Biochar and bioenergy production for climate change mitigation

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The world will increasingly depend on renewable energy with low or zero net greenhouse gas (GHG) emissions. This paper explores how science and the economic 'rules of the game' might realize the potential for the pyrolysis co-production of biochar and bio-oil to mitigate net GHG emissions while achieving other economic and environmental benefits. This pyrolysis process produces a high carbon biochar that can be sequestered almost permanently in soil, and energy that substitutes for fossil fuels. It is 'carbon negative', that is, it allows an ever-increasing carbon sink to be built up in soil. Biochar can reduce emissions of nitrous oxide and leaching of nitrates into water. It can also lift agricultural productivity through its effect on soil structure, microbiota and nutrient availability.

Background

In the late 19th century, European explorers in the Amazonia found patches of dark, high fertility soils amidst the highly weathered and acidic oxisols in the region. These soils were termed *terra preta* (dark soils) and they were created by indigenous people who incorporated biochar into them. *Terra preta* soils are very high in carbon, with soil structures and microbial activity that improve nutrient availability and plant growth. The biochar was made by smouldering biomass at moderate temperatures in the absence of oxygen, leaving charred vegetation that was then dug into the soil. The addition of biochar led typically to a doubling of crop production in these soils compared with unimproved soils nearby.

Although it is accepted that *terra preta* soils were created by the addition of biochar it is still not clear whether this fully explains their high crop productivity. Plant-available phosphorus and other nutrient content in the soils may result from other human inputs such as animal manures, and plant and fish wastes.

'The slash and char' methods in the Amazonia must be distinguished from 'slash and burn' agricultural practice. Slash and char sequesters around 50% of the initial carbon in the biomass, compared to the 3% or so from burning (Lehman et al. 2006). carbon from burnt (as opposed to pyrolysed) plant material is labile and is largely mineralised to carbon dioxide within a matter of months or a few years. While some carbon in biochar may well decay over the shorter term, biochar is a highly stable and long-term form of carbon sequestration overall, because charcoal is inert and resistant to biochemical breakdown.

Terra preta soils are up to several thousand years old. The average age of black carbon buried in deep-sea sediments has been found to be up to 13 900 years greater than the age of other organic carbon such as humic substances (Masiello & Druffel 1998). Charcoal from volcanic eruptions has been dated back over 20 000 years.

The *terra preta* soils are believed to have formed over periods of as little as 40–50 years. They range in depth from 0.5 to 2 metres. A hectare of 1 metre-deep *terra preta* soil contains around 250 tonnes of carbon as opposed to 100 tonnes in unimproved soils from similar parent material. The soil horizons within which carbon is stored may be far deeper in *terra preta* than in other soils, with a horizon enriched in organic matter that is up to 2 metres deep compared with average profiles of about 40–50 cm in other soils.

A ceiling has yet to be found to the amount of carbon a *terra preta* soil can sequester, although it is assumed that there will be a ceiling and it will be influenced by factors such as the underlying geology.

Soil sequestration of carbon through biochar offers a means of mitigating climate change while delivering other economic and environmental benefits. These benefits can include the restoration of degraded soils. Benefits from biochar depend on a clear understanding of the carbon and nitrogen cycles.

Carbon and nitrogen cycles

Carbon and nitrogen are circulated between the atmosphere, soil, and water. Carbon dioxide is fixed by plants and nitrogen by bacteria. The soil carbon pool is made up of different types of carbon with different turnover times. Labile carbon, as occurs in the microbial biomass, has a turnover time of about 1–5 years, humic carbon may turn over in decades, and inert organic matter such as charcoal may decay over thousands of years. Humic substances contain both carbon and nitrogen, so that soils acting as net sinks for carbon are also acting as sinks for nitrogen. Every tonne of carbon lost from soils adds 3.67 tonnes of carbon dioxide to the atmosphere. Soils losing carbon are also losing nitrogen, including nitrous oxide and other forms.

Humus improves soil structure, moisture retention, and microbial activity. As soils approach nitrogen saturation, and plants are unable to take it up, the risk of nitrates and nitrates

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Biochar and bio-oil from pyrolysis

When biomass is burnt in the absence of oxygen, pyrolysis occurs and the biomass can be turned into a liquid ('bio-oil'), a gas and a high-carbon, fine-grained residue: biochar. Biochar has been made from grasses, woody material, straw, corn stover, peanut shells, olive pits, bark, sorghum, and sewage wastes. However, experimentation with biochar and bio-oil has typically been on wood because of its consistency as a material and its relatively low ash content.

Pyrolysis can involve a range of different processes, including bubbling fluidised bed, rotating cone reactors, and mechanical or centrifugal ablative processes. Some of these processes are quite new and are still being refined. Other approaches to pyrolysis may also be developed.

Pyrolysis involves trade-offs between the production of biochar, bio-oil and gas, and the process can be calibrated to maximise the output of different products, depending on economic factors. This is illustrated in Table 1.

The energy used in the above processes is provided by the biomass itself in the form of gas and other byproducts. There are important challenges in reducing the costs of these processes, and there is extensive international research under way on them.

Biochar and its potential uses

While lump charcoal is a valuable product for industrial processes such as iron- and steel-making, biochar is finely ground charcoal with some similarities to activated charcoal. Lump charcoal has very limited ability to adsorb substances in the liquid or gas phase and that is why activation of charcoal is required to remove tarry materials which block the structure of the pure carbon 'skeleton' of the charcoal. This vastly increases the surface area of the porous carbon skeleton, providing large numbers of sites where molecules of other substances can be held. This is the basis for activated charcoal, and also explains something of the role biochar plays in relation to soil microbiota processes. Biochar offers an extremely high surface area to support microbiota that catalyse processes that, among other things, reduce nitrogen loss and increase nutrient availability for plants.

Biochar to sequester carbon

Wood has a carbon content of about 50%, whereas biochar has a carbon content of about 70–80%, which can be permanently sequestered in soil. Over and above this, biochar *may* have the potential to increase atmospheric carbon dioxide uptake in the form of glomalin, a major component of humus produced by plant mycorrhizal fungi. However, this possibility needs further research.

Biochar to reduce nitrous oxide emissions and nitrate leaching

Biochar can reduce nitrogen fertiliser requirements and nitrous oxide emissions (Baum & Weitner, 2006). New Zealand soils have a finite ability to store nitrogen and nitrogen-saturated soils create risks of nitrogen leaching into waterways and being discharged to the atmosphere. However, a soil with a high carbon:nitrogen ratio usually has a greater capacity to store nitrogen and thereby reduce nitrous oxide emissions and nitrate leaching. The carbon:nitrogen ratios of different land uses are set out in Table 2.

Biochar is an excellent support material for *Rhizobium* inoculants (Lal & Mishra 1998), and application of sufficient volumes of biochar could also reduce nitrous oxide emissions and nitrate leaching from New Zealand soils. This is extremely important, as nitrous oxide is a potent and long-lasting greenhouse gas that creates substantial Kyoto Protocol liabilities, while nitrification of waterways is another major form of environmental damage from agriculture. Although there may be a high initial cost of incorporating biochar in soils, it is a one-off cost with a permanent benefit.

There is reference in the literature to the ability of biochar to reduce methane emissions from soil, but this has yet to be substantiated.

Biochar to lift soil and crop productivity

The carbon in biochar does not directly provide nutrients to plants. However, it improves soil structure and water retention, enhances nutrient availability, lowers acidity, and reduces the toxicity of aluminium to plant roots and soil microbiota. Biochar may help reduce the bioavailability of heavy metals and endocrine disruptors in some production systems and may therefore have potential in bioremediation.

Some of the microbiological processes associated with biochar may be relevant to organic farmers with interests in the performance of high-carbon soils.

Productivity gains from biochar are well documented from *terra preta* soils and use of charcoal as a soil improver has been

Table 1: Typical product yields (dry wood basis) obtained by different modes of wood pyrolysis.

Mode	Conditions	Bio-oil	Biochar	Gas
Fast	Moderate temperatures (500°C) for 1 second	75%	12%	13%
Intermediate	Moderate temperatures (500°C) for 10–20 seconds	50%	20%	30%
Slow (carbonisation)	Low temperature, (400°C), very long solids residence time	30%	35%	35%
Gasification	High temperature, 800°C, long vapour residency time	5%	10%	85%

Source: International Energy Agency 2007

Table 2: Organic matter carbon:nitrogen ratios in New Zealand.

Land use	Mean C:N ratio	Number of sites
Plantation forestry	17.4	67
Indigenous forestry	16.7	58
Tussock grassland	14.7	20
Horticulture and orchards	12.8	37
Arable crop	12.3	42
Mixed crop	12.1	17
Sheep-beef pasture	12.1	140
Dairy pasture	11.3	123

Source: SURLI, 2005.

documented in Japan at least as far back as the 17th century. Modern experimental research demonstrates that biochar application can substantially lift the productivity of crops such as soybeans, sorghum, potatoes, maize, wheat, peas, oats, rice and cowpeas. Such productivity gains also depend, however, on factors such as soil and crop type, char concentrations, and nutrient levels, so optimal applications would need to be tailored to local conditions.

Evidence suggests that significant productivity gains are possible at application rates as low as 0.4 to 8 tonnes of carbon per ha, but at extremely high applications crop productivity may actually drop due to nitrogen limitation. There is evidence that legumes will thrive under high biochar applications, perhaps because their nitrogen-fixing ability enables them to compensate for limited nitrogen availability in the soil. This might suggest some potential for New Zealand's clover-based pasture systems.

Biochar for fertiliser production

Much synthetic fertiliser is currently produced by using natural gas to synthesise ammonia using nitrogen from the air, but this releases one molecule of carbon dioxide for each molecule of ammonia produced. Conventional urea-based fertilisers, made from this ammonia, also have other adverse environmental impacts when used inappropriately. Combining ammonia, carbon dioxide and water in the presence of biochar forms a solid, ammonium bicarbonate fertiliser, inside the pores of the char. This nitrogen-enriched char can be incorporated into the soil, where it serves three purposes: as a carbon store, as nitrogen fertiliser, and as a biologically active soil enhancer. Iowa State University and Eprida* are among the leaders in this field.

Properties and potential uses of bio-oil

Bio-oil is a complex liquid produced as part of biomass pyrolysis. It has only 42% of the energy content of fuel oil on a weight basis and 61% on a volumetric basis. Technical challenges with bio-oil include low volatility, high viscosity, coking, corrosiveness, and instability. Technical standards need to be developed for it.

The presence of water in bio-oil lowers its heating value but improves its flow characteristics, which is beneficial for combustion (pumping and atomisation). It also lowers nitrous oxide emissions. Bio-oil can be used as a basis for higher-value extracts and by-products, for example acetic acid, resins, food flavourings, agrichemicals, fertilisers, and emission-control agents.

There is extensive commercial and academic work under way to produce bio-oil through pyrolysis, with leading organisations including Dynamotive,* in Ontario, Canada BEST Technologies, research units at the State University of Iowa, RTI Canada, IWC Germany, Aston University, UK, VTT† in Finland, and the NREL‡ in the USA.

Bio-oil could only replace diesel as transport fuel if it is upgraded and work is under way internationally on this. Approaches include using mild oxidation with ozone and full deoxygenation, either through hydro-treating or catalytic vapour cracking. However, the economics of this are not currently attractive. Alternatively, although bio-oil is not miscible with hydrocarbons, it can be emulsified with diesel oil with the aid of surfactants. This means it could be used as a diesel oil extender, although both surfactants and the emulsification process are expensive.

It is possible to gasify bio-oil and to then synthesise high-quality transport fuels, but a substantial scale of operation is needed to justify the high cost of a processing operation and this in turn means high transport costs for diffuse biomass resources. Bio-oil is easy to transport and it would be possible for a network of smaller-scale or mobile pyrolysis plants to produce it for transport to a centralised plant for gasification and synthesis into transport fuels. Such a plant would produce substantial volumes of biochar as well, although valuing this is problematic. Mobile pyrolysis plants have been designed that not only convert biomass into bio-oil, biochar, and gas, but also use the energy from the gas to power the process, with no other energy needed.

With existing technology, bio-oil is best used directly (or with minor modifications) as process heat (including greenhouse heating) and in stationary engines, although electricity generation may be the most promising option.

Potential for biochar and bio-oil co-production in New Zealand

Biochar could be made from residues from plantation forestry harvesting. However, there are costs in collecting diffuse residues, and waste streams from processing are already used directly in process heat or have other valued uses.

One opportunity is short-rotation growing or coppicing of poplar, willow, or eucalypts on low-value land. Such production regimes also have potential for bioremediation of contaminated land. On erosion-prone hill country such regimes might prevent

* *See http://www.eprida.com/home/index.php4*

* *See http://www.dynamotive.com/*

† *See http://www.vtt.fi/?lang=en*

‡ *See http://www.nrel.gov/*

carbon loss (since plants grow more slowly on eroded soil and soil loss reduces carbon sequestration in both plants and soil). However, production and harvesting costs on steeper land may be excessive.

Willow (*Salix*) plantations in Sweden produce for up to 30 years and can yield 7–11 tonnes of dry biomass per ha per year (SVEBIO 2004). Cloned eucaplyts in Brazil can produce 40 tonnes of dry biomass per hectare per year – growth rates that would seem impossible in New Zealand. Production (as a rough estimate) of around 10–20 tonnes dry mass per hectare per year might be achievable in New Zealand, and application of advanced plant breeding technology may lift this further.

The balance between biochar and bio-oil would be driven by relative prices, and pyrolysis processes are flexible enough to adapt to these (see Table 1). While dollar values can be placed on bio-oil, the value of biochar for carbon sequestration, reduced nitrate leaching and nitrous oxide emissions, and higher agricultural productivity is still speculative at this stage. However, biochar may become increasingly attractive with rising concern about climate change, the negotiation of new post-Kyoto Protocol rules, and commercially-driven pressures to reduce the life-cycle net greenhouse gas impact of our major export products.

Some skeptical questions

There is no 'magic bullet' to mitigate climate change, and a very wide array of technologies needs to be developed or more widely deployed to address it.

On a large enough scale, it seems that biochar and bio-oil co-production could help address New Zealand's climate change and water quality problems, lift agricultural productivity, reduce the costs of imported fossil fuels and contribute to phasing out use of fossil fuels in electricity generation and industrial process heat. The ability of one process to help address so many different New Zealand problems suggests, of course, that it is 'too good to be true' and skeptical questions need to be asked:

Do we know enough about the science?

The basic scientific and technical underpinnings for biochar and bioenergy co-production are in place, but outstanding technical issues include:

- optimising wood feedstock production, harvesting, drying and grinding;
- choosing from fluidised bed, rotating cone, or mechanical or centrifugal ablative pyrolysis processes for further development;
- finding the best R&D paths to upgrade the use of bio-oil to make it a suitable substitute for diesel (unless it is used directly for electricity generation or process heat);
- scientific validation and ongoing fine-tuning of the environmental and agricultural productivity benefits of biochar.

We need to know more about New Zealand soils, biomass production regimes, and pyrolysis processing before we could optimise the biochar opportunity. There will be a need to fine-tune all stages of the production and use of biochar, since biochars can be very different in their nutrient component, carbon levels, and pH, so crops and soils will respond differently.

However, innovation does not need perfection and optimisation – it simply requires doing better than the status quo. People were making steel for hundreds of years before they 'learnt' how to make it in terms of perfect scientific understanding. It would be possible to spend decades researching biochar and achieving process optimisation in its manufacture and application. However, many of these issues are being addressed in overseas research that we do not need to duplicate. If biochar can be commercialised in New Zealand, supporting scientific research could be drawn on to improve the technology and its fitness for purpose.

What are the net energy balances from biochar and bio-oil?

Biofuel production using pyrolysis can produce a biochar by-product which sequesters around 30.6 kg carbon for each GJ of energy produced (Lehman *et al*. 2006). There would need to be a careful life-cycle analysis of all fossil fuel use in feedstock production and processing and biochar making and application before we could measure the net gains in both energy and carbon balance terms.

Would biochar applications be suited to New Zealand soils?

Many New Zealand soils are acidic and some have problems of aluminium toxicity, conditions amenable to biochar application. However, many soil profiles are shallow and this might limit the depth to which biochar can be added. This suggests that for some New Zealand soils an 'upper ceiling' of carbon sequestration might be reached much sooner than in the case of *terra preta* soils.

It is unclear what volume of biochar would be needed to make a difference to crop productivity and reduced nitrous oxide emissions and nitrate leaching. In overseas cropland trials, typically 10 tonnes per hectare are applied. However, many of our pasture soils are quite shallow and this suggests that smaller volumes of biochar might be effective if added only to the top few centimetres of soil.

The stability of biochar in soil will be affected by the specifics of the biochar process and its tailoring to local soil conditions. Likewise, the ceiling for carbon sequestration in soil will be heavily dependent on local soil conditions. Over time, we would learn to tailor biochar applications to different soil types and other conditions.

Soil carbon sequestration and New Zealand's position on the Kyoto Protocol

Addressing climate change involves the management of carbon flows between the atmosphere and terrestrial and ocean systems. Over 80% of organic carbon in terrestrial ecosystems is in soil rather than biomass (IPCC 2000). The Kyoto Protocol Article 3.4 allows for the recognition of enhanced soil carbon sequestration. However, New Zealand did not include this in its

Kyoto commitments because of a view that New Zealand soils in total may have been losing carbon. This exclusion has meant that little effort has gone into the potential for understanding and enhancing soil carbon sequestration, whereas a lot of effort has gone into forestry carbon sequestration because of its recognition within Kyoto Article 3.3.

It should, however, be noted that a landowner converting forest plantations to dairy pasture can use Article 3.3 to offset carbon losses in the above ground carbon pool by sequestering biochar in the soil carbon pool. This means that every tonne of carbon dioxide added as biochar would reduce deforestation liabilities. This could be incorporated into New Zealand's inventory and it could well be included in the design of a domestic deforestation regime, possibly as a component of an emissions trading regime. It is also possible that biochar incorporation in soils could at least partly substitute for lime and fertiliser inputs that are applied when forests are converted to pastures.

It is very likely that some means will be found of earning economic benefits from soil carbon sequestration. The 'grey market' for carbon credits could be used, and increased soil carbon in New Zealand agriculture could help ward off threats to our exports from 'food miles' and carbon labelling arguments. Progress with soil carbon sequestration might also be reflected in negotiation of any second Kyoto Protocol commitment periods, or in post-Kyoto or alternative agreements.

Economics of biochar and bio-oil

An important economic constraint will be the volume and cost of biomass feedstock. A vibrant forest processing industry would substantially improve the economics of both pyrolysis and energy from wood pellets and wood chips. It is possible that costs could drop with new technology, for example biological processing, or using advances that spin-off from cellulignin or from ligno-cellulosic research.

Only when the environmental benefits of biochar are recognised and valued, and entrepreneurs invest in it, will costs and prices be fully discovered, and technological innovation drive down costs and improve product and process performance.

Bio-oil research after the 1970s 'oil shocks' focused on transport fuel and largely considered the fine char by-product as waste. However, this 'waste' becomes valuable when markets recognise its environmental benefits and so future pyrolysis research may focus on optimising biochar rather than bio-oil.

An advantage of biochar is that it is one of the few technologies to address climate change that creates net economic as well as environmental benefits. In contrast, carbon capture and storage (CCS) from coal involves a net financial and energy loss and no compensating commercial benefits.

Economic studies have been done on the biochar option overseas. Baum & Weitner (2006) contend that 'production and application costs of biochar may be fully recovered, even in the absence of a carbon market, based solely on crop production benefits and fertiliser cost savings.' However, this would be highly dependent on soil type and production system variables. Lehman *et al*. (2006) contend that 'the most promising strategy for cropping of biomass as feedstock for biochar production is the concurrent production of bio-fuels by pyrolysis.' They conclude that biofuel production using pyrolysis 'has great potential to generate electricity at a profit in the long term, and at a lower cost than any other biomass-to-electricity system.'

Envirochem (2006) concludes that a 100 tonne per day bio-oil plant that includes carbon credits for reduced fossil fuel use would only be economic if it used residue from processing that did not involve harvesting costs, for example if processing waste was used. This study focused on bio-oil displacing fossil fuel use, and did not place a value on other environmental benefits.

Some New Zealand scientists estimate that extra organic matter in soils is worth $NZ27–151 per ha per year in increased milk solids production (Landcare Research 2005). This study estimated that soils depleted in organic matter took 36–125 years to recover and the accumulated lost production was worth $518–1,239 per hectare. This value was calculated as 42–73 times lower than the environmental value of the organic matter as a store of carbon and nitrogen, which varied between $22,963 and $90,849 depending on soil, region, valuation placed on credits, and so on. If anything like these figures are supported in prototype development and trials (and if value is placed on the bioenergy by-product), the economics of biochar seem very attractive.

One way of 'discovering' the economics of biochar and bio-oil co-production would be factoring in as notional or proxy prices the economic benefits of net carbon sequestration, reduced nitrous oxide emissions, and (in sensitive catchments such as Lake Taupo) reduced nitrate leaching. Based on these proxy prices, tenders could be called to deliver a commercial operation involving production of feedstock and its processing, and the marketing of biochar and bio-oil. Such an approach would help unleash industrial and scientific innovation and, over time, the property rights and institutional rules of the game would catch up with the innovation, and proxy prices would become real prices.

Possible ways forward

New Zealand is a biologically based economy with a lot of under-utilised industrial expertise and entrepreneurial spirit. There are a range of opportunities to progress biochar and bioenergy co-production and sequestration for its economic and environmental benefits. These opportunities typically involve convergence of technical information across traditional industry sector boundaries. Only business and scientific entrepreneurs are close enough to the market and science to identify and exploit these opportunities. Some of this entrepreneurship might come from state-owned enterprises as well as private businesses.

It is up to industry and science to choose the best way forward. However, to make the potential real, the following is an illustrative approach. Biochar and bio-oil co-production could be based on dedicated fast-rotation or coppicing hardwood forestry located on low-value land. To minimise transport costs this would need to be close to land that generates high nitrous oxide and nitrate leaching externalities. Dairy land in parts of Canterbury, the Waikato and Taupo catchments might be examples. Biochar could be applied very selectively to specific parts of farms carrying high nitrogen loadings, such as from urine patches. Pyrolysis processing would need to be close to lines connections for distributed generation opportunities through bio-oil electricity generation.

Biochar is likely to be relevant to intensive arable and horticultural soils and perhaps even to small niches such as compost blends for home gardening applications.

There are many other alternative (and probably superior) options that better informed scientists and business people may be able to identify.

Concluding comment

Biochar and bio-energy co-production is now technically feasible. It could be commercially profitable in New Zealand if we recognised economically its environmental benefits in soil carbon sequestration, reduced nitrous oxide emissions and reduced nitrate leaching into waterways. There is a need for publicly funded research support, including the validation and optimisation of biochar's crop productivity benefits.

Commitments need to be in place for emissions trading or other means of valuing environmental benefits. Over time, measuring soil carbon sequestration and nitrous oxide reductions from biochar would need to be exact enough to uphold property rights and to comply with any relevant international agreements. The rules around distributed generation must be supportive of use of bio-oil (as well as other renewables) for electricity generation from dispersed sites.

In climate change mitigation, and in creating new economic opportunities for sectors such as forestry, New Zealand needs some 'runs on the board'.

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