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Agricultural bio-char production, renewable energy generation and farm carbon sequestration in Western Australia: certainty, uncertainty and risk

Mark P McHenry

School of Engineering and Energy

Murdoch University

90 South Street, Murdoch, Western Australia, 6150

+61 430 485 306

E-mail address: mpmchenry@gmail.com

Abstract

Reducing the vulnerability of agriculture to climate change while increasing primary productivity requires mitigation and adaptation activities to generate profitable co-benefits to farms. The conversion of woody-wastes by pyrolysis to produce bio-char (biologically derived charcoal) is one potential option that can enhance natural rates of carbon sequestration in soils, reduce farm waste, and substitute renewable energy sources for fossil-derived fuel inputs. Bio-char has the potential to increase conventional agricultural productivity and enhance the ability of farmers to participate in carbon markets beyond traditional approach by directly applying carbon into soil. This paper provides an overview of the pyrolysis process and products and quantifies the amount of renewable energy generation and net carbon sequestration possible when using farm bio-waste to produce bio-char as a primary product. Whilst this research provides approximate bio-char and energy production yields, costs, uses and risks, there is a need for additional research on the value of bio-char in conventional crop yields and adaptation and mitigation options.

Keywords

Bio-char, charcoal, soil, carbon, renewable, biomass, Western Australia

1. Introduction

Working Group III, in their contribution to the IPCC's Fourth Assessment Report (AR4) stated the *high agreement* and *much evidence* that soil restoration and land use change mitigation measures can be implemented immediately by using existing technologies. Working Group III also stated the *high agreement* and *much evidence* that soil carbon sequestration is the mechanism responsible for most climate change mitigation potential (Paustian *et al.*, 1997). The IPCC's AR4 Synthesis Report confirmed that effective carbon-price signals can mobilise environmentally effective mitigation options in the agriculture and forestry sectors, including as improved land management practices that maintain soil carbon density and for soil carbon sequestration. However, to be able to successfully utilise soil carbon mitigation incentives, farmers will need to use iterative management processes that balance economic carbon sequestration benefits with conventional production co-benefits, and attitudes to risk (Intergovernmental Panel on Climate Change, 2000).

Decreasing the financial risks of farming in this period of relative climate policy uncertainty requires feasibility studies of synergies between conventional productivity and climate change mitigation and adaptation measures. Similarly, reducing farm investment risk in a changing climate will entail the greater use of monitoring to inform management practices that increase farm ecosystem stability and resilience to climate stress (Griffiths *et al.*, 2000; Tobor-Kaplon *et al.*, 2005; Harle *et al.*, 2006; Brussaard *et al.*, 2007). Therefore, sequestering carbon in agricultural soils is one such possible synergy that creates additional property rights for farmers, retains land values by soil conservation, and may improve conventional yields by modulating soil ecosystem variability (Klein *et al.*, 2007; Milne *et al.*, 2007).

There is considerable interest in finding reliable methods of sequestering carbon in agricultural soils to both reduce farm investment risk and cut atmospheric greenhouse gas concentrations, in a timeframe suitable to investors. Increasing the levels of soil organic carbon (SOC) by conventional agricultural management can take many years and involves significant uncertainty in regards to the resultant carbon fluxes (Denman *et al.*, 2007). A report by the National Carbon Accounting System (NCAS) authored by Valzano, Murphy and Koen (2005), focussed on the impact of tillage on changes in SOC density in Australia. The report found that low tillage and stubble retention

management practices only had an effect on SOC density up to depths of 30 cm in areas with mean annual temperatures between 12.8 and 17.4 degrees Celsius and an average annual rainfall above 650 mm (Valzano *et al.*, 2005). In Australian research plots that did show significant differences of SOC densities between using minimum disturbance methods and conventional tillage, the results have been modest. Farms using direct drill, retained stubble and moderate grazing production methods were found to have densities of around 57 t ha⁻¹ up to 30 cm of depth, while nearby heavily grazed farms using multiple crop tillage (with either tined or disc implements), had SOC densities of 43 t ha⁻¹ up to 30 cm soil depths (Valzano *et al.*, 2005). A study by Wright, Dou and Hons (2007) on SOC and nitrogen levels over 20 years of various tillage regimes, found the no-tillage practices only increased SOC, dissolved organic carbon and total nitrogen by 28, 18 and 33% respectively, when compared to conventional tillage (Wright *et al.*, 2007). While the benefit of using minimum tillage methods are clear for retaining natural SOC densities, sequestering sufficient volumes of SOC for carbon markets will likely require new approaches to purposefully add SOC to enhance existing carbon sinks.

The conversion of biomass to long-lived soil carbon species results in a long-term carbon sink, as the biomass removes atmospheric carbon dioxide through photosynthesis. Bio-char carbon species range in complexity from graphite-like carbon to high molecular weight aromatic rings, which are known to persist in soil for thousands to millions of years (Graetz and Skjemstad, 2003). Unlike fossil fuels, biomass is a renewable source of carbon and using it to produce bio-char can release energy with virtually no sulphur or mercury and very little nitrogen and ash waste (Antal and Gronli, 2003). Thus, producing bio-char from farm wood-waste appears to be one promising method of achieving greater levels of certainty and flexibility for integrating carbon sequestration accounting and renewable energy generation into conventional agricultural production (Lehmann, 2007). However, there remain large uncertainties of the effects of how bio-char applications to soil affect the surrounding ecology, and the productivity of particular crops in specific soil types and climates. This paper aims to reduce investment uncertainty for agriculturalists looking to diversify into converting biomass to bio-char and energy, with a special focus on experiences in Western Australia.

2. Bio-char production and feedstock

Worldwide, 41 million tonnes (t) of bio-char (charcoal) is estimated to be produced annually for cooking and industrial purposes (Food and Agriculture Organization of the United Nations, 2006) as cited in (Lehmann *et al.*, 2006). Conventional low efficiency production can result in losses of 80 – 90% of biomass weight (wet basis) and most of the energy content of the original biomass (Antal *et al.*, 1996; Okello *et al.*, 2001). If not produced according to sensible environmental parameters, the bio-char industry can lead to excessive deforestation, greenhouse gas emissions, particulate air pollution, and local health problems. However, many of these problems can be avoided by using the available clean and efficient bio-char production technologies (Lehmann *et al.*, 2006).

Using high efficiency technologies, it is possible to achieve mass yields of around 30 to 40% (wet basis), energy yields of around 30% (contained in the charcoal), with fixed carbon contents of up to 90% of the original biomass. Obtaining these excellent conversion figures are dependent on the production technology used and the initial biomass feedstock properties (Mok *et al.*, 1992; Antal *et al.*, 1996). In addition to the production of solid carbon, around two-thirds of the energy “lost” in the conversion process can be captured as a useful gas, or used as a source of heat (Antal *et al.*, 1996; Antal and Gronli, 2003). Therefore the myriad of uses and the higher efficiency of modern available technology has the potential to provide a profitable incentive to sustain local biomass resources (Lehmann *et al.*, 2006).

At the instant of burning, the biomass carbon exposed to fire has three possible fates. The first, and least possible fate of biomass exposed to fire is that it remains unburnt. The other two possible fates are that it is either volatized to carbon dioxide and numerous other minor gas species, or it is pyrolised to bio-char or black carbon (Graetz and Skjemstad, 2003). Pyrolysis is the temperature-driven chemical decomposition of biomass fuel without combustion (Demirbas, 2004). In nature, pyrolised bio-char particles fall to the ground surface and the black carbon is incorporated in the particulate phase of the smoke. (Graetz and Skjemstad, 2003; Demirbas, 2004). In commercial bio-char pyrolysis systems, the processes occurs in three steps: first, moisture and some volatiles are lost; second, unreacted residues are

converted to volatiles, gasses and bio-char, and; third, there is a slow chemical rearrangement of the bio-char (Demirbas, 2004).

Generally, the lower the temperature at which pyrolysis occurs, the higher the carbon recovery of the original biomass (Lehmann *et al.*, 2006). If the feedstock is dry and the bio-char yield is high, the heat produced can warm the incoming feedstock sufficiently to initiate the pyrolysing reactions to sustain the process (Antal and Gronli, 2003). The production of bio-char is favoured when there are low temperatures and low oxygen levels inside a pyrolysis chamber. At equal to, or greater than 400 degrees Celsius, the biomass material is converted into fused aromatic ring bio-char structures with the loss of carbon dioxide (CO₂), carbon monoxide (CO), water and hydrogen (H₂). The hot combustion products (CO₂ and H₂) are further converted to a useful synthetic gas (a mixture of carbon monoxide and hydrogen) with significant amounts of heat (Graetz and Skjemstad, 2003; Demirbas, 2004). This process has the potential to be the lowest cost biomass to electrical energy conversion systems (Bridgewater and Peacocke, 2000) as cited in (Lehmann *et al.*, 2006).

The energy content of oven dry wood varies from about 18 MJ kg⁻¹ for some hardwoods and up to 21 MJ kg⁻¹ for some softwood with high sap contents. As a rule of thumb, Western Australian hardwoods have 19 MJ kg⁻¹ and softwoods 20 MJ kg⁻¹ (Todd, 2001). This energy is more efficiently released when the feedstock is burnt directly, although direct burning diminishes the benefits of producing bio-char. The combustion of volatiles in the wood during pyrolysis releases around two-thirds of the energy in the wood as heat, which in turn may be used to raise steam or used for combustion in electricity generation technologies (Baker *et al.*, 1999). Pyrolysis at an elevated pressure improves bio-char yields as pyrolytic vapours are converted to secondary bio-char (Antal and Gronli, 2003). These slightly improved bio-char yields must be balanced against lower vapour yields used for energy generation. Also, higher bio-char production temperatures and pressures entail higher production costs than lower pyrolysis chamber temperatures and pressures. Therefore lower temperature pyrolysis at atmospheric pressure may be more suitable for small landholder production systems in rural areas, depending on the resources available (Kawamoto *et al.*, 2005).

Pyrolysis coupled with an organic matter return through bio-char applications addresses the dilemma soil degradation from widespread biomass extraction and bio-energy production. Bio-char production can also reduce transport costs of waste disposal as the bio-char mass is 70–80% less than the original wood-waste (Lehmann, 2007). In many cases, forestry and agricultural residues, such as mill off-cuts and nutshells have little value and their disposal incurs costs. Many of these wastes can be utilised in bio-char production. There is an extensive range of crop wastes that are suitable for pyrolysis in Australia include a variety of wasted species of broadacre grain trash, macadamia nut shells (*Macadamia integrifolia/tetraphylla*), olive pips (*Olea europaea*), wood blocks or woodchips, tree bark, and grass residues (Bridgewater and Peacocke, 2000). However, not all agricultural waste is suitable for bio-char production as it either a poor feedstock or may provide ecological services, such as vegetable crops and field residues respectively (Lehmann *et al.*, 2006).

3. Bio-char and agricultural suitability

At the local scale, soil organic carbon levels shape agro-ecosystem function and influence soil fertility and physical properties, such as aggregate stability, water holding capacity and cation exchange capacity (CEC) (Milne *et al.*, 2007). The ability of soils to retain nutrients in cation form that are available to plants can be increased using bio-char. The CEC of the bio-char itself can also be improved by producing the bio-char at higher temperatures (700-800 °C), although this is at the expense of lower carbon yields (~5% loss). The optimum bio-char production temperature in terms of carbon recovery, CEC and surface area is 500 degrees Celsius (Lehmann, 2007). The CEC of freshly produced bio-char is relatively low, although it will increase over a few months when stored between 30-70 °C (Lehmann *et al.*, 2003; Lehmann, 2007).

Farmers should be aware that certain production conditions and feedstock types can cause the bio-char to be completely ineffective in retaining nutrients or be susceptible to microbial decay. Bio-char produced under 400 °C has a low surface area and may not be useful as an agricultural soil improver (Lehmann, 2007). The type of biomass feedstock and pyrolysis conditions will also affect the amount and type of substances produced. Some feedstocks and conditions will generate phytotoxic and potentially

cancerogenous organic materials (Lima *et al.*, 2005) as cited by (Lehmann, 2007). Sub-optimal pyrolysis conditions can also result in negligible net sequestration from low carbon recovery (Lehmann, 2007). Therefore, a farmer must be careful when choosing a particular pyrolysis system and when setting the operational conditions during pyrolysis.

Further risk results from the lack of research about the safe level of bio-char application for many soil types. The levels of metal contaminants present in the original biomass feedstock often limit the safe level of bio-char addition. Exceeding the contaminant-limited biosolids application rate of copper, (based on the maximum allowable solid contaminant concentrations) can be achieved by applying as little as 38 tonnes of bio-char per hectare on a typical lateritic soil (Department of Environmental Protection *et al.*, 2002; Bridle, 2004). Other metal contaminants such as cadmium can exceed the contaminant rate by a bio-char application of 250 t ha⁻¹. Metals such as zinc, mercury, arsenic, lead and nickel require much larger applications. Providing total phosphorus loadings equivalent to 100 kg ha⁻¹ of Superphosphate (9 kg of phosphorus), requires 160 kg of bio-char per hectare (Bridle, 2004). These application rates suggest that very high levels of bio-char additions come with a risk of contaminating soils, but conservative use is comparably low risk in a similar manner to conventional fertiliser applications.

Methods used to apply bio-char into agricultural soils depend on the bio-char physical properties and its intended function. Uniform mixing of bio-char into topsoils is used for improving soil biology, water holding capacity and nutrient availability, however this approach disturbs much of the existing soil structure and creates dust and erosion issues. Forming deep layers of bio-char under the surface is used to intercept nutrients in surface soils with low CEC, although has similar drawbacks to uniform mixing. Mechanical broadcasting of bio-char is useful for adsorbing leachable nutrients and herbicides and is a minimal disturbance method, although it doubtful whether this form of application is suitable for carbon sequestration purposes (Blackwell *et al.*, 2008).

In addition to these common methods are deep-banding, seeding application, topdressing, aerial delivery, specific application to ailing vegetation at the root, and

even ecological delivery via animal excreta (Blackwell *et al.*, 2008). Understandably, the choice of application method for bio-char sequestration purposes should minimise impacts on the existing SOC species and primary crops. Disruption and compaction of soils should be kept to a minimum as disturbing organisms that contribute to aggregation can lead to lower microbial activity and lower productivity (Bronick and Lal, 2005). Tillage and mixing of soils also directly break up soil aggregates and exposes surfaces otherwise inaccessible to decomposers which increases the carbon turnover rate (Post and Kwon, 2000).

4. Bio-char and alternative biomass products and services

The integration of bio-char soil improver production and renewable energy generation in the form of biofuels, electricity and heat is a promising new industry (Lehmann *et al.*, 2006). Producing bio-char and energy from wastes may both reduce waste disposal costs and provide cost-effective energy services that can be used by agricultural industries (Marris, 2006). In contrast to other renewable energy technologies, biomass can be used to produce a number of liquid, solid and gaseous fuels (Bridgewater and Peacocke, 2000).

Currently hydrogen gas (as the energy carrier) and bio-oil are the two common fuels produced using pyrolysis technologies. Bio-oil production is the more advanced and more wide-spread technology of the two (Lehmann *et al.*, 2006). To maximise yields of liquid products from pyrolysis requires a low temperature and a high heating rate with a short gas residence time. High temperatures, low heating rates with long gas residence times maximise fuel gas yields. However, to maximise bio-char production a low temperature, low heating rate is required (Demirbas, 2004). The increased use of pyrolysis technologies can also complement the production of other biofuels, such as ethanol, as the waste products from these processes can also be pyrolysed.

Bio-char can also be produced from feedstocks with high initial nutrient content to produce a hybrid fertiliser/bio-char product alongside renewable energy (He *et al.*, 2000). S. Joseph of the Australian company Biomass Energy Services & Technology has produced a number of bio-char production systems that utilise production wastes such as dairy bedding and manure (Marris, 2006). Due to the high water content of

fresh manure being unable to sustain the pyrolysis process, manure is left to dry naturally to achieve a moisture content of 10% (Hatfield and Stewart, 1997; Shinogi and Kanri, 2003). Pyrolysis of wastes, such as manures can play a role in alleviating nitrogen run-off, which characterises the use of animal manures (Bridgewater and Peacocke, 2000; Lehmann, 2007). In addition, the odours, emissions and nutrient content of animal manure can be substantially reduced by direct pyrolysis, with the added benefit of a positive energy output in the form of gas, liquid or solid (Bridgewater and Peacocke, 2000; He *et al.*, 2000; Demirbas, 2004; Lehmann, 2007). As bio-char soil additions reduce nitrogen leaching and elevate nutrient availability in the soil, the use of manure alongside bio-char can be used to increase plant growth and nutrition to substitute for inorganic fertiliser use (Lehmann *et al.*, 2003; Lehmann, 2007).

The pyrolysis process can also utilise bio-char produced to remove flue gases such as carbon dioxide, nitrous oxide and sulphur dioxide in the bio-energy pyrolysis plant itself (Lehmann, 2007). The nitrogen and sulphur enriched bio-char may prove to be a valuable substitute for farm nitrogen fertiliser and to bio-sequestering these greenhouse gases, although these claims require full investigation (Lehmann *et al.*, 2006; Lehmann, 2007). In the USA, D. Day manufactures pyrolysis systems that allow farmers to use farm waste to produce biofuels and bio-char. Day has a pilot plant that processes 10 to 25 kg of biomass an hour and can produce 23 kg of charcoal and 5 kg of hydrogen from 100 kg of biomass feedstock. By combining the bio-char with ammonium bicarbonate produced with the steam recovered hydrogen, Day creates a saleable nitrogen fertiliser (Marris, 2006).

Bio-char itself may be sold as is, or activated with steam to produce activated carbon. The highly developed internal surface area and porosity of activated carbon results in considerable adsorptive abilities. Activated carbon has a wide range of high value uses that include water and gas treatments, material recovery, catalysts and gas storage applications (Zanzi *et al.*, 2001). Estimated gate prices for granular activated carbon and CSIRO activated wood pellets are around A\$3,000 per tonne, and prices for powdered activated carbon is approximately A\$1,000 per tonne (Enecon, 2001). During activation most of the remaining energy in the wood generates steam for the activation process, with some available for a gas engine or turbine (Baker *et al.*,

1999). However, this reduces the production of bio-char to near zero, as much of the bio-char is refined into activated carbon. This would erase the potential of soil organic carbon sequestration in farm soils, unless the activated carbon can be safely applied to agricultural land after fulfilling its primary use. A range of other products and services can be produced alongside bio-char, including wood preservatives, adhesives, meat browning or food flavouring (Lehmann, 2007). Other benefits of bio-char conversion are the elimination of pathogens in biomass feedstock and the speciation of some heavy metal contaminants into forms that can reduce levels of toxicity. However this hypothesis needs to be properly assessed by further research (Bridle, 2004).

The financial returns of biomass conversion investments are heavily dependent on the range and quality of the biomass inputs and the output products (Baker *et al.*, 1999). Land-based production of biomass for the sole purpose of producing bio-char may not be economically feasible due to the high production costs. Therefore biomass projects are often a complex blend of production streams that require integration (Lehmann *et al.*, 2006). A study on the prospects for bioenergy in Australia by the Australian Biomass Taskforce and the Australia IEA Bioenergy Task 17 Collaborators Group, looked at the feasibility of establishing a large-scale bio-energy plant using mallee trees (low-growing, multi-stemmed species of Eucalypt) in southwest Western Australia. A full-scale plant accepting 100,000 t of dried mallee (50,000 t each of wood and leaves annually) would yield 1,600 t of eucalyptus oil and either 8,300 t of bio-char or 5,000 t of activated carbon. The plant would clearly require a lot of trees. With a two-tree row hedges in alley systems 50 m apart requires 50,000 ha of integrated farming land. Work undertaken by CSIRO suggests that a plant this size producing bio-oil and bio-char would generate approximately 2.3 MWh of electrical energy via steam turbines with 8.6 MWh of energy remaining in the bio-char. If the plant produced bio-oil and activated carbon, the energy generated will be approximately 5.1 MWh using both steam and gas turbines (Baker *et al.*, 1999). In addition to these products the plant will generate large amounts of heat or low-pressure steam that may be used for other processes (Baker *et al.*, 1999).

A 1 MWe demonstration integrated wood processing facility partnered by Verve Energy, Enecon, the Oil Mallee Company and AusIndustry, has been successfully demonstrated in Narrogin in the southwest of Western Australia. The annual output of

the plant was 7,500 MWh of electricity, 690 t of activated carbon, and 210 t of eucalyptus oil. Expressions of interest have been invited by Verve energy in developing a new 5 MWe commercial scale plant (The Oil Mallee Company, 2008). The estimated capital cost of the 5 MWe integrated tree processing plant is \$28.4 million with an expected annual operating cost of \$7.9 million, including feedstock purchases. Each year, the 5 MWe plant is expected to produce 40,000 MWh of electricity, 1,050 t of eucalyptus oil, 2,720 t of granular activated carbon, 1,090 t of pelletised activated carbon and 294 t of powdered activated carbon. The intermediate bio-char output of the plant is 7,240 t y^{-1} , before it is converted to activated carbon species. The 5 MWe plants' preferred scenario exhibited an after tax IRR of 18.8% and a NPV of \$7.8 million, with a discount rate of 12.5% over a 15 year project (Enecon, 2001; Verve Energy, 2008).

Despite the successful demonstration plant and the establishment of millions of mallee trees, there remain some significant technical harvesting and processing hurdles before large integrated biomass plants can operate as an economically viable, low risk commercial mitigation technology in Australia (Bell, 2005). Investor confidence in the financial viability of biomass conversion technologies was recently bolstered by the expansion of the Federal Government's Australian Mandatory Renewable Energy (electricity) Target (MRET) and the development towards a national carbon emissions trading scheme.

5. Bio-char production and greenhouse gas emissions

There is a major role for biomass conversion technologies in the mitigation of climate change through soil sequestration (Milne *et al.*, 2007). Globally, up to 12% of all anthropogenic land use change emissions can be offset annually in soils if slash-and-burn agriculture is replaced by slash-and-char systems (Lehmann *et al.*, 2006). Despite the lack of reliable information, an estimated 29.1×10^6 ha of global secondary forests are exposed to slash-and-burn clearing annually, which represents an enormous opportunity to reduce emissions (Fearnside, 2000; Food and Agriculture Organization of the United Nations, 2006). Australia's current natural bio-char sink is currently sequestering carbon at an estimated median rate of 5.6 Mt of carbon every year. This is equivalent to 21 million tonnes of carbon dioxide annually, or 6% of

Australia's 1990 baseline carbon dioxide emissions (Graetz and Skjemstad, 2003). This carbon sink is not included in the Kyoto Protocol accounting methodology. The development of a controlled and sustainable domestic bio-char industry requires analyses of the life-cycle emissions to ensure a net negative greenhouse footprint.

The conversion of biomass carbon to bio-char leads to sequestration of about 50% of the initial carbon compared to the low amounts retained after burning (3%) and biological decomposition (less than 10-20% after 5-10 years) (Lehmann *et al.*, 2006). The reason why the carbon recovery in bio-char from wood is so high is because bio-char is approximately 85% carbon, whereas wood consists of around 45% to 50% carbon (Lehmann, 2007). This high efficiency of carbon conversion of biomass to bio-char is highly dependent on the type of feedstock, but is not significantly affected by the pyrolysis temperature within 350-500 °C (Lehmann *et al.*, 2006). Industrial scale production of bio-char from land-based biomass waste entails several additional carbon costs to the pyrolysis process itself: the transport emissions to the bio-energy plant; the plant equipment; transport to the land holder, and; application of the bio-char to the soil.

There are three ways that farmers could benefit from entering into carbon market contracts to sequester carbon while producing bio-char. First, farmers would be compensated for the carbon they sequester, based on the quantity and market price of carbon. Second, farmers would benefit from any gains in productivity associated with the adoption of carbon sequestering practices (Antal and Gronli, 2003). And finally, farmers who owned a share in bio-char and renewable energy production facilities would receive any net benefits from the investment. Preliminary calculations suggest that the carbon balance for various feedstocks, such as corn or switchgrass, is favourable with approximately 3-11 kg of carbon stored for every kg of carbon released when bio-char is produced and sequestered. These scenarios lead to a net withdrawal of carbon dioxide from the atmosphere while producing energy (Lehmann, 2007). Modern biomass pyrolysis technologies can use agricultural and forestry wastes (such as forest residues, mill residues, field crop residues or urban waste) to sequester around 30 kg of carbon for each GJ of energy produced (Lehmann *et al.*, 2006).

In 2003, the Japanese Kansai Electric Power Group and the local Oil Mallee Company established a 1,000 ha mallee plantation (*Eucalyptus loxophleba* ssp *lissophloia*, *E. kochii* ssp *plenissima*, and *E. horistes*) for a pyrolysis feasibility study in Western Australia. The aim was to develop a carbon sink by planting trees and pyrolysing the wood waste after eucalyptus oil extraction. If fully developed, the final size of the plantation will be 10,000 ha, with the bio-char used to remedy the acidity and the plantations used to ameliorate the salinity problems in the area (Enecon, 2001; Verve Energy, 2008). The harvest regime was expected to commence in the tenth year and the regrowth would be coppiced every three to five years and pyrolysed in a portable furnace operating at around 500 to 600 °C. Over a 35-year operation the total CO₂ sequestered is expected to be 14% in the aboveground tree biomass, 33% in the belowground biomass, and 53% from the soil bio-char. The total carbon sequestration was calculated to be slightly more than 1 million tonnes of carbon (tC), which represents around 3.7 million tCO₂-e (Ogawa *et al.*, 2006).

It appears that the soil represents a finite carbon sink of natural SOC and will provide a window of opportunity for farmers to capitalise on resultant climate change markets and policies (Lehmann *et al.*, 2006). Climatic change in mean temperature and rainfall variation will influence the rate of natural organic decomposition and the relative amount of carbon stored and released into the atmosphere (Grace *et al.*, 2006). Therefore farm mitigation strategies need to account for potential losses in total SOC fluxes from both climate change and land use change and should be able to measure such changes to reduce investment risk. Analysis of SOC below tree plantations and adjacent paddocks in areas of the southwest of Western Australia suggest a slight decline in SOC levels following the plantation establishment (Specht and West, 2003; Kirschbaum, 2000). In addition to sequestering carbon, some preliminary results from greenhouse experiments have shown that the presence of 20 g of bio-char per kg of soil may reduce nitrous oxide and methane emissions by 80% and 100% respectively (Lehmann and Rondon, 2005) as cited in (Lehmann, 2007). While the exact reason for this is unknown, this may provide an extra benefit of adding bio-char to soils in addition to sequestering carbon (Lehmann, 2007).

Verification and compliance of sequestration projects in national carbon accounting schemes require a soil sampling strategy that determines where the carbon sinks are,

when the carbon was sequestered, and how large the sinks are to a sufficiently high resolution (Graetz and Skjemstad, 2003; Lehmann *et al.*, 2006). The use of bio-char could allow the total SOC sequestered in soils to be orders of magnitude larger than is possible naturally, is relatively simple to verify for national accounts, and is more resistant to the climate than conventional SOC (Lehmann *et al.*, 2006). There are regions in South America with soils that contain high levels of bio-char residues as a consequence of human cultures burning large amounts of biomass centuries ago. Some of these areas contain around $250 \text{ tC ha}^{-1} \text{ m}^{-1}$ of depth, which far exceeds the potential for carbon sequestration in the existing forest above the soil (Sombroek *et al.*, 2003) as cited in (Lehmann *et al.*, 2006).

It is clear that biomass conversion sequestration projects have the potential to contribute significantly to climate change mitigation, although many options may not be economically attractive at current estimates of output product and carbon prices (Cacho *et al.*, 2004). Much investment depends on the stability of government policy, emission accounting frameworks, carbon market design and the enduring prices that carbon credits may achieve over the long-term. Therefore, policy formulation at the international, national and sub-national scales is required to provide enough incentive to the agricultural industry to employ their formidable resources to sequester carbon in their soils and reduce SOC lost to the atmosphere (Milne *et al.*, 2007).

6. Conclusion

Producing bio-char from farm or forestry waste provides an impressive list of potential co-benefits, including the generation of renewable electricity, liquid biofuels, gas biofuels, activated carbon, eucalyptus oil, large amounts of heat or low-pressure steam, and the potential of a net withdrawal of carbon dioxide from the atmosphere. With the introduction of new policies and initiatives, the sum profitability of these various production streams is likely to improve, especially if they are integrated into existing agricultural production and energy systems.

The lure of higher rates of soil sequestration and lower uncertainties in carbon asset verification, alongside the lower risks when storing carbon in soils, presents an air of inevitability of integrating bio-char applications and agricultural SOC into carbon

markets. Carbon markets that do include agricultural soil sequestration will enable farmers to trade their sequestered bio-char soil applications and facilitate the expansion of a range of new technologies that improve farm productivity, energy security, with the potential for large positive environmental outcomes. However, as much research, technology and policy is relatively immature or non-existent, further research is necessary to increase investment certainty before wide-scale dissemination can make a significant contribution to climate change adaptation and mitigation.

References

- Antal, M. J., Croiset, E., Dai, X., DeAlmeida, C., Mok, W. S. L., Norberg, N., Richard, J.-R., Al Majthoub, M., , 1996. High-yield biomass charcoal. *Energy Fuels*. 10, 652-658.
- Antal, M. J., Gronli, M., 2003. The art, science, and technology of charcoal production. *J. Am. Chem. Soc.* 42, 1619-1640.
- Baker, T., Bartle, J., Dickson, R., Polglase, P., Schuck, S. 1999. Prospects for bioenergy from short-rotation crops in Australia. Bioenergy from SRC in Australia http://www.bioenergy.org/reports/iea_task_17_prospects.htm [accessed 25 July, 2008].
- Bell, S., 2005. Constructing sustainable rural landscapes: oil mallees and the Western Australian Wheatbelt. *Geogr. Res.* 43, 194-208.
- Blackwell, P., Reithmuller, G., Collins, M. 2008. Biochar application to soil. Bio-char for environmental management: science and technology. Earthscan. London, United Kingdom, pp. 1-29.
- Bridgewater, A. V., Peacocke, G. V. C., 2000. Fast Pyrolysis processes for biomass. *Renewable and Sustainable Energy Rev.* 4, 1-73.
- Bridle, T. R. 2004. Use of pyrolysis to recover energy and nutrients from biosolids. http://www.wef.org/NR/rdonlyres/7DA581D9-C0D3-4E5C-B127-AC68B7ABA6DD/0/Bridle_Paper.pdf [accessed 25 July, 2008].
- Bronick, C. J., Lal, R., 2005. Soil structure and management: a review. *Geoderma*. 124, 3-22.
- Brussaard, L., de Ruiter, P. C., Brown, G. G., 2007. Soil biodiversity for agricultural sustainability. *Agric. Ecosyst. Environ.* 121, 233-244.

- Cacho, O. J., Wise, R. M., MacDicken, K. G., 2004. Carbon monitoring costs and their effect on incentives to sequester carbon through forestry. *Mitig. Adapt. Strat. Glob. Change.* 154, 273-293.
- Demirbas, A., 2001a. Biomass to charcoal, liquid, and gaseous products via carbonization process. *Energ. Source.* 23, 579-587.
- Demirbas, A., 1997. Calculation of higher heating values of biomass. *Fuel.* 76, 431-434.
- Demirbas, A., 2001b. Carbonization ranking of selected biomass for charcoal, liquid and gaseous products. *Energ. Convers. Manage.* 42, 1229-1238.
- Demirbas, A., 2004. Effects of temperature and particle size on bio-char yield from pyrolysis of agricultural residues. *J. Anal. Appl. Pyrol.* 72, 243-248.
- Denman, K. L., Brasseur, G., Chidthaisong, A., Ciais, P., Cox, P. M., Dickinson, R. E., Hauglustaine, D., Heinze, C., Holland, E., Jacob, D., Lohmann, U., Ramachandran, S., da Silva Dias, P. L., Wofsy, S. C., Zhang, X. 2007. Couplings between changes in the climate system and biogeochemistry. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., Miller, H. L. Cambridge, United Kingdom and New York, USA, Cambridge University Press.
- Department of Environmental Protection, Waters and Rivers Commission, Department of Health 2002. Western Australian guidelines for direct land application of biosolids and biosolid products. Perth, Western Australia. <http://www.agric.wa.gov.au/content/SUST/GREENHOUSE.PDF> [accessed 25 July, 2008].
- Encinar, J. M., Beltran, F. J., Ramiro, A., Gonzalez, J. F., 1998. Pyrolysis/gasification of agricultural residues by carbon dioxide in the presence of different additives: influence of variables. *Fuel Process. Technol.* 55, 219-233.
- Enecon. 2001. Integrated tree processing of mallee eucalypts. *Oil Mallees - Profitable Landcare* <http://www.rirdc.gov.au/reports/AFT/01-160.pdf> [accessed 25 July, 2008].
- Fearnside, P. M., 2000. Global warming and tropical land-use change: Greenhouse gas emissions from biomass burning, decomposition and soils in forest

- conversion, shifting cultivation and secondary vegetation. *Clim. Change*. 46, 115-158.
- Food and Agriculture Organization of the United Nations. 2006. Global Forest Resources Assessment 2005. Progress towards sustainable forest management. FAO Forestry Paper 147 <http://ftp.fao.org/docrep/fao/008/A0400E/A0400E00.pdf> [accessed 25 July, 2008].
- Grace, P. R., Post, W. M., Hennesey, K., 2006. The potential impact of climate change on Australia's soil organic carbon resources. *Carbo. Bal. Manage.* 1, 1-10.
- Graetz, R. D., Skjemstad, J. O. 2003. The charcoal sink of biomass burning on the Australian continent. CSIRO Atmospheric Research Technical paper No. 64 http://www.cmar.csiro.au/e-print/open/graetz_2003a.pdf [accessed 25 July, 2008].
- Griffiths, B., Ritz, K., Bardgett, R. D., Cook, R., Christensen, S., Ekelund, F., Sorensen, S. J., Baath, E., Bloem, J., de Ruyter, P. C., Dolfing, J., Nicolardot, B., 2000. Ecosystem response of pasture soil communities to fumigation-induced microbial diversity reductions: an examination of the biodiversity - ecosystem function relationship. *Oikos*. 90, 279-294.
- Harle, K. J., Howden, S. M., Hunt, L. P., Dunlop, M., 2006. The potential impact of climate change on the Australian wool industry by 2030. *Agric. Syst.* 93, 61-89.
- Hatfield, J. L., Stewart, B. A. 1997. Animal waste utilization: Effective use of manure as a soil resource. CRC Press. Boca Raton.
- He, B. J., Zhang, Y., Funk, T. L., Riskowski, G. L., Yin, Y., 2000. Thermochemical conversion of swine manure: an alternative process for waste treatment and renewable energy production. *Am. Soc. Agric. Eng.* 43, 1827-1833.
- Intergovernmental Panel on Climate Change 2000. Land use, land use change, and forestry. Cambridge University Press. Cambridge.
- Kawamoto, K., Ishimaru, K., Imamura, Y., 2005. Reactivity of wood charcoal with ozone. *Japan Wood Res. Soc.* 51, 66-72.
- Kirschbaum, M. U. F., 2000. What contribution can tree plantations make towards meeting Australia's commitments under the Kyoto Protocol? *Environ. Sci. Policy*. 3, 83-90.
- Klein, R. J. T., Huq, S., Denton, F., Downing, T. E., Richels, R. G., Robinson, J. B., Toth, F. L. 2007. Interrelationships between adaptation and mitigation. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on*

- Climate Change. Parry, M. L., Canziani, O. F., Palutikof, J. P., van der Linden, P. J., Hanson, C. E. Cambridge, United Kingdom, Cambridge University Press.
- Lehmann, J., 2007. Bio-energy in the black. *Front. Ecol. Environ.* 5, 381-387.
- Lehmann, J., Gaunt, J., Rondon, M., 2006. Bio-char sequestration in terrestrial ecosystems. *Mitig. Adapt. Strat. Glob. Change.* 11, 395-419.
- Lehmann, J., Pereira da Silva Jr, J., Steiner, C., Nehls, T., Zech, W., Glaser, B., 2003. Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertiliser, manure and charcoal amendments. *Plant Soil.* 249, 343-357.
- Lehmann, J., Rondon, M. 2005. Chapter 36: Bio-char soil management on highly weathered soils in the humid tropics. Uphoff, N. *Biological approaches to sustainable soil systems.* CRC Press. Boca Raton.
- Lima, A., Farrington, J., Reddy, C., 2005. Combustion-derived polycyclic aromatic hydrocarbons in the environment - a review. *Environ. Forensics.* 6, 109-131.
- Marris, E., 2006. Black is the new green. *Nature.* 442, 624-469.
- Milne, E., Powlson, D. S., Cerri, C. E., 2007. Soil carbon stocks at regional scales (preface). *Agric. Ecosyst. Environ.* 122, 1-2.
- Mochidzuki, K., Paredes, L. S., Antal, M. 2002. Flash carbonization of biomass. http://www.hnei.hawaii.edu/flash_carb_biomass.pdf [accessed 25 July, 2008].
- Mok, W. S. L., Antal, M. J., Szabo, P., Varhegyi, G., Zelei, B., 1992. Formation of charcoal from biomass in a sealed reactor. *Ind. Eng. Chem. Res.* 31, 1162-1166.
- Ogawa, M., Okimori, Y., Takahashi, F., 2006. Carbon sequestration by carbonisation of biomass and forestation: three case studies. *Mitig. Adapt. Strat. Glob. Change.* 11, 421-436.
- Okello, B. D., O'Connor, T. G., Young, T. P., 2001. Growth, biomass estimates, and charcoal production of *Acacia drepanolobium* in Laikipia, Kenya. *For. Ecol Manage.* 142, 143-153.
- Paustian, K., Andren, O., Janzen, H. H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., Woomer, P. L., 1997. Agricultural soils as a sink to mitigate CO₂ emissions. *Soil Use Manage.* 13, 230-244.
- Post, W. M., Kwon, K. C., 2000. Soil carbon sequestration and land-use change: processes and potential. *Glob. Change Biol.* 6, 317-327.

- Shinogi, Y., Kanri, Y., 2003. Pyrolysis of plant, animal and human waste: physical and chemical characterization of the pyrolytic products. *Bioresour. Technol.* 90, 241-247.
- Sombroek, W., Ruivo, M. L., Fearnside, P. M., Glasser, B., Lehmann, J. 2003. Amazonian dark earths as carbon stores and sinks. Lehmann, J., Kern, D. C., Glaser, B., Woods, W. I. Amazonian dark earths: origin, properties, management. Kluwer Academic Publishers. Dordrecht, pp. 125-139.
- Specht, A., West, P. W., 2003. Estimation of biomass and sequestered carbon on farm forest plantations in northern New South Wales, Australia. *Biomass Bioenergy.* 25, 363-379.
- The Oil Mallee Company. 2008. Website. <http://www.oilmallee.com.au> [accessed 25 July, 2008].
- Tobor-Kaplon, M. A., Bloem, J., Romkens, P. F. A. M., de Ruiter, P. C., 2005. Functional stability of microbial communities in contaminated soils. *Oikos.* 111, 119-129.
- Todd, J. J. 2001. Woody-biomass fuelled power stations. Renewable Energy Generators Association (REGA) Forum 2001. Launceston. [http://www.rega.com.au/Documents/2001 Forum/Paper Jtodd REGA Forum 2001.pdf](http://www.rega.com.au/Documents/2001%20Forum/Paper%20Jtodd%20REGA%20Forum%202001.pdf) [accessed 25 July, 2008].
- Valzano, F., Murphy, B., Koen, T. 2005. Report No. 43 - The impact of tillage on changes in soil carbon density with special emphasis on Australian conditions. National Carbon Accounting System. Canberra, Australian Greenhouse Office. <http://www.greenhouse.gov.au/ncas/reports/pubs/tr43final.pdf> [accessed 25 July, 2008].
- Verve Energy. 2008. Integrated Wood Processing (IWP). <http://www.verveenergy.com.au/mainContent/sustainableEnergy/OurPortfolio/iwp.html> [accessed 25 July, 2008].
- Wright, A. L., Dou, F., Hons, F. M., 2007. Soil organic C and N distribution for wheat cropping systems after 20 years of conservation tillage in central Texas. *Agric. Ecosyst. Environ.* 121, 376-382.
- Zanzi, R., Bai, Z., Capdevila, P., Bjornbom, E. 2001. Pyrolysis of biomass in presence of steam for preparation of activated carbon, liquid and gaseous products. 6th World Congress of Chemical Engineering. Melbourne. <http://hemfristorg.com/zanzi/paper/paper6.pdf> [accessed 25 July, 2008].

Fig. 1. The Narrogin Integrated Wood Processing Demonstration Plant. (Courtesy of Verve Energy).



Fig. 2. Approximate energy content (High Heating Value) of various biomass feedstock, and % of biomass carbon remaining in bio-char produced at 500-550°C. (Source: 'Demirbas, 1997; #Encinar *et al.*, 1998; ^Demirbas, 2001a; *Demirbas, 2001b; "Mochidzuki *et al.*, 2002; `Demirbas, 2004).

