UKBRC

Biochar, reducing and removing CO2 while improving soils: A significant and sustainable response to climate change

Evidence submitted to the Royal Society Geo-engineering Climate Enquiry in December 2008 and April 2009

Simon Shackley, Saran Sohi, Stuart Haszeldine, David Manning and Ondřej Mašek

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UKBRC Working Paper 2:

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www.biochar.org.uk

Summary

1. The focus of this response is evaluation of a single option – that of biochar for carbon storage in soils.
2. Biochar is primarily a response to climate change. Carbon savings come from carbon sequestered for the long-term (100's to 1000's years) in biochar, and from avoided emissions (from substituting fossil fuels and fertiliser; and through suppression of methane and nitrous oxide emissions).
3. A conservative estimate is that 1 gigatonne of carbon per year can be stored in biochar by 2050, and probably by 2030, mostly produced from agricultural residues and organic wastes. More ambitious proposals, which progressively use dedicated biomass stocks, could increase this to 5 – 9 gigatonnes C per year by 2100, and probably much earlier, though careful evaluation of the environmental and socio-political implications of such a scenario is necessary (e.g. to ensure that it does not simply lead to a massive expansion of unsustainable agri- and silvicultural plantations).
4. Whilst biochar is readily produced from a wide range of organic feedstocks and wastes, the efficient 'closed-system' slow pyrolysis technology is still at a relatively early stage of development and is consequently still relatively expensive. As experience grows, several dominant designs should emerge and unit costs and maintenance & operation costs should come down.
5. Biochar has been shown to improve productivity of crop growth in many different soil and agronomic conditions, though there is a lack of scientific understanding of what explains this effect. Biochar has also been reported to suppress CH_4 and N_2O emissions from soil and to improve water retention.
6. The UK's universities and research institutes are ideally placed to take biochar RD&D forward. A coordinated approach by the Research Councils will, however, be necessary.

Question 1: What do you consider to be the current state of knowledge regarding the feasibility, efficacy and predicted impacts of biochar schemes?

What is biochar? Biochar is a black carbon material produced from the decomposition of plant-derived organic matter (biomass) in a low- or zero-oxygen environment (i.e. pyrolysis or gasification) to release energy-rich gases which are then used for producing liquid fuels or directly for power generation. The carbon atoms in biochar molecules are strongly bound to one another, and this makes biochar resistant to attack and decomposition by micro-organisms. By contrast, the carbon in most organic matter is rapidly (between 1 and 5 years) returned to the atmosphere as CO_2 through respiration. Consequently, biochar is a potentially highly valuable way of stabilising carbon and storing it in soils and is one of very ways of removing CO_2 from the atmosphere. There are a very wide range of potential biochar feedstocks: e.g. wood waste, timber, agricultural wastes, manure, leaves, food wastes, straw, paper sludge, green waste, distillers grain, bagasse and many others.

The main technologies for producing biochar are fast, moderate and slow pyrolysis and gasification. Pyrolysis produces between 12 and 35% biochar (dry basis), with slow pyrolysis (at about 500^{o}c and with a very long vapour residence time of between 5 and 30 minutes) giving the best biochar yields. Gasification occurs at a higher temperature of at least 750^{o}c with a moderate vapour residence time of 10 to 20 seconds (Brown, 2009) and generates approximately 10% biochar (dry basis). Biochar has a unique porous structure and chemical composition which enhances soil fertility and allows for a more sustainable use of some soils. Biochar is first and foremost, however, a response to the problem of climate change. This is through the long-term storage of carbon in soils in a stable form as biochar, with additional carbon offsetting arising from the avoided emissions from fossil fuel combustion, fertiliser application and field operations.

Longevity of Biochar Carbon Storage: Biochar from forest fires has existed in some soils for 10,000 years, whilst radiocarbon dating of the *terra preta* soils of Amazonia show that the carbon can persist in the soil for between 500 and 7000 years before present (Lehmann et al., 2009). One conservative estimate is that the Mean Residence Time (MRT – the average time that biochar remains in the soil) is between 1000 and 2000 years for dryland conditions of northern Australia. A recent study confirmed that the MRT for black carbon in two Australian savannah regions was between 1,300 and 2,600 years (Lehmann et al., 2008). The half-life of biochar found in coastal temperate forests in western Vancouver has been calculated as 6623 years (Lehmann et al., 2009). There are, however, some other studies which show a much faster turn-over time for biochar. A study of fires in the Russian steppe concluded that the turn-over time of biochar was only 293 years. Meanwhile, biochar stocks formed after savannah burning in Zimbabwe had a MRT of only a few decades. Lehmann et al. (2009) suggest that these much lower residence times might be explained by processes other than mineralization alone (such as leaching or erosion).

The longevity of biochar in soils should not be overestimated: an unknown but large-scale mechanism for removing black carbon appears to exist. We know that more black carbon is produced than is found in possible long-term sinks (e.g. ocean sediments and the soil organic carbon pool) (Woolf 2008). Over-accumulation of black carbon in soils is also inconsistent with empirically-validated models of the response of carbon in soils. One of the critical research needs is better understanding of such processes on different timescales. In summary, whilst there are major scientific questions to be addressed regarding longevity, there is good evidence that biochar, if managed correctly, will remain in soils for at least 1000 years and possibly much longer. These timescales look sufficient for biochar to qualify as a viable option for atmospheric CO_2 reduction (since, to be effective in tackling anthropogenic climate change, the carbon must be removed from the atmosphere for hundreds to a thousand years) (Shackley and Gough 2006).

How Much Carbon Can Biochar in Soils Store? The amount of biochar that can be stored in soils is a function of the concentration of the material in the soil and the depth to which it is incorporated. To date, we have the evidence of the *terra preta* soils of Amazonia, which contain approximately 50 tonnes of black carbon per hectare to a one meter depth (Glaser et al., 2001). Applications of up to 140 tonnes of biochar per hectare on weathered soils in the tropics resulted in crop yields, and without reaching a point at which yield increases ceased (Lehmann et al. 2006). Several trials with particular crops have shown a threshold effect, and Lehmann concludes that: "crops respond positively to bio-char additions up to 50MgC ha^{-1} and may show growth reductions only at very high applications." Biochar is a variable substance whose properties are determined by feedstocks, conversion processes and the soils into which it is applied. Exactly how much biochar can be applied in different agricultural and land-use contexts, and on what timescales, is not well understood at present.

Lehmann et al. (2006) estimate that current global *potential* production of biochar is 0.6 ± 0.1 gigatonnes per year (10^9 tonne or $PgCyr^{-1}$). They estimate that by 2100 production of biochar could reach between 5.5 and 9.5 gigatonnes per year. There are very large uncertainties attached to these numbers, however, arising from competition for land-use, competition for use of biofuels and agricultural wastes and a huge divergence (of nearly 1000%) in different expert estimates of the potential future global supply of biomass for bioenergy purposes. Woolf (2008) estimates that if all existing agricultural crop residues were used to produce biochar, this would constitute 1 gigatonne of carbon storage. A reasonably conservative assumption would be that biochar has the potential to offset global atmospheric carbon emissions at the gigatonne per year scale by 2050 (and probably by 2030 if a concerted effort were made) - one of the climate 'wedges' in Pacala and Socolow's (2004) schematic, hence comparable to other major mitigation activities (CO_2 Capture and Geological Storage (CCS), renewables, efficient vehicles, etc.).

Positive Impacts of Biochar Upon Soils: Studies of biochar-rich *terra preta* and *terra mulata* soils in Amazonia have stimulated interest in the agricultural benefits of incorporating biochar into soils. Crop fertility appears to improve in many situations where biochar has been incorporated, whilst such soils appear to retain water more effectively, as well as possibly reducing run-off of agricultural inputs and, in some circumstances, limiting nitrous oxide and methane emissions. In tropical environments, biochar has sometimes increased crop yields 2- or 3-fold, although at the moment the impact is not predictable. Biochar can also reduce the number and intensity of field operations, thereby reducing diesel use. And biochar addition appears to stimulate the net primary productivity of many agri- and ecosystems, thereby resulting in a net uptake of carbon.

Reviews of the agronomic impacts of biochar have been undertaken by Woolf (2008) and Blackwell et al. (2009). The reason why soil productivity is improved appears to be related to the following factors: reduction in soil acidity, improvement in the cation exchange capacity, an improved habitat for soil microorganisms and better water holding capacity. The pore size allows beneficial microorganisms to find suitable shelter from predatory soil fauna. Meanwhile, water retention in biochar occurs because water molecules collect in the voids, though chars can be hydrophobic so there is some uncertainty on whether water retention will be a universal property of biochar (Woolf, 2008). Whilst most greenhouse- and field-trials generally show the beneficial impacts of biochar upon agronomic performance, there is a high degree of variability in the response - hardly surprising considering the diverse sources of biochar and the highly variable soils and agronomic systems into which biochars have been introduced.

The Efficacy of Biochar as a Form of Carbon Storage: Evaluating the efficacy of biochar requires consideration of the energy and carbon balance of the full life-cycle. What is the energy yield (i.e. energy inputs compared to the energy outputs) for pyrolysis biochar systems (PBS)? What is the net carbon benefit (i.e. avoided greenhouse gas emissions plus carbon that is sequestered in the long-term) of PBS and how does this compare to other ways of using biomass for sustainable energy (such as combustion for electricity or heat, Combined Heat and Power, anaerobic digestion, fermentation, etc.). Is it better in carbon terms to use biochar as an energy source rather than applying it to soils as a long-term carbon store?

Fowles (2007) found that in terms of carbon balance, it is better to use biomass for PBS than for straight combustion if the reference case (i.e. what is being replaced) is natural gas or the national grid mixture. On the other hand, if coal combustion is being replaced, then more carbon emissions are avoided by using the biomass for conventional electricity generation than to use PBS. Fowles assumed that 30% of the material is converted to, and permanently stored as, carbon as well as a 33% efficiency for biomass combustion. Furthermore, if biomass combustion is utilised with a Combined Heat and Power system (which typically reaches 80% efficiency), then use of biomass in such a way is preferable to PBS, except when the reference case is natural gas at 80% efficiency. Fowles did not include the avoided CO_2 emissions arising from the use of pyrolysis syngas or bio-oils, or suppression of non-CO_2 GHGs, so his estimate of the carbon value of biochar is almost certainly an underestimate.

As yet, very few Life Cycle Assessments (LCA) of pyrolysis + biochar have been undertaken so we cannot currently answer several key questions. Gaunt and Lehmann (2008) compared growing winter wheat with the production of bioenergy crops (BECs) (Miscanthus, switch grass and corn) and also explored the use of crop wastes (winter wheat straw and corn stover) to produce biochar. Their findings can be summarised in the key points below:

- The energy output is greater than the energy input by 2 to 7 times in the case where slow pyrolysis is optimised for biochar rather than for energy production (with a consequent 30% reduction in energy output). This energy balance compares favourably with comparable technologies such as ethanol from corn (which yields 0.7–2.2 MJ MJ^{-1}).
- The CO_2 emissions arising from pyrolysis are in the range 91 to 360 kg CO_2 per MWh (with no account taken of carbon sequestered in char, or other impacts of char on GHG emissions when applied to soils). This compares with emissions of 390 to 880 kg CO_2 per MWh for gas and coal respectively (in the UK).
- Including all the carbon avoided and sequestered, PBS accounts for 4 to 8 tonnes carbon avoided per hectare per year when PBS is optimised for energy generation; and between 12 and 19 tonnes avoided per ha per year when PBS is optimised for biochar production. Hence, optimising for biochar production rather than bioenergy avoids between 3 and 5 times more carbon. The carbon stored in biochar accounts for 41 to 64% of the overall carbon avoided, whilst avoided fossil fuel emissions, reduced fertiliser use and reduced non-CO_2 GHG emissions account for the remainder.

2. How do you think research into biochar should be taken forward, and by whom?

UK universities and research institutes are very well positioned to take forward RD&D on biochar. There are core competencies in the life sciences, soil and other geosciences, sustainable energy engineering, and systems analysis. The UK Biochar Research Centre will endeavour to play a coordinating and facilitating role to UK research activities, in addition to undertaking leading-edge research.

3. What factors need to be considered before deploying any biochar schemes? Who should be responsible for any deployment?

To our knowledge, there are no evident negative impacts arising from applying biochar to soils. According to Gaunt and Lehmann (2008), use of slow pyrolysis avoids the production of dioxins and polyaromatic hydrocarbons, which can be persistent organic pollutants. If biochar is deemed to be a by-product that is being disposed-of, then it is classified as a waste and the pyrolysis process and disposal of the biochar is subject to the onerous requirements of the Waste Directive. There are also regulations controlling what is put on to agricultural land in the UK and it is clear that a detailed environmental impact assessment will be necessary prior to any deployment of biochar, to ensure that there are no adverse impacts. Biochar projects in developing countries that are aiming to secure carbon credits, will be subject to evaluation under the Clean Development Mechanism. It is important that appropriate environmental impact assessment methodologies are developed and adopted internationally and the UK Government could play an important role here.

4. What do you consider to be the most important political, social, legal or ethical issues raised by biochar?

The use of PBS need to be carefully evaluated to ensure that there are no adverse impacts on land-use, potential conflict with food production or biodiversity protection. As is the case for biomass for bioenergy in general, if biochar becomes one of the principal carbon reduction 'wedges', there are inevitable implications for land-use change globally on a large-scale. Such land-use change raises important questions at a number of levels: environmental impacts from (potentially) intensive land-use; carbon emissions from forest clearing which may take years to 'pay back'; land ownership and equity issues regarding who benefits and who loses out from large-scale plantations; ethical issues regarding whether large-scale, intensive biomass cultivation is consistent with moves to a more sutainable zero-carbon society (e.g. see Ernsting and Rughani (2008) for a critical NGO perspective on biochar). If PBS is to contribute constructively to a sustainable response to carbon reduction, it is vital that the lessons of the past regarding the adverse environmental and socio-economic and political impacts of intensive plantations are learnt and acted upon.

5. What do you see as the main barriers to, and opportunities afforded by, biochar?

Biochar provides an opportunity for involving farmers and landowners as participants in carbon markets; this is important to rural livelihoods and diversification in all countries, and lends itself particularly well to poverty alleviation in developing countries. Creative approaches to certification and verification of biochar under the Clean Development Mechanism (CDM) could permit a much-needed step-change in the engagement of small farmers from developing countries in the CDM. There is, furthermore, an opportunity for biochar to contribute to low-carbon food chains, i.e. if the carbon stored in biochar (derived from crop residues) can be accounted for in the carbon footprint of foods. PBS may also provide important low- or negative-carbon alternatives to existing and emerging waste technologies.

A key barrier at present is the lack of reliable off-the-shelf pyrolysis technologies at a suitable price. Technology development is proceeding rapidly but there is, as yet, no 'dominant design' in the market, and it is likely that a variety of competing designs will be available to developers over the next few years before the market settles on a few preferred designs. At this stage of the technology cycle, costs per unit are likely to remain high and performance, reliability and operability parameters are still being formalised. Partly as a consequence of technological uncertainties, economic analyses of biochar are at present in their infancy. Gaunt and Lehmann (2008) found that the cost of reducing a tonne of CO_2 in the PBS they examined was between $9 and $16 (relative to maximising the plant for energy production). This is considerably less than the average cost of a tonne of CO_2 under the EU ETS over the past several years. The authors do not, however, provide a full economic costing of their PBS, so the abatement cost is not comparable with commonly quoted values for other technologies. McCarl et al. (2009) have undertaken a full economic costing of biochar for US conditions and find that the use of maize residue using fast or slow pyrolysis is not profitable. They do find, however, that the economic value of carbon storage in biochar is slightly greater than its value as an energy source, especially at the summer 2008 carbon price on the EU ETS ($40 tCO_2^{-1}). For slow pyrolysis to be economic, however, would require the carbon price to double to $79 tCO_2^{-1}.

6. **Where do you feel that biochar fits in the greater scheme of climate research and action to mitigate and adapt to climate change?**

PBS has a relatively low-capital intensity and a short lead-time. This means that, once good technology designs are available in the market at the right price, deployment could take place rapidly at the global scale. Herein lies an important advantage of biochar compared to low-carbon energy projects which are capital-intensive and have a long lead-time - such as CCS and nuclear power. More research is needed to explore the interactions between deploying biochar on a gigatonne scale and other elements of a c. 10 GtC reduction strategy to 2050. For example, is it consistent with other bioenergy and biofuels policies and ambitions? What would be the implications of an aggressive biochar strategy for land-use, food production and rural livelihoods? Biochar may also help in adapting to climate change through its role in water management, mitigation of erosion and creating a more resilient agricultural system.

7. **Are there any other issues related to biochar that you consider to be important**

Deploying PBS is complex because of the range of sectors and policy domains which are affected: energy & climate, soils, waste, agriculture & food, water, rural development, and so on. PBS is vulnerable to price fluctuations in products and services in a number of these different markets. Hence, PBS deployment would require recognition of multiple benefits and appropriately designed policies.

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To Bury or to Burn? Optimal use of Biochar for Cost-Effective Carbon Abatement

Supplementary evidence to the Royal Society Geo-engineering Climate Enquiry

1. Introduction

Charcoal and similar pyrolysed materials are potential fuels with an economic value. Furthermore, their use as a source of energy could offset carbon emissions arising from combustion of fossil fuels. Therefore, a critical question is whether it is better to burn biomass or char as a fuel, or to bury biochar in soils as a carbon store, with the additional indirect benefits arising from its impacts upon other greenhouse gas fluxes, crop and net primary productivity, and so on.

2. Definitions

Biochar: We refer to char as biochar where it is deliberately applied to land for carbon abatement and/or agricultural reasons; we refer to it simply as char where it is used as a fuel.

Bury: We use the term 'bury' to mean incorporation of biochar into soils, or into landfill or the sub-surface (disused mines, etc.), for carbon storage and/or for agronomic reasons.

Carbon abatement is defined here as the net effect of changes in greenhouse gas fluxes resulting from the production and application of biochar. This can include any or all of the following: carbon stored directly in the biochar; CO_2 released during pyrolysis; offset CO_2 emissions arising from avoided fossil fuel combustion; offset carbon emissions from reduced chemical inputs to agriculture; suppression of nitrous oxide and/or methane through biochar addition to soils; offset carbon emissions from reduced operations in the field. Which of these components is included will be specified in the text.

Carbon abatement efficiency is defined as the net carbon equivalent abatement delivered during the processing of a unit of feedstock.

3. Utilisation of Biomass for Energy or for Producing Biochar

We considered whether biomass feedstocks themselves are better utilised for a pyrolysis-biochar system (PBS) or for combustion in the evidence which we submitted in December 2008 (on page 3). It was noted that, in general, there is reasonably good evidence that PBS has a better carbon abatement efficiency than bioenergy alone, though this is dependent on the comparison reference case. Since we submitted the evidence in December 2008, we have undertaken our own analysis of the issue and have produced similar findings to Fowles (2007) and Gaunt & Lehmann (2008). Our simple calculations, focusing just on the thermal conversion processes, indicate that if the syngas and/or oil from pyrolysis can be effectively utilised, then the carbon balance from PBS (but not accounting for the indirect benefits of biochar to greenhouse gas fluxes) is slightly better than that of combustion. Any additional benefits arising from the indirect effects of biochar (reduced fertiliser, suppression of N_2O emissions, etc.) would increase the carbon abatement efficiency advantage of producing biochar over using biomass for combustion.

The McCarl et al. chapter (2009) takes a full Life Cycle approach to exploring fast and slow pyrolysis of maize stover, and subsequent biochar deployment, in mid-West USA conditions. For slow pyrolysis, 1.1 tonnes of CO_2 (equivalent) are abated per tonne of feedstock, whilst the value is 0.8 tCO_2e in the case of fast pyrolysis. We calculate that the offset CO_2 emissions from combustion of the maize stover would be approximately 0.4 tCO_2 per tonne feedstock (relative to coal, the reference case used by McCarl et al.). Hence, 2 – 3 times more carbon is abated by PBS than by biomass combustion; this is some what less than the numbers reported in Gaunt & Lehmann, probably because McCarl et al. make less optimistic assumptions. (Approximately half of the carbon abatement arising from use of biochar arises from the indirect impacts of biochar in the soil – these impacts are all currently subject to moderate to high uncertainty).

Having reviewed the available literature, and having done some analysis ourselves, it is clear that there are currently technical uncertainties in accounting for the energy outputs of the pyrolysis process. In the absence of a 'dominant design', there are a range of different technologies (different designs, scales, materials, costs, etc.) which are being explored for PBS. A further problem is that information on the technologies is frequently commercially confidential; hence not all the relevant information has been published in the literature. These factors currently limit our ability to provide a reliable and definitive carbon and energy balance for the pyrolysis process. The results of a comparison of PBS with biomass combustion also depends to some extent upon creating useful markets for the energy outputs of both, especially for the heat. More research is therefore needed to understand and properly model the thermal conversion that occurs during pyrolysis, at relevant scales and costs, etc.

The subsequent focus in this supplementary evidence is limited to the alternative uses of biochar once it is produced or to alternative versions of pyrolysis (fast and slow).

4. Literature Review

Two published studies have investigated this issue.

1. Gaunt and Lehmann (2008). Their Tables 3 and 4 compare total avoided emissions (kg CO_2 equivalent per hectare per year) from use of bioenergy crops (switchgrass, miscanthus, forage corn) and from use of crop residues (winter wheat straw and corn stover). The slow pyrolysis process either optimises energy generation, hence gasifies all the char to produce syngas that is used as an energy source, or alternatively produces as much biochar as possible. The results are summarised below in Table 1 for the case of off-setting natural gas. A greater carbon abatement efficiency is achieved by the addition of biochar to soils rather than using char for energy generation (200 to 400% increase in C abatement). Gaunt and Lehmann also calculate the costs of using biochar in soils rather than as a source of energy. The energy penalty from using biochar in soils is \$47 per tonne of biochar. Assuming that 85% of the biochar is stabilised carbon, the energy penalty (i.e. production cost) of a tonne of CO_2 equivalent abatement is \$55/3.67 = \$15.

This can be compared to the market value of CO_2 which has, in recent years and in different markets, varied from \$4 to \$40 tCO_2. Some analysts have argued that the true cost of a tonne of CO_2 emissions is higher: the UK government uses a shadow price of carbon of between £10 and £38 tCO_2 (\$15 to \$57 t tCO_2). (http://www.defra.gov.uk/environment/climatechange/research/carboncost/scc.htm). A reasonable argument can therefore be made that, where a reasonably high carbon price occurs, biochar production for soils (rather than use of char as a source of energy) makes good economic sense.

Table 1: Comparison of Slow Pyrolysis for Syngas Production versus Biochar Production for Different Bioenergy Crops and Agricultural Residues (expressed in kg CO_2 avoided per ha per year) (Off-setting Natural Gas)

Avoided emissions (kg CO_2 per ha per year)	Switchgrass	Miscanthus	Foragecorn	Winter wheat	Corn stover
Slow pyrolysis for syngas production	4234	4992	4083	2002	2173
Slow pyrolysis for biochar production	12551	15358	16912	9575	10688
Difference (biochar minus energy optimisation)	8317	10366	12829	7573	8515
Percentage increase in avoided emissions (biochar minus energy)	196	208	314	378	392

Source: Tables 3 & 4: Gaunt and Lehmann (2008)

2. McCarl, Peacocke, Chrisman, Kung & Sands (2009). A detailed life-cycle assessment model is developed for the case of maize residues arising from cultivation in the US Mid-West. The model is the most detailed analysis to date of the biochar production and application life-cycle. The pyrolysis plant envisaged is medium-scale (70,000 tonnes feedstock per year) and a fast and slow version of pyrolysis are compared. Because the biochar yield from fast pyrolysis is 4.5% compared to 35% from slow pyrolysis, this comparison allows the issue of whether biochar production is preferable to energy production from char to be examined. In the specific context of the US Mid-West, the net value of fast pyrolysis is -$45 per tonne of feedstock, whilst it is -$70 per tonne of feedstock for slow pyrolysis. Note, however, that this calculation assumes a very low value of carbon abatement of $4 t$CO_2$.

According to McCarl et al., the value of char as a fuel is $55 per tonne. Meanwhile, they estimate that the agronomic value of biochar applied to land is $33 per tonne. These numbers are sensitive to the price of coal, however. If the coal price as of December 2007 were used (rather than that at August 2008), the value of char as a fuel would drop to $18 per tonne, in which case biochar would have a higher value as a soil additive than as a fuel.

The calculations in the paragraph above do not include the value of offsetting carbon emissions from fossil fuel combustion, the value of the carbon stored, and the other changes in greenhouse gas fluxes. We can simply add the value of the stored carbon in a tonne of biochar to the agronomic value. Assuming 85% of the biochar consists of stabilised carbon, and a carbon abatement value of $40 per t$CO_2$e, then the carbon storage value of a tonne of biochar is: 0.85 x 40 = $34. Adding this to the agronomic value gives $67 per tonne biochar, which is greater than the value of char as a fuel.

Using a similar method to Gaunt & Lehmann, McCarl et al.'s data can also be used to derive an energy penalty for producing biochar for soils rather than biofuels of $40 per tonne of CO_2. This is considerably more than Gaunt & Lehman's estimate of $15 per tonne CO_2, though similar to other estimates in the literature (e.g. Lehmann, 2007).

Accounting for all changes in greenhouse gas fluxes over the lifecycle, McCarl et al. find that fast pyrolysis results in a net carbon abatement of -0.82 tonnes of CO_2 equivalent per tonne feedstock; whilst slow pyrolysis has a net carbon abatement of -1.11 tonnes of CO_2 equivalent per tonne feedstock. If we applied a carbon abatement value of $40 per t$CO_2$e, then the net present value of fast pyrolysis is -$15 per tonne feedstock, and that of slow pyrolysis is -$30 per t feedstock. With these assumptions, fast pyrolysis still appears to be more favourable than slow pyrolysis in terms of net present value.

McCarl et al. themselves conclude that: "… under current [August 2008] European levels of GHG offset prices, biochar use as a soil amendment in agriculture already exceeds its combustion value" (2009: 356). However, it is necessary to introduce a carbon price at the high end of recent historical experience ($40 per tCO_2) in order to get this result. Furthermore, their study still appears to favour fast pyrolysis, with a much lower char yield, over slow pyrolysis. McCarl et al.'s study is, inevitably, laced through with many assumptions: change in many of these can produce a quite different result.

5. Conclusions

The carbon abatement efficiency of PBS is higher than that for biomass combustion in most, though not all, cases. More research is required on the carbon and energy balance of pyrolysis utilising different feedstocks, conversion technologies, scales of operation, etc.

The two studies that have examined the issue of whether char from pyrolysis is best applied to fields as a biochar soil amendment, or utilised as a fuel for energy generation, come to somewhat different conclusions. This in itself is not that surprising, given that both studies are rather detailed case-studies that are highly context-specific: e.g. with respect to technology choice and performance, agricultural systems, costs, and so on. For example, Gaunt & Lehmann are comparing two versions of slow pyrolysis, whilst McCarl et al. are comparing slow and fast pyrolysis. Both studies exhibit a high degree of uncertainty due to the inevitable use of hard-to-validate assumptions.

Nonetheless, both studies indicate that in carbon abatement efficiency terms, biochar production is a better route to go down than char for energy generation / syngas production (the difference being far more marked in Gaunt & Lehmann than in McCarl et al.). More contentious is whether, in economic terms, it is more efficient to maximise biochar production rather than using char solely for energy production.

The Gaunt & Lehmann study is more UK-focused than McCarl et al.'s study, which is based upon the US Mid-West agricultural context. We intend to undertake several case-studies in the UK context in order to try and address this question further and will be happy to report back to the Royal Society with our results in due course.

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