plant growth. Potassium may be an exception and plant available K increased in soils with biochar application.
- Feedstock quality control is needed for biochar design.

2) Pyrolysis technology influenced chemical and physical properties of study biochars more than input biomass, hence each technology may meet different market needs. For example:
- Rapid thermal carbonisation may produce biochars ideal for enhancing agronomic physical, microbial and carbon sequestration soil function.
- Biochars from slow pyrolysis may be ideal as carbonaceous matrices for controlled release of compounds.

These assumptions will be validated in the *Closing the Green City Loop* project.

3) Biochar design is needed for consistency in plant and environmental quality promotion. For example, the interplay of chemical stimulants and inhibitors are likely responsible for species/crop specific plant establishment responses to

biochar; consistency can be achieved through feedstock quality control (e.g. minimal heavy metals) and by minimising inhibitors in biochars.

4) Compost and biochar, applied together, promise to be a winning combination for perennial crops. This product combination resulted in significantly greater fruit yields, soil quality and carbon sequestration in a long term commercial blueberry (*Vaccinium corymbosum* L. hybrid 'Opie') trial.

5) Urban horticulture may particularly benefit from novel biochar products:
- Plant establishment, a key for productivity and profitability, most benefited from certain biochar additions; better seed germination, faster and more robust seedling and plant establishment were observed.
- Biochar may replace or be used alongside existing amendments.
- Logistics of biochar transport, storage and use is easier than for many broad-acre applications.

6) Certain organic products significantly improved soil and growing media quality. For example, carbon, cation exchange, and water holding capacities were increased, pH buffered and bulk density improved over the short and long term.

Key study recommendations:

Biochar from pyrolysis is a new technology that promises benefits for horticulture. However, intelligent design is needed for consistency in plant and environmental promotion. For this, biochar should be manufactured by trained personnel who understand feedstock quality control and how the pyrolysis process can create biochars for specific market needs.

Intelligent biochar design promises new applications in horticulture, with biochars most useful as carbon rich matrices that:
- Can be dosed with compounds for release to plants in a more controlled manner,
- Provide homes for plant-promoting microbes,
- Provide physical structure and improved water holding and cation exchange capacities in medias,
- Can sequester carbon long-term.

Contributions to new technology and future work suggested:

The *Closing the Green City Loop* project will continue to work towards organic product design for specific market needs and to ensure consistent, cost-effective batch to batch plant and media promoting results for horticulture.

1. Introduction

Integrated organic recycling systems are emerging that protect human and ecosystem health, while conserving materials and energy. Leading the way in Australia, Brisbane City Council and regional councils in south-east Queensland are moving towards a 'Zero Waste Vision' (Brisbane City Council, 2009). Partly due to the massive financial burden of landfill as south-east Queensland's population escalates and partly due to its move to become a conserver society, city organics are now viewed as a resource to be reused as another product of value within a cradle to cradle life-cycle. Similarly, best management horticultural production systems that are productive and profitable, sustainable and adaptable while being resilient to climate change and climatic variability, but also minimise or sequester greenhouse gases, are a cross-commodity goal (Future Focus, 2008; Horticulture Australia Ltd, 2009).

This HAL and Brisbane City Council funded project has, since late 2010, explored emerging (biochar from pyrolysis) versus conventional (composting) processing technologies for their efficiency and ability to convert city and farm recycled organics into usable products that enhance productivity, with attendant benefits of carbon sequestration and improved environmental health. Importantly, the focus has been on real-world practicalities, comparing on-farm versus city-based systems. From this study, we now know that horticulture can benefit through enhanced plant establishment, long-term perennial plant success, enhanced soil quality and carbon sequestration. Stage II of this project, titled '*Closing the Green City Loop*' (2014-17), will continue to work towards organic product design for specific market needs and to ensure consistent, cost-effective batch to batch plant and media promoting results for horticulture.

Project processing technologies: Composting is a well understood technology that transforms organic matter via aerobic microbial activity into a stable end product (humus) which can be used to increase soil and plant growing media quality and carbon content (Vesilind *et al.*, 2002; Rhyner *et al.*, 1995). However, the long composting cycle and variable product quality are known bottlenecks (Tian *et al.*, 2012). Biochar from pyrolysis is an emerging technology. Organic biomass is transformed under oxygen limited or zero-oxygen high temperature conditions (pyrolysis, *c.* 350 to 700°C) into biochar; a solid, charcoal-like residue consisting of recalcitrant carbon that may be sequestered for hundreds to thousands of years (Laird, 2008; Sohi *et al.*, 2010; Ahmed *et al.*, 2012; Grierson *et al.*, 2011). The emissions balance of units can be further improved if bio-oils and gases from pyrolysis are used to generate heat and power and feedstocks (biomass inputs) are recycled organics rather than purpose-grown crops (Lehmann & Joseph, 2009).

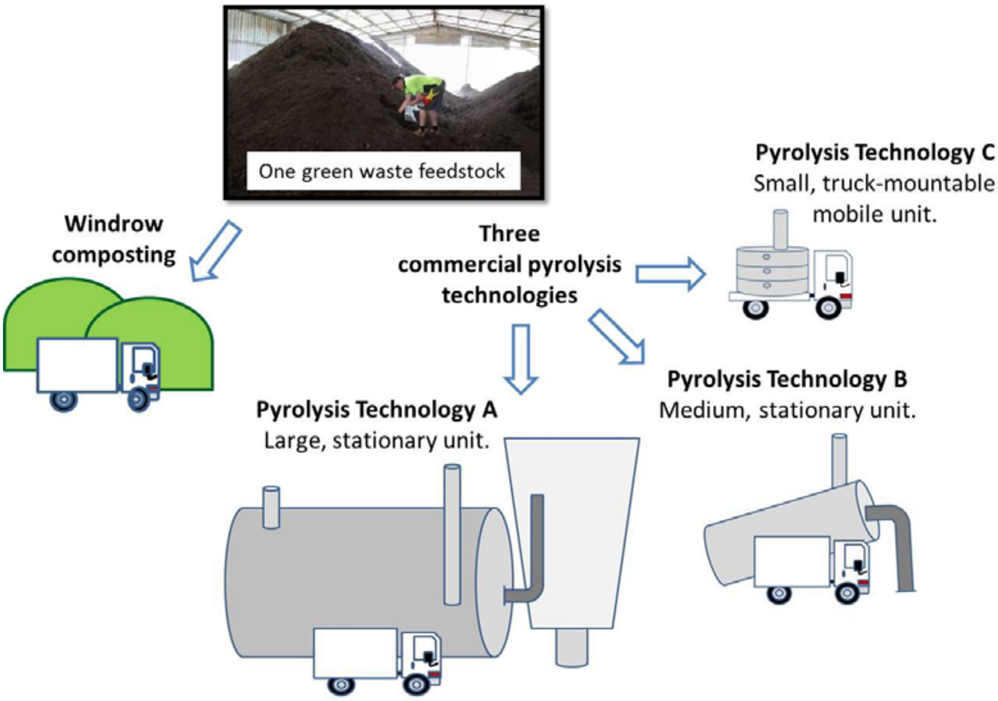
Project scope: In the literature, biochar is generally purported to enhance soil physical, chemical and biological properties and ecosystem health, often conferring plant growth and crop yield benefits. Just some reported mechanisms are enhanced water and nutrient retention, improved soil drainage, structure and pH and enhanced microbial communities (Joseph *et al.*, 2010; Sohi *et al.*, 2010; Beesley *et al.*, 2011; Elad *et al.*, 2011; Lehmann *et al.*, 2011; Jeffery *et al.*, 2011). However, biochar can vary with feedstock source and pyrolysis conditions (Laird *et al.*, 2009) resulting in plant growth that can be positive, negative or neutral (Dumroese *et al.*, 2011; Quilliam *et al.*, 2012; Brockhoff *et* *al.*, 2010). Also, the practicalities of biochar production, transport, use and application for a diverse industry such as horticulture have not been explored holistically, despite this being imperative for the development of commercial projects (Brown, 2009; Meyer *et al.*, 2011). Thus, this study employed a world-first systematic approach (Kochanek *et al.*, in prep.a) whereby test products (biochar and compost) were made by four commercial organic recycling technologies (three pyrolysis and one windrow composting, Figure 1.1), to align with broad stakeholder needs:

1) Urban waste managers: Brisbane City Council are decision makers for Australia's third largest city (population *c.* 2.1 million; Australian Government, 2013) and have a vision to reduce landfilled domestic waste from 75% in 2008 to 10% by 2026 (Brisbane City Council, 2009). Thus they are investigating emerging technologies (such as pyrolysis) to divert municipal organic waste from landfill into usable products and/or energy. The city currently composts 86 000 tonnes of green waste, but collection is projected to increase to >200 000 tonnes with new green waste recycling bins (C. Blanchard, *pers. comm.*). Hence, to process escalating volumes a large, centralised pyrolysis plant with a continuous throughput and energy production capacity would be required; Technology A is a pilot version of such a plant (Figure 1.1). Windrow composted green waste was also included in this study since it is currently utilised by Brisbane City Council to recycle green waste fines. Hence, this study also aimed to determine whether pyrolysis outperforms or complements composting as a means to recycling city green waste.

2) Cross-commodity horticulture: For Australian horticulture large distances mean that transport must be minimised and using on-farm or local feedstocks makes economic sense. One option is to establish a centrally located, stationary pyrolysis unit as part of a community undertaking, small business or co-operative, which is represented by Technology B in this study (Lehmann & Joseph, 2009; Brown, 2009). Conversely, processing options can be simple and less expensive, for example, a mobile, truck-mountable unit which is Technology C in this study.

Product preparation (Section 2) was throughout 2011 and concluded that compost and biochar production are readily synergistic. Further, products from other organic waste streams were explored and compared to green waste biochars: i) farm trash was made into biochar by the truck-mountable unit to represent an on-farm scenario and ii) a woodchip and paper mill waste were manufactured into biochar by Technology A (Figure 1.1) to compare city waste streams. To aid growers and waste managers in economic decisions, the cost of units and biochar, with current versus estimated costs after production up-scale, are presented in Section 6.1, while logistical recommendations for biochar transport, storage and handling are in Section 6.2.

Physicochemical properties were determined for biochar products and related to their production technologies, presented in Section 3 as scientific background. The aim was to determine and quantify the variation in biochar properties across different pyrolysis technologies and feedstocks and then to align biochar properties with agronomic performance. Specifically, biochar characteristics most likely to result in positive plant establishment outcomes were determined via modelling against plant growth indices (Section 3.2).



Technology	Unit description	Examples of organic processing scale
A	Large, stationary	City or large town
B	Medium, stationary	Small town, farmer co-operative
C	Small, truck-mountable	On-farm, small city/town projects

Figure 1.1 Test products were made by four technologies from one common green waste feedstock sourced from a single Brisbane location. Research was unbiased: materials were purchased from suppliers, hence ensuring research independence.

To validate the purported <u>agronomic and environmental benefits</u> of organic products, laboratory, glasshouse and field plant growth experiments were conducted across horticulture industries and are presented in Sections 4 and 5 as industry case studies. The broad aim was to determine if biochar (± compost) products benefit cross-industry horticulture or specific industries. Thus organic product usefulness was tested for:

Field Crop Production (Section 4): Long-term field trials with an annual vegetable crop rotation (tomato and lettuce, Section 4.1) and a perennial fruit crop (blueberry, Section 4.2) determined the logistics and practicality of product use for growers and quantified crop yield, soil health and carbon sequestration (Section 4.3).

Urban Horticulture (Section 5): By 2012, proof-of-concept focus turned to urban horticulture because plant establishment, a key for nursery and turf productivity and profitability, most benefited from biochar (± compost) additions. Better seed germination, faster seedling/plantlet establishment, more robust seedlings/plantlets and faster cutting strike rates were observed with certain biochars. Hence proof of concept trials tested products for enhanced establishment for various turf (Section 5.1) and nursery (Section 5.2) varieties.

By understanding the system from the feedstock source to the grower this study provides traceability that allows growers and waste managers to replicate positive outcomes, pinpoint where an emerging technology may fail and determine what must be improved. The following Sections provide materials and methods and research outcomes for the studies summarised above. The *Closing the Green City Loop* project (2014-17) will expand studies through grower trials to continue agronomic validation and create new markets for recycled organic products for horticulture.

2. Biochar and Compost Product Preparation

Section 2 has been condensed from a confidential report.

Section 2 describes the preparation of biochar and compost products. This Section is relevant for stakeholders processing organic waste into biochar and/or compost products and will be submitted as part of an international scientific paper:

Section 2 contributors:

Kochanek J, Kochanek MA, Flematti GR, Swift R. In prep (a). Properties of biochars prepared principally from one feedstock using three pyrolysis technologies. *Bioresource Technology*.

2.1 Materials and Methods

Three different commercial pyrolysis technologies, selected for relevance to stakeholders in the Australian horticulture and urban waste industries, were used to produce the study biochars and their specifications are described in Table 2.1. While green waste* was the primary feedstock, sugarcane trash was also made into biochar by Technology C (truck-mountable unit) to represent a farm by-product feedstock and a woodchip and paper mill waste feedstock were manufactured into biochar by Technology A to compare several city waste streams (Figure 2.1).

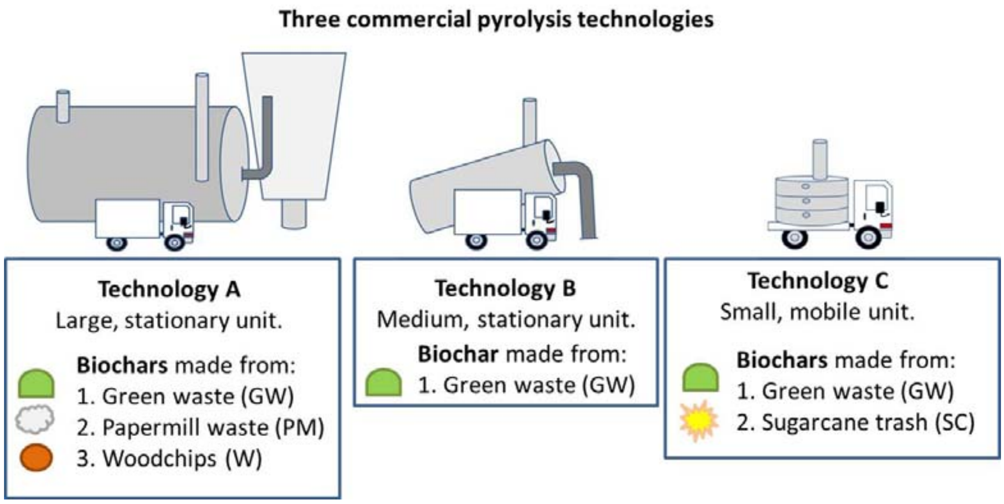


Figure 2.1 Biochar products from the three commercial pyrolysis technologies were from one common green waste feedstock (GW, all units) or from sugarcane trash (SC, Technology C), woodchip (W, Technology A) or paper mill waste (PM, Technology A) feedstocks to represent farm by-product or city waste streams.

*Seven tonnes of green waste (total) from Brisbane was transported by truck to three commercial sites in NSW and Victoria and manufactured into 1 tonne of biochar by Technology C, 500 kg of biochar by Technology A and 200 kg of biochar by Technology B. Additionally, 1.5 tonnes of biochar made from sugarcane trash was sourced from Technology C, while small quantities of biochar (for pot and laboratory trials) were made in a small batch reactor version of Technology A from woodchip and paper mill waste.

Table 2.1 Specifications for the three commercial scale pyrolysis technologies used to make study biochars (condensed from confidential report).

Pyrolysis technology	Production	Post-production	Feedstock
<u>Technology A</u> Slow, continuous pyrolysis. Fixed, non-relocatable unit. No oxygen ingress. Indirectly heated.	Pre-drying: Feedstock dried to 5-10% mc (dw‡) before feed to kiln. Kiln feed rate (kg h^{-1}): 300 HHT¥ (°C): 550 Residence time (min): 20 min in dryer, 20 min pyrolysis. Average yield (% dw‡): 35-45	Biochar wetted with cool water to avoid dust.	Optimal mc† (%): < 50. Optimal particle size (mm): < 12. Possible particle size: up to 45 mm.
<u>Technology B</u> Ablative auger-based slow, continuous pyrolysis. Fixed, relocatable unit. No oxygen ingress. Kiln indirectly heated.	Pre-drying: Feedstock pre-dried to *c.* 20% Kiln feed rate (kg h^{-1}): 250* HHT¥ (°C): 400-550* Residence time (min): 17 total. 7-9 min at 180-220°C (dryer), 8-10 min pyrolysis. Average yield (% dw‡): 40 Excess syngas can be cleaned for electrical power generation.	Biochar quenched with misting and hosed when added to drums to reduce residual heat.	Optimal mc† (%): 10 to 20. Optimal particle size (mm): 3 to 10. Possible particle size: < 15 mm Heating rate = 75 to 100°C min^{-1}
<u>Technology C</u> Truck-mountable unit, direct flaming system. Rapid thermal carbonisation in a rotary hearth operating as an updraft gasifier with interrupted combustion.	Kiln feed rate: 600 kg h^{-1} Target HHT¥ (°C): 460-580 Actual HHT¥ (°C): 400-600 Residence time (min): 1-4 Average yield (% dw‡): 18-28 Energy production is equivalent to 55-65% of Lower Heating Value of the biomass.	Biochar quenched with water, cooled and bagged.	Optimal mc† (%): <20 Optimal particle size: 20 mm for woody feedstocks.

Abbreviations: †mc is moisture content, ‡dw is dry weight, min is minutes, ¥ HHT is highest heating temperature, *based on a standard poultry litter feedstock. References: Technology A (A. Downie, J. Allen, P. Klatt, pers. comm.), Technology B (R. Burnett, pers. comm.), Technology C (J. Joyce, S. Joyce, B. Batchelor, pers. comm.).

Technologies A and B use pyrolysis units with a continuous throughput resulting in slow pyrolysis. Technology A has a target highest heating temperature (HHT) of 550°C and is a pilot version of a large, centralised plant with energy production capacity and Technology B has an optimal HHT of 400-550°C and is suited to community, small business or co-operative biochar production.

Technology C is a mobile, truck-mountable unit with interrupted combustion, ideal for on-farm processing and an optimal HHT of 460-580°C. The raw material manufactured into biochar by all technologies for this study was sourced from a common batch of a woody, medium-sized green waste feedstock sized *c.* 20 to 40 mm in diameter which is also sold commercially as mulch. This material was stockpiled undercover for one month until moisture content was below 50%, then transported to each commercial pyrolysis company for processing. Green waste feedstocks had 17% and 8% extraneous material removed prior to processing by Technology A and B, respectively. The green waste feedstock was unscreened when using Technology C. To represent a farm feedstock, sugarcane trash (SC) was made into biochar by the truck-mountable unit (Technology C) and to compare biochars made from other accessible organics a woodchip (W) and paper mill waste (PM) feedstock were manufactured into biochar using Technology A (Figure 2.1). Each study biochar was thoroughly mixed prior to storage in closed 240 L plastic bins at 4°C in the dark until use.

Compost was manufactured from green waste fines (smaller than 10 mm) into 1 tonne of 'PC100 compost' product by windrow composting for 7 months, using commercial production to comply with EPA standards and adhere to Australian Standard 4454 (AS4454).

2.2 Results and Discussion

Compost and biochar: Product preparation concluded that compost and biochar production are readily synergistic. Green waste fines (smaller than 10 mm) are best for compost production due to their rapid decomposition and low energy value. By contrast, woody materials (such as low-grade mulch) are best for biochar production due to high energy values and slow decomposition. Also, combining compost and biochar has been suggested by other studies to adsorb contaminants (Beesley & Dickinson, 2010) and to speed up the composting process (Jindo *et al.*, 2012). In Section 4 this study explores the effect of compost and biochar co-application for crop yield and soil health attributes.

Pyrolysis technologies: The actual conditions attained during study biochar manufacture are in Table 2.2 in the confidential report (removed here). Technology A was a pilot version of a large, centralised plant with a continuous throughput and energy production capacity, most applicable to high volume city requirements (Table 2.1). Compared to the other two technologies, Technology A heated the feedstock at the slowest rate, attained the lowest temperature during pyrolysis and maintained pyrolysis for the longest duration (heating rate, 24°C min^{-1}; highest heating temperature, HHT, 550°C; residence time, 40 mins). Technology B was engineered primarily to produce high quality biochar for agronomic applications, with similar degradation conditions to Technology A, albeit with a 10 minute shorter residence time, 3-4 times faster heating rate and 40°C hotter conditions. The vastly different Technology was C, a mobile, truck-mountable unit, included in the study for its on-farm processing capacity. This unit heated the feedstock very rapidly, attaining the highest temperatures, and had a pyrolysis residence time one order of magnitude shorter than the other two technologies (heating rate, 500°C min^{-1}; HHT ≥600°C; 2 to 2.5 min residence time versus ≥28 min for Technologies A and B). Further, this unit allowed air ingress and flaming combustion for direct heating of the incoming feedstock while Technologies A and B had no oxygen ingress and were indirectly heated. Thus the different technologies exhibited different thermal degradation conditions. HHT is the most important pyrolysis factor to determine biochar physicochemical properties, while residence time, air ingress and heating rate are also crucial (as are pre-pyrolysis factors such as feedstock moisture content; Downie *et al.*, 2009). Thus in Section 3 we test the hypothesis that each technology will produce different biochars, even when a common feedstock is used.

2.3 Summary and Recommendations

1) Product preparation concluded that compost and biochar production are readily synergistic. Green waste fines (smaller than 10 mm) are best for compost production due to their rapid decomposition and low energy value. By contrast, woody materials (such as low-grade mulch) are best for biochar production due to high energy values and slow decomposition.

2) The three pyrolysis technologies exhibited different thermal degradation conditions. However Technology C, a mobile, truck-mountable unit, was vastly different to Technologies A and B. This pyrolyser heated the feedstock most rapidly, attained the highest temperatures, and had a pyrolysis residence time one order of magnitude shorter than the other two technologies. In the following sections we test the hypothesis that each technology will produce unique biochars, even when a common feedstock is used.

3. Scientific Background

Section 3 has been heavily condensed from a confidential report. Only the summary and recommendations are presented here.

Section 3 describes the physicochemical properties for study biochars and relates them to the three pyrolysis production technologies. The aim of Section 3 is to: i) understand and quantify the variation in biochar properties across different pyrolysis technologies and feedstocks (Sections 3.1 and 3.2) and ii) align biochar properties with agronomic plant performance (Section 3.2). In Section 3.2 biochar characteristics are modelled against seed germination and plant establishment indices to begin to understand which characteristics determine positive and negative plant growth outcomes during establishment. Section 3 is being prepared for submission to two international scientific journals:

1. Kochanek J, Kochanek MA, Flematti GR, Swift R. In prep (a). Properties of biochars prepared principally from one feedstock using three pyrolysis technologies. *Bioresource Technology* (Section 3.1).
2. Kochanek J, Long RL, Flematti G. In prep (b). Unfolding the chemical mechanisms behind biphasic biochar. *New Phytologist* (Section 3.2).

3.1 Physicochemical Properties of the Biochar Matrix

Summary and Recommendations

Section 3.1 contributors:

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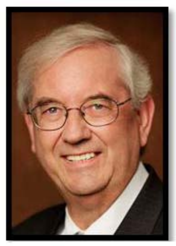

Roger Swift
Emeritus Professor, QAAFI

1) The carbon in study biochars was highly aromatic, hence likely to be environmentally recalcitrant and useful for carbon sequestration. Carbon aromatisation was consistently greater than 88%, suggesting stability against microbial decomposition (Krull *et al.*, 2009; Baldock and Smernik, 2002).

2) The pyrolysis technology used to make study biochars influenced organo-chemical and physical properties more than the input feedstock. Regardless of feedstock, biochars from the truck-mountable unit, with rapid thermal carbonisation (i.e. Technology C compared to Technologies A and B with slow, continuous pyrolysis), were the most thermally altered, contained less volatile matter and more fixed carbon and displayed a greater proportion of large pores (macropores) relative to micropores. Thus different pyrolysis technologies may produce biochars ideal for different market applications. For example:

- **Rapid thermal carbonisation** (Technology C) may be particularly useful for creating biochars that benefit agronomic physical and microbial soil function because macropore abundance is believed to enhance soil aeration, hydrology and root movement and provide habitats for soil microorganisms (Downie *et al.*, 2009). The greater abundance of fixed carbon also suggests higher carbon sequestration potential, although more carbon is consumed in the process.

- **Biochars from slow pyrolysis** (Technologies A and B), more abundant in micropores than macropores, may be more useful as carbonaceous matrices for biomolecule immobilisation or the slow release of compounds (Section 3.2, Gonzalez *et al*., 2012).
- **Biochars with very high surface areas**, such as the woodchip biochar, displaying a surface area twice that of other study biochars and equivalent to active carbon, may be most useful for restoration of contaminated land due to a large sorptive capacity (Section 3.2; Zhang *et al.*, 2004; Sarmah *et al.*, 2010).

These assumptions will be validated in the *Closing the Green City Loop* project.

3) **Biochar nutrient values are deceptive:** While analyses for study biochars generally revealed high macronutrients (i.e. elements such as NPK would be considered high to very high if sampled from a soil), most elements in biochar are not plant available, being either volatilised during pyrolysis or incorporated within the carbon matrix (Bagreev *et al*., 2001; Chan & Xu, 2009). In Section 3.3 we demonstrate the need for fertiliser co-application with biochar to optimise plant growth. Potassium is an exception because the water-soluble K fraction is lost during thermal degradation but plant available exchangeable K tends to increase (Chan & Xu, 2009). In this study exchangeable K in green waste biochars was very high relative to biochars from other feedstocks but does not explain plant performance trends (e.g. Section 3.2 and 4.3). Phosphates may also be present in ash-rich biochars (Wang *et al.*, 2012).

4) **Feedstock quality is important:** The quality of feedstocks used to make biochars should be as high as possible. In this study, the woody mulch used to make green waste biochars was or could be improved by:

- The removal of extraneous material prior to processing (e.g. rocks, metal fragments). The green waste feedstock had 17% and 8% extraneous material removed prior to processing by Technology A and B engineers, respectively (Section 2).
- Minimising heavy metal contaminants. Green waste biochars from Technologies B and C contained arsenic, chromium and lead at levels above typical minimum standards (e.g. National Environment Protection Council, 1999; Standards Australia, 2012; International Biochar Initiative, 2013).
- Ensuring that the feedstock is predominantly wood (i.e. minimising soil or compost ingress). Woody materials generally contain <1% ash while the green waste feedstock used in this study had an ash content of 21%, suggesting the ingress of non-woody materials such as grasses/straws (up to 24% ash; Amonette and Joseph, 2009, Ronsse *et al.*, 2013). Minimising ash is important because: i) feedstocks or biochars high in ash have a low energy value because energy is only from the organic fraction (Ronsse *et al.*, 2013); ii) high ash dilutes the fixed carbon content. Hence a given quantity of biochar high in ash will sequester less carbon than a biochar low in ash.

Pyrolysis is a **novel technology** that promises a myriad of benefits for horticulture but, if produced by untrained personnel, products that can harm plant performance and/or the environment. While the international biochar initiative is working towards standards for biochar (IBI, 2013), these will require optimisation to meet grower needs. We recommend that biochar is manufactured by trained personnel who understand feedstock quality control and biochar design for specific market needs.

3.2 Unfolding Biochar Chemical Mechanisms

Summary and Recommendations

Section 3.2 contributors:


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Explaining biochar effects on plant establishment: Section 3.2 provides an important step towards understanding the mechanisms behind the biochar-plant interaction, which is characterized by species specific biochar relationships (Solaiman *et al.*, 2012; Graber *et al.*, 2010; Oh *et al.*, 2012). Often the interaction is hill-shaped (biphasic) so that in dosage response studies where the biochar application rate is incrementally increased, plant performance increases to a species/crop specific maximal peak and then declines above the peak rate; i.e. the plant-biochar relationship is positive at small to moderate biochar doses and negative at high doses (Beckon *et al.*, 2008).

This hill-shaped growth curve has been explained in the literature as being the result of: i) the stimulation of beneficial microorganisms at low concentrations and impairment at high (Graber *et al.*, 2010; Warnock *et al.*, 2007; Warnock *et al.*, 2010), ii) inhibitors inducing hormesis, a mild stress response in plants that makes them grow better, at low concentrations but phytotoxicity at high (Graber *et al.*, 2010) and iii) increased ethylene production or decreased ethylene oxidation (Spokas *et al.*, 2010). In this study, we have revealed, for the first time, the interplay of chemical stimulants and inhibitors (such as heavy metals) that are likely responsible for the species/crop specific biochar response. Management of stimulants to inhibitors during pyrolysis is unlikely to be feasible.

Instead, to pave the way towards **biochars that provide consistent plant promoting results** from batch to batch we recommend:

1. Biochar manufacturers aim to create biochars that are as devoid as possible of inhibitors, for example, by ensuring an uncontaminated feedstock (e.g. free from heavy metals), upgrading pyrolysis technologies (possibly so volatile retention is minimised) and/or by post-pyrolysis scrubbing or leaching of inhibitors from biochars (Artiola *et al.*, 2012).

2. Growers: Biochar is likely most useful as a carbon-rich matrix that i) can be dosed with compounds, such as plant-promoting compounds and fertilisers, for release to plants in a more controlled manner (Gonzalez *et al.*, 2012), ii) provides homes for plant-promoting microbes (Warnock *et al.*, 2007; Warnock *et al.*, 2010) and/or can be dosed with such microbes (Gonzalez *et al.*, 2012), iii) provides physical structure and cation exchange capacity to improve soil and plant growing media quality (Sections 4 and 5) and iv) can sequester carbon long-term (Section 3.1 and 4).

The *Closing the Green City Loop* project will continue to work towards biochar design that provides consistent batch to batch plant promoting results for horticulture.

3.3 Biochar Application Rates and Fertiliser Inputs: A Preliminary Trial

Section 3.3 details a preliminary experiment conducted prior to study biochar manufacture that aimed to determine biochar application rates and the need (or otherwise) for fertiliser inputs to inform field and glasshouse experiments in Sections 4 and 5.

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3.3.1 Materials and Methods

The biochar used for this study was manufactured by Technology C in Maleny, Qld, and was a pre-trial test biochar generated in February 2011 from a green waste feedstock sourced from fallen and pruned trees and woody shrubs, thus was a woody and leafy mix. The feedstock was chipped on-site at Maleny by local contractors and stockpiled in late 2010. The biochar was stored at UQ Gatton in 50 L polyweave bags in a dry location until use (biochar chemical characteristics are in Appendix, Table A1).

Species selection used tomato (*Solanum lycopersicum* L.) cv. Grosse Lisse and lettuce (*Lactuca sativa* L.) cv. Archangel Nr. seeds purchased from Yates and South Pacific Seeds, respectively. These crops were selected because lettuce is highly sensitive to phytotoxins (Paradelo *et al.*, 2010; Koci *et al.*, 2010) and lettuce and tomato are sensitive to active compounds within smoke and ash (Drewes *et al.*, 1995; Kulkarni *et al.*, 2008).

The study used a completely randomised block design with five blocks and was maintained in a glasshouse at the UQ Gatton Plant Nursery Unit. Plastic pots (500 mL) were lined with white builders mesh to prevent media wash-out. <u>Media treatments</u> were a sand media control (two control pots per block) or biochar dosage treatments, whereby the sand was amended with the pre-trial biochar at 1, 3, 5 or 10% (w/v, *c.* 10, 30, 50 and 100 t ha^{-1}) or 100% biochar was used. The biochar was sieved through a 6 mm sized mesh prior to use. A slow-release fertiliser was incorporated into all medias at 2 kg m^{-3} (Basacote mini slow release fertiliser, NPK ratio 13:6:16). <u>Nutrient treatments</u> were a half strength or quarter strength Hoagland solution (Table 3.5). All pots were hand watered daily in the afternoon until runoff. The experiment began 30th March 2011 and pots were wetted until runoff and five seeds sown per pot onto the surface of the media for lettuce or at a depth of *c.* 5 mm for tomato.

Measurements: Germination was scored every second to third day for the first week after sowing, with seeds recorded as germinated once the radicle had visibly protruded to >1 mm (Section 3.2.2; Long *et al.*, 2010). Two weeks after sowing, once cotyledons were fully open in most pots, plants were thinned so one average sized seedling remained in each pot. The shoot and root length of the removed seedlings was measured and dry weight determined after drying in an oven at 65°C. Deformed seedlings were noted separately. The day after seedling thinning, pots were each fertigated with 50 mL of modified Hoagland solution as per nutrient treatments (i.e. pots were fertigated with half strength or quarter strength Hoagland solution). Fertigation was maintained thereon twice per week on Monday and Thursday mornings, followed by watering in the afternoon to prevent root damage from salt build-up. After seedling thinning, plant growth was measured weekly: plant height from the soil surface to the tip of the longest leaf (lettuce) or to base of the highest node (tomato) and length and width of the largest leaf on each plant. Plants were harvested on the 9th of May and growth parameters recorded (Kulkarni *et al.*, 2007): stem base thickness (tomatoes), plant height and leaf length and width and dry weight of shoots and roots after drying at 65°C. Statistical analysis used MINITAB, Version 16 (Minitab Inc., State College, PA, USA) as described in Section 3.2.

Table 3.5 The concentrations of (A) macronutrients and (B) micronutrients and their source salts supplied to plants during pot culture in half strength modified Hoagland's solution (Hoagland & Arnon, 1950; modified using Epstein & Bloom, 2004; Mattson & Lieth, 2008).

A. Macronutrients

Salt or acid	µM	Elements	µM
$Ca(NO_3)_2.4H_2O$	2000	N	9000
KNO_3	2000	P	1000
NH_4NO_3	1500	K	4000
KH_2PO_4	1000	Ca	2000
$MgSO_4.7H_2O$	500	Mg	500
K_2SO_4	500	S	1000
$CaCl_2.2H_2O$	-	Cl	0
H_3PO_4	-		

B. Micronutrients

Salt or acid	µM	Elements	µM
KCl	25	Cl	25
H_3BO_3	12.5	B	12.5
$MnSO_4.H_2O$	1.0	Mn	1.0
$ZnSO_4.7H_2O$	1.0	Zn	1.0
$CuSO_4.5H_2O$	0.25	Cu	0.25
$Na_2MoO_4.2H_2O$	0.25	Mo	0.25
$NiSO_4.6H_2O$	0.25	Ni	0.25
Fe EDTA (10.5% Fe)	-	Fe	18

Statistical analysis was carried out using MINITAB, Version 16 (Minitab Inc., State College, PA, USA). Analysis of variance (ANOVA) compared the effects of species and biochar incorporation rate on seed germination and plant growth parameters. Mean separation was performed by least significant difference (LSD) with a 5% significance level. All other analyses in this report use Section 3.2.1 statistical methods.

3.3.2 Results and Discussion

Biochar incorporation into the sand media at 1, 3 and 5% had a significant positive effect on plant establishment and growth for the lettuce and tomato crop compared to the control (sand without biochar). However, the optimal rate of biochar application differed between crops, as shown in Figures 3.13 to 3.15. For example:

- Tomato seeds germinated most rapidly in sand amended with 5% biochar, while lettuce germination was unaffected by biochar additions (Figure 3.13).
- Lettuce plants at 2 and 6 weeks after sowing accumulated 2-3 times more biomass in the media amended with 1% biochar than in the control without biochar. However, biomass accumulation declined above 1% biochar application rates (Figures 3.14, 3.15).
- By contrast, tomato plants at 2 and 6 weeks after sowing accumulated 1.5-2 times more shoot biomass in media amended with 5% biochar relative to the control. However, biochar rates below and above 5% accumulated less biomass (Figures 3.14, 3.15).

Both crops performed well with 3% biochar (equivalent to *c.* 30 t ha^{-1} assuming a 10 cm incorporation depth) hence this rate was selected for most trials in Sections 4 and 5.

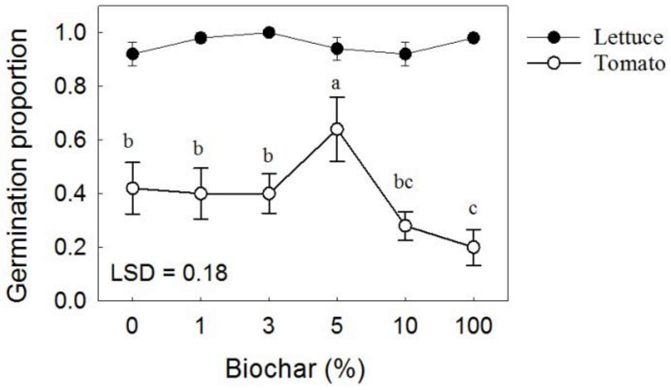

Figure 3.13 Germination proportion of lettuce (●) and tomato (○) seeds at one week after sowing into sand with biochar at various concentrations (mean ± SE, *n* = 10). Analysis of variance and means tested the influence of biochar incorporation at 0% (control), 1, 3, 5, 10% into sand and 100% biochar on seed germination when crops were supplied with luxury nutrition. Least significant difference (LSD) compared means within each crop and different letters indicate significant differences between treatment means within a species. Lettuce seed germination was not significantly different across treatments. ANOVA: Species $P<0.001$, Biochar rate $P=0.044$, Species × Rate $P=0.014$.

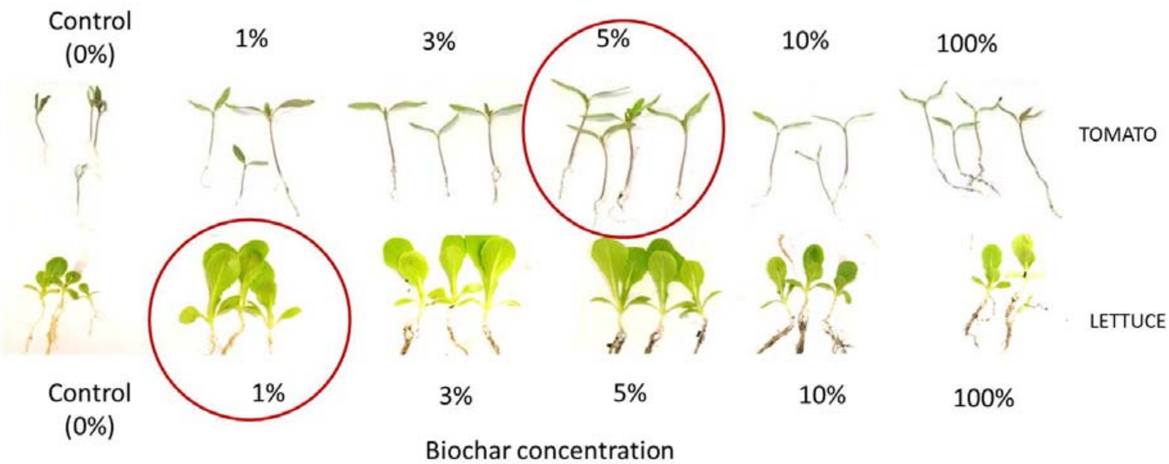

Figure 3.14 Two week old seedlings grown in sand with biochar at various concentrations. Tomato seedlings (top) were the heaviest and germinated most rapidly in sand amended with 5% biochar and the best treatment is depicted by a red circle. Lettuce seedlings (bottom) were heaviest with 1% biochar while lettuce germination was not affected by biochar. ANOVA for shoot dry weight at 2 weeks after sowing: Species $P<0.001$, Biochar rate $P<0.001$, Species × Rate $P=0.002$.

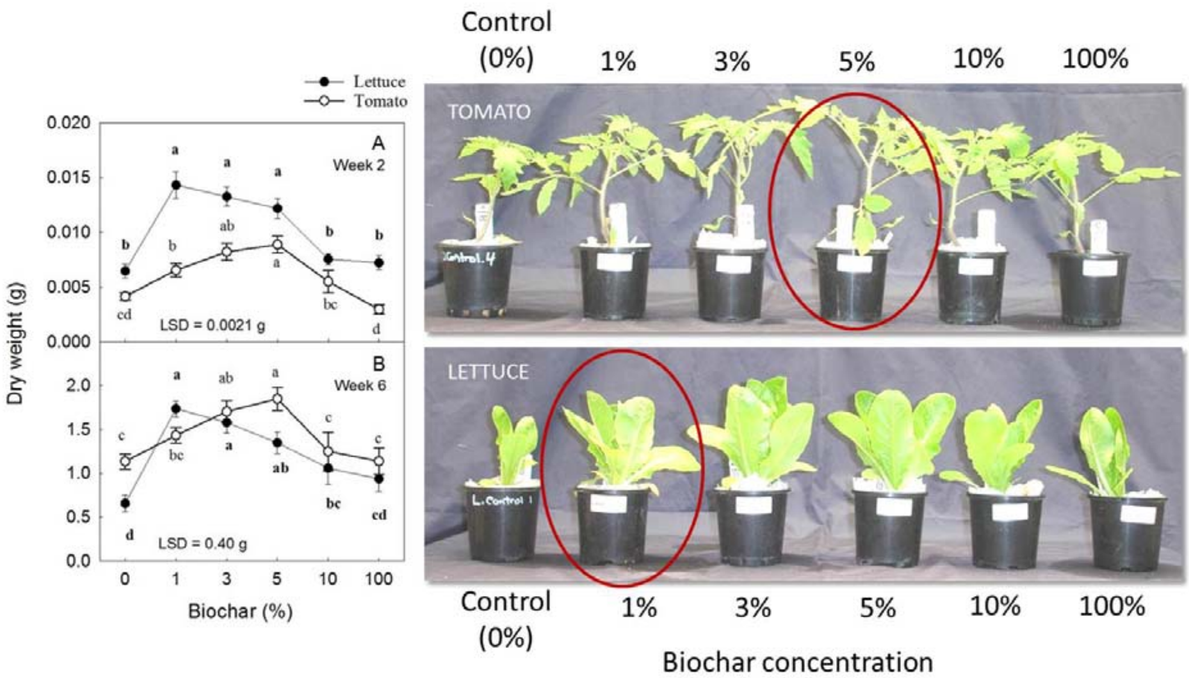

Figure 3.15 Shoot dry weight of lettuce (●) and tomato (○) at two and six weeks after sowing into sand with biochar at various concentrations. (*Left*) Analysis of variance and means tested the influence of biochar incorporation at 0% (control), 1, 3, 5, 10% into sand and 100% biochar on shoot biomass accumulation (mean ± SE) at 2 and 6 weeks after sowing when crops were supplied with luxury nutrition. Least significant difference (LSD) compared means within a crop and different letters indicate significant differences between treatment means. (*Right*) Six week old plants grown in sand with biochar at various concentrations. Tomato plants (top) were the heaviest in sand amended with 5% biochar, depicted by a red circle. Lettuce plants (bottom) were heaviest with 1% biochar due to wider leaves (plants were slightly shorter than in medias amended with 3 and 5% biochar). ANOVA for shoot dry weight at week 6: Species $P=0.013$, Biochar rate $P<0.001$, Species × Rate $P=0.032$.

The nutrient trial determined that both crops performed better in biochar treatments with a full strength nutritional regime compared to the half strength (Figure 3.16), hence trials in Sections 4 and 5 used agronomic best practice nutrient regimes, unless stated otherwise.

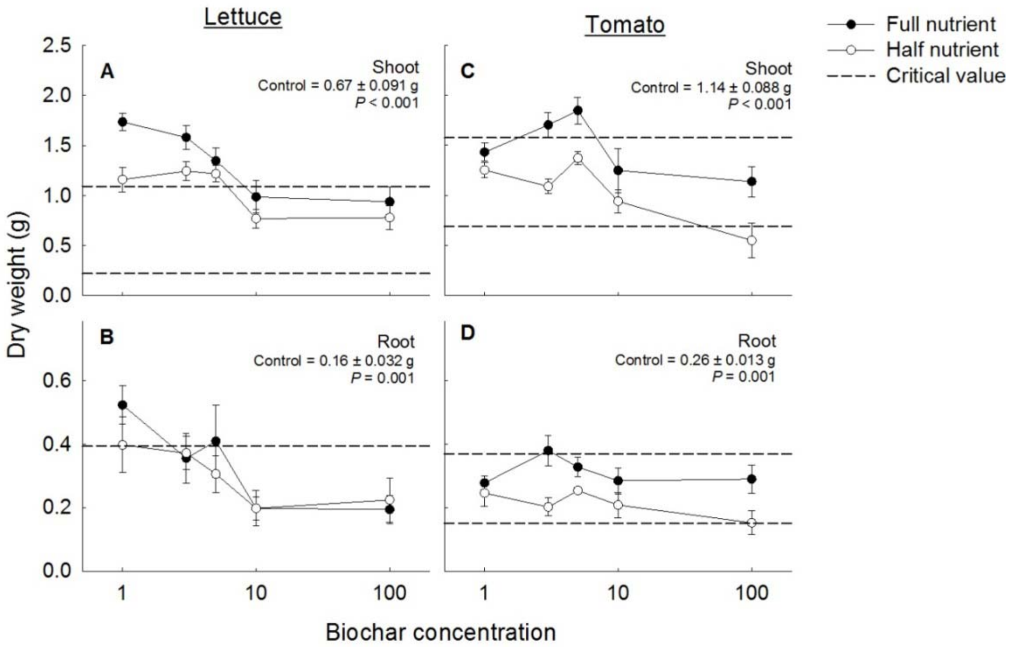

Figure 3.16 Effect of biochar rate at full and half strength nutrition on shoot growth (mean ± SE) of tomato and lettuce plants at six weeks after sowing. Panels compare the plant response to the pre-trial biochar made from green waste by Techology C. Biochar concentrations are $\log_{10}$ transformed and equivalent to 1, 3, 5, 10 and 100% biochar (left to right). Dashed lines indicate Dunnett's critical difference; means above the upper line or below the lower line are significantly different to the control.

3.3.3 Summary

1) Biochar incorporation into sand at 0, 1, 3, 5, 10 and 100% biochar showed a dosage response for a lettuce and tomato crop, whereby rates of 1, 3 and 5% had a significant positive effect on plant establishment and growth compared to the control (sand without biochar), while higher doses did not improve plant growth or harmed plants.

2) The optimal rate of biochar application differed between crops:

- Tomato seeds germinated most rapidly and plants accumulated 1.5-2 times more shoot biomass at 2 and 6 weeks after sowing in media amended with 5% biochar relative to the control.
- Lettuce germination was unaffected by biochar additions, while plants accumulated 2-3 times more biomass at 2 and 6 weeks after sowing in the media amended with 1% biochar than in the control without biochar.

3) Both crops performed well with 3% biochar (equivalent to *c.* 30 t ha^{-1} assuming a 10 cm incorporation depth) and a full strength nutritional regime (compared to half strength), hence agronomic best practice nutrient regimes and *c.* 30 t ha^{-1} application rates were used throughout the study, unless stated otherwise.

4. Field Crop Production Case Studies

Background: Two long-term field trials were set up during spring 2011 to test the usefulness, logistics and practicality of organic products for annual versus perennial field crop production. Both trials documented crop performance and yield (Section 4.1 and 4.2) and soil health and carbon sequestration of organic products over consecutive seasons and/or years (Section 4.3).

The first field site trial (Section 4.1) examined the effects of organic products on the crop establishment and yield of two annual vegetable crops planted in rotation, *viz.* a spring/summer determinate tomato crop (*Lycopersicon esculentum* Mill. cv. Rebel) in rotation with a winter/spring lettuce crop (*Lactuca sativa* L. cv. Archangel Nr. babyleaf Cos lettuce). The site was on a brown vertisol soil of pH 6.6 at the University of Queensland, Gatton.

The second field site trial (Section 4.2) examined the effects of organic products on vegetative growth, berry yield and soil health of a perennial southern highbush blueberry crop (*Vaccinium corymbosum* L. hybrid 'Opie') on a red ferrosol soil. This trial continues to be run in collaboration with soil scientist Justine Cox (NSW DPI, Wollongbar, NSW) on a commercial blueberry farm, Mountain Blue Orchards Pty Ltd, together with the farm Director, 2010 NSW farmer of the year, Mr Ridley Bell.

Both studies aimed to determine whether biochar outperforms or complements compost in agronomic contexts. Hence three biochars, a green waste compost and a compost and biochar combination, incorporated at 30 t ha^{-1} each into the top 10 cm soil surface were tested at both field sites (Table 4.1). The three biochars were made from green waste by Technologies A and C and from sugarcane trash by Technology C. Amendment application rates were determined from biochar dosage response studies (Section 3.3).

Table 4.1 Treatments used in long term field trials and pot trials in Section 4.

#	Treatment	Feedstock	Technology	
1	Control	none	No amendment	
2	Biochar	Green waste	A	Large, stationary pyrolyser
3	Biochar	Green waste	C	Small, truck-mountable pyrolyser
4	Biochar	Sugarcane trash	C	Small, truck-mountable pyrolyser
5	Compost	Green waste	Windrow composting	
6	Biochar + Compost		Combination	

Research exemptions to undertake field trials with novel biochar products were granted in 2011 from the Qld Department of Environment and Resource Management (DERM, Qld) and NSW Office of Environment and Heritage, Department of Premier and Cabinet. Agronomic practices, such as nutritional and irrigation regimes, were best practice as recommended by farm managers (Section 3.3), unless stated otherwise. Soil and compost chemical results are in Appendix Table A1.

Both trials will continue as part of the *Closing the Green City Loop* project; berry yields will be determined in 2014 and 2015 for the blueberry trial, and soil quality and carbon sequestration indices collected annually at both sites.

4.1 Annual Vegetable Crop Production

Background: Directly sowing seeds into soil (direct seeding) is a tempting option for horticultural producers; seeding is cheaper than purchasing transplants (Heisswolf *et al.*, 1997) and a taproot forms, providing a deeper root system than from transplants with 'air-pruned' taproots (Ryder, 1999). However, direct seeding is also more risky because adverse conditions, such as high temperatures, drought and disease, during germination and early establishment can kill the young seedlings or reduce uniformity. Also, transplanting provides a shorter cropping cycle, reducing irrigation and herbicide requirements (Heisswolf *et al.*, 1997).

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Given that various study biochars had enhanced plant establishment (Sections 3.2 and 3.3) this study aimed to determine if such benefits extend into the field by testing organic products effects on i) seed germination and seedling and/or transplant establishment and ii) crop yield for a tomato and lettuce crop over two seasons.

4.1.1 Materials and Methods

The study used a completely randomised block design with four blocks. Plots were 5 m long by 1 m wide, with 80 cm between rows, a 1 m buffer between plots along rows and a buffer row between treatment rows. The vegetable trial had **two additional treatments** apart from those in Table 4.1: i) in season I and II an additional plot tested the sugarcane trash biochar without fertiliser, the aim being to confirm that plants perform better in biochar with nutrients added (as in Section 3.3 pot trials) and ii) in season II an additional plot was added (fallow in season I) with fresh green waste biochar made from Technology A. The aim was to compare the effects of aged versus fresh green waste biochar on lettuce germination, establishment and yield. Thus, the perennial fruit trial compared six treatments (Table 4.1), the season I tomato trial seven treatments and the season II lettuce trial eight treatments.

Site preparation is summarised in Figure 4.1. Raised beds were formed with the soil surface fine, friable and clod-free for uniform seed germination and transplant development. A dry basal fertiliser (CK88) and the organic products were evenly distributed on the soil surface, watered to minimise dust and rotary hoed into the top 10 cm soil layer. The soil pH was not modified since it was close to the optimal range (i.e. 6.6, optimal is 6-6.5; Csizinszky, 2005). During stand establishment the soil was drip irrigated and supplemented by overhead sprinkler irrigation daily (Heuvelink, 2005). Once established, plants were watered every 5-7 d with drip irrigation, or as required (more water was used during critical times such as establishment, flowering, fruit set and fruit fill; Fullelove & Meurant, 1998). Weeds were controlled by chipping to ensure herbicides did not impact plant establishment (herbicide bioavailablity can be modified by biochars; Kookana, 2010) while pests and diseases were sprayed as required.

a) Tomato crop performance – Season I

The tomato (*Lycopersicon esculentum* Mill.) is one of the most widely eaten vegetables in the world and is the second most important vegetable crop, after potatoes, in Australia (Costa & Heuvelink, 2005). Queensland produces about 75% of Australia's fresh fruit tomatoes and a small percentage of processing tomatoes. In south-east Queensland, tomatoes are a trellised summer to autumn crop (Fullelove & Meurant, 1998).

Figure 4.1 A summary of site preparation for the annual vegetable crop field trial that compared seed germination and seedling/transplant establishment and yield for a tomato and lettuce crop over two seasons. A wire fence ensured that animal damage was minimised (e.g. hares).

The tomato is a model research crop, being easy to grow, easy to manipulate, possessing a short life cycle, grown commercially from seeds and transplants (Costa & Heuvelink, 2005) and being sensitive to active compounds within smoke and ash (hence potentially responsive to chemicals in biochar, Section 3.2; Kulkarni *et al.*, 2008). Also, a large proportion of plant water and nutrient absorption is from the amendment incorporation zone, in the upper soil profile. Although lateral roots can explore the soil to a depth of 2 m, 60% of roots are in the top 30 cm, while adventitious roots, developing from the stem, will initially explore the surface profile (Heuvelink, 2005). Thus tomato was selected as it was deemed likely to display a plant growth response to soil amendments (Csizinszky, 2005). The selected tomato cv. Rebel is a determinate processing and fresh market variety chosen for its highly uniform and compact growth, good yields and extreme weather tolerance (South Pacific Seeds, 2010).

Table 4.2 Basal and side-dressing fertiliser applications at weeks after seeding used for the season I tomato crop trial showing.

Weeks	Fertiliser applied	Date	Rate (kg ha^{-1})	N	P	K	Ca	S
-1	Basal fertiliser - CK88	31st Oct	350	52.9	15.4	40.25		47.6
4	Calcium nitrate - $Ca(NO_3)_2$	5th Dec	100	23.3			28.5	
6-7	Potassium nitrate - KNO_3	22nd Dec	100	13		38.3		
10	Potassium nitrate - KNO_3	16th Jan	50	6.5		19.15		
12	Potassium sulfate - K_2SO_4	23rd Jan	25			10.25		4.5
14	Potassium sulfate - K_2SO_4	13th Feb	25			10.25		4.5
			TOTAL (kg ha^{-1})	95.7	15.4	118.2	28.5	56.6

Agronomy: A basal fertiliser (CK88) was applied one week before seeding. Side-dressings, shown in Table 4.2, were broadcast evenly onto the soil surface and watered in. Plants were trellised to assist air flow, disease control and fruit harvest (Csizinszky, 2005), as recommended for south-east Queensland due to high summer humidity and rainfall (R. Edser, pers. comm.); 150 cm high stakes were driven into the soil at 5.5 m intervals and plants tied to the trellis from 7 weeks after sowing. The crop was not pruned since this is not recommended for determinate varieties in Queensland (Fullelove & Meurant, 1998).

Two tomato seeds were sown to a 1.5 cm depth on 3rd November 2011 and thinned to one seedling at the 3-4 true leaf stage (Csizinszky, 2005). Dead plants were replaced by transplants grown in the open at the UQ Gatton nursery. The crop was grown four months and the trial terminated in early March 2012 after a 5 week fruit harvest (Figure 4.2). Data were collected from 10 plants per plot.

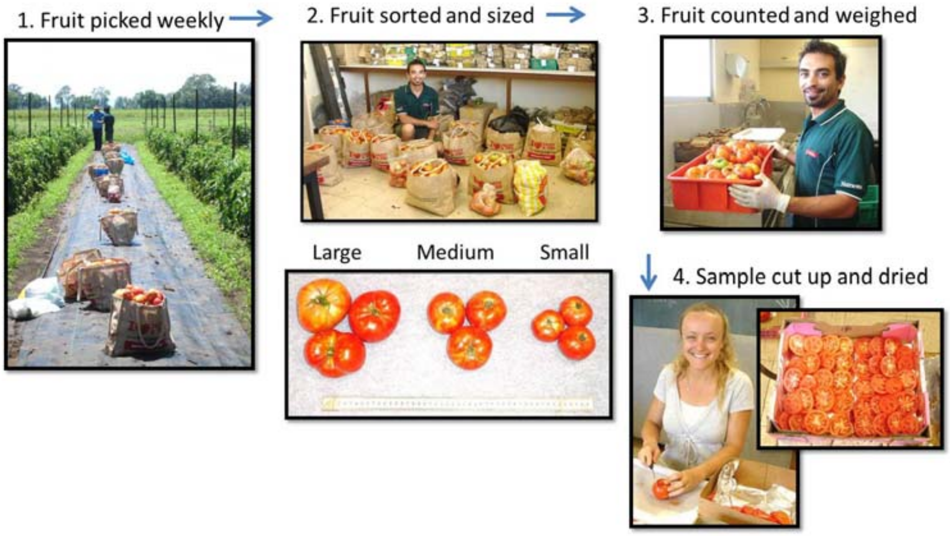

Figure 4.2 The tomato fruit harvest began on 30th January 2012 and continued for five weeks. The harvested fruit were categorised as small (smaller than 150 g, 65 mm diameter), medium and large (larger than 250 g, 80 mm diameter) and their respective number and mass recorded. A sample of fruits from each treatment were also sliced, dried and stored for analyses.

Measurements recorded: i) germination percentage, seedling and plant survival every 2-5 days for the first fortnight, ii) disease incidence, plant height from the soil surface to the highest meristem, stem diameter and number of flowers weekly or fortnightly and iii) fruit yield harvested weekly from 30th January for five weeks. Yield was the number and mass of small (smaller than 150 g, 65 mm diameter), medium and large ripe fruit (larger than 250 g, 80 mm diameter; Figure 4.2) and the number and mass of immature fruits remaining at the trial termination. Also at trial termination plant dry mass was recorded and leaf, fruit (for macronutrient analyses) and soil (to asses soil quality *viz.* pH and electrical conductivity, carbon and nitrogen content) samples collected from each plot.

b) Lettuce crop performance – Season II

Lettuce (*Lactuca sativa* L.) is an annual leaf crop selected because it was likely to show a plant growth response to amendment application. For example, this crop is highly sensitive to phytotoxins (Paradelo *et al.*, 2010; Koci *et al.*, 2010) and active compounds within smoke and ash (Drewes *et al.*, 1995) and biochar (Artiola *et al.*, 2012). Also, a large proportion of plant water and nutrient absorption (Ryder, 1999) is in the top 10 cm soil layer, the zone for soil amendment incorporation (Heisswolf *et al.*, 1997). **Agronomy:** The lettuce cultivar Archangel Nr., a babyleaf direct sow Cos lettuce, was selected for its year-round production. This cultivar displays resistance to Downy Mildew, Lettuce Mosaic Virus and Lettuce Aphid Nr (South Pacific Seeds, 2010). The basal fertilizer CK88 (Incitec Pivot Ltd, Southbank Victoria, Australia; 15.1% N, 4.4% P, 11.5% K, 13.6% S) was incorporated into the soil at 300 kg ha $^{-1}$ (kg ha $^{-1}$ of NPKS = 46.5, 13.2, 34.5, 40.8, respectively) as suggested by farm managers. A calcium nitrate side dressing equivalent to 25 kg N ha $^{-1}$ was spun onto the crop and watered in at five weeks after sowing (Heisswolf *et al.*, 1997). The crop was overhead irrigated.

Split-plot design: For the season II lettuce trial, each plot was subdivided longitudinally into two sub-plots, randomly allocated to a direct seeded crop versus transplants (Figure 4.3). Each sub-plot was sown with a single row of 12 plants, with 40 cm between plants. The inner 10 plants were used for data collection while one plant at each end was a buffer plant. Hence there were 16 treatment sub-plots in the season II trial, i.e. eight treatment plots per row subdivided into direct seeded vs. transplanted sub-plots. The **aim** was to compare the effect of organic products on lettuce plant establishment and yield for a direct seeded vs. transplanted crop (i.e. to assess whether growers may be better off direct seeding their crop if using organic products).

For the directly seeded plots, three seeds were planted as shallow divots on the soil surface on the 13th September 2012, thinned to one plant on 3rd October (Figure 4.4). Transplants were grown for 3 weeks at the UQ Gatton nursery prior to sowing in the field. One seed per cell was sown into 48-celled propagation trays containing a peat-based propagation media on the 11th September (Figure 4.4). Transplants were sown into the field at the three to four leaf stage (Heisswolf *et al.*, 1997; Ryder, 1999) on the 3rd of October (Figure 4.5). Direct seeded seedlings that did not survive were replaced by transplants at this time (not used for data collection). Plants were harvested at vegetative maturity, which was at 9 weeks after seed sowing and 6 weeks after transplanting, i.e. when lettuce heads were well filled and before elongation of the core (Figure 4.5; Ryder 1999).

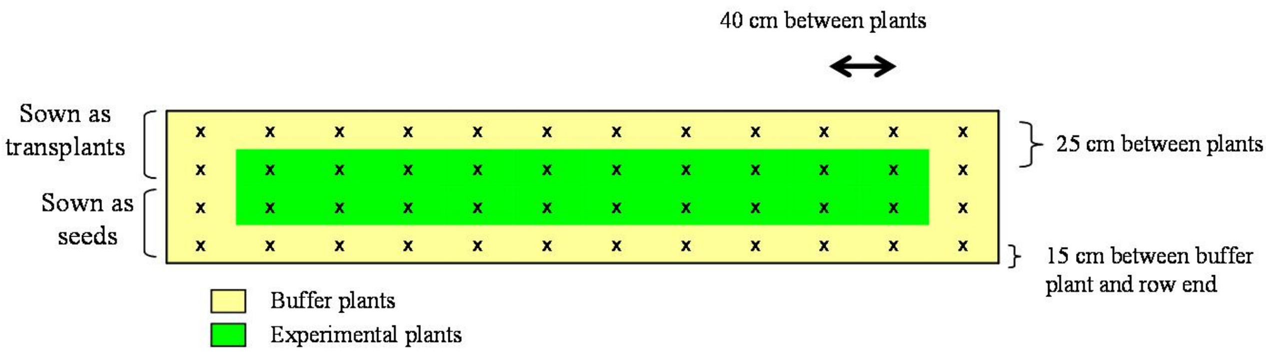

Figure 4.3 The season II lettuce crop plot was a split-plot with half of each plot randomly planted with transplants or seeds. Crosses depict individual lettuce plants and the inner 20 plants (green) were used for experimental measurements. The outer plants (yellow) were buffer plants.

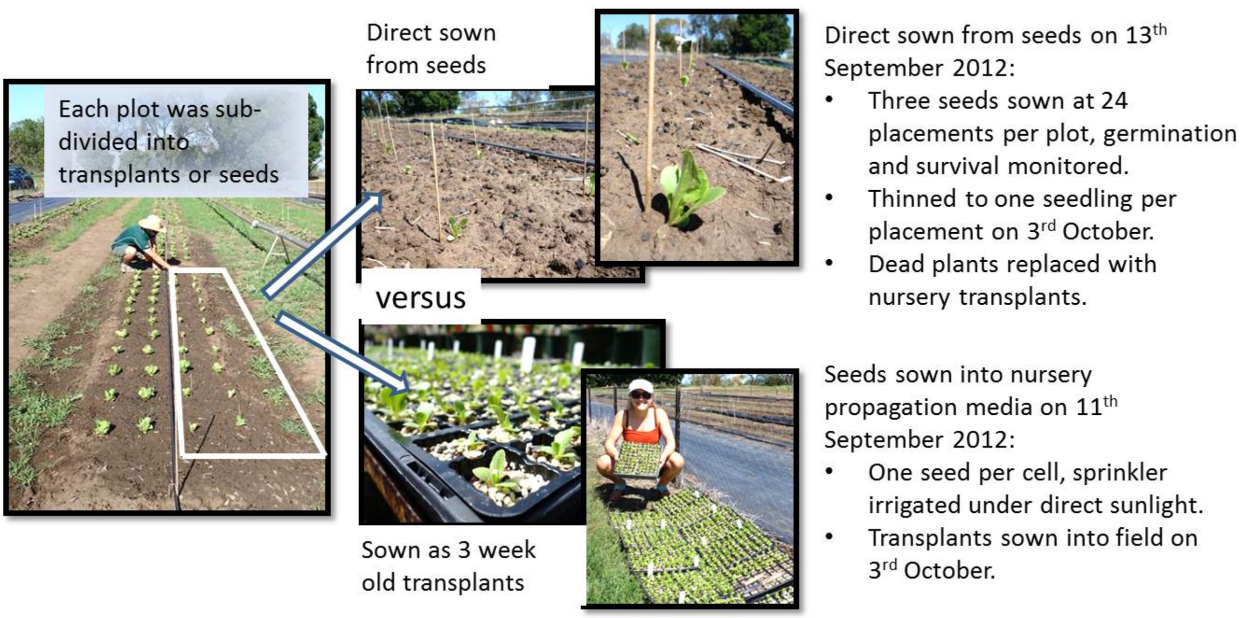

Figure 4.4 The season II lettuce crop plot was a split-plot with half of each plot randomly planted with transplants or seeds. The aim of this trial was to compare the effect of organic products on lettuce plant establishment and yield for a direct seeded vs. transplanted crop.

Figure 4.5 Events for the season II lettuce crop trial which compared plant establishment and yield for a direct seeded vs. transplanted crop across seven organic product treatments plus one control (no organic products). Plant size and health were monitored throughout the trial and the crop harvested at 9 or 6 weeks after sowing (direct seeded vs. transplanted crop, respectively). Yield was quantified from 10 plants per sub-plot using fresh and dry weight and lettuce size.

Measurements were i) seed germination and seedling survival for the direct seeded crop at 3, 5, 7 days and 3 weeks after sowing, ii) shoot growth and disease incidence at every 1 to 2 weeks and iii) yield, as above ground lettuce size and fresh and dry plant weight upon trial termination. A sample of leaves was collected from each treatment for NPK analysis. Parallel pot trials conducted for tomato and lettuce in ferrosol and vertisol soils revealed that leaf nutrient analyses were within the optimal range for both crops across treatments after 5 weeks growth (data not shown).

4.1.2 Results and Discussion

a) Tomato crop performance – Season I

The season I tomato trial tested the effects of seven organic product combinations (i.e. three biochars, one compost and a compost plus biochar combination with fertilizer and one biochar without fertiliser) and one control (no organic products) on the establishment, growth and fruit yield of the determinate tomato cv. Rebel.

Importantly, the organic product that most benefitted plant growth and yield was the biochar manufactured from green waste by Technology A (biochar A|GW, Figures 4.6 and 4.7), while the compost least benefitted growth. This outcome supports findings in Section 3.2 which showed that chemical stimulants in this biochar were likely responsible for enhanced shoot elongation (e.g. Figure 3.9C). Specifically, this biochar resulted in:

1. **The tallest plants after three months:** Plants growing in soil amended with this biochar (biochar A|GW, Figure 4.6) were the tallest (*c.* 100 mm taller than the control) while those growing in the compost were the shortest at 75 days after sowing. However, there were no significant differences between treatments in seed germination, plant survival or plant size before this date.
2. **More immature fruits at trial termination:** 226 immature fruits per plot were harvested from plants growing in soil amended with this biochar (A|GW, Figure 4.7) compared to 183 fruits from control plots. Fruit yield was otherwise not significantly different across treatments in weeks 1-5.

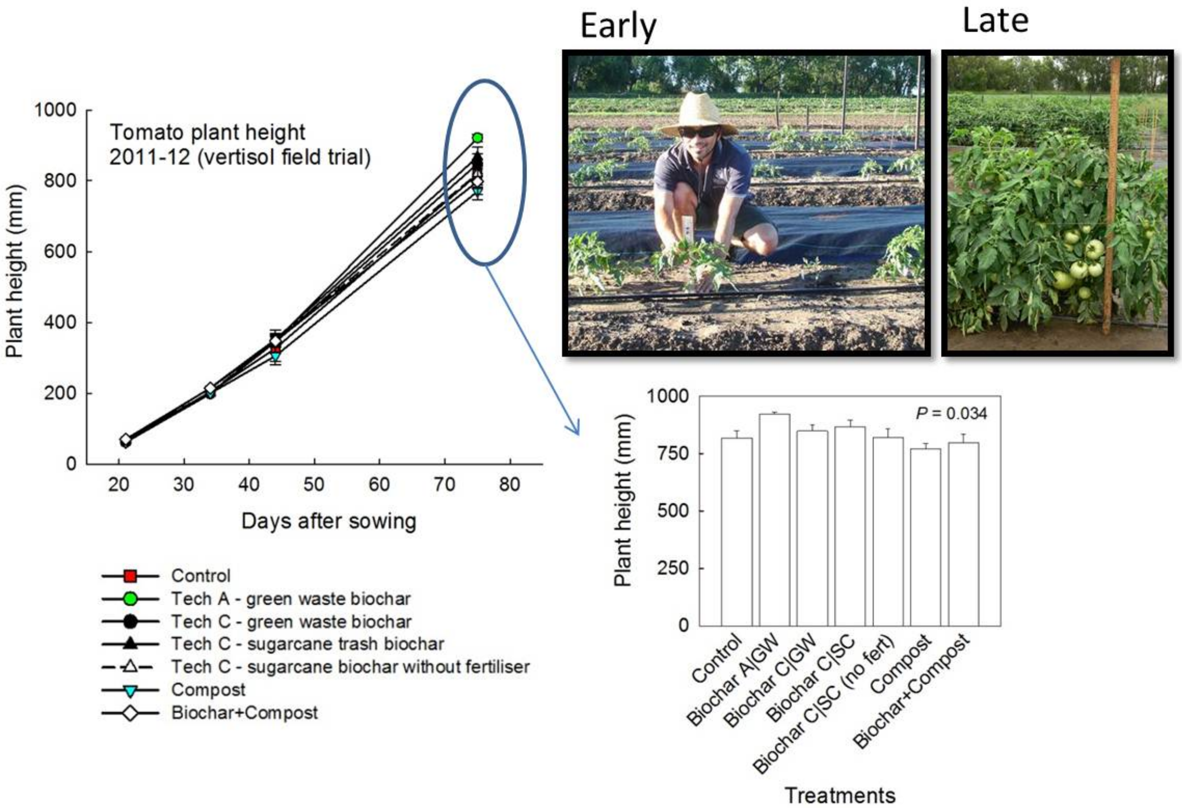

Figure 4.6 The height of tomato cv. Rebel plants at 20, 35, 45 and 75 days after seed sowing. Early plant size measurements were not significantly different across treatments. At 75 days after sowing (circled blue and shown as a bar graph, where bars are mean ± SE) the ANOVA showed a significant difference between treatments (P=0.034). Although no treatments were signficantly different to the control (Dunnett's test), the tallest plants were from soil amended with the biochar made from green waste by Technology A (biochar A|GW), while the shortest plants were from the compost treated plots. The 75 day old plants are depicted as 'late' in the photograph.

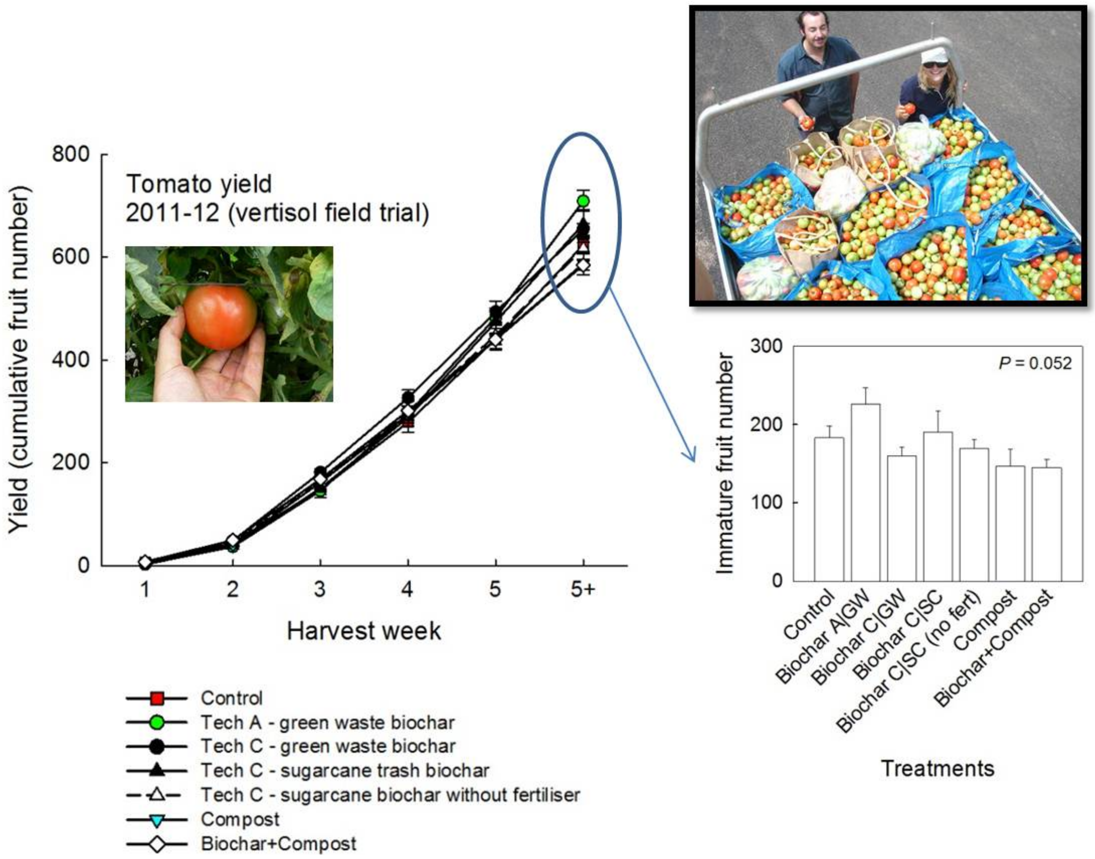

Figure 4.7 The fruit yield of tomatoes cv. Rebel over a 5 week harvest from 30th January until March 2012. Fruit yield was not significantly different across treatments in weeks 1-5. However, the ANOVA showed a near significant difference between treatments (P=0.052) for the number of immature fruit after the final harvest (circled blue and bar chart, where bars are mean ± SE). Although no treatments were signficantly different to the control (Dunnett's test), plants growing in soil amended with the biochar made from green waste by Technology A (biochar A|GW) produced the largest quantity of immature fruits. The immature fruits at the final harvest are green in the photograph.

One **important observation** was that the sugarcane trash biochar wicked irrigation water further from the irrigation pipe than the control, while the compost wicking width was less than the control (Figure 4.8). This wicking ability may significantly benefit plant performance in sandy or loamy soils or in non-irrigated situations and is supported by high water holding capacities measured for the sugarcane trash biochar in Section 5.2.

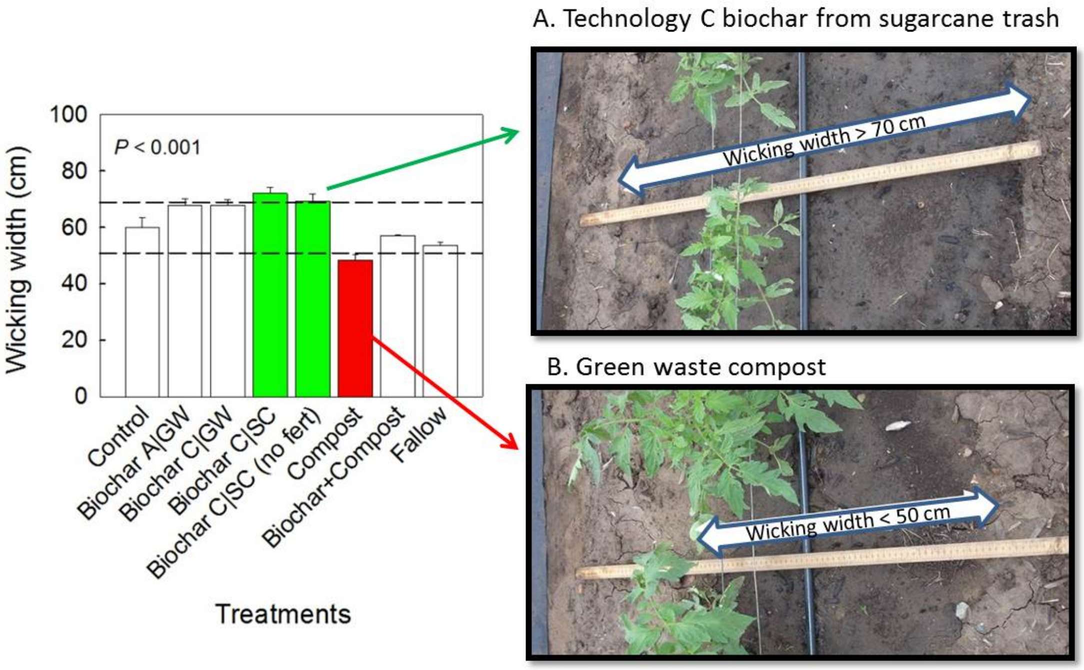

Figure 4.8 Sugarcane trash biochars (green bars) wicked irrigation water further from the dripper than the control, while the compost wicking width was less than the control (red bar). The white arrows in photographs show the distance that irrigation water travelled from the dripper for the sugarcane trash biochar (A) and a compost plot (B). In the bar chart: bars are mean ± SE and dashed grey lines indicate Dunnett's critical difference; means above the upper line or below the lower line are significantly different to the control (ANOVA $P<0.001$). Biochars were made from green waste by Techologies A and C (A|GW, C|GW, respectively) or sugarcane trash by Technology C (C|SC). Compost was made from green waste fines.

b) Lettuce crop performance – Season II

The season II lettuce trial tested the effects of seven organic product combinations (i.e. from season I: three biochars, one compost and a compost plus biochar combination with fertilizer and one biochar without fertilizer; from season II one fresh green waste biochar) and one control (no organic products) on the establishment, growth and yield of a directly sown vs. transplanted babyleaf Cos lettuce cv. Archangel Nr.

No significant differences of organic products were observed for most plant indices across seed germination, plant establishment or crop harvest. There were, however, important trends and exceptions. Specifically, biochars fertilised with CK88 tended to harm seedlings sown from seeds more than the control (Figure 4.9). We surmise that the CK88 may have harmed plants as a result of 'jelly butt stunt' (a debilitating condition in lettuce to excessive chloride; Heisswolf *et al*., 1997) and the CK88 was retained for longer within biochars than in the control plots, resulting in more plant deaths. Plant harming effects of the fresh biochar (made from green waste by Technology A) continued until week 7, whereby plants growing in soils amended with the fresh biochar were significantly smaller than from control plots (Figure 4.10A). However, detrimental effects were no longer significant by week 9 (Figure 4.10B). To what extent the presence of inhibitors in the fresh biochar (Section 3.2) exacerbated harmful effects on early plant establishment is unclear.

Recommendations for growers: Growers need to exercise caution when co-applying biochars and compounds during sensitive plant growth stages (e.g. fertilisers at excessively high rates, herbicides) since the retention of compounds within biochars has the potential to harm plants.

Parallel glasshouse pot trials using tomato and lettuce grown in the vertisol soil with the same organic product treatments for 5 weeks revealed no differences in biomass accumulation between treatments (data not shown). Hence we surmise that biochar amendments would likely have had a larger positive effect on plant growth and yield on a lighter soil, such as sand or a loam (as confirmed for lettuce in Section 5).

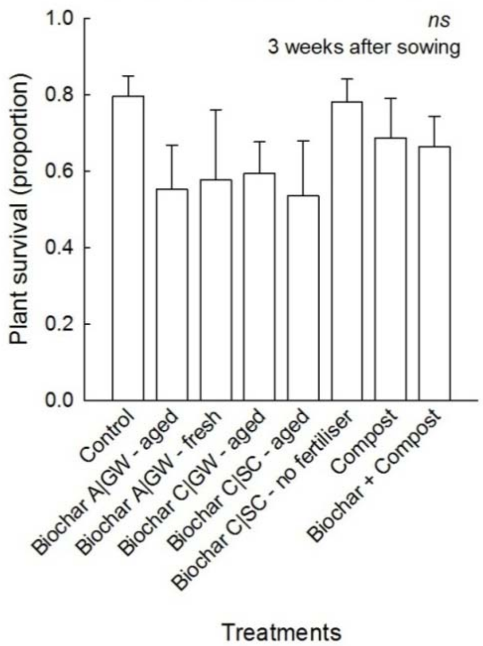

Figure 4.9 Plant survival at 3 weeks after sowing for lettuce seedlings sown from seed (bars are mean ± SE). Although not significant (P=0.693), there was a trend towards poorer plant survival in plots amended with biochars and fertilised with CK88, relative to the control (also fertilised with CK88) or the plots amended with sugarcane trash biochar but no CK88 (i.e. treatment: Biochar C|SC – no fertiliser). Biochars were made from green waste by Techologies A and C (A|GW, C|GW, respectively) or sugarcane trash by Technology C (C|SC). Compost was made from green waste fines. The fresh biochar was applied in growing season II, aged biochars in growing season I.

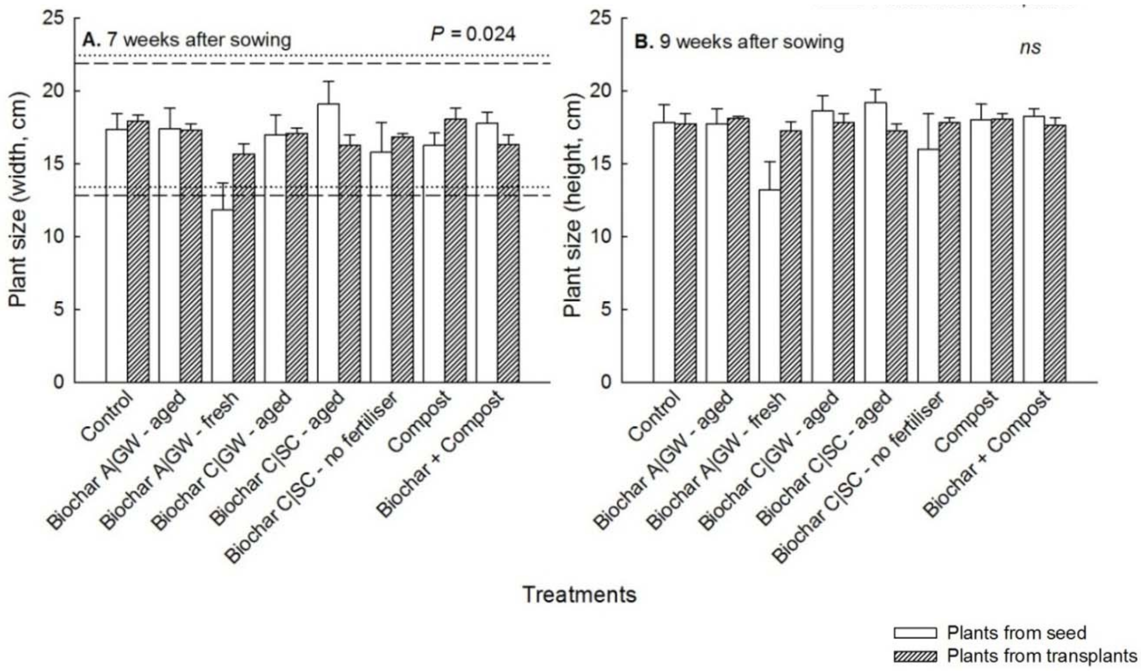

Figure 4.10 Plant size at 7 and 9 weeks after sowing for lettuce plants sown from seed (white bars; bars are mean ± SE) or transplants (striped bars). At 7 weeks the fresh biochar made from green waste by Technology A (Biochar A|GW – fresh) resulted in significantly smaller plants relative to the control, but this effect was no longer significant at 9 weeks after sowing (ANOVA P=0.068). Lines in the week 7 bar chart indicate Dunnett's critical difference; means above the upper line or below the lower line are significantly different to the control (ANOVA P=0.024). The dotted lines (•••) compare means to the transplant control and the dashed lines (---) to the seed sown control. Biochars were made from green waste by Techologies A and C (A|GW, C|GW, respectively) or sugarcane trash by Technology C (C|SC). Compost was made from green waste fines. The fresh biochar was applied in growing season II, aged biochars in growing season I.

4.1.3 Summary

This study tested the usefulness, logistics and practicality of biochar and compost products for annual vegetable crop production. A summary of key findings:

1) For **tomato** (*Lycopersicon esculentum* Mill. cv. Rebel) one biochar benefitted plant growth and yield more than other organic products, *viz.* a biochar made from green waste, found in Section 3.2 to be high in chemical stimulants. Tomato plants grown in plots with this biochar were larger and produced more fruits for longer than from other plots.

2) For **lettuce** (*Lactuca sativa* L. cv. Archangel Nr) the growth of plants sown from seed was harmed by biochar additions, possibly as a result of excess fertiliser retention within biochars. Thus, for growers we recommend caution when co-applying biochars and compounds during sensitive plant growth stages (e.g. fertilisers at excessively high rates, herbicides) since the retention of compounds within biochars has the potential to harm plants.

3) Glasshouse pot trials using the same soil, species and organic products revealed no differences in biomass accumulation between treatments. Hence amendments would likely have had a larger effect on plant growth and yield on a different soil (e.g. ferrosol and sand, Sections 4.2 and 5, respectively).

4.2 Perennial Fruit Crop Production

Background: In 2011, a long-term field trial was set up on commercial blueberry farm 'Mountain Blue Orchards' in collaboration with soil scientist Justine Cox (NSW DPI) and farm Director, Ridley Bell. The aim of this study was to collect long term data on the effects of biochar and compost products on i) the growth and berry yield of a perennial blueberry crop (Section 4.2), and ii) soil physicochemical properties over multiple years, including carbon sequestration (Section 4.3).

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4.2.1 Materials and Methods

The experiment is a completely randomised block design, with four blocks of each of six treatments, creating 24 plots. Each plot is 11.7 m long with 10 blueberry bushes (variety Opie) planted per plot and three buffer plants between plots. Canopy volume has been measured monthly since 2011 and berry yield during the first 18 week harvest in winter and spring 2013.

Figure 4.11 summarises key trial events. The experiment was established in spring 2011 on a red ferrosol soil limed to a pH of 5.9 (originally pH 4-4.5). Soil amendments (Table 4.1) were applied to the flat mounded surface (50 cm wide) at a 30 t ha^{-1} application rate and ploughed by hand into the top 10 cm mound surface. Irrigation tape, planting and mulching with woodchips occurred in early summer 2011. Until October 2012 plants were small and produced few fruits. After October 2012 the plant canopy began to expand and plants produced their first berry harvest in winter to spring 2013. For yield indices, berries were sorted into firsts (large, marketable fruit) and seconds and total and individual berry fresh weight recorded.

Figure 4.11 Key events in the long term blueberry field trial at Wollongbar, NSW, set up in 2011 on commercial blueberry farm 'Mountain Blue Orchards' in collaboration with soil scientist Justine Cox (NSW DPI) and farm Director, Ridley Bell. Agronomic practices were grower best practice.

4.2.2 Results and Discussion

This study has revealed that compost and biochar, applied together, promise to be a winning combination for perennial crops over the long term. This product combination resulted in significantly greater fruit yields in 2013, particularly during the latest stages. For example, in week 18 the mass of marketable fruit collected from bushes grown in soils with the compost and biochar combination was almost twice that of any other treatment plots (Figure 4.12, Table 4.3).

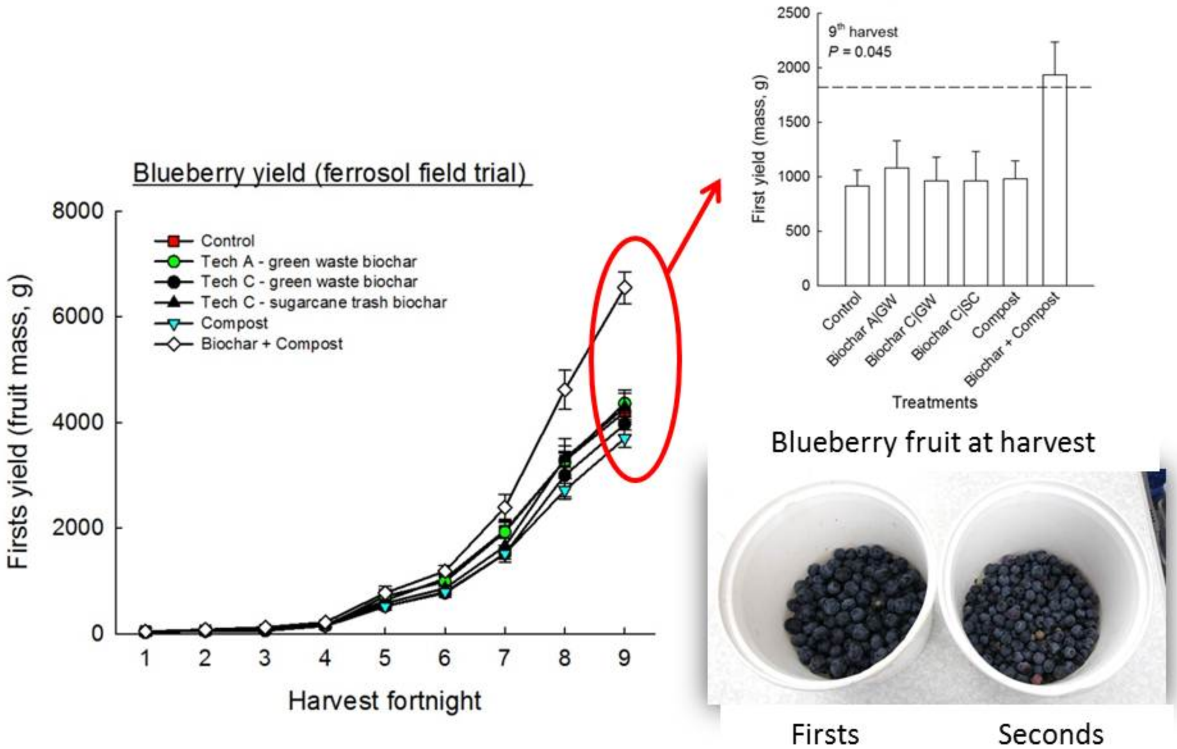

Figure 4.12 The cumulative fruit yield of marketable blueberry fruits (firsts) collected during the first harvest in 2013 from bushes grown since 2011 in plots amended with one of five biochar and/or compost combinations versus a control plot (no organic products). Individual harvests were not significantly different until the last harvest at week 18 (circled red and shown as a bar graph, where bars are mean ± SE) which showed that significantly more fruits were produced in the compost and biochar combination plots than in control plots. The dashed grey line in the bar graph indicates Dunnett's critical difference; means above this line are significantly different to the control (ANOVA *P*=0.045). Photograph: marketable fruits (firsts) are shown beside seconds.

Significant results showed that:

- The cumulative fruit harvest in winter and spring 2013 revealed a 65% increase in fruit yield from trees grown in plots containing a biochar and compost combination (30 t ha^{-1} each) compared to compost alone and a 30% increase in yield above biochar alone (three were tested) or no amendments (control).

- Certain amendments also significantly increased soil carbon, CEC and buffered pH above the control, promising long term soil health and spill-over environmental benefits (discussed in Section 4.3).

Table 4.3 General linear model analysis of variance and means testing the effect of five organic product combinations and a control (Treatment) and early versus late harvest times (Harvest, weeks 1-6 vs. weeks 7-9) on median blueberry yields of firsts (marketable fruits) and total yields (firsts + seconds).

	Firsts fruit mass (g)	Total fruit mass (g)	Degrees of Freedom
Block	*	**	3
Treatment	*	*	5
Block × Treatment	ns	ns	15
Harvest	***	***	1
Treatment × Harvest	ns (*P*=0.088)	ns	5

Within each column, nonsignificant differences (*P*>0.10 unless shown otherwise) and significant differences at *P* ≤ 0.05, 0.01 and 0.001 are indicated by ns, *, ** and ***, respectively. Values are the mean of four replicates of median fruit mass (one replicate per block, four blocks). Residual degrees of freedom = 18.

Other results showed enhanced plant growth trends with the biochar and compost combination plots, but these were not significant (Table 4.4). For example, there was a trend towards a larger canopy volume for plants from the biochar and compost combination plots relative to the control, but differences were not significant (Figure 4.13, Table 4.4).

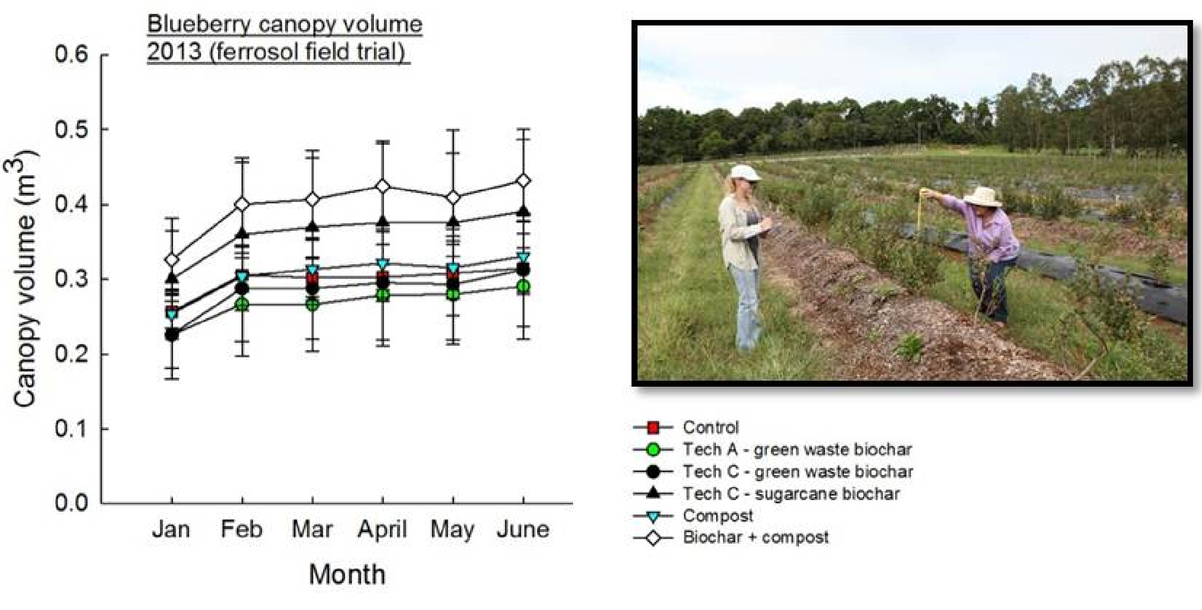

Figure 4.13 Canopy volume dimensions during the first 6 months of 2013 from bushes grown since 2011 in plots amended with one of five biochar and/or compost combinations versus a control plot (no organic products). Indices from treatment plots were not significantly different to the control (*P*>0.50).

The long term aspect of this trial, large increases in 2013 berry yields with the biochar and compost combination and improved soil health, warrant the continuation of this trial. Thus the *Green City Loop* project will continue to monitor blueberry yields during the 2014 and 2015 harvests and soil health and carbon sequestration annually until autumn 2016.

Table 4.4 General linear model analysis of variance and means testing the effect of five organic product combinations and a control (Treatment) and measurement month (Month, January to June, 2013) on canopy volume and the number of plants per plot that had started to flower or fruit.

	Plant canopy volume (m^3)	Proportion individuals flowering	Proportion individuals fruiting	Degrees of freedom
Block	*	*	***	3
Treatment	ns	ns	ns	5
Block × Treatment	***	***	*	15
Month	***	***	***	5
Treatment × month	ns	ns	ns	25

Within each column, nonsignificant differences (all P>0.10) and significant differences at $P \leq 0.05$, 0.01 and 0.001 are indicated by ns, *, ** and ***, respectively. Values are the mean of four replicates (one replicate per block, four blocks). Residual degrees of freedom = 90.

4.2.3 Summary

This study tested the usefulness, logistics and practicality of biochar and compost products for a perennial blueberry crop (*Vaccinium corymbosum* L. hybrid 'Opie'). The results showed that compost and biochar, applied together, promise to be a winning combination for perennial crops over the long term. This product combination resulted in significantly greater fruit yields in 2013, particularly during the late fruiting stage. For example, in week 18 the mass of marketable fruit collected from bushes grown in soils with the compost and biochar combination was almost twice that of any other treatment plots. This study will continue monitoring blueberry yields and soil health until 2016 as part of the *Green City Loop* project.

4.3 Field Soil Quality and Carbon Sequestration

Section 4.3 has been heavily condensed from a confidential report. The results, discussion and summary are presented here without Figures and Tables. This section is being prepared for submission to an international scientific journal:

Cox J and Kochanek J. In prep (c). Biochar and compost combinations are superior to single ameliorant inputs in a blueberry orchard soil. *Journal undecided.*

4.3.1 Materials and Methods

A key aim of the long-term field trial set up in 2011 at 'Mountain Blue Orchards' commercial blueberry farm was to monitor soil physicochemical and carbon sequestration properties over multiple years and across seasons. Hence, soil was sampled at 0, 3, 12, 18, 24 and 48 months and quality parameters quantified. Soil chemical properties were analysed in NATA (National Association of Testing Authorities, Australia) accredited facilities to ISO17025. Just some of the parameters tested were electrical conductivity, pH, total carbon, total nitrogen, nitrate (NO_3^-), ammonium (NH_4^+) and phosphorus levels, cation exchange capacity (CEC) and exchangeable cations such as potassium, calcium, magnesium and sodium. Physical measurements included bulk density and water holding capacity. Annual soil quality measurements will continue as part of the *Closing the Green City Loop* project and will be expanded to explore possible microbial effects behind improved yields in the biochar and compost combination plots. Soil quality parameters are also compared to those from the vegetable crop trial (Section 4.1).

4.3.2 Results and Discussion

Soil quality parameters were collected biannually in summer and autumn/winter. The most important <u>soil quality improvements</u> from biochar and/or compost product additions were:

1. **Soil carbon content increased** significantly with certain organic product additions. For example, all biochars increased soil carbon in the summers of 2011 and 2012. However, only the green waste biochar made by Technology A (GW, Tech A) and the compost and biochar combination continued to significantly increase soil carbon in 2013. In fact, soil carbon was 6.5-7% for soils with these organic products but only 5% for the control without amendments. Importantly, these same organic products also significantly improved soil carbon content in the vegetable crop trial. <u>For the grower</u>, a soil organic carbon rating of >3 % means a very high carbon content that promises good soil structure and stability (Hazelton & Murphy, 2007). The proportion of carbon that is organic will need to be determined.
2. **Soil pH was buffered** significantly by certain organic product additions. However, only the green waste biochar from Technology C continued to significantly raise pH above the control into 2013; soil amended with this biochar had pH 6.2, while the control was pH 5.6. This corresponds to the high neutralising capacity of this biochar, which was about six times greater than for

the other biochars used in this field trial (i.e. 6 versus 0.7-1.4 for the other two biochars, Section 3.1).

3. **Cation exchange capacity (CEC) increased** significantly with certain organic product additions. For example, during 2012 the compost, the biochar and compost combination and the two green waste biochars all increased CEC above levels in the control soil. In fact, the control soil would be classified as having a low CEC (*c.* 12 $cmol_c kg^{-1}$), while the amended soils would have moderate CEC (> 15 $cmol_c kg^{-1}$). For the grower, this increased CEC means that their soil is likely to be healthier, for example, better able to i) hold and exchange cations such as potassium, calcium and magnesium, ii) maintain a desirable pH, iii) retain available nutrients and iv) maintain good soil structure (Hazelton & Murphy, 2007).

4. **Plant available potassium increased** significantly with all organic additions in the first year, thus supporting the theory that one way in which biochars improve plant growth directly is by contributing plant available potassium (Chan & Xu, 2009). All organic additions increased soil potassium to 'high' in 2011 (> 0.9 $cmol_c kg^{-1}$), in contrast to the control which was 'moderate' (0.5 $cmol_c kg^{-1}$; Hazelton & Murphy, 2007). However, only the green waste biochars and biochar and compost combination soils continued to retain high plant available potassium in 2012, possibly corresponding to their increasing CEC.

5. **Soil bulk density was reduced** significantly with certain organic product additions. For example, soils amended with the sugarcane trash biochar and biochar and compost combination showed a lower bulk density in 2013 than the control soil (i.e. amended soils were <0.68 g cm^{-3} while the control was 0.77 g cm^{-3}, $P<0.001$). For the grower, a lower bulk density means that their soil is likely better aerated and provides easier root movement, hence healthier plants.

Other notable observations were that:

1. **Organic products did not result in saline soils**. Although salinity was slightly elevated in the first year by certain organic products, all soils remained non-saline. For example, soil electrical conductivity was increased by the green waste biochar from Technology C and the biochar and compost combination treatment in summer 2011, but even after conversion to ECe these amended soils were still 'non-saline' (i.e. 0.2 dS m^{-1} × multiplier of 8.6 for a clay loam to medium clay = ECe = 1.72 dS m^{-1}; non-saline soils have an ECe of < 2 dS m^{-1}; Hazelton & Murphy, 2007). Similarly, slightly elevated sodium levels with certain amendments were still 'low' in all soils (i.e. < 0.3 $cmol_c kg^{-1}$; Hazelton & Murphy, 2007).

2. **Organic products did not elevate phosphorus or nitrogen** in year 1, hence supporting the theory that these elements are not plant available, being either volatilised during pyrolysis or incorporated within the carbon matrix (Bagreev *et al.*, 2001; Chan & Xu, 2009). For the grower, this means that such organic products cannot be used as fertilisers (with the possible exception of plant available potassium).

3. **Organic products did not retain nitrate and ammonium** in soils above control values. This finding is important because literature suggests that nitrate and ammonium retention is possible but likely to be variable between biochars (Yao *et al.*, 2012). For the grower, this means that organic products will not necessarily retain nitrates and ammonium for plant growth or to prevent leaching into waterways.

4.3.3 Summary

A key aim of the long-term blueberry field trial was to monitor soil physicochemical and carbon sequestration properties over multiple years and across seasons. Key soil health and carbon sequestration improvements collected so far from field trials show:

- Soil carbon content increased significantly with certain organic product additions.
- Soil pH was buffered significantly by certain organic product additions.
- Cation exchange capacity (CEC) increased significantly with certain organic product additions, increasing CEC from low for the control to moderate with additions.
- Plant available potassium increased significantly with all organic additions in the first year, supporting the theory that one way in which biochars improve plant growth directly is by contributing plant available potassium.
- Soil bulk density was reduced significantly with certain organic product additions. Soils amended with the sugarcane trash biochar and biochar and compost combination showed a lower bulk density in 2013 than the control soil.

Other notable observations were that:

- Organic products did not result in saline soils.
- Organic products did not elevate phosphorus or nitrogen in year 1, supporting the theory that these elements are not plant available in biochar, being either volatilised during pyrolysis or incorporated within the carbon matrix. For the grower, this means that such organic products cannot be used as fertilisers.
- Organic products did not retain nitrate and ammonium in soils above control values. For the grower, this means that organic products will not necessarily retain nitrates and ammonium for plant growth or to prevent leaching into waterways.

5. Urban Horticulture Case Studies

Background: A significant part of year 3 proof-of-concept focus turned to urban horticulture because earlier studies had revealed that plant establishment, a key for nursery and turf productivity and profitability, most benefited from biochar (± compost) additions (e.g. Section 3.2). For example, better seed germination, faster seedling and plant establishment and more robust seedlings and plantlets were observed with certain biochars. Also, a plant growth enhancing compound was quantified in study biochars and high concentrations were correlated with accelerated plant establishment and enhanced plant survival (for example, allowing young plants to thrive in suboptimal environments, Section 3.2). The systems used for nursery and turf production make the logistics of biochar transport, storage and use easier than for field applications (discussed in Section 6). Beyond plant benefits, biochar additions promise improvements in urban environmental quality, hence warrant further investigation. For example, biochars can:

- **Improve urban soil and landscaping medias:** Improvements to turf and landscaping medias with biochar additions have been attributed to higher aggregate stability (Ghosh *et al.*, 2012) and higher water and nutrient retention (Brockhoff *et al.*, 2010; Artiola *et al.*, 2012) compared to medias without biochar. Section 4.3 in this study also confirmed that soil quality can improve with biochar additions, for example through increased CEC, soil carbon, pH buffering and reduced bulk density.
- **Runoff water improvement:** Biochar additions to medias and soils in the urban landscape can reduce runoff water leachates, improving environmental health. For example, greenroof water retention was increased and runoff water quality improved by the incorporation of 7% biochar compared to media without biochar. The turbidity and discharge of leachates such as total nitrogen, total phosphorus, nitrate, phosphate, and organic carbon, were reduced by biochar incorporation (Beck *et al.*, 2011). Also biochar can reduce the mobilisation of trace elements, such as heavy metals, from composted green waste (Beesley & Dickinson, 2010) or contaminated urban soils (Jindo *et al.*, 2012; Beesley & Dickinson, 2010; Karami *et al.*, 2011). These assumptions need to be validated.
- **Reduced weed infestation:** Fresh biochars incorporated into soils can reduce weed seed germination and infestation, thereby reducing the requirement for herbicide application (Quilliam *et al.*, 2012). Section 3.2 in this study confirmed interplay of plant promoting and inhibiting compounds in biochar and it is very possible that germination inhibitors in biochars can reduce weed seed germination.

The aim of Section 5 is to begin to validate the benefits and shortcomings of biochar products for Australian urban horticulture, specifically turf (Section 5.1) and nursery production (Section 5.2). This section provides preliminary case studies that will be validated and expanded through grower trials in the *Closing the Green City Loop* project.

5.1 Turf Production

Background: Studies into biochar use for turf production have been limited, but significant improvements to turf yields and drought tolerance warrant more research. For example, greenhouse pot experiments with a loamy sand sown with bermudagrass (*Cynodon dactylon*) seeds showed 25% higher leaf yields from plots amended with 2% biochar compared to 0% or 4% biochar. In a follow-up one month drought trial i) 100% of the turf sod survived in the 4% biochar amended plots, ii) 50% survived on plots with 2% biochar and iii) the entire sod died in plots without biochar (Artiola *et al.*, 2012). However, in other studies biochars had no effect on turf yields and even reduced rooting depths. For example, additions of biochar amendments at <10% into sand had no effect on creeping bentgrass (*Agrostis stolonifera* L.) plant growth, while >10% biochar rates reduced rooting depth compared to sand alone (Brockhoff *et al.*, 2010).

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Section 5.1 uses the three biochar products (Table 5.1) that most consistently improved plant establishment for other crops in Sections 3 and 4 with the aim to begin to understand the usefulness of biochar for the Australian turf industry. Specifically, Section 5.1 aimed to determine whether i) positive plant establishment outcomes extend to two turf varieties, ii) seed and vegetative establishment from a sod are similarly affected by biochar additions.

Table 5.1 Treatments used in turf establishment trials.

#	Treatment	Feedstock	Pyrolysis technology	
1	Control	None	No biochar	
2	Biochar	Green waste	A	Large, stationary
3	Biochar	Green waste	B	Medium, stationary
4	Biochar	Sugarcane trash	C	Small, truck-mountable

5.1.1 Materials and Methods

The study was carried out in a glasshouse at the UQ Gatton Plant Nursery Unit using a completely randomised block design with 10 blocks arranged along a slight light gradient and with 24 treatments in each block (Figure 5.1). Treatments were the three biochars shown in Table 5.1 incorporated at about 3% w/v (30 t ha^{-1} into the top 10 cm equivalent) into a coarse sand or composted pine bark potting media versus each media without biochar (control). Two turf varieties and propagation strategies were tested: i) a couch turf (*Cynodon dactylon* (L.) pers.) propagated from vegetative plantlets extracted from a turf sod (Jimboomba turf, Brisbane) versus establishment from seed (Yates lawn seed, Yates Australia, NSW) and ii) a kikuyu turf established from seed (*Pennisetum clandestinum* Hochst. ex Chiov., Brunnings lawn seed, Gardman Ltd, Victoria). **Agronomy:** Media pH was raised prior to biochar incorporation with dolomite at 1.3 g L^{-1}, (Mudgee, neutralising value 98) and plants were grown in forestry tubes. Flowfeed Ex 7 (Grow Force, Ruralco Holdings Limited, Qld) was applied in irrigation water every Monday, Wednesday and Friday. In weeks 1 to 2 the trial used 50 mL of solution per pot using 1 g Flowfeed per litre of water (1 g L^{-1}), in weeks 3 to 4 used 25 mL of solution at 1.5 g L^{-1} and in week 5 used 25 mL of solution at 2 g L^{-1}. The pots were irrigated daily with a hose using a rosette head attachment.

Propagation: For seed establishment trials the number of seeds required per pot for glasshouse studies was determined from laboratory seed germination bioassays conducted over 2 weeks in an incubator at 25°C. For glasshouse studies, six kikuyu and 15 couch seeds were sown per pot to ensure at least 5 seeds germinated in each pot (bioassays revealed 94% and 40% seed germination, respectively). The trial began on 11th September 2012 and seed germination was recorded at 7 and 14 days after sowing, when the radicle had protruded from the seed to >1 mm. Couch plantlet establishment trials used two uniform cuttings per pot extracted from a turf sod, with each cutting having at least 3 offsets. At one week after sowing, all plantlets were trimmed to a 2 cm height to ensure uniformity.

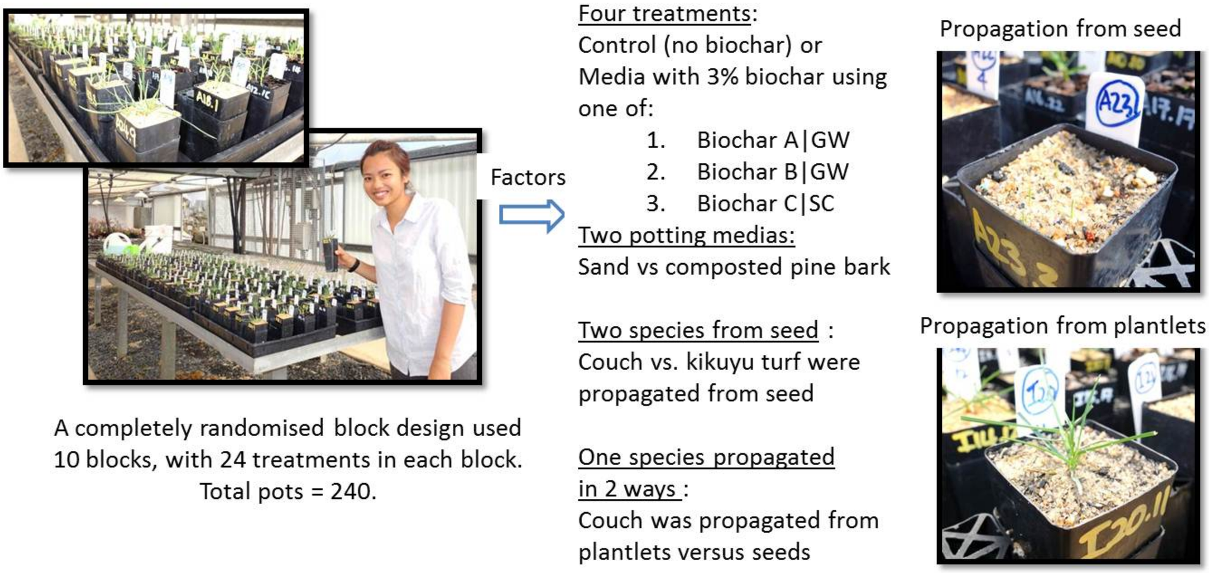


Figure 5.1 The turf trial was a completely randomized block design with 10 blocks arranged along a slight light gradient. Treatments were three biochars incorporated at *c.* 3% into a coarse sand or composted pine bark potting media versus a control without biochar. Two turf varieties and propagation strategies were tested: a couch turf propagated from vegetative sod plantlets or established from seed and kikuyu turf established from seed.

Plants were harvested at 30 days after sowing and measurements recorded were i) root and shoot length for each cutting and ii) shoot and root dry weight per plantlet for all treatments following drying at 65°C (Figure 5.2).

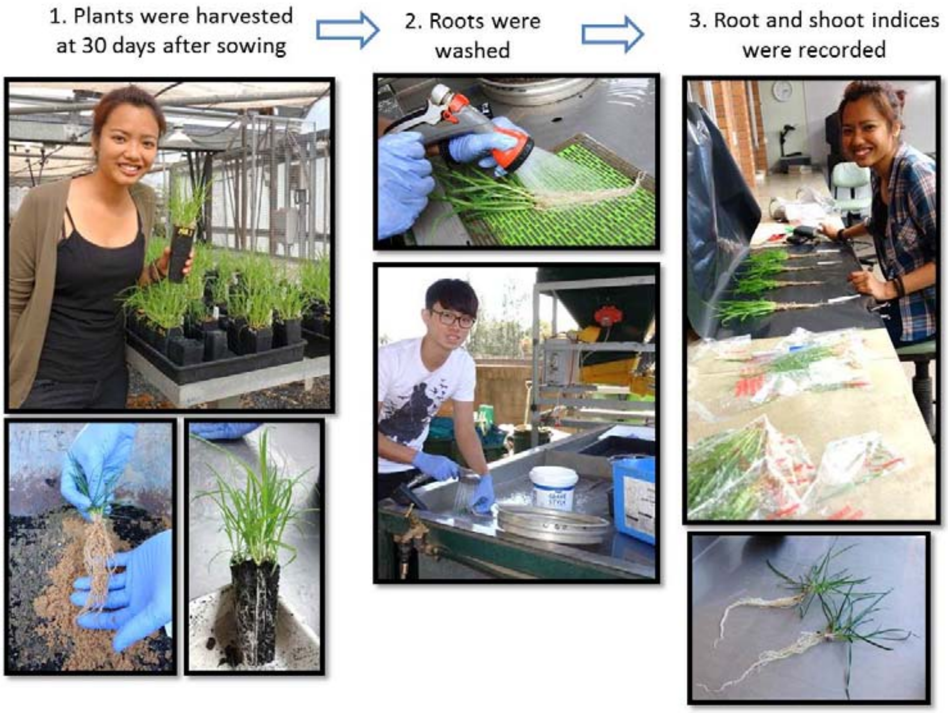


Figure 5.2 Turf plants were harvested at 30 days after sowing, their roots were washed and root and shoot indices recorded for each plantlet.

5.1.2 Results and Discussion

This study demonstrated for a couch and kikuyu turf that biochar products can significantly enhance turf establishment. In fact, for both varieties the shoots and roots of plantlets at 30 days after sowing from seed accumulated up to <u>twice as much biomass</u> when grown in media containing certain biochars relative to the control (i.e. media without biochar, Figure 5.3A and B). There was a trend towards vegetatively propagated couch shoots also benefitting from biochar additions, but we surmise that inadequate time had elapsed to show a significant difference (Figure 5.3C, ANOVA: shoots P=0.088, roots P=0.654).

For the seed propagated varieties, there was a clear <u>species specific</u> biochar response (i.e. a treatment × species interaction, Table 5.2A), possibly as a result of <u>inhibitors</u> in certain biochars slowing couch turf establishment at the seed germination stage (Figure 5.4). Specifically:
Shoot and root performance was almost doubled for both varieties when grown in sand amended with the green waste biochar from Technology B (B|GW, Figure 5.3), relative to the control without biochar. However, kikuyu turf shoot and root biomass was most enhanced by the green waste biochar from Technology A (biochar A|GW, Figure 5.3A) while the couch turf was either not affected or harmed by this same biochar (Figure 5.3B). This poor response of the couch turf to biochar A|GW may have been due to inhibitors because:

- <u>Seed germination</u> of the couch turf was possibly slowed by inhibitors in the A|GW biochar (red arrows in Figure 5.4). For example, at 10 days after sowing, fewer couch seeds had germinated in the potting media amended with the A|GW biochar than for the control (Figure 5.4A).
- Kikuyu responded differently to the couch, its seed germination was not significantly slowed by the A|GW biochar (i.e. there was a significant

Treatment × Species interaction for seed germination at 10 days after sowing, which disappeared by day 30, Table 5.3).

Thus the findings from this trial concur with Section 3.2, *viz.* an interplay of chemical stimulants and inhibitors is likely responsible for species and crop specific biochar responses.

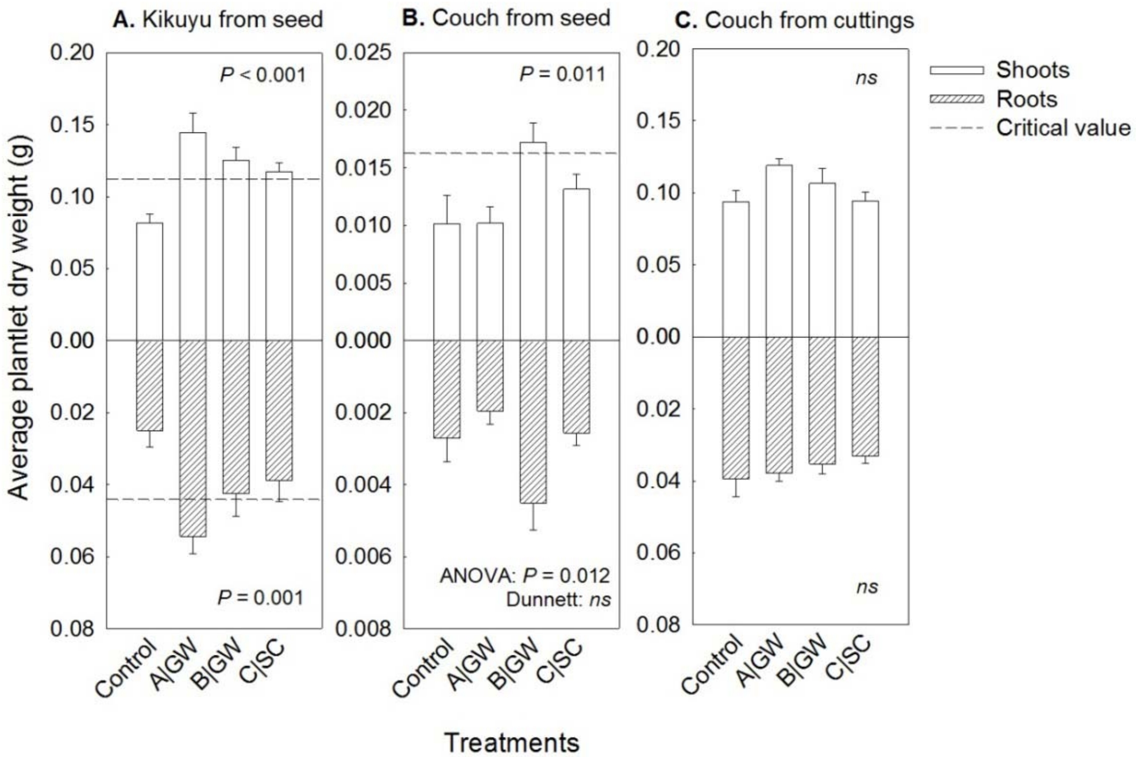


Figure 5.3 Turf establishment as shoot and root biomass at 30 days after sowing (bars are mean ± SE). Establishment was for a kikuyu and couch turf sown from seed (graph A and B, respectively) or couch from vegetative cuttings (graph C) grown in sand amended with one of three biochars or no biochar (control). Biochars were made from green waste by Technology A or B (A|GW and B|GW, respectively) or from sugarcane trash by Technology C (C|SC). The dashed grey line in the bar graph indicates Dunnett's critical difference; means above this line are significantly different to the control. ANOVA significance is shown in each panel. For root biomass for couch from seed (graph B), the Dunnett's test showed no significant difference between treatment means and the control (ANOVA P=0.012).

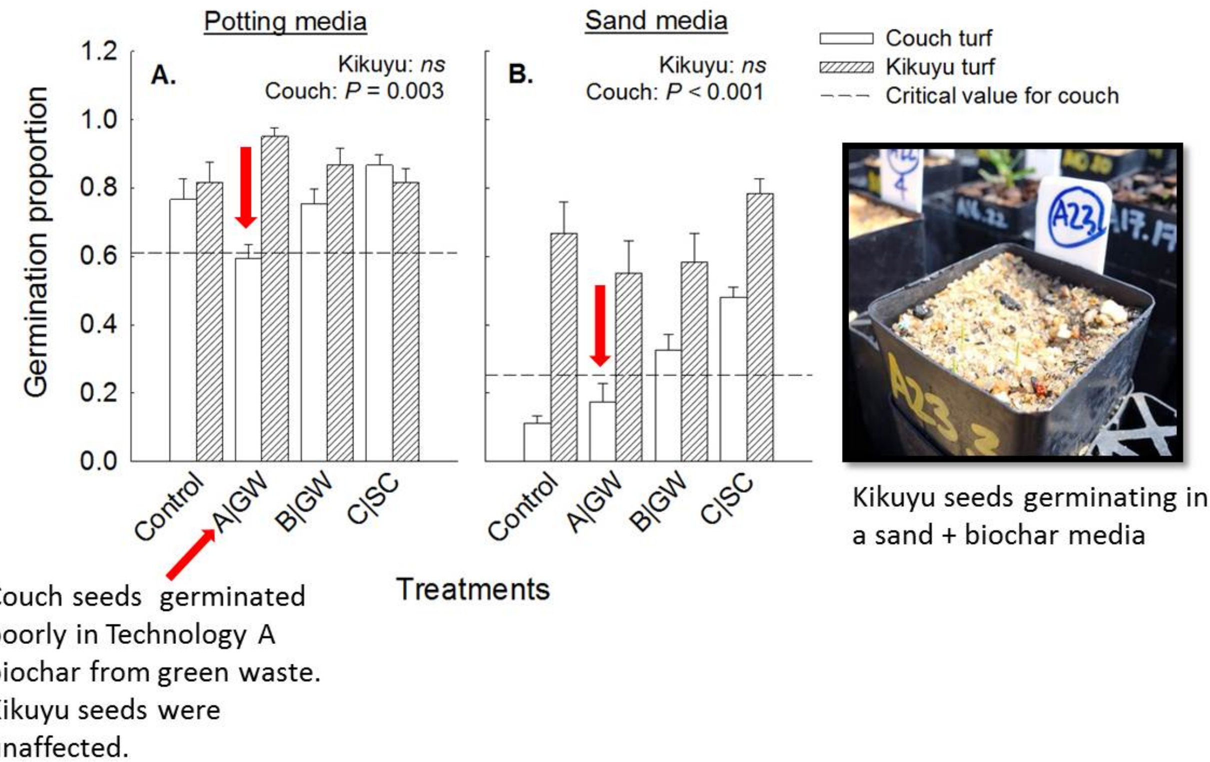


Figure 5.4 Seed germination proportion at 10 days after sowing (bars are mean ± SE) for a kikuyu and couch turf sown from seed (striped and white bars, respectively) into a pine bark potting media or sand amended with one of three biochars or no biochar (control). Biochars were made from green waste by Technology A or B (A|GW and B|GW, respectively) or from sugarcane trash by Technology C (C|SC). The dashed grey line in the bar graph indicates Dunnett's critical difference; means below (graph A) or above (graph B) this line are significantly different to the control. ANOVA significance is shown in each graph.

Table 5.2 General linear model analysis of variance and means testing the effect of three biochars and a control (Treatment) and growing medium (Potting media, sand or pine bark) for a couch vs. kikuyu turf sown from seed (i.e. Species, Table 5.2A) or for a couch turf established from seed vs. vegetative cuttings (i.e. Propagation method, Table 5.2B) on shoot and root dry weight at 30 days after sowing.

A. Kikuyu vs. couch grown from seeds

Treatment	Shoot DW	Root DW
Block	ns	*
Treatment	***	*
Block × Treatment	ns	ns
Potting media	***	***
Treat × Media	***	**
Species	***	***
Treat × Species	**	**
Media × Species	***	***

B. Couch grown from seeds vs. plantlets

Treatment	Shoot DW	Root DW	DF
Block	ns	ns	9
Treatment	*	*	3
Block × Treatment	ns	ns	27
Potting media	ns	ns	1
Treat × Media	ns	ns	3
Propagation method	***	***	1
Treat × Propagation	*	*	3
Media × Propagation	**	ns	1

Within each column, nonsignificant differences and significant differences are $P \le 0.05$, 0.01 and 0.001 are indicated by ns, *, ** and ***, respectively. Values are the mean of 10 replicates (one replicate per block, 10 blocks). Residual degrees of freedom 107-110. Data were not transformed, transformation did not improve the homogeneity of variance.

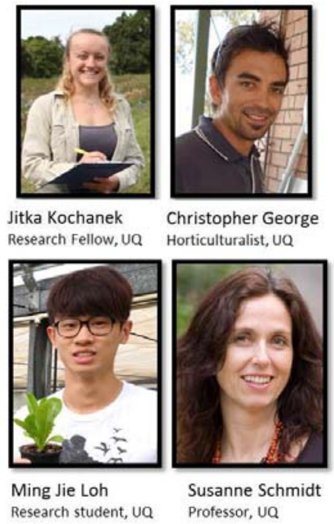
Table 5.3 General linear model analysis of variance and means testing the effect of three biochars and a control (Treatment) and growing medium (Potting media, sand or pine bark) for a couch vs. kikuyu turf sown from seed (Species, Table 5.2A) on seed germination at 10 and 30 days after sowing.

Treatment	Germination (% 10 days)	Germination (% 30 days)	Degrees of freedom
Block	ns	ns	9
Treatment	**	ns	3
Block × Treatment	ns	ns	27
Potting media	***	***	1
Treat × Media	*	ns	3
Species	***	***	1
Treat × Species	**	ns	3
Media × Species	**	ns	1

Within each column, nonsignificant differences and significant differences are $P \leq 0.05$, 0.01 and 0.001 are indicated by ns, *, ** and ***, respectively. Values are the mean of 10 replicates (one replicate per block, 10 blocks). Residual degrees of freedom is 111. Proportions were arcsine transformed prior to analysis to improve the homogeneity of variance.

5.2 Nursery Production

Section 5.2 contributors:



Background: As the cost of commonly used amendments escalate or growers look to more environmentally friendly products, biochar could replace or be used alongside conventional amendments for plant growing medias (Dumroese *et al.*, 2011).
Examples from literature of products that biochar may enhance or replace (relevant for the nursery industry) include:
<u>Vermiculite</u>: A pelleted biochar was useful as a substitute for vermiculite in a peat-based nursery mix, exhibiting desirable characteristics for small volume (<500 ml) container production for reforestation and ecosystem restoration at rates below 50% (by dry weight, Dumroese *et al.*, 2011).
<u>Peat</u>: Biochar was useful as a substitute for peat at rates below 50%, having high water and nutrient retention capacity but not readily decomposing like peat moss in turf, landscaping (Brockhoff *et al.*, 2010) and container medias (Tian *et al.*, 2012).
<u>Activated charcoal</u>: Biochar may replace activated charcoal in tissue culture, being a less expensive product with equal benefits (Di Lonardo *et al.*, 2013). Biochar behaved in the same way as activated charcoal for the growth of white poplar (*Populus alba* L.) in tissue culture. Both biochar and activated charcoal increased root dry biomass, rootability of shoots, number of roots and shoot length (by up to 100%) compared to media without these products. The mechanism suggested was reduced ethylene accumulation in the vial atmosphere (Di Lonardo *et al.*, 2013).

While these results are promising, the usefulness of biochar for nursery production requires more research, as was also concluded by an Australian Nursery and Garden Industry study that found no plant growth benefits for viola, pansy or lilly pilly from potting medias amended with a biochar derived from Sydney Blue Gum (NGIA, 2011).

Previous studies have rarely compared multiple biochars, hence in Section 5.2 the effects of five biochars (Table 5.4) at two application rates (*c.* 3 and 10%) are tested. The aim of this study was to determine whether biochars i) enhance seed germination and establishment of a common nursery line grown in a nursery setting and ii) enhance plant growth in nursery potting medias as well as sand.

Table 5.4 Treatments used in the Section 5.2 nursery production trial.

#	Treatment	Feedstock	Pyrolysis technology	
1	Control	None	No biochar	
2	Biochar	Green waste	A	Large, stationary
3	Biochar	Green waste	B	Medium, stationary
4	Biochar	Sugarcane trash	C	Small, truck-mountable
5	Biochar	Papermill waste	A	Large, stationary (batch reactor)
6	Biochar	Woodchip	A	Large, stationary (batch reactor)

5.2.1 Materials and Methods

The study was carried out in a glasshouse at the UQ Gatton Plant Nursery Unit using a completely randomised block design with 5 blocks arranged along a slight light gradient and with 22 treatments in each block. Treatments were the three best biochar products identified previously (Sections 3, 4, 5.1) and two additional biochars made from broader organic feedstocks (i.e. woodchip and paper mill waste, Table 5.4) incorporated at a rate equivalent to *c.* 3 and 10% w/v into a coarse sand or composted pine bark potting media versus each media without biochar (control). Lettuce cv. Archangel Nr., a babyleaf direct sow Cos lettuce (South Pacific Seeds, 2010) was selected as a nursery transplant line for its sensitivity to phytotoxins (Paradelo *et al.*, 2010; Koci *et al.*, 2010) and active compounds within smoke and ash (Drewes *et al.*, 1995). **Agronomy:** Media pH was raised prior to biochar incorporation with dolomite at 1.3 g L^{-1}, (Mudgee, neutralising value 98) and plants grown in 100mm black plastic pots lined with white marex mesh to prevent media wash-out. Plants were fertigated with Flowfeed Ex 7 solution every Monday, Wednesday and Friday. Seeds and young seedlings were watered until runoff with a half strength Flowfeed solution in weeks 1 and 2 (i.e. 1 g Flowfeed per litre of water, 1 g L^{-1}), with 50ml of 1.5 g L^{-1} FlowFeed solution per pot in week 3, and with 2 g L^{-1} FlowFeed solution in week 4. Pots were irrigated daily with a hose using a rosette head attachment.

Nursery plant establishment trials began on 11th September 2012 and are summarised in Figure 5.5. Five lettuce seeds were sown per pot on the media surface and wetted until runoff. Seed germination was recorded at 3, 5 and 7 days after sowing, when the radicle had protruded from the seed to >1 mm. Two weeks after sowing plants were thinned to one average sized seedling per pot and the trial was terminated at 4 weeks after sowing. Measurements recorded at the 2 and 4 week harvests were shoot and root length and fresh and dry weight after drying at 65°C. Other data recorded was media pH, water holding capacity and bulk density of all medias and leaf samples were collected for nutrient analyses at trial termination (to be analysed).

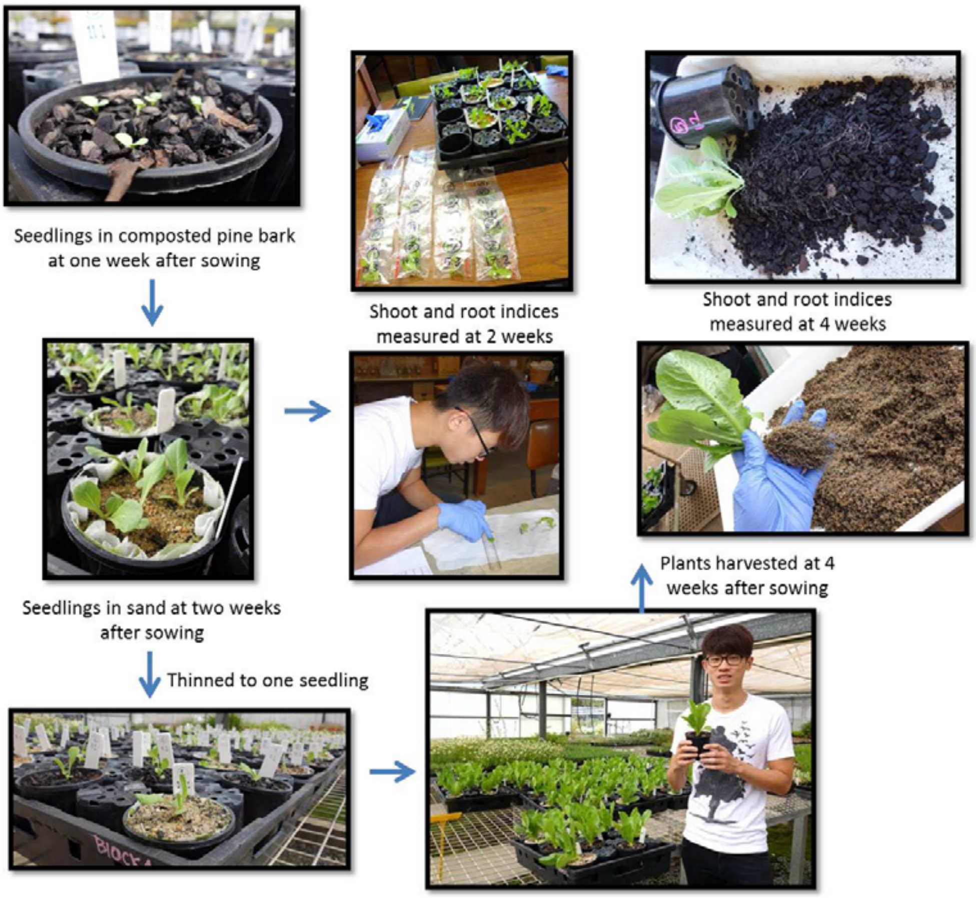


Figure 5.5 Lettuce plants were harvested at 14 and 28 days after sowing and their shoot and root indices recorded to quantify plant establishment rates within different biochar amended medias.

5.2.2 Results and Discussion

This study has demonstrated for a lettuce line grown in a nursery setting that biochar additions at 3 and 10% into composted pine bark potting and sand medias can significantly enhance plant establishment by increasing shoot biomass at 2 and/or 4 weeks after seed sowing (Figure 5.6). These results suggest <u>increased profitability for the grower</u> because through-put of seedlings in nurseries, such as vegetable transplants, stand to benefit from biochar additions, i.e. bigger seedlings were produced more rapidly in medias amended with certain biochars.

However, biochar products behaved differently in each media (i.e. there was a significant Treatment × Media interaction, Table 5.6 and 5.7). Importantly:

1. **Potting media:** Two week old plant shoots accumulated almost twice as much biomass when grown in media containing a green waste biochar incorporated at 10% and a sugarcane trash biochar at 3% relative to the potting mix alone (control, Figure 5.6A). By week 4, shoot biomass was not significantly enhanced by biochar in the nursery media (Figure 5.6C).
2. **Sand media:** Almost all biochars incorporated into the sand media enhanced plant performance at weeks 2 and 4 relative to the sand alone (control, Figure 5.6B and D, respectively). Those biochars that contained the highest

concentrations of plant promoting compounds (identified in Section 3.2) were the most beneficial for shoot biomass accumulation in week 4, particularly at 10% additions (i.e. green waste biochars from Technology A and B, Figure 5.6D).

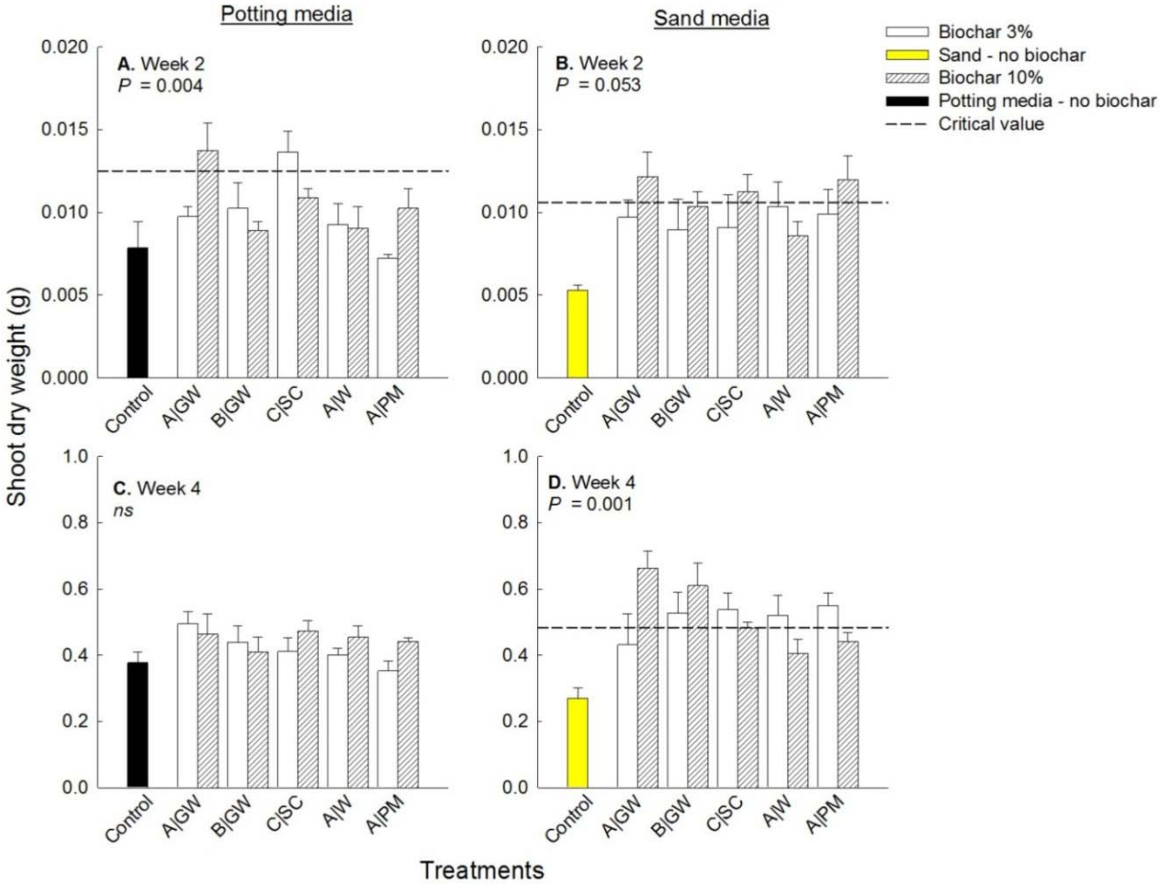


Figure 5.6 Lettuce plant establishment as shoot biomass (bars are mean ± SE) recorded at 2 and 4 weeks after sowing in a pine bark potting media or sand amended with one of five biochars or no biochar (control). Biochars were made from green waste by Technology A or B (A|GW and B|GW, respectively), from sugarcane trash by Technology C (C|SC) or from woodchips or paper mill waste by Technology A (A|W and A|PM, respectively) and applied at 3 and 10% (white and striped bars, respectively). The dashed grey line in the bar graph indicates Dunnett's critical difference; means above this line are significantly different to the control. ANOVA significance is shown in each panel.

Other notable results from Section 5.2 trials:

1. **Water holding capacity** (WHC) was significantly increased above the control by all but one biochar addition in both sand and potting medias (Table 5.5). In fact, the potting media WHC was increased by up to 35% by the sugarcane trash biochar (i.e. the potting media control had a 52% WHC, at 10% this biochar increased WHC to 71%).
2. **Bulk density** of the potting media was improved by a 10% biochar addition (Table 5.5). The control potting media without biochar had a bulk density of 0.25 g cm^{-3} while media containing the green waste biochar from Technology B at 10% raised bulk density to a more desirable 0.29 g cm^{-3} (ideal media bulk density is 0.3-0.6 g cm^{-3}; Handreck & Black, 2010). In the sand media, almost all biochars significantly reduced bulk density to more desirable levels relative to the control without biochar. As in Section 4.3, the sugarcane trash biochar was

most effective at reducing bulk density (i.e. sand control was 1.78 g cm^{-3}, the sugarcane biochar at 10% reduced bulk density to 1.22 g cm^{-3}).

3. **pH** was significantly increased by most 10% biochar additions into sand relative to the sand control (Table 5.5). While there was a trend towards increased pH in the potting media with biochar additions, these differences were not significant.

4. **Seed germination** was not significantly improved or harmed by biochar additions into either sand or potting medias (data not shown, concurs with Section 3.2 for lettuce cv. Archangel Nr).

5. **Root biomass** was not significantly affected by biochar additions into either sand or potting medias (Table 5.6 and 5.7).

Table 5.5 Growing media pH, bulk density and water holding capacities for a composted pine bark nursery potting media or sand amended with one of five biochars or no biochar (control). Biochars were made from green waste by Technology A or B, from sugarcane trash by Technology C or from woodchips or paper mill waste by Technology A and applied at *c.* 3 or 10%. Stars indicate means significantly different to the control (Dunnett's test).

		Treatment	pH	Bulk density (g cm^{-3})	Water holding capacity (%)
Potting media					
No biochar		Control	5.2 ± 0.02	0.25 ± 0.000	51.7 ± 1.15
Green waste biochar	Tech A	Biochar 3%	5.4 ± 0.03	0.27 ± 0.005	63.0 ± 0.50*
		Biochar 10%	6.1 ± 0.03	0.27 ± 0.005	64.3 ± 0.55*
Green waste biochar	Tech B	3%	5.8 ± 0.04	0.25 ± 0.010	61.4 ± 0.05*
		10%	6.2 ± 0.03	0.29 ± 0.010*	64.5 ± 0.05*
Sugarcane trash biochar	Tech C	3%	5.8 ± 0.02	0.25 ± 0.000	67.7 ± 0.10*
		10%	6.0 ± 0.01	0.25 ± 0.005	71.1 ± 0.28*
Woodchip	Tech A	3%	5.6 ± 0.04	0.25 ± 0.005	64.1 ± 0.10*
		10%	5.4 ± 0.02	0.24 ± 0.005	64.0 ± 0.75*
Paper mill waste	Tech A	3%	6.5 ± 0.02	0.26 ± 0.005	65.3 ± 0.15*
		10%	6.7 ± 0.00	0.27 ± 0.005	67.1 ± 0.25*
Sand media					
No biochar		Control	7.2 ± 0.11	1.78 ± 0.005	17.9 ± 0.20
Green waste biochar	Tech A	Biochar 3%	7.5 ± 0.01	1.67 ± 0.035*	18.7 ± 0.15
		Biochar 10%	7.9 ± 0.08*	1.55 ± 0.005*	20.8 ± 0.25*
Green waste biochar	Tech B	3%	7.3 ± 0.05	1.67 ± 0.030	19.4 ± 0.00*
		10%	7.7 ± 0.09*	1.47 ± 0.045*	22.0 ± 0.30*
Sugarcane trash biochar	Tech C	3%	7.2 ± 0.05	1.58 ± 0.005*	20.1 ± 0.40*
		10%	7.9 ± 0.02*	1.22 ± 0.035*	25.4 ± 0.00*
Woodchip	Tech A	3%	6.8 ± 0.01*	1.34 ± 0.015*	22.6 ± 0.40*
		10%	6.8 ± 0.08*	1.63 ± 0.000*	19.2 ± 0.20*
Paper mill waste	Tech A	3%	8.8 ± 0.08*	1.58 ± 0.005*	19.2 ± 0.15*
		10%	8.6 ± 0.04*	1.55 ± 0.015*	21.4 ± 0.00*

Table 5.6 General linear model analysis of variance and means testing the effect of five biochars and a control (Treatment) and growing medium (Potting media, sand or pine bark) on shoot and root indices for lettuce at 2 and 4 weeks after sowing.

	A. Week 2				B. Week 4		
Treatment	Shoot length	Root length	Shoot DW	Root DW	Shoot DW	Root DW	DF
Block	ns	ns	ns	ns	**	ns	4
Treatment	*	ns	**	ns	***	ns	10
Block × Treatment	ns	ns	ns	ns	ns	ns	40
Potting media	***	***	ns	ns	**	*	1
Treat × Media	**	ns	ns	ns	***	ns	10

Within each column, nonsignificant differences and significant differences are $P \leq 0.05$, 0.01 and 0.001 are indicated by ns, *, ** and ***, respectively. Values are the mean of 5 replicates (one replicate per block, 5 blocks). Residual degrees of freedom = 44. Data were not transformed, transformation did not improve the homogeneity of variance.

Table 5.7 General linear model analysis of variance and means testing the effect of five biochars and a control (Treatment), growing medium (Potting media, sand or pine bark) and harvest week (Week, 2 vs. 4) on shoot and root dry weight of lettuce.

Treatment	Shoot DW	Root DW	Degrees of Freedom
Block	**	ns	4
Treatment	**	ns	10
Block × Treatment	ns	ns	40
Potting media	**	**	1
Treat × media	**	ns	10
Week	***	***	1
Treat × week	**	ns	10
Media × week	**	**	1

Within each column, nonsignificant differences and significant differences are $P \leq 0.05$, 0.01 and 0.001 are indicated by ns, *, ** and ***, respectively. Values are the mean of 5 replicates (one replicate per block, 5 blocks). Residual degrees of freedom = 142. Data were not transformed, transformation did not improve the homogeneity of variance.

5.3 Summary and Recommendations

Recommendations for urban horticulture:

1. **Turf producers:** Biochars can significantly enhance turf establishment. In this study, certain biochars doubled shoot and root biomass after 1 month for a kikuyu and couch turf growing in biochar amended sand relative to a control without biochar.
2. **Nursery producers:** Through-put of seedlings in nurseries, such as vegetable transplants, stand to benefit from biochar additions. In this study, bigger lettuce seedlings were produced more rapidly in medias amended with certain biochars, suggesting increased profitability for the grower.
3. **Media quality** was improved by biochar additions into sand and nursery potting media. Water holding capacity was increased and bulk density became more favourable with most biochar additions into medias.
4. **For consistent plant promoting results**, biochars should be produced without inhibitors or inhibitors leached from biochars post-manufacture (Section 3.2; Artiola *et al*., 2012). Once inhibitors are removed, biochar application rates can be based on cost-effectiveness and physical growing media requirements rather than species-specific application rates (as is currently required).
5. Biochar has high potential to **improve establishment for growers**, being a carbon-rich matrix in nursery, soil or landscaping medias that can be dosed with compounds, such as plant-promoting compounds and fertilisers, for release to plants in a more controlled manner (Gonzalez *et al*., 2012) while potentially also improving soil or media structure, water holding capacity, CEC and carbon content (Section 4.3).

The *Green City Loop* project is validating findings from this study through grower trials and working towards biochars that consistently promote plant establishment for the Australian Turf and Nursery and Garden Industries.

6.1 Economics of Pyrolysis Technologies and Biochars

The aim of Section 6.1 is to aid growers and waste managers in economic decisions. The current costs of pyrolysis technologies used in this study and the market price of biochar from these units, where applicable, are summarised in Figure 6.1 and below:

- **Technology A:** To process 29,000 tonnes of waste annually into 7,000 tonnes of biochar and 6,000 MWh of energy, this centralised pyrolysis plant with a continuous throughput would cost $8.5 million in capital costs and $1 million in development costs.
- **Technology B:** To process 250-300 kg of feedstock per hour this centrally located, stationary pyrolysis unit would cost *c.* $212,000 to purchase. This company currently sells poultry litter biochar at $1000 per tonne (+GST, factory door price) and is manufacturing a mobile unit that they estimate will cost $12,000-50,000.
- **Technology C:** This mobile truck-mountable unit can process up to 600 kg of feedstock per hour and generate 2.5-3 MW of heat for applications such as grain drying, hot water production or steam generation. The company provides a four year serviced monthly lease for *c.* $15,000 per month (equivalent to *c*. $20 per tonne of input biomass, assuming the system is run for 24 hours, 7 days per week). This company currently sells biochar at $250 m^3 (factory door price) using various feedstocks (e.g. green waste, hardwood chips, cotton gin trash, almond shells, rice husks, grape marc, olive wastes). They predict that in **2015 this biochar price will halve** as production efficiencies improve.

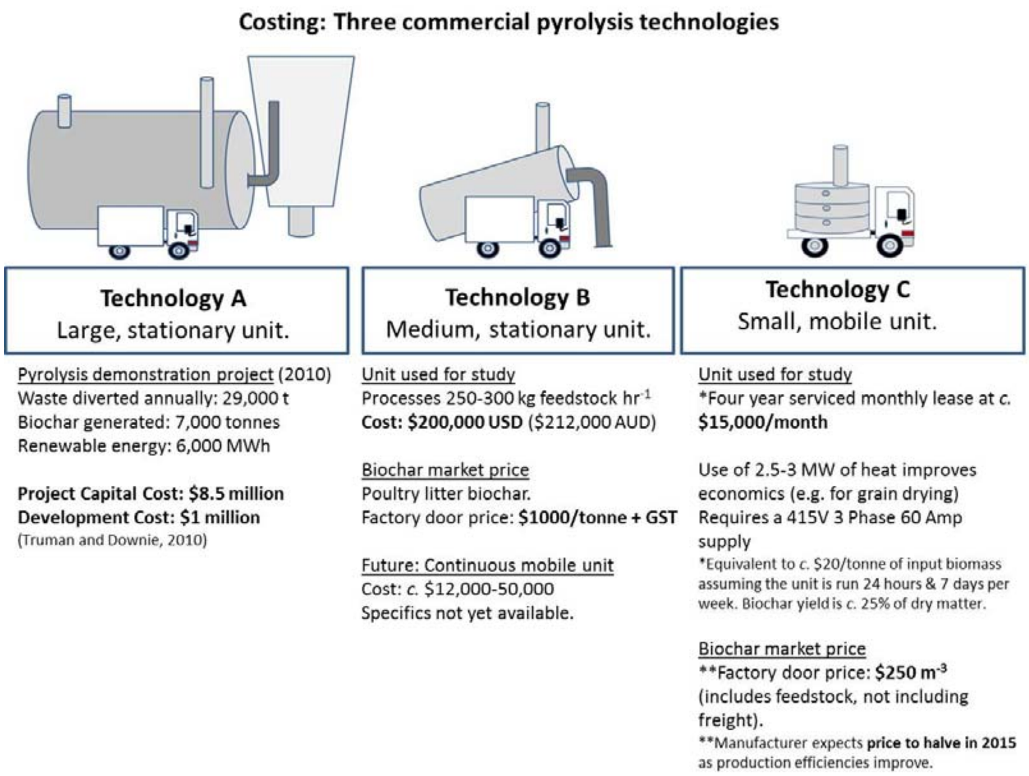


Figure 6.1 Costing for the three pyrolysis technologies used to make study biochars, the current biochar market price (where applicable) and future units and biochar costs. Technology B (R. Burnett, pers. comm.), Technology C (J. Joyce, pers. comm.)

Throughout this study (2010-14), pyrolysis has been a **novel technology** with few existing markets and only small-scale biochar production. As new markets for biochar products emerge and manufacturers upscale production (i.e. economies of scale improve), the cost of delivering new units and products will decline. The *Closing the Green City Loop* project will provide detailed cost analyses in 2017 using updated biochar and composting pricing together with productivity indices from grower systems to determine the cost-effectiveness of products within commercial enterprises.

6.2 Logistics of Biochar Use for Horticulture

The logistics of **storage, transport, application** and **use** of biochar in horticulture is discussed in Section 6.2. Overall, we recommend that:
1. For transport and handling biochars are kept at >20% moisture content* where possible.
2. For transport, storage and handling biochar is either:
i) Packaged in <450 L bags* for ease of storage, safety during transport and handling, or
ii) Mixed into medias such as soil, potting media or compost.

* Material Safety Datasheets for biochar caution that dry biochars with <20% moisture:
- Pose a flammability risk and require specialised transport if in packages larger than 450 L.
- Are dusty, covering the body with a fine black film and pose an inhalation hazard. Users handling dry biochar must wear appropriate PPE such as dust masks, goggles and cover their skin.

Broad-acre application of biochar has logistical issues that need to be overcome:
1. Biochars float away after heavy downpours when applied into topsoil (10 cm in this study). Thus we recommend:
    a. Growers cover the amended site with, for example, mulch, plastic or turf, or
    b. Plants are raised in containers with biochar amended medias prior to planting in the field. For example, into medias for vegetable transplants or fruit and ornamental trees and shrubs.
2. Tillage for broad-acre crop production will mix biochars into lower soil layers, diluting the quantity of biochar available to plant roots. Thus, a one-off biochar application will only be realistic for zero-till systems.
3. Field application of biochars requires wetting, otherwise the biochar can be blown away.

Urban Horticulture: The Turf and Nursery and Garden Industries are well set up for the logistics of biochar storage and application, as alluded to above. For example:

1. Currently used amendments are often already packaged into <450 L bags,
2. Currently used amendments are already mixed into medias such as soil, potting media or compost.
3. Biochars are less likely to float away and are easier to handle. For example:
    a. For turf, the sod can be rolled onto biochar-amended soils.
    b. For nursery producers, biochar amended medias are contained in pots.
    c. For landscapers, mulch can cover biochar-amended soils.

Biochar use logistics* for urban horticulture are being validated in the *Closing the Green City Loop* project with growers.

*Material Safety Data Sheets provided by commercial companies A, B and C classify biochar as a soil or potting media amendment with a low health hazard. Also, biochars made from woody feedstocks and pyrolysis temperatures similar to those used in this study (*c.* 500-600°C) tend to produce the cleanest biochars (Rogovska *et al*., 2012; Hale *et al*., 2012). As part of the *Closing the Green City Loop* project, the toxicology of biochars will confirm handling safety for growers.

Technology Transfer

2011

- Jitka was awarded a UQ Early Career Research Grant ($30K) to expand biochar experiments.
- April 4-7th 2011 attended the '*Managing Compost and Organic Matter in Horticulture*' International Symposium in Adelaide.
- Contact made with soil scientist Justine Cox – set up Section 4.2 and 4.3 field trial.
- A short powerpoint presentation titled 'Novel, Sustainable and Profitable Horticultural Management Systems: Soil Amendments, Waste Reuse and Carbon Sequestration' was authored by Jitka and presented by Prof Stephen Joseph, as part of a summary of Australian biochar-related projects, at the 2nd Asia Pacific Biochar Conference in Kyoto (Sep 2011).
- A talk titled 'Effects of Biochar and Compost on Soil Properties, Blueberry growth and Berry Yield' was co-authored by NSW DPI soil scientist Justine Cox and UQ scientist Dr Jitka Kochanek. Justine presented the talk at a Soil and Climate DPI workshop (Sep 2011).
- Working relationships were formed with the four amendment manufacturers used to make study biochars and composts. Logistics for compost and biochar manufacture continued from summer to spring, 2011.
- Qld Recycled Organics Council Inc. (Q-ROC): Jitka attended the first general meeting of Q-ROC on 4th November 2011.
- Research exemptions to undertake field trials were granted by the Qld Department of Environment and Resource Management (DERM) and NSW Office of Environment and Heritage, Department of Premier and Cabinet. The process began in Feb 2011 and continued to Oct 2011.
- University of Western Australia (UWA) collaboration: A Collaborative Research Agreement was drafted between UQ scientist Dr Jitka Kochanek and natural products chemist Dr Gavin Flematti and plant physiologist Dr Rowena Long from UWA.
- Jitka became a mentor for the Horizon Scholarship Program (formerly the Investing in Youth program), providing mentorship and career guidance to HAL supported Agricultural Science student Mr Samuel Adams in 2011-12.
- Jitka supervised Industrial Placement student Mr James Fleming from March to June 2011.

2012

- Jitka was awarded a UQ New Staff Grant ($12K) to expand seed germination and plant establishment experiments.
- Poster presentation - Frontiers of Science symposium, Menzies Hotel, Sydney, 2-4th Dec 2012. Dr Jitka Kochanek was invited by the Australian Academy of Science to the 2012 Frontiers of Science symposium titled 'Science for a Green Economy'. This symposium "brings together the very best young Australian scientists to discuss emerging technologies, new opportunities and exciting cutting-edge advances in their fields." All expenses were paid by the Theo Murphy (Australia) Fund, courtesy of the Royal Society of London. Jitka presented a poster titled: '*Biochar from recycled wastes for novel applications in horticulture*' which showcased the HG10025 project, as well as work with UWA scientists. The audience of *c.* 100 was multidisciplinary, including economists, business groups, lawyers, climatologists, ecologists, agricultural scientists and more. The poster and project were very well received.
- Guest lectures - Jitka presented multiple guest lectures to horticultural and plant science students at UQ, giving a detailed overview of the HG10025 project.
- Student project supervision - The reception to lectures was overwhelmingly positive, and resulted in four excellent second and third year students volunteering their time towards the project during second semester 2012
- Public release of information - UQ School of Agriculture and Food Sciences website.
- Field day at Wollongbar NSW DPI, 6th June 2012. A biochar workshop was held at the Wollongbar Primary Industries Institute, with an attendance of *c* . 100 farmers

and other stakeholders. Soil scientist Justine Cox and farmer Ridley Bell presented the long-term blueberry field trial while Dr Jitka Kochanek presented an overview of the entire HG10025 project. Brochures explaining the HG10025 project were disseminated during the blueberry trial site visit.

2013

- Jitka attended the Turf Producers Australia Conference field day at Australian Lawn Concepts on 3rd May 2013. This was a fantastic opportunity to meet key industry personnel, gain production know-how, showcase findings from project HG10025 and discuss future project opportunities.
- Jitka met with key industry stakeholders to ensure industry relevance of proof of concept trials and to guide the project's future direction. She met with Brisbane City Council executives at Rochedale Education Centre on 19th March, Mr Robert Prince (CEO, NGIA) in Sydney on 4th April, Mr John Keleher (Chairman, TPA) at Australian Lawn Concepts on 24th April. At the TPA field day she also met and discussed her project with Mr Craig Perring (HAL) and Mr Richard Stephens (Business & Industry Development Manager, TPA).
- Project communication, UQ Science Faculty business development manager, May 22nd.
- Project communication, UQ Dean of Agriculture, Prof Neal Menzies, June 5th. Outcome: $10K committed towards capital (plant growth cabinet) for projects MT13042 and MT13058.
- Project innovation and commercialisation discussions, Uniquest:
    - Dr Richard Haas (Manager, Innovation and Commercial Development, June 6th),
    - Dr Judy Halliday (Senior Director, Commercial Engagement – Science, 19th June).
- Brisbane City Council project communication and strategy development:
    - Mr James Fox (Senior Environmental Officer), Mr Oliver Furbur (Brisbane Waste Minimisation Manager), Rochedale Waste Education Centre, 30th May. Outcome: City demonstration sites added as in-kind for project MT13042.
    - Ms. Christine Blanchard (new HG10025 project manager), UQ, 27th June.
    - Field day with Christine Blanchard at NSW DPI, meeting with Justine Cox, 16th Oct.
- Turf Producers Australia Liaison:
    - Industry strategy meeting for projects HG10025 and MT13042, Mr John Keleher (TPA executive), Mr Danny Anderson (Senior Economic Development Officer, Qld State Development), Ms Christine Blanchard, Mr James Fox (BCC) – Australian Lawn Concepts, 2nd August. Outcome: voluntary contribution ($35K) secured towards project MT13042.
    - Project strategy discussions with Richard Stephens, September.
    - Permission received for trials at Australian Lawn Concepts, Yvette Morgan, Senior Environmental Officer, Environmental Services, South Region, Department of Environment and Heritage Protection (EHP), 6th September.
    - Project communication and strategy development with the Industry Advisory Committee for Turf Producers Australia, Dr Jitka Kochanek presented to IAC with Dr Chris Lambrides, 11th Nov.
- Chemical analyses of all six biochars completed with Assoc. Prof. Gavin Flematti (UWA), 13th Sep.
- Nursery and Garden Industry Liaison:
    - Project strategy discussions with Dr Anthony Kachenko, 30th July, 24th Sep.
    - Industry and researcher strategy and collaboration meeting, 24th October, UQ.
    - Industry experts present: Dr Anthony Kachenko (NGIA), Mr John McDonald (NGIQ), Christine Blanchard (BCC),
    - UQ researchers present: Prof Neal Menzies, Prof Ian Godwin, Prof Susanne Schmidt, Prof Jimmy Botella, Assoc. Prof. Victor Galea, Dr Margaret Johnston, Dr Chris Lambrides, Dr Don Loch, Dr Jitka Kochanek.

    - Outcome: Support from NGIA for levy contribution towards HAL project NY14006 (grant not successful)
    - Meeting with industry leaders suggested by Mr John McDonald (NGIQ): Mr Steve McGovern (general manager) and Mr Alistair Pritchard (CEO), 23rd Oct. Outcome: one grower trial site will be at Zoom Garden nursery (Burpengary, Qld).
- Proposal submitted to HAL Strategic Investment Call 13/14, 15th Oct ($35K from BCC, $10K UQ).
    - Funding gained for VC project "Closing the Green City Loop, Phase I", began Jan 2014.
- Other applications submitted for grants or awards in 2013:
    - Rising Star Award for Women in Technology, submitted 31st July (not successful).
    - HAL young researcher award, submitted 20th September (not successful).
    - HAL 2014/15 call, submitted Oct 2013 (not successful)

2014

- Poster presentation showcasing projects HG10025 and MT10342 presented at the Australian Nursery and Garden Industry Conference in Sydney: *Blue Sky Thinking, Real Green Living*, Darling Harbour, 10-13th March 2014.
- Project MT13042 was publicised as an oral paper by Christine Blanchard (Waste Minimisation Manager, BCC) at the *2014 Annual Arboriculture Conference and Australian Tree Climbing Championships* $_{TM}$ at the Novotel Twin Waters on the Sunshine Coast, 4 - 8 April 2014. The oral presentation and handouts were prepared by Jitka, Christine presented the paper.
- VC partner found in June 2014 for "Closing the Green City Loop, Phase II"
- Funding gained for VC project "Closing the Green City Loop, Phase II" in June 2014 for the HAL 2014/15 call (MT13058).
- Project strategy meetings with Turf Australia, BCC and NGIA delegates, multiple.
- Project innovation and commercialisation discussions, Uniquest, to patent new technologies arising from pyrolysis research.
- An oral paper will be presented at the 29th International Horticultural Congress: *'Horticulture - sustaining lives, livelihoods and landscapes' in August 2014.* Title: *A systems approach to recycling organics for horticulture: comparing emerging and conventional technologies*, Authors: Kochanek, J, Swift, RS, Flematti, GR.
- A field day on 23rd August 2014 will be held for the 29th International Horticultural Congress to view the long term perennial field site, set up in 2011 on a commercial blueberry farm with soil scientist Justine Cox.

Key Outcomes and Recommendations

Product preparation (Section 2) and quantification of physical and chemical properties of biochar products (Section 3.1) revealed that:

1) Compost and biochar production are synergistic. Green waste fines are best for compost production due to their rapid decomposition and low energy value, woody materials are best for biochar production.

2) The carbon in study biochars was highly aromatic, hence likely to be environmentally recalcitrant and useful for carbon sequestration.

3) The pyrolysis technology used to make study biochars influenced organo-chemical and physical properties more than the input feedstock. Thus different pyrolysis technologies may produce biochars ideal for different market applications. For example:

- Rapid thermal carbonisation (Technology C) may be particularly useful for creating biochars that benefit agronomic physical and microbial soil function. The greater abundance of fixed carbon also suggests higher carbon sequestration potential.
- Biochars from slow pyrolysis (Technologies A and B) may be more useful as carbonaceous matrices for the slow release of compounds.

These assumptions will be validated in the *Closing the Green City Loop* project.

4) Biochar nutrient values are deceptive as elements in biochar tend to be plant unavailable, being volatilised during pyrolysis or incorporated within the carbon matrix. Fertiliser co-application with biochar is required to optimise plant growth (Section 3.3, 4.3). Potassium may be an exception and plant available exchangeable K increased in soils with biochar application (Section 4.3).

5) Quality feedstock inputs are important for making quality biochars. For example, extraneous material such as rocks and metal fragments should be removed and heavy metal contaminants minimised. Using predominantly woody feedstocks will minimise ash content of biochars and maximise their energy value and fixed carbon content.

In Section 3.2 this study revealed, for the first time, the interplay of chemical stimulants and inhibitors are likely responsible for species/crop specific plant growth responses to biochar.

Key recommendations:

- Management of stimulants to inhibitors during pyrolysis is unlikely to be feasible as this is too complex.
- To provide **consistent plant promoting results** manufacturers should aim to create biochars devoid of inhibitors or inhibitors be leached from biochars post-pyrolysis.

In Section 4 two long term field trials tested the usefulness, logistics and practicality of organic products for annual vegetable versus perennial field crop production. Both studies aimed to determine whether biochar outperforms or compliments compost in agronomic contexts. Hence both field sites tested three biochars, a green waste compost and a compost and biochar combination, incorporated at 30 t ha^{-1} each into the top 10 cm soil surface.

1) Annual vegetable crop rotation (Section 4.1):

- **Tomato** (*Lycopersicon esculentum* Mill. cv. Rebel): Biochar made from green waste, found to be high in chemical stimulants and most beneficial for tomato shoot growth in Section 3.2, resulted in the largest plants at 75 days after sowing and the greatest number of immature fruits at the trial termination (i.e. produced more fruits for longer than from other plots).

- **Lettuce** (*Lactuca sativa* L. cv. Archangel Nr): Growth of plants sown from seed was harmed by biochar additions, possibly as a result of excess fertiliser retention within biochars. Recommendation: Growers need to exercise caution when co-applying biochars and compounds during sensitive plant growth stages (e.g. fertilisers at excessively high rates, herbicides) since the retention of compounds within biochars has the potential to harm plants.
- Glasshouse pot trials using the same soil, species and organic products revealed no differences in biomass accumulation between treatments. Hence amendments would likely have had a larger effect on plant growth and yield on a different soil (confirmed for a ferrosol and sand, Sections 4.2 and 5, respectively).

2) Perennial field crop production (Section 4.2):

- **Blueberry** (*Vaccinium corymbosum* L. hybrid 'Opie'): Compost and biochar, applied together, promise to be a winning combination for perennial crops over the long term. This product combination resulted in significantly greater fruit yields in 2013, particularly during the latest stages of fruiting. For example, in week 18 the mass of marketable fruit collected from bushes grown in soils with the compost and biochar combination was almost twice that of any other treatment plots.

3) Key soil health and carbon sequestration improvements from field trials (Section 4.3):

- Soil carbon content increased significantly with certain organic product additions.
- Soil pH was buffered significantly by certain organic product additions.
- Cation exchange capacity (CEC) increased significantly with certain organic product additions, increasing CEC from low for the control to moderate with additions.
- Plant available potassium increased significantly with all organic additions in the first year, supporting the theory that one way in which biochars improve plant growth directly is by contributing plant available potassium.
- Soil bulk density was reduced significantly with certain organic product additions. Soils amended with the sugarcane trash biochar and biochar and compost combination showed a lower bulk density in 2013 than the control soil.

Other notable observations were that:

- Organic products did not result in saline soils.
- Organic products did not elevate phosphorus or nitrogen in year 1, supporting the theory that these elements are not plant available in biochar, being either volatilised during pyrolysis or incorporated within the carbon matrix. For the grower, this means that such organic products cannot be used as fertilisers.
- Organic products did not retain nitrate and ammonium in soils above control values. For the grower, this means that organic products will not necessarily retain nitrates and ammonium for plant growth or to prevent leaching into waterways.

Section 4 trials will continue as part of the *Closing the Green City Loop* project; berry yields will be determined in 2014 and 2015 for the blueberry trial, and soil quality and carbon sequestration indices collected annually at both sites.

Section 5 began to validate the benefits and shortcomings of biochar products for Australian urban horticulture, specifically turf (Section 5.1) and nursery production (Section 5.2).
Recommendations for urban horticulture:

1. **Turf producers:** Biochars can significantly enhance turf establishment. In this study, certain biochars doubled shoot and root biomass after 1 month for a kikuyu (*Pennisetum clandestinum* Hochst. ex Chiov.) and couch turf (*Cynodon dactylon* (L.) pers.) growing in biochar amended sand relative to a control without biochar.
2. **Nursery producers:** Through-put of seedlings in nurseries, such as vegetable transplants, stand to benefit from biochar additions. In this study, bigger lettuce seedlings (*Lactuca sativa* L. cv. Archangel Nr) were produced more rapidly in medias amended with certain biochars, suggesting increased profitability for the grower.
3. **Media quality** was improved by biochar additions into sand and nursery potting media. Water holding capacity was increased and bulk density became more favourable with most biochar additions.
4. **However, for consistent plant promoting results**, biochars should be produced without inhibitors or inhibitors leached from biochars post-manufacture (Section 3.2). Once inhibitors are removed, biochar application rates may be based on cost-effectiveness and physical growing media requirements rather than species-specific application rates.
5. Biochar has high potential to **improve establishment for growers**. With intelligent design biochar promises to be a carbon-rich matrix that can be dosed with compounds for release to plants in a more controlled manner in nursery, soil or landscaping medias, while potentially also improving media structure, water holding and cation exchange capacities and carbon content.

Section 6.1 provides the current and predicted costs of the three study pyrolysis technologies and the market price of biochars to aid growers and waste managers in economic decisions. As new markets for biochar products emerge and economies of scale improve, the cost of delivering new units and products will decline. The *Closing the Green City Loop* project will provide cost analyses in 2017 using updated biochar and compost pricing.

Section 6.2 discusses the logistics of storage, transport, application and use of biochar in horticulture. Recommendations are:
1. For transport and handling biochars are kept at >20% moisture content.
2. For transport, storage and handling biochar is either:
i) Packaged in <450 L bags for ease of storage, safety during transport and handling, or
ii) Mixed into medias such as soil, potting media or compost.
3. Broad-acre application of biochar has logistical issues that need to be overcome, for example, biochars float away after heavy downpours when applied into topsoil and tillage will mix biochars into lower soil layers.
4. The Turf and Nursery and Garden Industries are likely already well set up for the logistics of biochar storage and application, but this needs to be validated.

In summary, biochar from pyrolysis is a new technology that promises plant growth, yield and environmental promotion for horticulture. However intelligent design is needed for consistency in plant and environmental benefits; biochar should be manufactured by trained personnel who understand feedstock quality control and how the pyrolysis process can create biochars for specific market needs. Biochar is likely most useful as a carbon-rich matrix that can:

- Be dosed with compounds for controlled release to plants,
- Be dosed with and/or provide homes for plant-promoting microbes,
- Provide physical structure and improve water holding and cation exchange capacities to improve soil and growing media quality,
- Sequester carbon long-term.

The *Closing the Green City Loop* project will continue to work towards biochar design that provides consistent batch to batch plant promoting results and ease of handling for horticulture.

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References

Ahmed S, Hammond J, Ibarrola R, Shackley S, Haszeldine S. 2012. The potential role of biochar in combating climate change in Scotland: an analysis of feedstocks, life cycle assessment and spatial dimensions. *Journal of Environmental Planning and Management* **55**(4): 487-505.

Amonette JE, Joseph S. 2009. Characteristics of biochar: microchemical properties. In: Lehmann J, Joseph S eds. *Biochar for Environmental Management: Science and Technology*. Sterling, VA: Earthscan, 33-52.

Artiola JF, Rasmussen C, Freitas R. 2012. Effects of a biochar-amended alkaline soil on the growth of romaine lettuce and bermudagrass. *Soil Science* **177**(9): 561-570.

Australian Government. 2013. *State of Australian Cities 2013 - Brisbane*. A Report by the Australian Government, Department of Infrastructure and Transport MCU.

Bagreev A, Bandosz TJ, Locke DC. 2001. Pore structure and surface chemistry of adsorbents obtained by pyrolysis of sewage sludge-derived fertilizer. *Carbon* **39**(13): 1971-1979.

Baldock JA, Smernik RJ. 2002. Chemical composition and bioavailability of thermally altered *Pinus resinosa* (Red Pine) wood. *Organic Geochemistry* **33**(9): 1093-1109.

Beck DA, Johnson GR, Spolek GA. 2011. Amending greenroof soil with biochar to affect runoff water quantity and quality. *Environmental Pollution* **159**(8-9): 2111-2118.

Beckon WN, Parkins C, Maximovich A, Beckon V. 2008. A general approach to modelling biphasic relationships. *Journal of Environmental Science and Technology* **42**: 1308-1314.

Beesley L, Dickinson N. 2010. Carbon and trace element mobility in an urban soil amended with green waste compost. *Journal of Soils and Sediments* **10**(2): 215-222.

Beesley L, Moreno-Jimenez E, Gomez-Eyles JL, Harris E, Robinson B, Sizmur T. 2011. A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environmental Pollution* **159**(12): 3269-3282.

Brisbane City Council. 2009. Don't Throw it all Away: Towards Zero Waste, *Brisbane City Council, Waste Minimisation Strategy 2009-2026*. Brisbane City Council Information, Brisbane.

Brockhoff SR, Christians NE, Killorn RJ, Horton R, Davis DD. 2010. Physical and mineral-nutrition properties of sand-based turfgrass root zones amended with biochar. *Agronomy Journal* **102**(6): 1627-1631.

Brown R. 2009. Biochar production technology. In: Lehmann J, Joseph S eds. *Biochar for Environmental Management: Science and Technology.* London; Sterling, VA: Earthscan, 127-146.

Chan KY, Xu Z. 2009. Biochar: Nutrient properties and their enhancement. In: Lehmann J, Joseph S eds. *Biochar for Environmental Management: Science and Technology*. Sterling, VA: Earthscan, 67-84.

Costa JM, Heuvelink E. 2005. Introduction: the tomato crop and industry. In: Heuvelink E ed. *Tomatoes*. Oxfordshire, UK; Cambridge, USA: CABI Publishing, 1-19.

Csizinszky AA. 2005. Production in the Open Field. In: Heuvelink E ed. *Tomatoes*. Oxfordshire, UK; Cambridge, USA: CABI Publishing, 237-256.

Cox J and Kochanek J. In prep (c). Biochar and compost combinations are superior to single ameliorant inputs in a blueberry orchard soil. Journal undecided.

Di Lonardo S, Vaccari FP, Baronti S, Capuana M, Bacci L, Sabatini F, Lambardi M, Miglietta F. 2013. Biochar successfully replaces activated charcoal for in vitro culture of two white poplar clones reducing ethylene concentration. *Plant Growth Regulation* **69**(1): 43-50.

Downie A, Crosky A, Munroe P. 2009. Physical properties of biochar. In: Lehmann J, Joseph S eds. *Biochar for Environmental Management : Science and Technology*. Sterling, VA: Earthscan, 13-29.

Downie A, Truman J. 2010. Ballina Pyrolysis Demonstration Project (Report).

Drewes, FE, Smith, MT, Vanstaden, J. 1995. The effect of a plant-derived smoke extract on the germination of light-sensitive lettuce seed. *Plant Growth Regulation* **16**: 205-209.
Dumroese RK, Heiskanen J, Englund K, Tervahauta A. 2011. Pelleted biochar: Chemical and physical properties show potential use as a substrate in container nurseries. *Biomass & Bioenergy* **35**(5): 2018-2027.
Elad Y, Cytryn E, Harel YM, Lew B, Graber ER. 2011. The Biochar Effect: plant resistance to biotic stresses. *Phytopathologia Mediterranea* **50**(3): 335-349.
Epstein E, Bloom AJ. 2004. *Mineral Nutrition of Plants: Principles and Perspectives.* Sinauer Associates, Inc., Sunderland, Mass.
Fullelove G, Meurant N. 1998. *Growing Tomatoes in Queensland*. Brisbane: Deptartment of Primary Industries.
Future Focus. 2008. Strategic Actions: Stage 2 Report. *The Australian Horticulture Plan: Future Focus*.
Ghosh S, Yeo D, Wilson B, Ow LF. 2012. Application of char products improves urban soil quality. *Soil Use and Management* **28**(3): 329-336.
Gonzalez ME, Gonzalez A, Toro CA, Cea M, Sepulveda N, Diez MC, Navia R. 2012. Biochar as a renewable matrix for the development of encapsulated and immobilized novel added-value bioproducts. *Journal of Biobased Materials and Bioenergy* **6**(3): 237-248.
Graber ER, Harel YM, Kolton M, Cytryn E, Silber A, David DR, Tsechansky L, Borenshtein M, Elad Y. 2010. Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. *Plant and Soil* **337**: 481-496.
Hale SE, Lehmann J, Rutherford D, Zimmerman AR, Bachmann RT, Shitumbanuma V, O'Toole A, Sundqvist KL, Arp HPH, Cornelissen G. 2012. Quantifying the total and bioavailable polycyclic aromatic hydrocarbons and dioxins in biochars. *Environmental Science & Technology* **46**(5): 2830-2838.
Handreck K, Black N. 2010. *Growing Media for Ornamental Plants and Turf*. Sydney: University of New South Wales Press Ltd.
Hazelton P, Murphy B. 2007. *Interpreting Soil Test Results : What do all the Numbers Mean*. Collingwood, Victoria: CSIRO Publishing.
Heisswolf S, Carey D, Henderson C, R. OB, Deuter P, Lovatt J. 1997. *Lettuce Information Kit*: Department of Primary Industries, Queensland.
Heuvelink E. 2005. Developmental Processes. In: Heuvelink E ed. *Tomatoes*. Oxfordshire, UK; Cambridge, USA: CABI Publishing, 53-83.
Hoagland DR, Arnon DI. 1950. The water-culture method for growing plants without soil. *California Agricultural Experiment Station Circular* **347**: 1-32.
Horticulture Australia Ltd. 2009. Horticulture climate change action plan.
Grierson CS, Barnes SR, Chase MW, Clarke M, Grierson D, Edwards KJ, Jellis GJ, Jones JD, Knapp S, Oldroyd G, Poppy G, Temple P, Williams R, Bastow R. 2011. One hundred important questions facing plant science research. *New Phytologist* 192(1): 6-12.
International Biochar Initiative. 2013. Standardized Product Definition and Product Testing Guidelines for Biochar that is Used in Soil. *Product definition and specification standards. Version 1.1 (IBI-STD-01.1)*.
Jeffery S, Verheijen FGA, van der Velde M, Bastos AC. 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture Ecosystems & Environment* **144**(1): 175-187.
Jindo K, Suto K, Matsumoto K, Garcia C, Sonoki T, Sanchez-Monedero MA. 2012. Chemical and biochemical characterisation of biochar-blended composts prepared from poultry manure. *Bioresource Technology* **110**: 396-404.
Joseph SD, Camps-Arbestain M, Lin Y, Munroe P, Chia CH, Hook J, van Zwieten L, Kimber S, Cowie A, Singh BP, Lehmann J, Foidl N, Smernik RJ, Amonette JE. 2010. An investigation into the reactions of biochar in soil. *Australian Journal of Soil Research* **48**(6-7): 501-515.

Karami N, Clemente R, Moreno-Jimenez E, Lepp NW, Beesley L. 2011. Efficiency of green waste compost and biochar soil amendments for reducing lead and copper mobility and uptake to ryegrass. *Journal of Hazardous Materials* **191**(1-3): 41-48.
Kochanek J, Kochanek MA, Flematti GR, Swift R. In prep (a). Properties of biochars prepared principally from one feedstock using three pyrolysis technologies. *Bioresource Technology*.
Kochanek J, Long RL, Flematti GR. In prep (b). Unfolding the chemical mechanisms behind biphasic biochar. *New Phytologist*.
Koci V, Mocova K, Kulovana M, Vosahlova S. 2010. Phytotoxicity tests of solid wastes and contaminated soils in the Czech Republic. *Environmental Science and Pollution Research,* **17**: 611-623.
Kookana RS. 2010. The role of biochar in modifying the environmental fate, bioavailability, and efficacy of pesticides in soils: a review. *Australian Journal of Soil Research* **48**(6-7): 627-637.
Krull ES, Baldock JA, Skjemstad JO, Smernik RJ. 2009. Characteristics of biochar: Organo-chemical properties. In: Lehmann J, Joseph S eds. *Biochar for Environmental Management: Science and Technology*. Sterling, VA: Earthscan, 53-65.
Kulkarni MG, Ascough GD, Van Staden J. 2007. Effects of foliar applications of smoke-water and a smoke-isolated butenolide on seedling growth of okra and tomato. *Hortscience* **42**(1): 179-182.
Kulkarni MG, Ascough GD, Van Staden J. 2008. Smoke-water and a smoke-isolated butenolide improve growth and yield of tomatoes under greenhouse conditions. *Horttechnology* **18**(3): 449-454.
Laird DA. 2008. The charcoal vision: A win-win-win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal* **100**(1): 178-181.
Laird DA, Brown RC, Amonette JE, Lehmann J. 2009. Review of the pyrolysis platform for coproducing bio-oil and biochar. *Biofuels Bioproducts & Biorefining* **3**(5): 547-562.
Lehmann J, Joseph S. 2009. Biochar systems. In: Lehmann J, Joseph S eds. *Biochar for Environmental Management: Science and Technology.* London; Sterling, VA: Earthscan, 147-168.
Lehmann J, Rillig MC, Thies J, Masiello CA, Hockaday WC, Crowley D. 2011. Biochar effects on soil biota - A review. *Soil Biology & Biochemistry* **43**(9): 1812-1836.
Long RL, Williams K, Griffiths EM, Flematti GR, Merritt DJ, Stevens JC, Turner SR, Powles SB, Dixon KW. 2010. Prior hydration of *Brassica tournefortii* seeds reduces the stimulatory effect of karrikinolide on germination and increases seed sensitivity to abscisic acid. *Annals of Botany* **105**(6): 1063-1070.
Mattson N, Lieth H. 2008. Kardinal' rose exhibits growth plasticity and enhanced nutrient absorption kinetics following nitrate, phosphate, and potassium deprivation. *Journal of the American Society for Horticultural Science* **133:** 341-350.
Meyer S, Glaser B, Quicker P. 2011. Technical, economical, and climate-related aspects of biochar production technologies: a literature review. *Environmental Science & Technology* **45**(22): 9473-9483.
National Environment Protection Council 1999. Schedule B (I) - Guideline on Investigation Levels for Soil and Groundwater. *National Environment Protection (Assessment of Site Contamination) Measure 1999*. Australia.
Nursery and Garden Industry Australia. 2011. The effect of biochar amended growing media on plant nutrition and growth. *Nursery Paper*s Issue no. 9.
Oh TK, Shinogi Y, Chikushi J, Lee YH, Choi B. 2012. Effect of aqueous extract of biochar on germination and seedling growth of lettuce (*Lactuca sativa* L.). *Journal of the Faculty of Agriculture Kyushu University* **57**(1): 55-60.
Paradelo R, Moldes AB, Prieto B, Sandu RG, Barral MT. 2010. Can stability and maturity be evaluated in finished composts from different sources? *Compost Science & Utilization,* **18**: 22-31.
Quilliam RS, Marsden KA, Gertler C, Rousk J, DeLuca TH, Jones DL. 2012. Nutrient dynamics, microbial growth and weed emergence in biochar amended soil are

influenced by time since application and reapplication rate. *Agriculture Ecosystems & Environment* **158**: 192-199.
Rhyner CR, Schwartz LJ, Wenger RB, Kohrell MG. 1995. *Waste Management and Resource Recovery.* Lewis Publishers, CRC Press, Inc., Boca Raton, Florida.
Rogovska N, Laird D, Cruse RM, Trabue S, Heaton E. 2012. Germination Tests for Assessing Biochar Quality. *Journal of Environmental Quality* **41**(4): 1014-1022.
Ronsse F, van Hecke S, Dickinson D, Prins W. 2013. Production and characterization of slow pyrolysis biochar: influence of feedstock type and pyrolysis conditions. *Global Change Biology Bioenergy* **5**(2): 104-115.
Ryder EJ. 1999. *Lettuce, Endive and Chicory*: CABI Publishing.
Sarmah AK, Srinivasan P, Smernik RJ, Manley-Harris M, Antal MJ, Downie A, van Zwieten L. 2010. Retention capacity of biochar-amended New Zealand dairy farm soil for an estrogenic steroid hormone and its primary metabolite. *Australian Journal of Soil Research* **48**(6-7): 648-658.
Sohi SP, Krull E, Lopez-Capel E, Bol R. 2010. A review of biochar and its use and function in soil. *Advances in Agronomy* **105**: 47-82.
Solaiman ZM, Murphy DV, Abbott LK. 2012. Biochars influence seed germination and early growth of seedlings. *Plant and Soil* **353**(1-2): 273-287.
Spokas KA, Baker JM, Reicosky DC. 2010. Ethylene: potential key for biochar amendment impacts. *Plant and Soil* **333**(1-2): 443-452.
Standards Australia 2012. Australian Standard - Composts, Soil Conditioners and Mulches. AS4454 - 2012 (Incorporating Amendment No. 1): Committee CS-037, Garden Soils and Potting Mixes.
Tian Y, Sun XY, Li SY, Wang HY, Wang LZ, Cao JX, Zhang L. 2012. Biochar made from green waste as peat substitute in growth media for *Calathea rotundifola* cv. Fasciata. *Scientia Horticulturae* **143**: 15-18.
Vesilind PA, Worrell WA, Reinhart DR. 2002. *Solid Waste Engineering.* Brooks/Cole, Pacific Grove, California, USA.
Wang T, Camps-Arbestain M, Hedley M and Bishop P. 2012. Predicting phosphorus bioavailability from high-ash biochars. *Plant Soil* **357**: 173-187.
Warnock DD, Lehmann J, Kuyper TW, Rillig MC. 2007. Mycorrhizal responses to biochar in soil - concepts and mechanisms. *Plant and Soil* **300**(1-2): 9-20.
Warnock DD, Mummey DL, McBride B, Major J, Lehmann J, Rillig MC. 2010. Influences of non-herbaceous biochar on arbuscular mycorrhizal fungal abundances in roots and soils: Results from growth-chamber and field experiments. *Applied Soil Ecology* **46**: 450-456.
Yao Y, Gao B, Zhang M, Inyang M, Zimmerman AR. 2012. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. *Chemosphere* **89**(11): 1467-1471.
Zhang TY, Walawender WP, Fan LT, Fan M, Daugaard D, Brown RC. 2004. Preparation of activated carbon from forest and agricultural residues through CO_2 activation. *Chemical Engineering Journal* **105**(1-2): 53-59.

Appendix Table A1. Agronomic properties of the vertisol and ferrosol soils used in Section 4, Qld and NSW composts (NSW compost used for Section 4.2 and 4.3, otherwise all compost is Qld) and the pre-trial biochar used in Section 3.3.

	Unit	Vertisol soil	Ferrosol soil	Qld compost	NSW compost	Pre-Trial Biochar
EC	dS/m	0.086	0.14	2.5	1.7	2.7
pH	(CaCl2)	6.6	5.9	7.1	7.9	8.7
Total Nitrogen	%	0.1	0.27	0.89	0.75	0.85
Total Carbon	%	1.4	3.4	26	18	65
Ammonium	mg/kg	0.89	8.2	86	5.3	*
Nitrate	mg/kg	29	15	5.1	0.54	*
Colwell Phosphorus	mg/kg	150	*	420	700	380
Bray #1 Phosporus	mg/kg	*	6.9	*	*	*
Acid Neutralising capacity	% CaCO3	*	*	*	*	7.1
Exchangeable Cations						
Aluminium	cmol(+)/kg	<0.01	0.011	<0.01	<0.01	<0.01
Calcium	cmol(+)/kg	14	9.3	24	35	6
Potassium	cmol(+)/kg	1.1	0.44	11	11	13
Magnesium	cmol(+)/kg	9.7	0.95	10	8.6	3.1
Sodium	cmol(+)/kg	0.2	0.041	6	4	11
CEC	cmol(+)/kg	25	11	51	59	33
Calcium/Magnesium	Ratio	1.4	9.7	2.4	4.1	1.9
Aluminium Saturation	%	<0.04	0.11	<0.04	<0.04	<0.04
Exchangeable Calcium	%	56	87	47	60	18
Exchangeable Potassium	%	4.3	4.1	21	19	40
Exchangeable Magnesium	%	39	8.9	19	15	9.1
Exchangeable Sodium	%	0.79	0.38	12	6.8	34
DTPA Micronutrients						
Copper	mg/kg	1.2	1.1	3.5	3.5	1.4
Iron	mg/kg	13	28	140	180	20
Manganese	mg/kg	6.5	15	51	88	38
Zinc	mg/kg	1.2	1.2	37	25	49
ICP Elements						
Aluminium	%	1.3	5.6	0.28	0.87	0.46
Arsenic	mg/kg	<5	<5	10	<5	<5
Boron	mg/kg	<4	<4	12	10	33
Calcium	%	0.55	0.38	1.1	1.6	2
Cadmium	mg/kg	<0.3	<0.3	<0.3	0.4	<0.3
Cobalt	mg/kg	27	19	3.9	11	2.8
Chromium	mg/kg	60	87	120	120	71
Copper	mg/kg	25	14	25	31	22
Iron	%	4.3	7.5	0.86	2.4	1.2
Potassium	%	0.19	0.03	0.54	0.52	0.71
Magnesium	%	0.79	0.044	0.26	0.36	0.25
Manganese	mg/kg	590	1200	190	490	390
Molybdenum	mg/kg	<0.3	<0.3	0.64	0.48	0.61
Sodium	%	0.016	0.0035	0.14	0.1	0.36
Nickel	mg/kg	58	13	17	22	34
Phosphorus	%	0.14	0.085	0.12	0.22	0.19
Lead	mg/kg	3.1	7.2	20	57	3.5
Sulfur	%	0.011	0.062	0.12	0.11	0.097
Selenium	mg/kg	<4	<4	<4	<4	<4
Zinc	mg/kg	74	32	91	140	450