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# **AN ASSESSMENT OF THE BENEFITS AND ISSUES ASSOCIATED WITH THE APPLICATION OF BIOCHAR TO SOIL**

A report commissioned by the United Kingdom  
Department for Environment, Food and Rural Affairs, and  
Department of Energy and Climate Change

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## GLOSSARY

**Bespoke biochar:** (conceptual): For the purpose of this report, biochar can be described as bespoke if it has been produced under conditions optimised toward delivery of a particular function in soil, such as maximum biological stability, maximum agronomic benefit, mitigation of trace gas emission, etc., or any combination of the same.

**Biochar** (see also Char, Charcoal): In this report, biochar is the *porous carbonaceous solid produced by thermochemical conversion of organic materials in an oxygen depleted atmosphere which has physiochemical properties suitable for the safe and long-term storage of carbon in the environment and, potentially, soil improvement*. There are other definitions both more and less specific, such as that used by the International Biochar Initiative (IBI).

**Biomass:** The biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste (OPSI, 2004).

**Black carbon:** The continuum of solid combustion products ranging from slightly charred degradable biomass to highly condensed, refractory soot. All components of this continuum are high in carbon content, chemically heterogeneous and dominated by aromatic structures (Masiello, 2004).

**Carbon abatement (CA):** Defined for this report as the net effect of changes in greenhouse gas fluxes that result from the production and application of biochar. This can include any or all of the following: carbon stored in biochar; carbon and CO<sub>2</sub> released during pyrolysis; offset CO<sub>2</sub> 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; accumulation of carbon in soil organic matter arising from enhanced Net Primary Productivity; and offset carbon emissions from reduced operations in the field. Which of these components is included will be specified in the text.

**Carbon abatement efficiency (CAE):** The net carbon equivalent abatement delivered for a given function unit (e.g. processing of a unit of feedstock, delivery of a kWh of electricity or heat, utilisation of a given area of land, etc.).

**Carbon credit:** Any mechanism for allocating an economic value to a unit of carbon (dioxide) abatement. The most common units are EU Allowances (EUAs) (under the EU ETS), Emission Reduction Units (ERUs) (Joint Implementation, UNFCCC), Certified Emission Reductions (CERs) (Clean Development Mechanism, UNFCCC), and Verified Emission Reductions (VERs) (voluntary carbon market).

**Carbon (dioxide) equivalent:** Common measure of global warming potential constructed by converting the emissions of the six 'Kyoto' greenhouse gases into the equivalent radiative forcing units of CO<sub>2</sub>.

**Carbon sequestration:** The process of removing carbon from the atmosphere and depositing it in a reservoir (UNFCCC, 2009).

**Carbon Stability Factor (CSF):** The proportion of the total carbon in freshly produced biochar which remains fixed as recalcitrant carbon over a defined time period (10 years, 100 years, etc. as defined). A CSF of 0.75 means that 75% of the carbon in the fresh biochar remains as fixed carbon over the defined time horizon and that 25% of the carbon has been converted into CO<sub>2</sub>.

**Certified Emission Reduction (CER):** Carbon credits issued under the Clean Development Mechanism (CDM) for emission reductions achieved by CDM projects, and verified under the rules of the Kyoto Protocol and UNFCCC COP/MOP. They may be used to a limited extent by Annex 1 countries in order to comply with their emission limitation targets, or by operators of installations covered by the European Union Emission Trading Scheme (EU ETS) to comply with their obligations to surrender EU Allowances.

**Char** (see also Biochar, Charcoal): For the purpose of this report, char is the solid, possibly composite, product of pyrolysis in general.

**Charcoal** (see also Biochar, Char): For the purpose of this report, charcoal is the solid product of natural fire and traditional biomass conversion under partially pyrolytic conditions without yielding bioenergy co-products.

**Clean Development Mechanism (CDM):** A Kyoto Protocol mechanism that allows Annex I Parties to purchase emission reductions from projects in non-Annex I Parties that reduce or remove emissions. The emission allowances from CDM projects are called certified emission reductions (CERs) (UNFCCC, 2007).

**Delivered energy:** Amount of useable energy delivered to the end-user

**Global warming potential:** The cumulative radiative forcing effects of a gas over a specified time horizon resulting from the emission of a unit mass of gas, relative to CO<sub>2</sub>

**Half life:** The time that elapses before half of the biochar decomposes and can be obtained by multiplying the mean residence time by the natural logarithm of 2 (Lehmann and Joseph, 2009).

**Leakage:** The net change of anthropogenic emissions by sources of greenhouse gases (GHG) that occurs outside the project boundary, and which is measurable and attributable to the project activity (UNFCCC, 2007).

**Macropore:** See porosity.

**Mean residence time (MRT):** Inverse of decay rate, this is the average time for which carbon in new biochar remains present in a stabilised aromatic form.

**Mesopore:** See porosity.

**Micropore:** See porosity .

**Net primary productivity (NPP):** A measure of plant growth and the additional CO<sub>2</sub> fixed and stored into plant biomass over a period of, for example, one year; technically it is calculated as the balance between photosynthesis and respiration

**Non-virgin biomass resource:** Any biomass that does not fall under the definition of virgin biomass resource.

**Oven dry:** Freshly harvested biomass and particularly some waste biomass resources are moist or wet; biochar has a high affinity for moisture due to its microporous structure; it is therefore important to indicate at which temperature (if any) such materials have been dried when expressing test results on a feedstock or product mass basis. Oven dry in this report and conventionally indicates drying at 105°C and reliably removes almost all moisture; air drying is much less complete and much more variable between materials as it depends on materials porosity, air temperature and humidity. Note that oven-dry material may acquire moisture over time, initially quite rapidly in the right ambient conditions.

**Polycyclic aromatic hydrocarbons (PAH):** Aromatic hydrocarbons containing more than two unsubstituted benzene rings. Some PAHs are strong carcinogens, i.e. benz(a)pyrene and benz(a)anthracene.

**Porosity:** In general terms, the volume of pores or interstices in a material, as a proportion of the total volume. Since porous materials tend to show inconsistency and non-uniformity in the diameter of their pores or their number per unit volume, there are many functional measures of porosity such as connectivity and neck diameter, and pore-size distribution rather than mean pore diameter. Categorisation of pores into 'large' (macro), 'medium' (meso) and 'small' (micro) is context specific: in material science their minimum diameters are <2 nm, 2–50 nm, >50 nm (Rouquérol et al.), whereas in soil science functionality may be considered at scales relevant to the microbial cell (approximately 1 µm diameter). In this report absolute size ranges are indicated where possible.

**Priming:** Accelerated decomposition of soil organic matter from introduction of biochar (biochar priming of soil carbon), or accelerated decomposition of biochar by proximity to labile substrates in soil (substrate-primed decomposition of biochar).

**Pyrolysis-Biochar System (PBS):** A combination of a specified pyrolysis technology, transport, distribution and storage infrastructure and application of biochar. See table SPM1 for definitions of fast and slow pyrolysis.

**Specific surface area (SSA):** Material property of solids reflecting total surface area per unit mass or bulk volume, and of importance to adsorption and surface reactions. It is typically derived experimentally by adsorption, a method referred to as BET (initials of the inventors). This accounts for area of fine structure surfaces and deep texture, but results differ markedly depending on the substance adsorbed, which is typically nitrogen gas.

**Renewable obligation certificate (ROC):** Certificates issued to accredited electricity generators for eligible renewable electricity generated and supplied within the UK. Between 0.25 and 2.0 ROCs are issued for each MWh of eligible renewable output generated, depending on the source of the renewable electricity. The Renewables Obligation under which the certificates are issued obliges UK suppliers to source an increasing proportion of their electricity from renewable sources; for 2008–9 this figure was 9.1% (3.0% in Northern Ireland).

**Terra preta:** Localised soils, intensively studied, whose dark colour appears to result from historic and prolonged management with charcoal, probably for the enhancement of agricultural productivity in and around the Amazon Basin.

**Virgin biomass resource:** Biomass derived from whole plants and trees or from the processing of virgin biomass, where this does not involve chemical or biological transformation, amendment or treatment.

## ACRONYMS AND ABBREVIATIONS

<b>AD</b>	Anaerobic digestion
<b>ALULUCF</b>	Agriculture, land-use, land-use change and forestry
<b>AFOLU</b>	Agriculture, Forestry and Other Land Use
<b>APS</b>	Assured Produce Scheme
<b>BEAT</b>	Biomass Environmental Assessment Tool
<b>BESP</b>	Break-even selling point
<b>ca.</b>	circa (approximately)
<b>CA</b>	Carbon abatement
<b>CAE</b>	Carbon abatement efficiency
<b>CCC</b>	Committee on Climate Change
<b>CCS</b>	Carbon Dioxide Capture and (Geological) Storage
<b>CDW</b>	Commercial and demolition waste
<b>CEF</b>	Carbon emission factor
<b>CH<sub>4</sub></b>	Methane
<b>C&amp;I</b>	Commercial and industrial (wastes)
<b>CLO</b>	Compost-like outputs
<b>CO<sub>2</sub></b>	Carbon dioxide
<b>DECC</b>	Department for Energy and Climate Change
<b>eq</b>	equivalent
<b>EA</b>	Environment Agency
<b>EPA</b>	Environmental Protection Agency (USA)
<b>EPSRC</b>	Engineering and Physical Sciences Research Council
<b>GHG</b>	Greenhouse gas
<b>Gt</b>	Gigatonne (1 billion, i.e. 10 <sup>9</sup> tonnes)
<b>GWP</b>	Global warming potential
<b>HSE</b>	Health and Safety Executive
<b>IPCC</b>	Intergovernmental Panel on Climate Change
<b>IQR</b>	Inter-quartile range
<b>kg</b>	kilogram
<b>kWh</b>	kilowatt hour
<b>LCA</b>	Life Cycle Assessment
<b>MAC</b>	Marginal abatement cost
<b>MBT</b>	Mechanical and biological treatment (of municipal waste)
<b>MSW</b>	Municipal solid waste

<b>MVAR</b>	Monitoring, verification, accounting and reporting
<b>MW</b>	megawatt
<b>MWh</b>	megawatt hour
<b>N<sub>2</sub>O</b>	Nitrous oxide
<b>NO<sub>3</sub><sup>-</sup></b>	Nitrate
<b>NH<sub>4</sub><sup>+</sup></b>	Ammonium
<b>NIEA</b>	Northern Ireland Environment Agency
<b>NIR</b>	National Inventory Report
<b>NVZ</b>	Nitrate vulnerable zone
<b>o.d.</b>	oven dry
<b>PAH</b>	Polycyclic aromatic hydrocarbon
<b>PBS</b>	Pyrolysis–biochar system
<b>PCB</b>	Polychlorinated biphenyl
<b>PM<sub>10</sub></b>	Particles <10 µm diameter
<b>PU</b>	Pyrolysis unit
<b>ppmv</b>	parts per million by volume
<b>RDF</b>	Refuse-derived fuel
<b>ROC</b>	Renewable Obligation Certificate
<b>SCC</b>	Stabilisation of plant captured carbon
<b>SEPA</b>	Scottish Environmental Protection Agency
<b>SOC</b>	Soil organic carbon
<b>SOM</b>	Soil organic matter
<b>SPM</b>	Summary for Policy Makers
<b>SPS</b>	Single Payment System
<b>UKBRC</b>	UK Biochar Research Centre
<b>UK GHGI</b>	UK Greenhouse gas Inventory
<b>UNFCCC</b>	United Nations Framework Convention on Climate Change
<b>VCS</b>	Voluntary Carbon Standard
<b>WFD</b>	Waste Framework Directive
<b>WID</b>	Waste Incineration Directive

## EXECUTIVE SUMMARY

**What is biochar?** Biochar is a porous carbonaceous solid produced by thermochemical conversion of organic materials in an oxygen depleted atmosphere which has physiochemical properties suitable for the safe and long-term storage of carbon in the environment and, potentially, soil improvement. For the purpose of this report, we define a *sustainable biochar system* as one which: a) produces and deploys biochar safely and without emitting non-CO<sub>2</sub> greenhouse gases; b) reduces net climate forcing; and c) does not increase inequality in access to and use of resources. Systems which meet the above criteria do not exist at demonstration or commercial scale at the current time, and do not include traditional charcoal production (implicitly or explicitly encompassed by other definitions).

**How stable is biochar?** Biochar comprises stabilised plant material in which carbon is stored mainly in a highly recalcitrant chemical form. Although little research has been published on the long-term stability of biochar, studies suggest a mean residence time (MRT) for charcoal in soil in the order of millennia, compared to 50 y for bulk soil organic matter. By analogy to charcoal, biochar could provide an effective long-term store of carbon in soil, and thus provide an abatement option for anthropogenic carbon emissions.

As yet, there is no agreed-upon methodology for calculating the long-term stability of biochar. This is a major weakness in the case for carbon storage in biochar since re-return of carbon as CO<sub>2</sub> into the atmosphere on too short a timescale could exacerbate, rather than alleviate, climate change. Nevertheless, there are grounds for believing that a focused research effort over the next five years should be able to make rapid progress on development of methods for determining the longevity of carbon storage in biochar.

**What are the potential benefits of biochar in soil?** Charcoal and biochar addition to tropical soils has been shown to improve crop yields, sometimes dramatically. In more fertile soils, or in soils that receive high levels of external inputs, and are not liable to water-stress, the corresponding impacts of biochar (and charcoal) on agronomic performance have yet to be demonstrated. Emerging evidence from field trials using charcoal in the UK, and other temperate countries, indicates a modest benefit to the limited number arable systems tested so far. The most important beneficial functions of biochar are listed below.

- a) **pH, mineral nutrients and labile carbon:** The typically alkaline pH and mineral constituents of biochar (ash content, including N,P,K and trace elements) could provide important agronomic benefit in many soils, at least in the short- to medium-term, during which time small labile fractions of organic carbon might also be important. Certainty of knowledge of impact: moderate.
- b) **Water retention:** Elsewhere in the world, particularly in poorer-quality sandy or silty soils, the addition of charcoal has been demonstrated to enhance crop yield. This is likely to result, in part, from the enhanced water retention of a typically porous material. Certainty of knowledge of impact: low.
- c) **GHG suppression, limiting diffuse water pollution:** Other beneficial properties of biochar have been proposed: suppression of soil-based emission of nitrous oxide (a potent greenhouse gas) and prevention of diffuse water pollution through ammonium sorption, or mediation of the dynamics of soil solution containing nitrate, phosphorus, and other nutrients. The evidence for such effects is still sparse in the peer-reviewed literature and non-peer reviewed reports are not entirely consistent. Certainty of knowledge of impact: very low.
- d) **Long term impacts:** A combination of physical and chemical properties may be sufficiently and fundamentally altered that a sustained change in microbial community results, with altered and potentially more efficient patterns of carbon utilisation and nutrient cycling.

## What are the risks arising from using biochar?

**a) Contaminants:** if the feedstock contains potentially toxic elements (in particular heavy metals) they will be retained during thermochemical conversion, hence will remain in the ash contained in the biochar. During conversion, organic compounds called polycyclic aromatic hydrocarbons (PAHs) can be generated. Some PAHs, such as benzo(a)pyrene, are carcinogenic and their content in food substances is strictly regulated. The longevity and soil impacts of PAHs (which are present already in most soils, especially those close to urban areas) are not well known. Care must be taken in the feedstock selection and in the operation of the thermochemical conversion to ensure that the risks to the environment and human health are properly assessed and managed. Certainty of knowledge of impact: medium (potentially toxic elements) to very low (PAHs).

**b) Damage to soils:** Shifting large amounts of biochar onto fields could cause soil compaction, but the land-owner or tenant will limit this risk. Biochar could have some slow or relatively subtle negative impacts on soils that have not currently been recognised, with the majority of the research focusing on establishing potentially beneficial effects. Certainty of knowledge of impact: low.

**c) A possible 'priming effect':** An accelerated decomposition of soil organic matter from the introduction of biochar has been proposed in the context of charcoal added to forest humus (Wardle et al., 2008). Methodological limitations to the study have been debated (Lehmann and Sohi, 2008), but a mechanism to support the enduring enhancement of decomposition in mineral-dominated agricultural soils has yet to be proposed. Indeed, work studying the fate of organic matter added to *terra preta* soils reported that the presence of ancient anthropogenic charcoal seemed to increase its stabilisation, and therefore the accumulation of soil organic matter (Liang et al., 2010). Certainty of impact: low to very low.

**d) Feedstock availability and-use impacts:** It has been claimed by some environmental organisations that biochar would encourage plantations with deleterious environmental and social impacts. Given the tightly-woven controls over land-use in the UK, it is very unlikely that this would occur in the UK and importing large amounts of biochar from overseas is hard to envisage. There is increasing competition for organic feedstocks in the UK and policy incentives need to be designed to promote their sustainable and efficient use. Certainty of knowledge of impact: high.

**Life Cycle Assessment (LCA) of pyrolysis-biochar systems (PBS)** in this report suggests abatement of 1.0–1.4 t CO<sub>2</sub>eq per oven dry tonne (t<sup>-1</sup> o.d.) feedstock used in slow pyrolysis. Expressed in terms of delivered energy PBS abates 1.5–2.0 kg of CO<sub>2</sub>eq kWh<sup>-1</sup>, which compares with average carbon emission factor (CEF) of 0.5 kgCO<sub>2</sub>eq kWh<sup>-1</sup> for the national electricity grid in 2008, and current CEF for many biomass feedstocks of 0.05–0.30 kgCO<sub>2</sub>eq kWh<sup>-1</sup>. Expressed in terms of land-use, PBS might abate approximately 7–30 t CO<sub>2</sub>eq ha<sup>-1</sup> yr<sup>-1</sup> using dedicated feedstocks compared with typical biofuel abatement of between 1–7 t CO<sub>2</sub>eq ha<sup>-1</sup> yr<sup>-1</sup>. By each of these measures PBS appears to offer a more efficient way to abate carbon than alternative uses of biomass feedstock, or land to grow such feedstocks. The largest contribution to PBS carbon abatement (40–50%) is from the feedstock carbon stabilised in biochar. The next largest contribution (25–40%) arises from the more uncertain indirect effects of biochar in the soil (reduced fertiliser needs, reduced N<sub>2</sub>O emissions, increased soil organic matter, etc.). Finally, off-setting emissions from fossil fuels accounts for 10–25%. The carbon abatement efficiency of PBS depends, however, on the Carbon Stability Factor (CSF) of biochar, which is the proportion of total carbon in freshly produced biochar that remains fixed as recalcitrant carbon over a defined time period. The LCA in this report suggests that provided the CSF remains above 0.45, PBS will out-perform direct combustion of biomass at 33% efficiency in terms of carbon abatement, even if there



is no beneficial indirect impact of biochar on soil greenhouse gas (GHG) fluxes, or accumulation of carbon in soil organic matter.

**Economic evaluation** in this report has provided data on costs of producing, transporting, storing and delivering biochar to the field. A range of values from £0–430 t<sup>-1</sup> biochar was derived, according to diverse feedstock, pyrolysis unit costs (capital and operational) and storage requirements. It was not attempted to provide figures for the agronomic and other soil-related costs and benefits that might arise from use of biochar, due to a lack of reliable data upon which to base any estimates. Lowest price biochar will likely arise from large-scale production units using non-virgin biomass wastes that already have to be managed, such as wood, green and food wastes and sewage sludge (£0–200 t<sup>-1</sup>). Use of such material in soils will potentially pose higher risks, however, and face greater regulatory controls. We do not currently know whether this material would meet the requirement of biochar to be safe and to improve soils.

Less controversial, and requiring fewer regulatory controls, will be biochar from virgin biomass sources, though these are typically more expensive, with a few exceptions such as arboricultural arisings (supply of which is relatively modest). If a low cost (£10–20 t<sup>-1</sup>) straw feedstock can be utilised, the analysis suggests biochar could be produced at £11–200 t<sup>-1</sup>. If biochar costs £100 t<sup>-1</sup> a carbon abatement price of £30–40 t CO<sub>2</sub><sup>-1</sup> would be required for the operation to break-even. At present, however, the only revenue stream for biochar would be (currently uncertain) agronomic benefits as there is no existing mechanism for including stabilised soil carbon in existing UK- or internationally-focused carbon trading arrangements.

**Regulation of biochar** is as yet an un-resolved matter, and applications to regulators may be necessary before the legal position is clarified. Whether biochar is defined as waste or not will influence how it is controlled, though in either case there are general powers of pollution prevention which can be used to control the deployment of biochar in the event of adverse impacts. There are provisions for exempting wastes from the requirement for permitting or licensing if a benefit to agriculture can be demonstrated: biochar is not presently exempted. The Environment Agency in England and Wales is moving towards standard rules and standard permitting for all uses of waste upon land and this is one route to regulation for biochar. The quality protocol approach used for wood, recovered aggregates, compost and other low risk materials is another good model for biochar regulation – provided, of course, that further research demonstrates low levels of risk. Developing a matrix governing application of biochar to agricultural land similar to that used for treated sewage sludge is equally important. Consideration should also be given to suppliers' quality schemes for crops, and livestock fed on crops or grassland where biochar has been applied. Ultimately, more information is required on the properties and behaviour of different biochar products in order to better understand potential risks and determine appropriate levels of regulation.

**Quantities of biochar that might be produced in the UK by about 2020** have been evaluated according to existing and likely future availability of biomass feedstock from all sources, and thus three biomass supply scenarios defined as low, high and very high supply, depending on the proportions of each available to PBS. Virgin biomass resources could produce 1–3 Mt y<sup>-1</sup> of biochar, and non-virgin biomass resources 0–3 Mt y<sup>-1</sup> biochar. Assuming that only 50% of the non-virgin biomass-derived biochar is used on agricultural land for safety reasons, the total carbon abatement from biochar (from LCA) is 1–6 Mt C y<sup>-1</sup> (0.3–3.0% of 1990 emissions, or up to 1.5–10% of emission reductions required by 2020). Between 0.5 Mha (low supply scenario) and nearly 5.0 Mha (high supply scenario) land could be treated at a rate of just under 1.5 t ha<sup>-1</sup> y<sup>-1</sup> biochar and over a 20 y period (against a total of 17.5 Mha agricultural land in 2008). Potato and horticultural land could be treated fairly rapidly – in the first 3 to 10 y – the larger areas of cereals, other arable and grassland would each taking longer. There is evidence that biochar returns some nutrients and small amounts of labile organic carbon to soils. Depending on the origin of the biochar feedstock, the dynamic balance of inputs and outputs of nutrients with respect to land area has to be

carefully considered. The three supply scenarios imply considerable infrastructural development – from 1000–7500 small pyrolysis units, 30–250 medium-scale units, or 10–30 large-scale units (ranges reflecting low to high and very high feedstock supply in each case). Unless biochar could be produced at time of harvesting (e.g. using a mobile pyrolysis unit), the scenarios also imply considerable additional truck movements (ca. 220,000 Mt<sup>-1</sup>) as well as on-farm or dedicated storage requirements. The collection and incorporation of biochar into agricultural soils is a logistical and technological challenge that has not been explored in great detail, and is in need of innovation.

In addition to the economic and logistical challenges, there are many scientific uncertainties surrounding the role and potential of biochar, in particular concerning its mean residence time, Carbon Stability Factor and how to monitor it *in situ*. Nevertheless, in principle, biochar has a high carbon abatement efficiency and there are some potentially viable options which may deserve more careful attention, such as pyrolysis of arboricultural arisings and low-cost straw. Integrated, well-design pilot demonstrations of such possible front-runners could, potentially, advance rapidly the science, engineering, regulation and socio-economic evaluation of biochar systems in the UK context.

## SUMMARY FOR POLICY MAKERS

### Introduction

Biochar is the porous carbonaceous solid produced by thermochemical conversion of organic materials in an oxygen depleted atmosphere which has physiochemical properties suitable for the safe and long-term storage of carbon in the environment and, potentially, soil improvement.

The UK Biochar Research Centre (UKBRC) was commissioned by the United Kingdom Department for Environment, Food and Rural Affairs (Defra), and Department of Energy and Climate Change (DECC) to undertake a review of the potential benefits, costs and issues surrounding the addition of biochar to soil. The objectives of the research are set out in Box 1, together with the number of the chapter which deals with the objective. The results of our review are presented in the summary for policy makers (SPM) according to these seven objectives. The report concludes with an examination of critical issues regarding the deployment of biochar in the UK context, and a list of research needs.

### Box 1: The Objectives of the Review

To review evidence on the nature of biochar and the effects of different feedstocks and variations in the pyrolysis process on the final composition and properties of biochar **Chapters 3 and 4**

To assess and review evidence on the methods by which biochar could be incorporated into soils and how this may affect, or be affected by, land use, land management practices and regulations, and the addition of other organic materials **Chapters 5 and 6**

To assess and review evidence on the subsequent fate and behaviour of biochar in soil, including its interaction with other soil components **Chapter 4**

To assess and review evidence on the impact of biochar on soil properties and functionality and the benefits and disbenefits associated with biochar addition - including consideration of wider environmental effects **Chapters 4 and 3**

To assess and review the effects, and implications, of biochar addition on soil carbon monitoring **Chapter 7**

To evaluate, review and develop life cycle assessments of biochar, including its various possible feedstocks, land-use and energy system applications, for the UK context as far as is feasible given current data availability **Chapter 8**

To evaluate the costs of biochar from different configurations of feedstocks, energy conversion technologies and biochar utilization, including regulatory and quality assurance issues **Chapters 9 and 6**

A survey was undertaken to gauge wider opinion on issues that relate to the above objectives **Chapter 10**

A brief scoping of biochar deployment in the UK context is reported in **Chapter 11**, should emerging evidence suggest biochar production and application might prove a useful and safe innovation

An analysis of key research needs that may assist in assessing this possibility is presented as **Chapter 12**.

## Methodology

A database was compiled for published, peer-reviewed research literature on pyrolysis and charcoal relating to biochar, as defined here, along with a small number of studies using biochar consistent with the present definition. For studies with findings relevant to an understanding of the potential impact of biochar on soil, a systematic categorisation was undertaken to assess the nature and level of research effort expended to date, and to identify research gaps. The summary used in the categorisation is published as Appendix 1 to this report. Non-peer reviewed literature was also drawn upon, along with as yet unpublished manuscripts that were shared during the research. These have been valuable in scoping and forming general opinion, but for obvious reasons less reliance can be placed on their apparent findings. A second method was to conduct an online survey to gauge a wider view. The survey was complex and required detailed knowledge of biochar and therefore targeted at experts, mainly those whom, for academic, environmental or commercial reasons, have investigated PBS. A link to the survey was sent out to approximately 1000 individuals, but the ultimate number of recipients is unknown. A total of 145 useable responses were obtained of which 118 were complete; this is not a large number, but the community of active biochar researchers in the UK, and indeed globally, is currently small, and hence the sample is considered to represent a significant proportion of qualified individuals. The third method was to draw upon a panel of approximately 30 leading experts on biochar internationally as authors, contributors and reviewers of this report. The final method was to undertake original research to fill in gaps on two key aspects: life cycle assessment (LCA) and economic analysis.

### **Objective 1: To review evidence on the nature of biochar and the effects of different feedstocks and variations in the pyrolysis process on the final composition and properties of biochar**

Variation in pyrolysis feedstock, even if nominally from a single source, is likely to be one of the main causes of variability in biochar yield and properties. However some properties are likely to be more feedstock dependent (e.g. physical structure, contaminant content) than others. Current evidence shows that it is possible to influence properties (such as pH and surface area) of char considerably through controlling the pyrolysis operating conditions. In general, higher production temperatures yield char of higher pH and, to some extent, higher surface area. The specific surface area (SSA) of char can be further increased by physical or chemical activation post-process. However, the benefits and potential disbenefits of additional surface area in soil are not well established. Most of the enhanced surface area is due to development of micropores (<2 nm), a scale much too small to hold plant-accessible water and soil solution or provide for attachment of microorganisms.

The yield of char is strongly dependent on the production conditions, ranging from 0–73% oven dry (o.d.) feedstock, depending on the yield of liquid and gaseous products (Table SPM 1). The most important parameters affecting char yield are: the heating rate, peak temperature and residence time at peak temperature. In general, higher heating rate and temperature and shorter residence time lowers char yield, while long residence time and slow heating rate increase it. However, the resulting char itself consists of fractions of contrasting recalcitrance, and therefore higher char yield does not necessarily mean a higher yield of stabilised carbon, the proportion that remains ‘fixed’ when added to soil. It is known, however, that the fraction of carbon in char that is fixed from an analytical perspective increases with peak production temperature. A trade-off exists between char yield and this fixed fraction, but the strength of the relationship between fixed carbon and carbon stable in the context of PBS (as defined by the CSF) is yet to be established. Nonetheless, it does appear that, broadly, lower temperature pyrolysis yields more char, but char with a greater proportion that is unstable and therefore unsuitable for long-term carbon storage in soil. Whilst a higher temperature produces more stable carbon, but the char yield is lower. The

addition of less stable, i.e. labile carbon to the soil may provide short-term agronomic benefit and hence, in some circumstances, biochar might be designed to deliver both carbon storage and some benefits of labile carbon. The utility of specified grades or 'bespoke' biochar should be context specific, in some cases focused on fixed carbon, in others on the short-term agronomic value, etc.

	Slow pyrolysis	Intermediate pyrolysis	Fast pyrolysis
<i>Process</i>			
<i>Temperature (° C)</i>			
Range	250-750	320-500	400-750
Typical	350-400	350-450	450-550
<i>Heating and residence time</i>			
Range	mins-days	1-15 mins	ms-s
Typical	2-30 mins	4 mins	1-5 s
Yields (as % o.d. feedstock mass)			
<i>Char</i>			
Range	2-60	19-73	0-50
Typical	25-35	30-40	10-25
<i>Liquid</i>			
Range	0-60	18-60	10-80
Typical	20-50	35-45	50-70
<i>Gas</i>			
Range	0-60	9-32	5-60
Typical	20-50	20-30	10-30

Table SPM 1: Scope of pyrolysis process control and yield ranges

Note: Based on review of over 30 literature sources (Brownsort, 2009)

Biochar could potentially contain two types of contaminants: a) those introduced in the feedstock itself (e.g. heavy metals, dioxins, polycyclic aromatic hydrocarbons (PAHs), etc.) and b) those produced during pyrolysis (e.g. PAH). Careful selection of feedstock is necessary to avoid or minimise the first category of contaminants, though some could be separated and removed during biochar production. The formation of PAH can be minimised by appropriate selection of operating conditions, specifically temperature range, and biochar with negligible PAH content should be achievable. Consistent analytical methods for quantifying contaminants such as PAH in the inherently stable matrix presented by pyrolysis char are yet to be defined. Better identification of specific PAHs is required, and targeted according to their toxicity.

**Objective 2: To assess and review evidence on the methods by which biochar could be incorporated into soils and how this may affect, or be affected by, land use, land management practices and regulations, and the addition of other organic materials**

Biochar is a new proposition so no specific agricultural equipment exists for its deployment. Experimental application of charcoal to arable soil using existing farm equipment such as lime and fertiliser spreaders has been illustrated in several experimental trials. These seem to permit straightforward application to surface soil for subsequent incorporation by ploughing, disking or harrowing. The low bulk density of biochar perhaps makes moderate and large applications in this way impractical and potentially undesirable in terms of passes and compaction. Minimising the separation of soil surface from the point of disposal is an obvious way to limit the potential for airborne dispersion, and associated issues around human health, environmental contamination and monitoring. Managing particle size at the point of application is clearly relevant too, and a function of feedstock characteristics, production method and post-production processing (e.g. the feedstock particle size and the effect of its composition on the physical strength of the product). The bulk density of biochar

can be increased by simple addition of water, improving rather than diminishing handling characteristics (i.e. dust control).

If the low bulk density of biochar is largely explained by porosity infiltrated on immersion, 1m<sup>3</sup> biochar mixed into livestock slurry may displace less than 0.4 m<sup>3</sup> volume. Mixing with slurry may have the potential to increase the amount of biochar carbon applied per unit additional volume handled by an enterprise or additional equipment. Increasing the dry matter content of slurry by 50% would increase the volume of slurry material stored and spread by 1–3%, but with potential benefits to nutrient dynamics and soil structure. If biochar does suppress nitrous oxide emissions, there would be considerable additional benefit to greenhouse gas abatement in these systems.

Compatibility with liquid injection systems should also be possible and analogous application to arable land at rates of 1–2 t ha<sup>-1</sup> has been possible by using conventional or adapted seed drilling equipment, but not demonstrated in the UK. Relatively straightforward modifications could be devised by machinery engineers to redress some of these constraints, and retrofitting existing equipment for the purpose of biochar application has been reported in Australia (Krull, 2009).

In horticulture and other high value crops, biochar could be introduced to supplement or substitute existing organic amendments or growing media that are already brought onto the site. If biochar deployment took place on an extensive scale, large volumes would have to be handled, necessitating efficient transportation, storage and application solutions. It is likely that more radical equipment and handling innovation will be required at this stage to bring down the deployment costs.

The current situation with respect to the control of the human health and safety and environmental risks of biochar lack clarity and would benefit from a position statement agreed by all UK regulators. It is complicated by the need to consider regulation of the production, and also of a variety of potential end-uses, for biochar. Regulation needs to be proportional to any risks to human health and the environment and there will need to be distinctions made between lower-risk biochar from virgin biomass sources and (potentially) higher-risk biochar derived from non-virgin biomass (waste). Biochar addition to soils will need to be regulated if biochar is defined as a waste. Even if biochar is not classified as a waste, environmental regulators have pollution prevention powers to intervene should biochar appear to have adverse environmental impacts. Biochar is not an exempted waste, and hence an application would need to be made to the regulator.

In England and Wales, the Environment Agency is moving towards standard rules and standard permitting for all uses of wastes (exempted or otherwise) upon land; this is intended to simplify and streamline the regulatory process for waste materials to be approved for application. More information is required on the properties and behaviours of different types of biochar to better understand potential risks and allow appropriate levels of regulation. The quality protocol approach used for wood, recovered aggregates, compost and other low risk materials may provide a starting point for this. Another potential avenue for regulation would be to develop a matrix governing application of biochar to agricultural land similar to that used for treated sewage sludge. Consideration should also be given to supplier quality schemes for crops, and livestock fed on crops or grassland where biochar has been applied (assuming that a strong case for the safety of biochar can be made). If the risks of biochar can be demonstrated to be low, a supportive regulatory framework will give confidence to producers and buyers and minimise barriers to widespread biochar deployment.

### **Objective 3: To assess and review evidence on the subsequent fate and behaviour of biochar in soil, including its interaction with other soil components**

Published research on the stability of biochar produced in continuous feed systems under near zero-oxygen is extremely scarce, and comparability in terms of stability between carbon

stabilised this way and that present in stable charcoal has yet to be confirmed. The methods to do such analysis are currently under development. The evidence for an unusually high level of recalcitrance of carbon in charcoal is comparatively abundant, however, with estimates of mean residence times falling in the order of millennia, compared to 50 y for carbon in the bulk of soil organic matter under temperate conditions. The evidence for this longevity is indirect, i.e. based on observation of its chemical composition or inferred from, for example, concentrations present in soils where natural fire has resulted in regular inputs through history (Lehmann et al., 2008). Examination of old and ancient charcoal fragments indicates partial oxidation or possibly chemisorption of oxygen only at the surface. Although the rate at which oxidation progresses to the interior cannot easily be determined, it appears that surface oxidation is strongly affected by ambient temperature (suggesting abiotic reaction). Rapid diminution of particle size appears to occur in soil, presumably through abrasion or other weathering, and with both an apparent persistence of charcoal in particulate organic fractions and intimate association with mineral particles, tillage and soil disturbance does not appear to modify the fate of charcoal disappearance over at least a timescale of decades.

Priming the acceleration of charcoal decomposition by glucose and other labile substances has been observed in the laboratory using charcoal manufactured under conditions intended to simulate natural fire. Short term responses contrast with the high level of stability inferred for much longer periods. This may indicate a role for a labile (rapidly mineralised) fraction of biochar carbon, possibly primed by the effect of mineral nutrients or modification of soil pH resulting from char addition. The majority of published studies have used either this “synthetic” charcoal in the context of natural fire (and thus at relatively low temperatures with partial restriction of oxygen), or commercial charcoal produced using traditional techniques at higher temperatures.

The movement of biochar incorporated into soil is hard to predict spatially, but it is unlikely that charred material abundant in ocean sediments and evidently transported from sites of natural fire, had previously been incorporated substantially into soil. In addition, greater disparity would be expected between estimates for rate of physical decomposition between laboratory and field studies if physical movement should be accounted for as a substantial loss pathway. In other words, much of the apparent loss of biochar-carbon is probably a consequence of the movement of biochar down the soil profile rather than a result of mineralization.

#### **Objective 4: To assess and review evidence on the impact of biochar on soil properties and functionality and the benefits and disbenefits associated with biochar addition - including consideration of wider environmental effects**

Transient beneficial impacts of biochar on soil may be chemical (direct addition of gradually leachable ash, modification of soil pH), biological (promotion of short-term microbial proliferation), and physical (soil bulk density, water holding capacity, thermal properties, aggregation in combination with soil biological effects). Enduring benefits may be chemical (cation exchange and specific surface area), biological (some association with plant roots), or physical (mediating the connection of microbial substrates and biomass, favouring of meso-faunal activity).

Disbenefits of biochar application could arise where potentially useful crop nutrients in biochar (such as nitrogen, phosphorus and metals) become detrimental through poor management, for example through an inappropriate manner, rate and frequency of biochar application. Potentially problematic substances in biochar could include PAHs and other benzene-like molecules from biochar feedstock, concentrated by, or created during, pyrolysis. The physical and chemical alteration that occurs during pyrolysis may change the bio-availability of elements and compounds. The pattern of release of the nutrients within biochar would need to be well understood in order for the management of nutrients from other sources (fertiliser, manure, slurry and other organic wastes, etc.) to be adjusted and

thereby avoid eutrophication. Better understanding of the propensity for biochar to move across the soil surface (and also down the soil profile) is necessary to understand the spatio-temporal distribution of nutrients and contaminants that might arise from biochar application. Development of appropriate management (techniques and procedures) for physical application of biochar to the land will need to be developed accordingly. The transfer of nutrients from biochar into watercourses would depend on the timing and extent of field application and factors such as slope and prevailing weather conditions. Wind erosion could cause an environmental nuisance by wide-spread dispersion of dust and application in conditions of high wind speed would be inadvisable. In agronomic terms, the use of biochar would be negative overall if there are no beneficial effects in soils, because of the financial and environmental costs of utilising machinery for transporting, applying and integrating it into soils. Biochar would be difficult to remove if it was shown to be causing some negative impacts.

Based on a body of literature that is concerned with static comparisons (soils with and without charcoal), chronosequence studies (pseudo long-term studies), and direct observations over short time frames, the impacts of biochar are likely to be dependent on both the product, the soil into which it is introduced, and the timeframe under consideration. The available evidence does not provide great capacity to extrapolate short-term observations (made over one or two seasons) to a decade or more (medium-term) – in the absence of process understanding the dynamics of the effects cannot be predicted. To date, experimentation has been with products that approximate wildfire charcoal, made under conditions less relevant to PBS. Possibilities to engineer biochar from pyrolysis to control or to accentuate particular functions are under-explored. In terms of short term effects on soil organic matter, the nutrient content of the feedstock, the pH of the product (relative to the receiving soil), and the abundance of labile fractions will be important.

Although microbial proliferation has been reported, there is no evidence to suggest an enduring priming of organic matter mineralization in mineral soils, or a mechanism put forward to account for such an effect. There is evidence for the accumulation of soil organic matter in soils rich in charcoal, which could be a feedback from increased plant productivity, and increased stabilisation of organic matter added to soil. Approximately one-quarter of responding experts in the survey considered the increased loss of soil organic carbon by priming a 'very serious' or 'moderate' risk, while 40% considered it a 'minimal risk'. This suggests that the 'jury is still out' on this important question, and a strategic evaluation of the mechanisms of interaction between biochar and soil organic matter using laboratory and field-based research is necessary to develop certainty. A resolution on the issue should be achievable quite rapidly once, in combination with studies of crop productivity, protocols for preparing aged samples of biochar have been established so that short-term effects of nutrient flux, pH and labile carbon can be discriminated from long-term physical interactions.

The physical structure of wood charcoal is distinct from that of mineral soil in terms of its macroporosity (micron-size pores) but no published work directly demonstrates the effect of adding such material on soil pore-size distribution, though changes in water holding capacity at least in the short term (or at high rates or application, which have a large impact upon the soil's bulk density) have been reported. The general effect of biochar on water holding capacity, especially biochar produced from non-woody feedstock, has yet to be quantitatively established. In addition to resistance to drought, water holding capacity determines the volume of water held by the soil before reaching saturation, and pore-size distribution the size of pores within which water will reside as the water content increases. Together these parameters give the potential for modifying soil-based N<sub>2</sub>O emission, though currently published data does not extend to field-based study. A number of relevant studies are available as conference proceedings, and progressing toward publication.

In the natural environment charcoal develops high cation exchange capacity over time exceeding, mass for mass, that exhibited by soil organic matter and also many clay minerals. Translation of this observation to practical value in the field, for example in



moderation of leaching or increasing soil nutrient supply is lacking, especially for temperate systems. Plant growth tests in pots (pot trials) and plot-scale field experiments in tropical environments seem to suggest that charcoal and biochar addition can increase crop nutrient uptake in the longer term, provided an initial immobilisation of nitrogen can be managed. An effect of charcoal in soil on soil temperature has been reported, and could be of significant benefit to crop establishment in temperate zones.

**Objective 5: To assess and review the effects, and implications, of biochar addition on soil carbon monitoring**

Monitoring to determine the proportion of soil carbon arising from biochar can be difficult, since available methods for distinguishing black carbon from other forms of soil organic matter are complex. Despite an extensive and coordinated effort in a 'ring-trial', no strong consensus on a universal, practical method for quantification of charcoal in soil has emerged. Such methods could not, in any case, directly discriminate added biochar from charcoal or even coal naturally or historically present, and possibly not from recalcitrant forms of soil organic matter.

Nevertheless, provided a site has baseline soil carbon measurement, the addition of carbon-rich biochar should be detectable using combustion-based analyses, given that the amount of carbon is also likely to be broadly stable and not subject to spatial variation and within-season fluctuation associated with typical organic amendments. Biochar addition should, however, be excluded from existing soil monitoring sites if uncertainty over its possible impacts could detract from the value of long-term records.

For routine purposes, it will probably not be cost or time effective to use techniques that seek to measure directly the fate of biochar by monitoring the soil. Instead it is expected that methodologies will emerge based on models the amount of biochar added to the soil is recorded, and calibrated against a decay rate dictated by the material and the context (e.g. the site, the receiving soil and the product, including its CSF). The UK Greenhouse Gas Inventory (UK GHGI) would require some modifications to allow the category of stabilised soil carbon to be included.

It is likely that some biochar applied to soil will erode from the application site. Methods may be required to track or monitor the movement of biochar to offsite sinks, including watercourses, depending on the regulatory regime. Monitoring of biochar will be desirable during periods of initial adoption, to compare expected and actual erosion rates and fate pathways. High sorption capacity and low mineralisation and nitrogen content reported for charcoal suggests that eutrophication would be an unlikely consequence. However for biochar this to some extent be affected by the feedstock and production process involved.

**Objective 6: To evaluate, review and develop life cycle assessments of biochar, including its various possible feedstocks, land-use and energy system applications, for the UK context as far as is feasible given current data availability**

The carbon balance of pyrolysis, including both the stabilised carbon and the offset CO<sub>2</sub> emissions from fossil fuels, was estimated from an extensive literature review. One of the representative technologies, the Haloclean intermediate pyrolysis process (Hornung et al., 2009), results in a carbon abatement of 0.82 t CO<sub>2</sub> t<sup>-1</sup> o.d. feedstock, compared to 0.63 t CO<sub>2</sub> t<sup>-1</sup> o.d. for straight combustion (assuming a CSF of 0.68). Therefore, pyrolysis abates approximately a quarter more carbon than combustion. The carbon balance across the life-cycle was examined from feedstock production to long-term impacts on soil by developing a new LCA model for PBS, drawing upon other existing LCAs (e.g. BEAT<sub>2</sub>), the literature, and expert elicitation. Three biomass resource scenarios for PBS were also developed using the 'resource pyramid' approach: lower, higher and very high, for virgin and non-virgin biomass (Table SPM 2).

Virgin biomass resource is here defined as that derived from whole plants and trees or from the processing of virgin biomass (where that does not involve chemical or biological transformation, amendment or treatment); non-virgin biomass is any other bio-material.

Feedstock	Viable available resource assumed available for pyrolysis (t yr <sup>-1</sup> )		
	Lower	Higher	Very high
<i>Virgin biomass resources</i>			
Wheat straw	1,181,250	3,543,750	4,725,000
Small scale	413,438	1,240,313	1,653,750
Large scale	767,812	230,343	307,1250
Barley straw	450,000	1,350,000	1,800,000
Small scale	157,500	472,500	630,000
Large scale	29250	877500	1170000
Oil seed rape and other cereal straw	590,625	1,771,875	2,362,500
Small scale	206,719	620,156	826,875
Large scale	38,390	115,171	1535625
Forestry residues	200,000	600,000	600,000
Arboricultural arisings	85,250	255,750	341,000
Sawmill co-product	21,500	64,500	86,000
Wood pellets	0	0	0
Miscanthus, switchgrass & short rotation coppice - agricultural land	503,125	1,509,375	2,012,500
Reed canary grass	12,500	37,500	50,000
Short rotation forestry - contaminated or public land	52,500	105,000	157,500
<b>Total virgin biomass resource</b>	<b>3,096,750</b>	<b>9,237,750</b>	<b>12,134,500</b>
<i>Non-virgin biomass resources</i>			
Construction and demolition wood waste	0	1,260,000	1,890,000
Commercial and industrial wood waste	0	1,120,250	1,680,375
Municipal solid waste - wood	0	399,375	599,063
Mechanical and biological waste	0	3,125,000	4,687,500
Green and food waste	0	1,800,000	2,700,000
Sewage sludge	0	754,500	1,509,000
Commercial and industrial animal and vegetable waste	0	202,500	303,750
Poultry litter	0	1,069,000	1,603,500
<b>Total non-virgin biomass resource</b>	<b>0</b>	<b>9,730,625</b>	<b>14,973,188</b>
minus MBT and poultry waste	0	5,536,625	8,682,188
<b>Total virgin and non-virgin biomass resource (including MBT and poultry waste)</b>	<b>3,096,750</b>	<b>18,968,375</b>	<b>27,107,688</b>
<b>Total virgin and non-virgin biomass resource (excluding MBT and poultry waste)</b>	<b>3,096,750</b>	<b>14,774,375</b>	<b>20,816,688</b>

Table SPM 2: Feedstocks potentially available in the UK for bioenergy and pyrolysis–biochar systems  
Source: Chapter 8

Depending upon feedstock and technology-scale, avoided emissions were 1.0–1.4 t CO<sub>2</sub>eq t<sup>-1</sup> o.d. feedstock in slow pyrolysis (Figure SPM 1). This compares with an avoided emission of 0.55 t CO<sub>2</sub>eq t<sup>-1</sup> o.d. for straw combustion at 33% efficiency. Hence, for straw, there is an additional 80% carbon abatement from PBS (on an LCA basis) compared to combustion. The Carbon Abatement Efficiency (CAE) of PBS compared to combustion improves as the full life-cycle impacts are incorporated, this being due to the indirect effects of biochar in the soil. The largest contribution to total PBS abatement (40–50%) is from stabilised feedstock carbon. The next largest contribution is from the indirect impacts of biochar in the soil (lower crop fertiliser requirement, lower soil N<sub>2</sub>O emissions, increased SOC, etc): these hypothesised impacts are based only upon a few studies and stand in need of far better evidence. The indirect impacts account for 25–40% of CA, the proportion changing with the size of other CA categories. The final major CA category is fossil-fuel offsets from renewable electricity generation, 10–25% of total CA. The values derived from the LCA model for PBS agree reasonably well with the three other studies in the literature (Gaunt and Cowie, 2009; Gaunt and Lehmann, 2008; McCarl et al., 2009).

Expressed in terms of carbon emissions per unit of delivered energy, PBS abates (i.e. avoids the emission of) between 1.5–2.0 kg CO<sub>2</sub>eq kWh<sup>-1</sup>. This compares with an average emission of 0.5 kg CO<sub>2</sub> kWh<sup>-1</sup> arising from the national electricity grid in 2008. The Environment Agency estimates that the carbon emission factor for electricity generation from many biomass feedstocks is between 0.05–0.30 kg CO<sub>2</sub>eq kWh<sup>-1</sup> (Environment Agency, 2009). Hence, PBS may be a more efficient way of abating carbon than alternative uses of biomass feedstock. Likewise, PBS results in the abatement of approximately 7–30 t CO<sub>2</sub>eq ha<sup>-1</sup> yr<sup>-1</sup> for dedicated feedstocks (Figure SPM2). These numbers fall within, but also exceed, the range of the first generation biofuel system with the highest CAE – namely bioethanol from sugarcane (10–16 t CO<sub>2</sub>eq ha<sup>-1</sup> yr<sup>-1</sup>) and are much larger than most bioenergy crops and biofuel feedstocks (e.g. biodiesel from rapeseed, soy or sunflower gives a saving of 0.5–4.0 t CO<sub>2</sub>eq ha<sup>-1</sup> yr<sup>-1</sup>) (Cherubini et al., 2009); UK bioelectricity systems, meanwhile, give a saving of between 1–7 t CO<sub>2</sub>eq ha<sup>-1</sup> yr<sup>-1</sup> (Thornley, 2009).

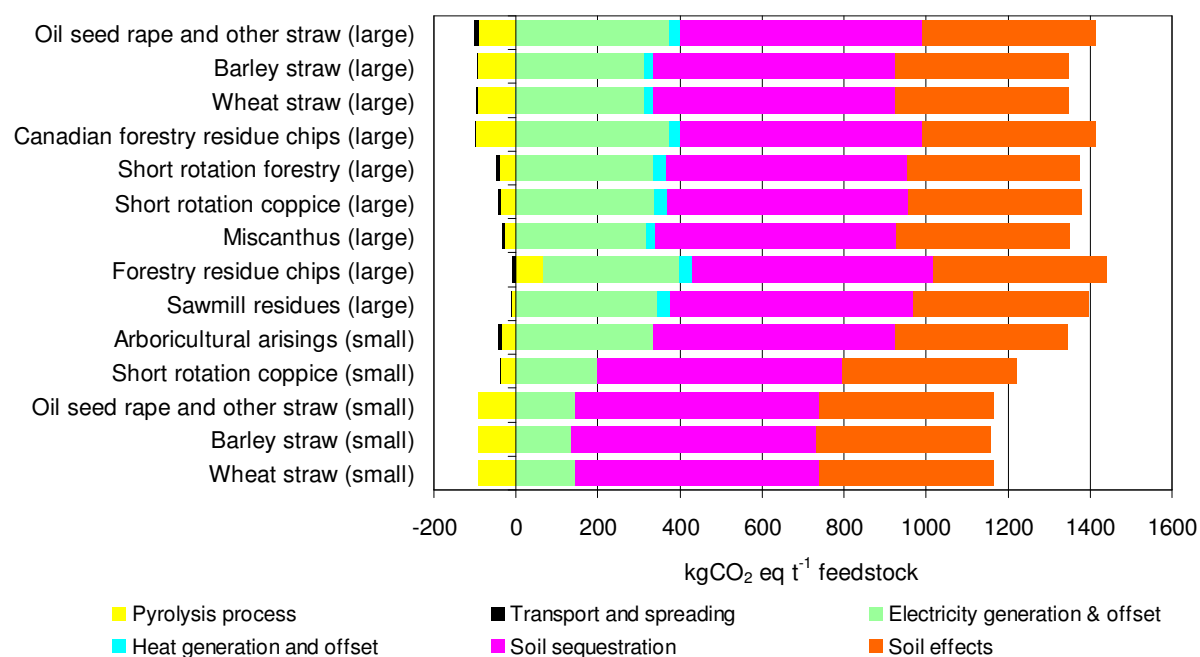


Figure SPM 1: Carbon equivalent abatement arising from pyrolysis-biochar systems for a range of feedstock and small and large scale technology

Whilst, on the face of it, PBS appears to be a more efficient form of carbon abatement than conventional, or even novel, biomass conversion technologies such as combustion, anaerobic digestion (AD) or gasification, there are some large existing uncertainties which temper that evaluation. In particular, the indirect benefits of biochar in reducing soil-based emissions are all quite uncertain. If the abatement arising from such indirect effects is removed from the LCA, and assuming that the CSF is 0.45 (i.e. 55% of the total carbon in fresh biochar added to the soil is lost through early and subsequent decomposition) the saved carbon equivalent emissions from PBS are approximately the same as those arising from straight combustion at 33% efficiency. If the decomposition of biochar is less than this (e.g. a CSF above 0.45) then PBS out-competes straight combustion with respect to avoided greenhouse gas emissions – even without the indirect soil effects; if biochar does reduce soil GHG fluxes, then carbon abatement will be further enhanced. On the other hand, if the efficiency of biomass combustion increases, say to 42% to reflect the most efficient coal-powered stations which might use biomass co-firing, the indirect soil effects of biochar need to be evident for PBS to prove more efficient in CA than combustion.

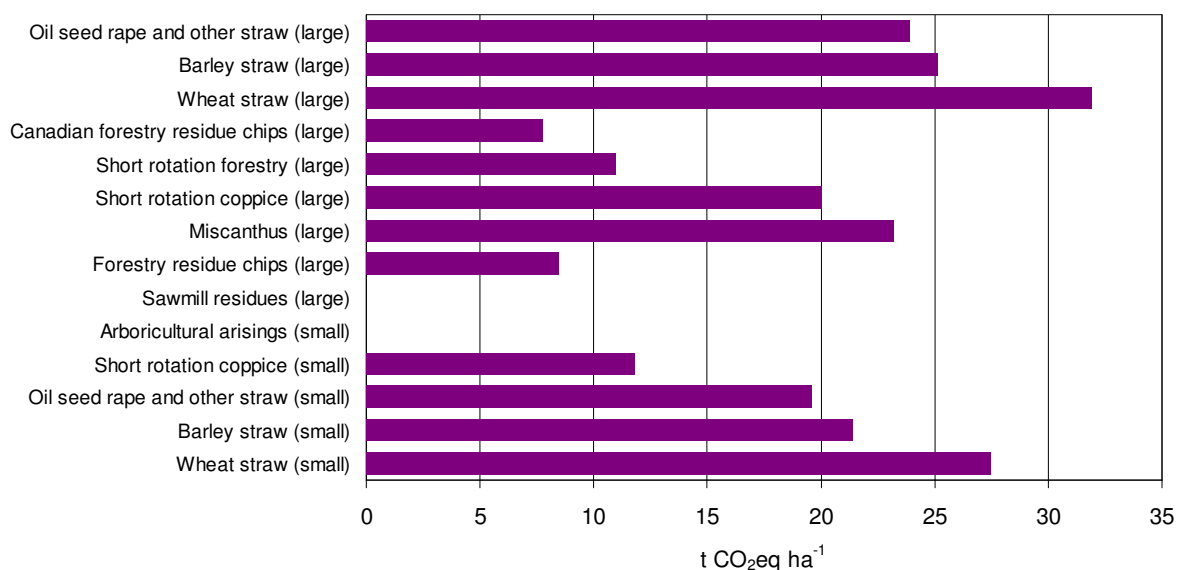


Figure SPM 2: Carbon equivalent abatement per hectare cultivated arising from pyrolysis-biochar systems for a range of feedstock and small and large scale technology

**Objective 7: To evaluate the costs of biochar from different configurations of feedstocks, energy conversion technologies and biochar utilization, including regulatory and quality assurance issues**

It is not currently possible to undertake a full cost-benefit analysis of biochar due to many uncertainties, especially regarding the economic benefits of biochar. An alternative approach, adopted here, is to calculate the break-even selling point (BESP) of biochar: i.e. the minimum charge for a tonne of biochar for the operation to at least break-even. This has been done by estimating the costs of collecting or growing a range of feedstocks, transporting feedstocks to a pyrolysis facility, transporting the resultant biochar to a suitable storage unit, and then onwards to a point of application; and, finally, the costs of applying the biochar to the soil. Three types of pyrolysis unit have been modelled: small-, medium- and large-scale; and three storage scenarios are envisaged (on-farm, dedicated storage unit, field margin storage unit). Two sources of revenue have been identified: electricity at £50 MWh<sup>-1</sup> (also attracting double renewable obligation certificates, ROCs, worth a further £100 MWh<sup>-1</sup>), and in the case of some feedstocks which have to be collected and managed in waste management units (e.g. arboricultural arisings, wood waste, sewage sludge, etc.), an avoided 'gate fee' in the range £22–45 t<sup>-1</sup> o.d. feedstock. The analysis is from the perspective of the firm producing biochar and it assumed that the firm has to purchase the feedstock. No attempt was made to evaluate costs and benefits at the societal level.

The analysis has been undertaken for the three biomass supply scenarios identified in Table SPM 2. For each scenario, a mixture of different feedstocks has been assumed and costs calculated to reflect the 'average' tonne (Table SPM 3).

	Total cost of biochar production: feedstock production to field deployment (£ t <sup>-1</sup> biochar)		
	On-farm storage	Dedicated storage	Innovative field-margin storage
Small-scale farm-based pyrolysis facilities (c. 2000 t yr <sup>-1</sup> o.d. feedstock)			
Average feedstock	291	not relevant	276
Low-cost straw (£10 t <sup>-1</sup> )	211	not relevant	194
Medium-scale pyrolysis facilities (c. 16,000 t yr <sup>-1</sup> o.d. feedstock)			
Very high feedstock resource scenario	311	358	304
Higher feedstock resource scenario	334	379	318
Lower feedstock resource scenario	397	430	380
Food waste	68	117	52
Green waste & sewage sludge	131	181	115
Arboricultural arisings (higher resource)	220	275	210
Low-cost straw (£10 t <sup>-1</sup> )	261	304	214
Wood waste	280	329	263
Large-scale pyrolysis facilities (c. 185,000 t yr <sup>-1</sup> o.d. feedstock)			
Very high feedstock resource scenario	206	280	181
Higher feedstock resource scenario	170	246	158
Lower feedstock resource scenario	309	363	282
Green waste & sewage sludge	0	0	0
Food waste	0	0	0
Arboricultural arisings (higher resource)	47	112	4
Low-cost straw (£10 t <sup>-1</sup> )	78	156	11
Wood waste	118	199	91
Low-cost straw (£20 t <sup>-1</sup> )	123	204	96

Table SPM 3: Total cost of biochar production: feedstock production to deployment on farmland.  
Note: Zero value means that the operation makes money; whilst a simplification, it is assumed that biochar production in those cases occurs at zero cost.

Depending on the assumptions used, biochar may cost up to £430 t<sup>-1</sup> delivered and spread on farmland. There appear, however, to be a number of smaller-scale but low cost opportunities using cheaper virgin feedstocks such as arboricultural arisings and, in some situations, straw. If straw costs £20 t<sup>-1</sup>, biochar can be produced for under or just over £100 t<sup>-1</sup> assuming cheaper storage options. The price of straw is temporally- and spatially-variable, depending upon nearness to markets, transport costs, weather conditions, and so on. Long-term contracts which guaranteed the farmer a constant price for straw at a lower-than-average market price may be attractive, as appears to be the case for the Ely straw-burning power plant<sup>1</sup>. The issue of pricing straw is complex, however, and markets and prices will respond to new demand from PBS: more detailed research is required before a more accurate assessment of straw as an available feedstock could be attempted. Under scenarios where non-virgin feedstocks – such as green waste, sewage sludge or food waste – are used, biochar can be produced as a product at no cost. This is because taking waste feedstocks can bring an additional income stream to the operator through charging gate-fees. Because of the high cost of waste disposal in landfills, gate-fees can make a large difference to the economics of PBS. By using wastes, instead of more expensive wood or

<sup>1</sup> [www.epri.co.uk/assets/ely/overview.html](http://www.epri.co.uk/assets/ely/overview.html)

straw feedstocks, it is possible to reduce the costs per tonne of biochar produced in a medium-scale unit by several times. On the other hand, the risk of contamination will be greater and the regulatory hurdles higher – with respect to the materials transportation, handling, preparation, processing and the resultant biochar. For biochar produced from arboricultural arisings in a large-scale unit (relative to the cost of biochar in the high feedstock scenario), the cost reduction is from 80 to nearly 100%.

The greatest costs are the cost of borrowing capital, the feedstock costs and the operational costs. Small-scale on-farm biochar production benefits from lower transport costs. Large-scale production benefits from much lower capital costs. The feedstock costs for non-virgin biomass resources are low except for waste wood, whilst avoided gate fees provide an important revenue stream. Transport costs are also low for such feedstocks because PBS introduces few additional transport requirements (beyond transport needs already accounted for in waste management). On the other hand, pyrolysis of such non-virgin biomass materials will pose the greatest potential risk and possibly require greater regulatory controls, and will likely encounter some scepticism and resistance from farmers and other land-owners. The most attractive option is, therefore, to use virgin feedstocks that are also relatively low cost, such as arboricultural arisings. *There is a moderate to high level of uncertainty attached to all the numbers presented in this section.*

### **Conclusions and the potential for biochar deployment in the UK**

This report provides preliminary evidence that PBS are an efficient way to abate carbon, and tend to out-compete alternative ways of using the same biomass (in terms of carbon abated per tonne of feedstock, or in terms of abatement per hectare of land). PBS tends to be carbon negative if it is assumed that the cultivation of the biomass is carbon neutral, though it may be more accurate to include considerations of land-use change and the feedstock carbon cycle explicitly. There is an, in principle, credible case that biochar deployment in UK soil will produce agronomic gains (and possibly suppress GHG emissions): however, these effects still remain to be demonstrated in the peer-reviewed literature.

There has been relatively little attention to the logistics of PBS, even though this is likely to be very important to the economic and practical viability. The issues raised include the need for (and cost of) storage, the acceptability of truck movements, and how economies of scale in producing and distributing biochar might be achieved. Biochar is currently expensive to produce due to feedstock, capital and operational costs. Extensive PBS implies an extensive infrastructure, involving pyrolysis units (PU) probably at a range of scales that will take some time to be built and operated, especially given the current lack of dominant design.

At present, biochar has no economic value. It is not possible to obtain a value for carbon stabilised in biochar under any policy framework, with the possible exception of the voluntary carbon market. For a carbon value to be realised in the future, it is necessary for basic procedures to assess the long-term stability of biochar to be devised. Also, biochar currently does not have any clear value as an agricultural input, until sound evidence exists to predict an agronomic or soil quality benefit with certainty.

Biochar could, however, increase quite significantly the opportunities for carbon abatement in the agriculture and land-use sectors. In the UK the availability of land is unlikely to present an absolute barrier to biochar deployment, although the land potentially providing the highest returns from biochar addition (such as horticulture) is relatively small in extent. The supply and cost of biochar also depends upon the extent to which organic waste feedstocks could be utilised. There are some 'niche' areas where PBS could have particular advantages over alternative ways of dealing with organic residues, even within current economic conditions.

## 1 OUTLINE OF REPORT

The concept of biomass pyrolysis for biochar production, particularly in the context of carbon abatement, will be outlined in **Background, Chapter 2**.

The process of pyrolysis itself is described in **Biochar production, Chapter 3**. Process parameters dictate the balance of solid, liquid and gaseous products and therefore energy yield. Contaminants present in feedstock may be transformed or retained in the various fractions during pyrolysis, and under certain conditions PAH compounds may form.

Literature information that addresses key questions around the longevity, trajectory and ultimate extent of various positive and negative effects that addition of biochar may have in soil is reviewed in **Impacts of biochar on soil, Chapter 4**. Uncertainties in the understanding of biochar function are identified, with an indication of how these may be addressed.

Logistical and practical challenges face the application of biochar to soil, and it is during application that the greatest immediate risk for human exposure and physical transport may occur. This is covered in **Application to soil, Chapter 5**.

In **Regulation, Chapter 6**, biochar is considered in the context of existing legislative controls over materials that may be applied to land and the frameworks that might be required to facilitate deployment of biochar in the UK.

Soil is a biologically active medium in which even highly resistant materials are known to slowly degrade. Confirmation or quantification of the absolute stability of biochar in soil has to be established if biochar is to be deployed in carbon abatement and carbon trading – **Monitoring, verification, accounting and reporting, Chapter 7**.

Biochar is likely to have a low moisture content and high residual heating value relative to pyrolysis feedstock materials. The CO<sub>2</sub>eq benefit that arises from stabilising biomass carbon and fossil fuel substitution through pyrolysis versus combustion must be considered through **Life cycle assessment, Chapter 8**. The methodology developed here could enable potential benefits of PBS to be assessed, or integration of biochar into UK Greenhouse Gas Inventory or carbon markets.

Pyrolysis–biochar systems that may be considered in the UK will integrate biomass feedstock processing with heat and energy production, and biochar with agriculture via soil amendments. In rural systems they will utilise crop and forest residues (such as cereal straw and tree bark), virgin biomass wastes (from crop and timber processing), livestock waste (manure) and processed biomass waste (e.g. oil cake). Around urban centres they may use green waste, mixed waste streams (compost like output, municipal waste) and sewage sludge.

The availability of feedstock limits the potential for PBS to abate carbon. Availability can be potential (absolute), feasible (practical or achievable) and realistic (currently viable). The focus in **Economic analysis, Chapter 9** is on the costs of producing biochar, mainly in the context of what is realistically achievable given certain assumptions about the current and future economic environment. Logistical and economic issues have been addressed.

Quantitative certainty around the non-carbon related benefits of biochar use, primarily in soil, are high but may be important in conferring economic value. These possible benefits currently have associated uncertainty concerning trajectory and timescale that affect feasibility. Regulatory and market acceptability may confer barriers or obstacles to the implementation of pyrolysis–biochar systems. Lack of experience in pyrolysis and resistance to novel products are relevant, as are infrastructure constraints and the possible requirement for new types of farm machinery.

Biochar may have applications in agriculture beyond soil application, and also in non-agricultural sectors, including those where activated charcoal is already used. The use of

biochar for these purposes has not been widely researched, and they will not be listed here. It is also envisaged that a different and wider range of PBS will be feasible outside the UK, and discussion of these is beyond the scope of this report. However, the import of biomass feedstock and the use of pyrolysed biomass in UK soil are considered.

For the principal scenarios envisaged, an attempt has been made to evaluate or list the possible benefits and risks. In many cases these cannot be quantified on the basis of existing evidence, but the likely relative importance can be subjectively assessed. In addition to published evidence concerning biochar and related issues, expert opinion gauged, in part, from, as yet, unpublished findings, has been assessed and the findings are described in **Survey results, Chapter 10**.

A forward look at the issues that may arise in the use of biochar in the UK is provided in **Deploying biochar in the United Kingdom, Chapter 11**.

In **Research needs, Chapter 12** provides an indication of potential further work to evaluate and support PBS evaluation and deployment.



## 2 BACKGROUND

*Saran Sohi and Simon Shackley*

Biochar is the porous carbonaceous solid produced by thermochemical conversion of organic materials in an oxygen depleted atmosphere which has physiochemical properties suitable for the safe and long-term storage of carbon in the environment and, potentially, soil improvement. Biochar comprises stabilised plant material in which carbon is stored mainly in a highly recalcitrant chemical form, and although little research has been published on the long-term stability of biochar in soil the mean residence time (MRT) of charcoal, and analogous material, is in the order of millennia (Lehmann et al., 2008). Biochar should provide an effective long-term store of carbon in soil, and thus offer a potential abatement option for anthropogenic carbon emissions (Lehmann, 2007b).

Combined with the apparently deliberate and beneficial use of charcoal in historical soil management practices, most evidently in tropical environments<sup>2</sup> but also elsewhere in the world and possibly in the UK (Young, 1804), biochar could present important opportunities in a modern context. In the UK biochar could address carbon storage, the provision of bioenergy, management of certain organic waste streams, and facilitate this through positive effects on crop performance via the soil. Elements of the technologies required to test this exist, but these have not been brought together in a system context. In addition, the robustness of the case for the stability of biochar in soil, the predictability of benefits to soil and in particular the potential risks have not been widely investigated.

Later in this report the nature and extent of the evidence that is currently available for the function of biochar in soil is assessed, and the potential carbon equivalent savings that might be achieved are scoped. Some of the main logistical, economic and regulatory considerations that would have to be addressed for biochar deployment to occur in the UK are considered. The purpose of the current chapter is to outline the basic concepts and context for pyrolysis–biochar systems (PBS).

### 2.1 Stabilisation of plant-captured carbon

Carbon dioxide (CO<sub>2</sub>) concentration in the atmosphere is increasing, and is considered to be the main influence on radiative forcing and the perturbation of global climate. A key strategy to limit climate change is to reduce the emission of CO<sub>2</sub> from fossil fuel burning, currently 7.5 Gt C y<sup>-1</sup> globally (IPCC, 2007), and from loss of plant biomass in land-use change (0.8–1.6 Gt C y<sup>-1</sup> during 1990s). It will not be possible to eliminate emissions, and it is not possible to lower them as fast as is required to avert climate change. Some technological approaches to this problem are widely advocated, notably chemical capture of CO<sub>2</sub> from power stations, and its storage in geological strata (CCS). The technology to achieve this is still at an early stage, but it is considered achievable in the medium term (e.g. by 2025). There is likely to be a significant energy cost associated with the capture of CO<sub>2</sub> from flue gas, which has implications for supply of fossil fuel.

Annually plants draw down 15–20 times the amount of CO<sub>2</sub> emitted from fossil fuel, which is up to 20% of the entire atmospheric pool. About half of this is returned immediately to the atmosphere through plant respiration, but about 60 Gt C y<sup>-1</sup> (Prentice et al., 2001) is classed as net primary productivity (NPP), i.e. invested in new plant growth (about 45% of plant biomass is carbon). Since the plant biomass is relatively constant globally, the magnitude of new plant growth must be approximately matched by harvest, litterfall, exudation by roots, etc. The annual CO<sub>2</sub> release from decomposition of these products by natural pathways and human cycling of plant-derived materials and products occurs at various characteristic rates,

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<sup>2</sup> The *terra preta* soils of Amazonia

but in sum total roughly equal to NPP. The annual return of carbon to the atmosphere from the decomposition of all prior cohorts of plant material is thus approximately equal to NPP.

Intercepting and stabilising plant biomass production reduces the return of carbon to the atmosphere, with a relative reduction in atmospheric CO<sub>2</sub> (see Figure 2.1). This reduction can be quite immediate if the default rate of decomposition is months to years, as it is for the dominant portion of biomass returned to soil in managed (agricultural and forest) ecosystems. Controlled charring (pyrolysis) can convert up to half of the carbon in plant biomass into chemical forms that are biologically and chemically recalcitrant i.e. will not significantly degrade through microbial activity or chemical reaction in the environment. In principle managed soils have a capacity to store pyrolysed biomass at a rate significant in terms of emissions of carbon from fossil fuel.

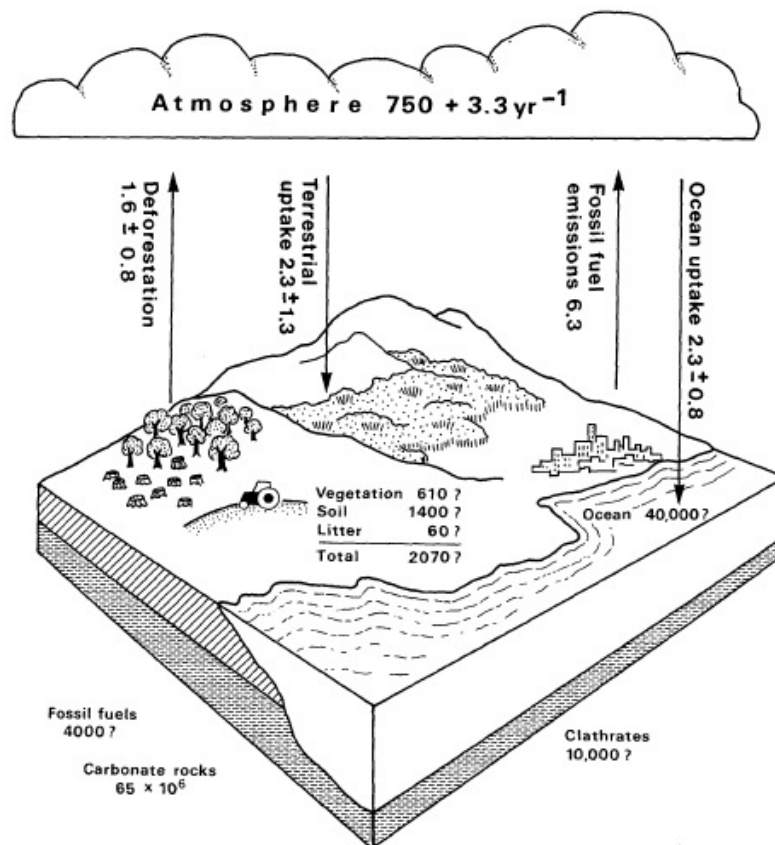


Figure 2.1: Schematic for the scale of the global carbon cycle  
Source: Grace (2004)

The conversion of carbon in plant biomass to charcoal during natural fire is only about 1–5%, but the high level of stability established for such material in soil, which is generally a highly active biological medium, leads to expectation for similar stability in deliberately produced biochar. Biochar deployed as a “carbon negative” technology at the scale of 1 GtC y<sup>-1</sup> would be equivalent to expanding the natural cycle of fire-derived charcoal storage in geographic terms, and increasing its global magnitude by a factor of 4–20 (Kuhlbusch, 1998).

Methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) are the second- and third-largest contributors to radiative climate forcing after CO<sub>2</sub>. Soil is a key source of both gases, which are emitted through natural microbial processes. The global significance of these processes has increased with agricultural expansion, since higher emission is associated with flooded soil conditions and with an enhanced nitrogen cycle provided by the use of fertiliser, manures and slurry. Since both CH<sub>4</sub> and N<sub>2</sub>O are also associated in part with organic matter

decomposition, stabilising degradable organic matter could have a direct impact on soil-based emissions of these gases. Interventions in the nutrient or water balance of soil through changes in the dynamics of water in soil, or through the adsorption of nitrogen (as ammonium) may indirectly modify emissions of these gases from the soil.

To be a significant response to climate change, carbon equivalent abatement on a scale of millions of tonnes needs to occur, preferably hundreds of millions of tonnes. To intercept net primary productivity (NPP) and produce biochar at this scale presents a practical challenge, but still only involves a small fraction of total plant NPP ( $60 \text{ GtC y}^{-1}$ ) of which 30% is already calculated to be 'co-opted' by humans (Vitousek et al., 1986). Increased efficiency of biomass recovery in managed ecosystems, diversion of biomass from current uses where it has a low value, and utilisation of used biomass (organic waste) streams provide three ways in which it might be achieved. The fourth option is to sustainably harvest more biomass, which might be achieved by growing more productive plants, increasing the area of managed land, or adjusting harvesting regimes. Clearly, demonstrable effects on NPP arising from the deployment of biochar could be factored into such strategies.

## **2.2 Biochar bioenergy**

Biomass and organic wastes have energy value and can be burned as fuel. In the process of biomass pyrolysis, thermal degradation consumes energy and emits  $\text{CO}_2$ , but liberates sufficient quantities of energy-rich combustible gases such as hydrogen and methane to make the overall process net exothermic. In traditional production of charcoal some of the gases may be lost to the atmosphere together with oils and tar as smoke, which may contain the greenhouse gas (GHG) nitrous oxide ( $\text{N}_2\text{O}$ ) as well as methane. In controlled pyrolysis, oil can be condensed or combusted with tar in the vapour form, to utilise its energy value. The solid by-product of pyrolysis, char, which may comprise charred volatiles as well as charred primary feedstock, also has an energy value.

In effect pyrolysis transfers a portion of potential energy in biomass into gaseous and liquid phases in variable proportion, which can then be captured or immediately burned for bioenergy (heat or heat and power). Some of this energy may be required to maintain pyrolysis of further biomass, and to dry pyrolysis feedstock. The energy in gas and liquid should exceed that required to sustain the process, but this surplus diminishes with the proportion of carbon retained as solid char.

Until recently processes to capture energy from biomass using pyrolysis focused on the liquid (oil) product, which can be maximised by heating very rapidly (fast pyrolysis). Slow pyrolysis favours production of solid over liquid, and technologies to produce larger proportions of char could emerge at a range of scales and diverse socioeconomic contexts.

In still largely conceptual pyrolysis–biochar systems (PBS), energy production from slow pyrolysis is linked to agriculture or forestry not only through provision of feedstock, in the form of straw, brush, etc, but the return of char to the soil as biochar after potential contaminants formed during pyrolysis have been evaluated. Pyrolysis of organic waste streams may provide an alternative source of feedstock for PBS, although with consideration for potentially harmful elements or compounds that may be present in the feedstock and retained in the biochar product.

## **2.3 Carbon sequestration as biochar in soil**

Adopting biomass stabilisation by pyrolysis as a climate change mitigation option, deployment at adequate global scale, assurance of the necessary level of stability for carbon in char and evaluation of the overall sustainability (e.g. with respect to direct and indirect land-use change and social impacts) would be prime requirements.

Reliable and secure storage for annual storage and large cumulative amounts would have to be available, and whilst simple burial (for example in landfill or disused mines) has been

considered (Seifritz, 1993), these possibilities would be limited and costly and potentially dangerous. However, many studies have shown that charcoal from natural sources may persist in soil, in the presence of high levels of biological activity, for centuries or millennia.

The broader land surface, and in particular soils that are already actively managed, may therefore provide the capacity required for a large and enduring strategy for storing carbon in biochar (Lehmann et al., 2006). The key assumptions are that the estimates for stability of charcoal made so far are typical and accurate, that biochar from pyrolysis and more diverse feedstock exhibits broadly similar levels of stability as natural charcoal and that appropriate feedstocks can be provided sustainably and without adverse environmental or socio-political impacts.

## **2.4 Indirect CO<sub>2</sub>equivalent Impacts**

The viability and practicality of adding biochar to soil may depend on benefits being provided to agricultural productivity, and with no other negative impact on the agri-environmental system. Furthermore, delivering this must not compromise significantly the stability of biochar carbon. Charcoal is an element of growing media marketed in horticulture, where practitioners contend that it improves root health and water supply. In the field, the porous structure of charcoal (Bird et al., 2008) suggests that improved consistency in crop performance might be expected especially in drought prone land.

Produced under contrasting temperature and from materials with more or less endogenous structure e.g. wood compared to cereal straw, the impacts of biochar on soil physical and chemical properties may differ from those provided in soils historically or traditionally managed with charcoal. The retention and availability of biomass-derived nutrients in biochar appears to offer potential for some exhaustible agronomic value, as could alkaline pH substituting for agricultural lime in acidic soils (Van Zwieten et al., 2009). Persistent or evolving properties, such as capacity for cation exchange (Liang et al., 2006), etc, may be significant, and more or less valuable depending on time horizon.

Cation exchange offers capacity for soil to store plant-available N, in the form of ammonium (NH<sub>4</sub><sup>+</sup>), and high cation exchange capacity (CEC) can be associated with enhanced use-efficiency for nutrients. In soils that are low in clay minerals that provide most indigenous CEC, maintaining higher stocks of active soil organic matter through regular addition of crop residues and manure is one possibility. Some forms of biochar may display, or over time develop, high CEC. In some soils it is possible that CEC might be slowly increased by the addition of stable biochar, and incrementally enhanced by repeated addition.

Soils with ideal pore-size distribution retain plant-available nitrogen in the soil, increasing plant uptake and increasing fertiliser-use efficiency. This implies lower fertiliser requirement and lower eutrophication risks. If the accumulation of biochar results in beneficial change in pore-size distribution, it would result in a change more permanent than can be achieved through the effects of degradable and thus transient organic matter that can be used to condition soil.

The release of nitrogen by soil microbes from decomposition of crop residues in the low-growth winter period is a key source of nitrogen lost to water and the atmosphere. Increasing the use-efficiency of nitrogen in recoverable crop residues is therefore of relevance to eutrophication through leaching, and N<sub>2</sub>O emissions. At least half of the nitrogen in biomass is eliminated from the feedstock during pyrolysis but is, potentially, recoverable (Day et al., 2005). The availability of the remainder is likely to be low relative to that of nitrogen in the pyrolysis feedstock.

Changing the abundance or physical position of aerobic space in soil (with respect to loci of microbial activity) has the potential to mitigate CH<sub>4</sub> emission. The emission of N<sub>2</sub>O from soil could be suppressed by adsorption of nitrogen in the form of ammonium (NH<sub>4</sub><sup>+</sup>). Emissions of both CH<sub>4</sub> and N<sub>2</sub>O are notoriously variable temporally and spatially and also sensitive to

soil pH. However, these mechanisms may be relevant in suppression of CH<sub>4</sub> and N<sub>2</sub>O by biochar observed at certain locations or under certain controlled conditions (Van Zwieten et al., 2009).

The Haber-Bosch process used to fix atmospheric nitrogen into solid soluble (ammonium) form is an energy intensive process that accounts for about 40% GHG emissions associated with arable agriculture. Typical use-efficiency for fertiliser nitrogen in the UK is high relative to the global average of 30–50% (Ladha et al., 2005) attributable to leaching, immobilisation and gaseous loss, and leaching. Technologies that improve the management of these processes through the soil can therefore offer an indirect gain in agricultural carbon equivalent balance.

Liming of agricultural soil also transfers carbon from the geological pool to the atmosphere through production (calcining of limestone) and subsequent neutralisation in the soil (Houghton et al., 1997; West and McBride, 2005). The alkalinity typical of biochar can potentially substitute for the use of lime in the management of soil pH without emission of CO<sub>2</sub> (Van Zwieten et al., 2009).

## **2.5 “Carbon negative” energy**

Combustion of biomass cycles atmospheric CO<sub>2</sub> with capture of energy but without net removal. The suggestion that PBS can be carbon negative may be correct in the sense that some CO<sub>2</sub> removed by plants would become effectively sequestered into a stable store of carbon in soil. However, the description may be considered somewhat erroneous in that the energy value of pyrolysis products other than char will be lower than that obtained from biomass in combustion, the sequestered carbon also representing sequestered energy. Whether pyrolysis or combustion then provides more carbon abatement depends crucially on the efficiency of both pyrolysis and systems otherwise used to generate energy.

### 3 BIOCHAR PRODUCTION

*Ondřej Mašek and Peter Brownsort*

Pyrolysis is a thermochemical conversion process in which organic materials decompose in an atmosphere depleted of oxygen. Until recently technology for acquiring the solid products of pyrolysis ranged from primitive kilns inspired by ancient charcoal making practices, to devices drawing from developments in pyrolysis for biofuel (oil) production. However, both charcoal making and oil production are processes distinct from the production of biochar in objective, reflected in process design and operation.

The main objective of charcoal production is fuel for cooking, iron production or as a starting material for preparation of activated carbon. As such, the requirements for charcoal (i.e., good combustion and minimum impurities) are clearly different from the requirements for biochar, i.e., long term carbon stability, beneficial impact on soil properties, e.g., CEC, pH, specific surface area, etc. These are far more complex and not well understood, due to the intricate interaction of biochar with soil and plants.

On the other hand, pyrolysis systems for biofuel production have been successfully developed to maximise the yield of pyrolysis liquids, while minimising the yield of undesirable by-products, i.e. char and gas. This resulted in development of technologies such as fast pyrolysis and flash pyrolysis, which produce a minimum yield of solid and are therefore unsuitable for biochar production and will not be covered in this chapter.

Only a small number of pyrolysis systems optimised for char production, so called slow pyrolysis systems, have been developed to date. This chapter will not attempt to describe different pyrolysis systems for biochar production, as this has been already done elsewhere (Collison et al., 2009; Lehmann and Joseph, 2009; Sohi et al., 2009), but instead will focus on analysing those aspects of production that will play a crucial role in any biochar deployment.

These include the effects of feedstock and pyrolyser operating conditions on biochar yield and quality, and system carbon and energy balance. The analysis is based on a thorough review of publicly available literature, assisted by data and opinions obtained from experts on pyrolysis via direct communication. Wherever possible, data from at least pilot scale facilities have been used in the analysis, to obtain an assessment as close as possible to reality.

#### 3.1 Effect of operating conditions on char yield and properties

The main objective of this review was to assess the variability of product yields from pyrolysis processes as a function of operating conditions and feedstock properties. Alternative approaches to biochar production, such as hydrothermal carbonisation and microwave pyrolysis were not considered in this report, as at present insufficient information is available on these processes, their variability and yields, and the quality of the char produced.

In terms of variation in the pyrolysis process, variability may be either intentional or unintentional. Intentional variability refers to a change in product yield and mix that results from deliberate change in set operating conditions such as pyrolysis temperature. Unintentional variability refers to unplanned changes in operating conditions resulting from issues of homogeneity in feedstock composition and a limited control of process conditions. Sources of variability will relate to the main controlling parameters, i.e., feedstock, temperature, heating rate, etc.

Heating rate is predominantly defined by the design of the pyrolysis facility and cannot be readily varied to any great extent for a given pyrolyser. With respect to heating rate, pyrolysis processes are commonly divided into four categories as follows, starting from the highest

heating rate: flash (very high), fast (high), intermediate (medium) and slow (low). The main impact of heating rate on pyrolysis is on the product mix, where high heating rates (and short residence times) favour high liquid (oil) yields and low heating rates (and long residence times) high yields of solids (char).

Variation in biomass feedstock, even if nominally from a single source, is likely to be one of the main causes of variability (Downie, 2009). The exact composition of a type of biomass depends on many factors and will vary according to when, where and how it was grown, harvested, and stored. The absolute carbon content in nominally the same biomass feedstock may differ by as much as 10% (Gaur and Reed, 1995). The composition of a single supply of a particular biomass type should be more consistent but is not likely to be truly homogenous, except at small scale, unless special provisions for mixing and blending are made. Feedstock moisture content and particle size may vary within and between loads and affect process yields.

Temperature control is also likely to be an important cause of variability, particularly for slow pyrolysis. The lower heat fluxes and longer residence times of slow pyrolysis give scope for unintentional variation in heating rate and peak temperature. For example, a slow pyrolysis demonstration plant in Australia considered to be “a highly controlled process” (Downie, 2009), is reported to operate within a  $\pm 30^\circ\text{C}$  temperature range under continuous steady state conditions at  $550^\circ\text{C}$  (Downie et al., 2007). Figure 3.1 indicates variation of this magnitude may impact char composition and properties, char yield and pyrolysis products.

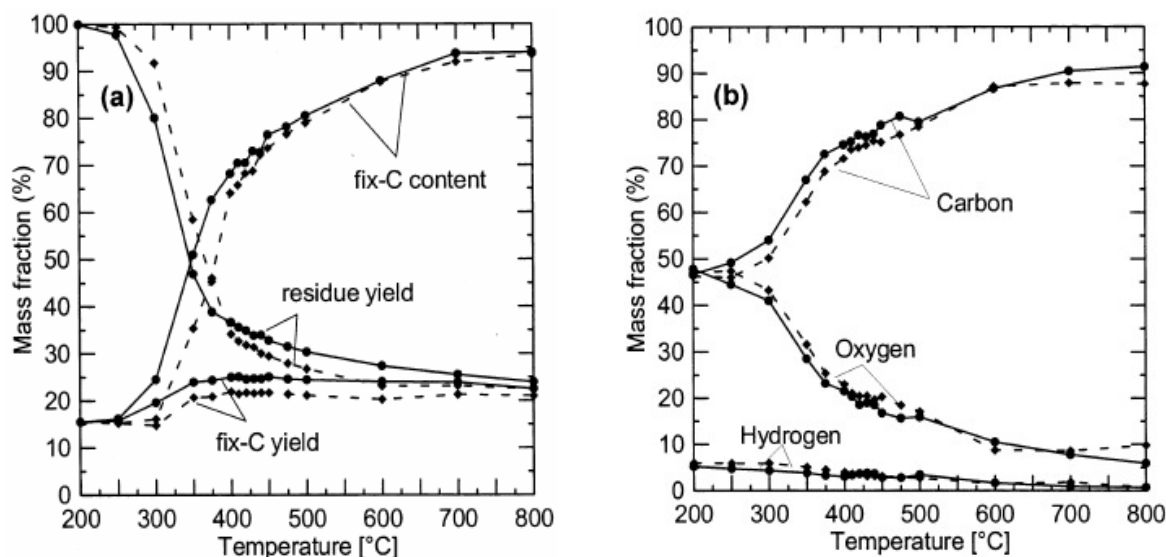


Figure 3.1: Effects of temperature and heating rate on (a) char yield, and (b) carbon, hydrogen and oxygen content of beech chars

Note: Solid and dashed lines are  $2^\circ\text{C}$  and  $10^\circ\text{C}$   $\text{min}^{-1}$  heating respectively (Antal and Gronli, 2003)

In addition to impacting product mix, feedstock and pyrolysis conditions influence the properties of solids that might be applied to soil as biochar.

## pH

It has been reported that biochar can be produced at almost any pH between 4 and 12 by appropriate selection of feedstock and operating conditions (Lehmann, 2007a). Typically, low pyrolysis temperatures (up to approximately  $400^\circ\text{C}$ ) yield acidic biochar ( $\text{pH} < 7$ ), with pH increasing with pyrolysis temperature above this point to produce alkaline biochar ( $\text{pH} > 7$ ). At very high temperatures ( $\sim 800^\circ\text{C}$ ) biochar can reach  $\text{pH} 12$ .

## Cation exchange capacity

Biochar has the capacity to exchange cations (such as nitrogen in the form of ammonium,  $\text{NH}_4^+$ ) with soil solution, and thus store crop nutrients. The extent of this capacity (cation

exchange capacity, CEC) is effectively absent at very low pH and increases at higher pH (Lehmann, 2007a). Experimental results show that the CEC of fresh biochar is typically very low, but increases with time as the biochar ages in the presence of oxygen and water (Cheng et al., 2008a; Cheng et al., 2006; Liang et al., 2006). The possibility of producing biochar with higher CEC is under investigation.

### Specific surface area

Extensive literature review has shown that biochar with a broad range of specific surface area (SSA) can be produced (Figure 3.2). The main parameters influencing SSA are pyrolysis temperature, heating rate, residence time and presence of active reagents (e.g., steam, CO<sub>2</sub>, O<sub>2</sub> etc.). Figure 3.2a shows that the total surface area of biochar from most feedstocks tends to increase with increasing pyrolysis temperature. This is mainly due to the development of micropores that are responsible for most of the surface area, see Figure 3.2b. At present it is not clear whether the additional surface area, presented by micropores, plays as important a role in soils as macropores, and therefore whether it is beneficial to produce a biochar with extremely high SSA. It may be possible to produce biochar with high SSA in the macropore range. However, biochar physical structure tends to be defined by the starting material, so fine milling or compaction of the feedstock before pyrolysis is necessary to achieve a well defined macroporous product (Kurosaki et al., 2007).

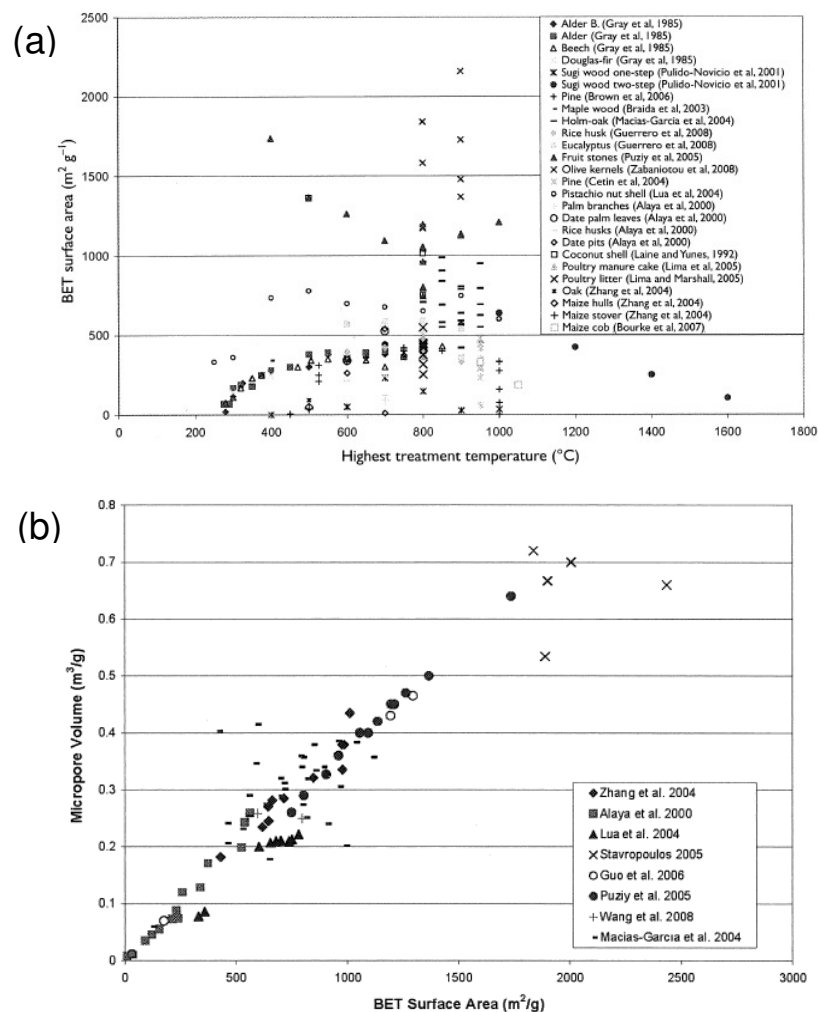


Figure 3.2: Biochar surface area (a) plotted against treatment temperature and b) its apparent relationship with micropore volume  
Source: Analysis and original graphics from Downie (2009) with permission of Earthscan Ltd.



### 3.2 Process variables

Typical and wider reported ranges for key process variables and product yields of slow, intermediate and fast pyrolysis processes are shown in Table 3.1.

	Slow pyrolysis	Intermediate pyrolysis	Fast pyrolysis
<i>Process</i>			
<i>Temperature</i>			
Range	250-750	320-500	400-750
Typical	350-400	350-450	450-550
<i>Time</i>			
Range	mins-days	1-15 mins	ms-s
Typical	2-30 mins	4 mins	1-5 s
Yields (% o.d.)			
<i>Char</i>			
Range	2-60	19-73	0-50
Typical	25-35	30-40	10-25
<i>Liquid</i>			
Range	0-60	18-60	10-80
Typical	20-50	35-45	50-70
<i>Gas</i>			
Range	0-60	9-32	5-60
Typical	20-50	20-30	10-30

Table 3.1: Scope of pyrolysis process control and yield ranges  
Note: Based on review of over 30 literature sources (Brownsort, 2009)

### 3.3 Sensitivity of pyrolysis–biochar systems to pyrolysis yield

Limited evidence concerning the effect of unintentional variation in pyrolysis process suggests assuming a relative standard deviation (RSD) of  $\pm 5\%$  for char yield is reasonable (Brownsort, 2009). Sensitivity analysis indicates that control over the yield of char can be important when comparing the net benefit of PBS and combustion, depending on the areas in which biochar most affects the calculation outcome.

### 3.4 Carbon mitigation potential of alternate production technologies

From the sections above and Table 3.1 it is clear that biomass pyrolysis processes can be optimised and operated to prioritise the production of char, liquids or gases in a wide range of product distribution. Therefore, it is important to identify where in the range lies the “optimum”. The optimum as defined in this report is taken from the point of view of carbon equivalent abatement. The overall effect of pyrolysis-biochar on carbon abatement can be described as the sum of two main factors: the carbon stored in char (related to CO<sub>2</sub> removed from the atmosphere) and the CO<sub>2</sub> emissions avoided through substitution of fossil fuels by use of pyrolysis products for energy. From this the three prevailing technologies for biochar production (slow, intermediate and fast pyrolysis) were analysed, and a simplified model developed to calculate the net effect of biochar on CO<sub>2</sub> emissions and on the electricity output available from each process (Brownsort, 2009). The data required for the model (Table 3.2) were gathered in a comprehensive literature review complemented by direct communication with relevant experts (Downie, 2009; Downie et al., 2007; Dynamotive Energy Systems Corporation, 1999; Gaunt and Cowie, 2009; Hornung, 2008; Hornung et al., 2006; Redlein and Kingston, 2007).

Model inputs	Slow pyrolysis	Intermediate pyrolysis	Fast pyrolysis
<i>Process input</i>			
<i>Biomass</i>			
Carbon content (%)	46	43	50
Energy value (MJ kg <sup>-1</sup> )	17 *	16	19
<i>Pyrolysis process data</i>			
Gas yield (% input mass)	45	32	13
Liquid yield (% input mass)	15 *	35	72
Char yield (% input mass)	40	34	15
Energy loss (% input)	6 *	0 *	3
Process energy (% input)	10 *	10 *	10
<i>Primary process output</i>			
<i>Gas</i>			
Energy value (MJ kg <sup>-1</sup> )	13.1	11.0	11.5
Carbon content (%)	37.4	30.0 *	36.0 *
<i>Liquid</i>			
Energy value (MJ kg <sup>-1</sup> )	0.0 *	12.0	17.9
Carbon content (%)	0.0 *	30.0 *	46.5
<i>Char</i>			
Energy value (MJ kg <sup>-1</sup> )	25.0 *	24.7	27.0
Carbon content (%)	72.3	70.0 *	78.0 *

Table 3.2: Data required for the pyrolysis process model

Note: \* = estimated. See text for sources of other figures

The model calculates CO<sub>2</sub> emissions avoided when fossil fuel is substituted by use of a biomass based renewable energy source for the generation of electricity and compares it to direct combustion of biomass for electricity production. The reference case used in this model relates to the average CO<sub>2</sub> equivalent emission (including contributions of CH<sub>4</sub> and N<sub>2</sub>O) from generation of UK grid electricity. The carbon dioxide emission factor (CEF) of the UK grid varies over time with the mix of fuels used. It has decreased over recent decades with the trend away from coal toward use of natural gas. Expressed as kg CO<sub>2</sub>eq kWh<sup>-1</sup> electricity CEF has fallen from 0.78 in 1990 to 0.55 in 2007 (Defra, 2008). Given this trend the UK government recommend using a CEF of 0.43 kgCO<sub>2</sub>eq kWh<sup>-1</sup> for comparisons when considering renewable electricity (Defra, 2009a) and this figure is used in the model as UK grid average reference case.

Model outputs, carbon stability factor 0.75	Slow pyrolysis	Intermediate pyrolysis	Fast pyrolysis
Energy product (kWh eq kg <sup>-1</sup> o.d. feedstock)	0.38	0.56	1.18
Net CO <sub>2</sub> benefit (kg CO <sub>2</sub> eq kg <sup>-1</sup> o.d. feedstock)			
Pyrolysis	-0.96	-0.88	-0.80
Combustion	-0.67	-0.63	-0.75

Table 3.3: Pyrolysis process model results

Reiterating, the model calculates the net effect on CO<sub>2</sub> emissions and the electrical energy output of biomass pyrolysis processes, and compares these to alternative direct use by combustion of the same biomass resource for electricity generation, both with reference to a projected UK grid average carbon dioxide emission factor. The model boundaries cover only the pyrolysis process and immediate use of products for electricity generation and it is limited by a lack of available data. Model outputs are all expressed on a feedstock dry weight basis.

Using the model case input data summarised in Table 3.2 with a default value of 33% for electrical conversion efficiency the main model output data is given in Table 3.3. The results in Table 3.3 are calculated using the assumption that of the carbon present in fresh biochar 75% will remain in the soil indefinitely, and that there is no use of spare process heat.

Results of the model show that fast pyrolysis may give the highest electrical energy product. This is due to the high liquid (oil) yields from the process, which can then be used for power generation. On the other hand, the electrical energy product is lowest for the slow pyrolysis process where much of the energy value of the feedstock is stored in the biochar product. There are benefits in terms of CO<sub>2</sub> removal from the atmosphere in each case, arising from a combination of sequestration of carbon in char, and the avoidance of emission from fossil fuel use. The magnitude of the benefit is greatest for slow pyrolysis where most carbon is retained in biochar and least for fast pyrolysis where char yield is low. The differences across most of the data outputs can be linked back to the product yields in a similar way.

### **3.5 Contaminants**

There are two main potential sources of contamination in biochar: feedstock and the conversion process. Depending on the origin and nature of the pyrolysis feedstock, biochar may contain contaminants such as heavy metals and organic compounds. Some of these compounds will undergo changes in the conversion process and might be destroyed (or converted to benign compounds) while others will remain unchanged or give rise to potentially harmful substances. In addition to the contaminants introduced in the feedstock, some contaminants can be formed also in the conversion (pyrolysis) process. These include polycyclic aromatic hydrocarbons (PAH) and potentially, in some cases, dioxins. The physical form of pyrolysis products may present a direct health risk, or increase or decrease the risk of elements, compounds or crystalline material both in feedstock or formed during pyrolysis.

#### **Heavy metals**

Heavy metals present in the feedstock (e.g., MSW, sewage sludge, treated wood, etc.) are most likely to remain and concentrate in the biochar (Helsen et al., 1997; Lievens et al., 2009; Ryu et al., 2007; Vassilev and Braekman-Danheux, 1999; Vassilev et al., 1999). Therefore, careful selection and analysis of feedstock is necessary to avoid contamination of biochar with increased levels of heavy metals. Heavy metals are stable materials and therefore retained (conserved) during volatilisation of associated organic molecules. The majority of metals will, therefore, be present as ash within biochar (together with nutrient elements such as phosphorus and potassium). It may therefore be possible to manipulate contaminant loadings through selective removal of ash (Hwang et al., 2008).

#### **Polycyclic aromatic hydrocarbons**

PAH can be formed from any carbonaceous feedstock. The major chemical pathways for PAH formation in the pyrolysis process are the high temperature secondary and tertiary pyrolysis reactions (homogeneous and heterogeneous), as shown in Figure 3.3 and Figure 3.4. The formation of these tertiary pyrolysis products increases with the pyrolysis severity (i.e., temperature and residence time) and becomes significant at temperatures around 750 °C.

However, there exists also a second, less explored route for PAH formation. Evolution of PAHs from the solid substrate has been reported in the temperature range of 400–600 °C (Hwang et al., 2008; McGrath et al., 2001). This pathway yields predominantly lower molecular weight PAHs, although higher molecular weight PAHs, such as Benzo[a]pyrene, are also formed (McGrath et al., 2001; McGrath et al., 2003; McGrath et al., 2007).

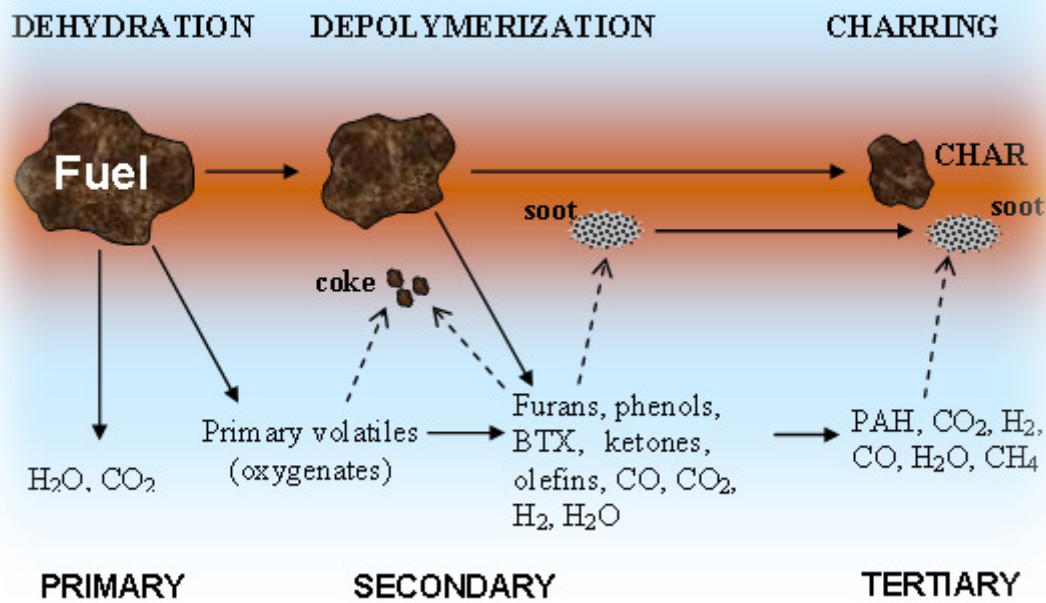


Figure 3.3: Progress of fuel particle pyrolysis  
Source: Mašek (2007)

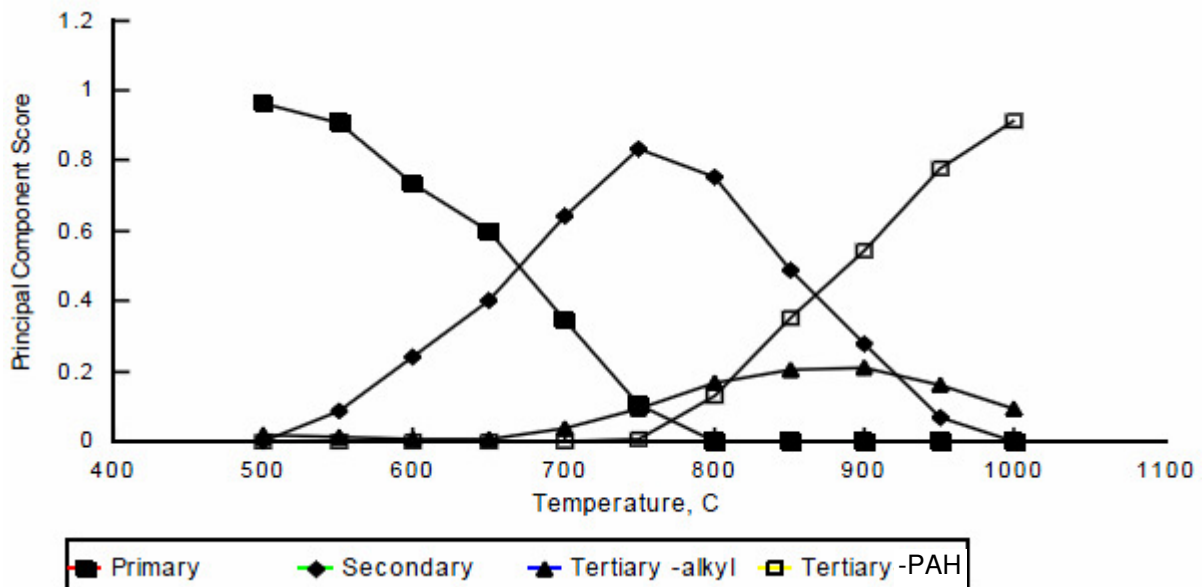


Figure 3.4: The distribution of the four “tar” component classes as a function of temperature with 0.3 s gas-phase residence time.  
Source: Milne et al. (1998)

As the optimum temperature for biochar production lies in the region 450–550°C, in a well controlled system (without hotspots) formation of PAH would proceed mainly by the evolution from solid substrates. PAH formation in the gas phase should be minimal, due to the low pyrolysis temperature. Data on PAH content in pyrolysis char are scarce, but indicate that the concentration and composition of PAH in biochar are feedstock dependent (Zhurinsk et al., 2005). Other data show that PAH concentrations in biochar produced from untreated biomass at temperatures of up to 600°C are lower than those in urban soils in England, in the order of 10–100 mg kg<sup>-1</sup> (Creaser et al., 2007). Biochar produced from chemically treated biomass is liable to contain considerably higher levels of PAH than biochar from

virgin feedstock, due to the possibility of indigenous PAH and apparent in a study of biochar produced from railway sleepers previously treated with tar and creosote (Zhurinsh et al., 2005). Available published data on the concentration of benzo(a)pyrene, one of the most toxic PAH compounds, is shown in Table 3.4

benzo[a]pyrene content ( $\mu\text{g kg}^{-1}$ )				
Birch char	Pine char	Pine sleeper char	Urban soil (England)	Rural soil (England)
310	570	4040	714	67

Table 3.4: Concentration of benzo(a)pyrene in biochar and UK soil  
Sources: Zhurinsh et al. (2005), Creaser et al. (2007)

### 3.6 Dioxins

Dioxins, unlike PAH, require the presence of chlorine as an essential building block. Consequently, only biochar produced from feedstock containing significant amounts of chlorine (e.g. halogenated plastics) would be prone to generation of dioxins under certain conditions. However, the dioxin formation process is heavily dependent on the temperature history of the pyrolysis products, and relatively high temperatures (around 750 °C) (Froese and Hutzinger, 1996a, b) are required for the formation of dioxin precursors (chlorinated benzenes and phenols). In addition, oxygen is required for the de-novo mechanism for dioxin formation (one of the possible mechanisms for dioxin formation). Without precursor it is unlikely that dioxins would be produced in pyrolysis due to anoxic conditions, even at 450–550 °C and from feedstock containing chlorine - pyrolytic conditions also at least partially destroy dioxins present in feedstock. If precursors such as chlorophenols were present in feedstock, these could conceivably acquire dioxins through condensation reactions in pyrolysis. It would nonetheless be desirable or necessary to confirm absence of dioxins analytically, wherever there was reason to suspect dioxin or dioxin precursors in feedstock, not least since disruption to process conditions could temporarily result in conditions more conducive to their formation.

### 3.7 Bespoke biochar

The properties of biochar can be manipulated across a wide range by deliberate matching feedstock and production conditions. This suggests that it might be possible to produce (engineer) biochar that displays well defined properties fit for a specific purpose, e.g., for increasing soil available nutrients, increasing stable carbon in soils, mitigating nitrogen leaching, etc. At the moment, however, the concept of ‘bespoke biochar’ requires much greater understanding of how different biochar properties impact soil and plant processes and how they may interact. Most relevant research to date has been undertaken using available charcoal products prepared under uncertain or arbitrary conditions (Chapter 4), rather than a systematic assessment of individual properties and functions.

Categorisation of biochar may be possible once the extent to which key functions can be independently controlled during pyrolysis, and the extent to which they are mutually exclusive, or may be integrated. To address this, research into the impact of a set of well-defined biochar products on key soil processes is required. Research into the design of pyrolysis for cost-effective biochar and energy production is also necessary.

## 4 IMPACTS OF BIOCHAR ON SOIL

*Saran Sohi*

Biochar is the solid product of biomass pyrolysis and potentially bioenergy co-products, where the process and product is designed for safe and beneficial application to soil. Material that meets the criteria of this definition currently does not exist at significant scale, in part because no specification or certainty can be provided for the soil-derived benefits available to the agricultural enterprise, or the timescale over which they will be realised. In addition to the risk of seeing no positive effect, there is the potential for negative impacts to arise from biochar, either short-term or more permanently, if it is not applied with a good understanding of its origin, production and functional properties. Users may be unclear about the possibility of negative effects, or the position regarding regulatory compliance.

The capacity to predict the function of biochar in agronomic terms, and a measure of its capacity to store carbon for the period relevant to climate change mitigation, appear pre-requisite to assignment of monetary value to biochar, and potentially a market in its production and sale. The corresponding projected UK costs for biochar are discussed in Chapter 9. The purpose of this Chapter is to review the current status of scientific understanding of biochar as it pertains to soil function and soil carbon storage.

Although the definition of biochar used in this report excludes charcoal (implicitly or explicitly encompassed by other definitions), charcoal is an analogous material. As well as being available, charcoal in the natural environment provides the only source of relevant direct evidence for long term stability of biochar, having been used historically by humans and in many natural ecosystems deposited through periodic fire.

The more temporary beneficial impacts may be chemical and result from leachable ash and modification of soil pH, promotion of short-term microbial activity including the effect of small labile fractions. Physical benefits may arise from modification of soil bulk density, water holding capacity and promoting soil aggregation (possibly in combination with soil biological effects). These effects may be temporary or long term. Thermal properties may change as well (Oguntunde et al., 2008).

Other effects relate to the provision of cation exchange capacity (CEC) and specific surface area (SSA), biological associations (with micro-organisms, fungi and with plant roots), and bio-physical benefits (mediating the connection of micro-organisms and microbial substrate, promotion of meso-faunal activity, including earthworms). The potential for detrimental effects on the soil would depend on the source of the biochar applied, and the rate and timing of its application. Negative impacts could include leaching of nutrients, addition of toxic elements (metals), or the introduction of organic contaminants. Where biochar has a high affinity for nitrogen there may be negative short-term effects on crop nutrient supply, i.e. potentially reducing nitrogen availability to the plant in the period after application.

Scientific research of biochar is a relatively new topic, and therefore generality in site-specific observations is not yet apparent, while extrapolation from individual observations is not yet possible. At this point a convergence in methodologies has not emerged, and until recently there have been no strategic research programmes to provide a systematic evaluation. The nature of PBS also demands coordination and consolidation of research effort with pyrolysis engineering, in order to produce biochar that expresses particular, possibly multiple functions in soil.

The review undertaken for this Chapter has systematically assessed the published scientific literature relevant to the function of biochar in soil, and to convey the balance of research effort and evidence to date and, as mentioned above, and draws heavily on studies of analogous products, i.e. various types of charcoal. Research papers accessed and categorised are summarised in tabular format in Appendix 1.

The literature review has assisted in identifying key areas for future directed research (Chapter 12), and has been interpreted in the context of elicited expert opinion reflecting a wide body of emerging evidence, as well as perceptions based on an interpretation of the literature.

#### **4.1 Key functions of biochar**

To effectively assess the literature it was necessary to establish the key relevant potential functions of biochar in soil. These are listed and defined below prior to addressing what is not yet known with respect to the basic questions. The potential risks arising from the use of biochar are dealt with toward the end of this Chapter as well as in Section 3.5.

##### **Provision of labile organic mater**

Rapid utilisation of labile substrates in soil can build a store of nutrients in soil microbial biomass, which may become available for plant acquisition and growth over time. The potential benefits of labile carbon in soil can create a constraint to crop growth if substrate nitrogen is low, and if at the time of addition inorganic (i.e. available) nitrogen in the wider soil is limited. This is because nitrogen as well as carbon is required to build new biomass and microbes out-compete roots.

Nitrogen is progressively volatilised during pyrolysis so the ratio of carbon to nitrogen in biochar is generally much higher than in the feedstock. However, if biochar is entirely stable will not present the readily accessible carbon substrate necessary to create microbial demand for external nitrogen. Whether significant nitrogen immobilisation of soil nitrogen occurs should therefore depend on the size of the biochar addition, the size of the labile fraction, and whether the ratio of nitrogen to carbon of the labile fraction reflects that of the bulk biochar sample.

##### **Storage of stable in carbon**

The stable portion of biochar is the fraction for which, in the future, a carbon credit might be claimed. In the context of climate change mitigation an in situ mean residence time (MRT) exceeding 100 y is essential (see section 7.5). There is, as yet, no robust methodology for establishing the MRT of a specific biochar product: this is one of the key scientific uncertainties and policy needs. The sum of stable and labile carbon should not reflect the total carbon content of biochar, as fractions of intermediate stability are also likely to be present.

##### **Supply of plant available nutrients**

Aside from nitrogen, most potential nutrients in pyrolysis feedstock are largely conserved during pyrolysis (as also are potentially toxic elements). Progressive elimination of carbon, oxygen and hydrogen during pyrolysis therefore increases the total concentration of minerals in the char residue, and in potentially extractable forms as ash. Biochar ash content increases in inverse proportion to retained carbon feedstock, analogous to that which arises in combustion but distributed within a complex physical matrix.

Solubilisation of ash may result in minerals becoming available to plants on addition to soil, although since phosphorus (as phosphate) is rapidly complexed with minerals in soil this may depend on scavenging directly from char by roots or symbiotic mycorrhizal fungi. In general, introduction of readily-available crop nutrients can promote mineralisation of organic matter, especially in marginal environments.

However, porosity and more specifically pore connectivity may control the release of soluble nutrients from char, making release progressive rather than instantaneous as may be the case in the solubilisation of combustion ash. This process could be associated with the mineralisation of condensed tars and oils that appear to block biochar pores (Fernandes et al., 2003).

## **Modification of soil pH**

The typically alkaline nature of biochar may increase microbial activity in acidic soils by increasing pH and with this, another source of 'priming' for the decomposition of pre-existing organic matter, although modification of soil pH may also increase plant productivity and thus the amount of carbon substrate added to the soil through roots and residues. Mass for mass, the value of char in pH modification may be up to one-third that of agricultural lime (Van Zwieten et al., 2010) and, at experimental rates, can increase soil pH by 1 unit.

## **Modification of soil physical characteristics**

Depending on the distribution of particle size in the soil, the rate and nature of biochar applied and the time since application, soil pore-size distribution and water holding capacity may be affected. Porosity in char may occur at a range of scales, which affects the proportion of water that can be retained, and equally the accessibility of held water and solutes to plants which can exert sufficient tension to extract the contents of macropores (0.1–30 µm diam) that may not drain naturally. Structurally sound pores of this dimension are abundant in fresh wood-derived charcoal (Brodowski et al., 2005a), and the connectivity of the relatively small number of larger pores has been investigated in three dimensions by tomography (Bird et al., 2008).

However, the fresh particle size of powdery charcoal created from grass feedstocks appears to be less than 50 µm (Janik et al., 1998), and weathered charcoal while generally found in larger fragments, also resides in this size range (Brodowski et al., 2006). In clayey soils particles may be less than 5 µm (Schmidt and Noack, 2000). During weathering, and particularly for char from woody substrate, the position of char fragments within the soil mineral matrix is likely to alter over time. The effect that this has on total porosity, accessible pores, and accessible surface areas has not been explicitly examined.

Nonetheless, while initially macro-porous it is established that the great majority of total porosity in wood-derived charcoal may reside in micropores of nm-size (Pignatello et al., 2006). Oils and tars could represent less stable components of biochar around which microbial activity could promote micro-aggregation, relevant to water infiltration, and resistance to water erosion. An apparent role for charcoal in aggregation in has been observed in field soils (Brodowski et al., 2006), although short term incubation with activated charcoal did not cause aggregation under controlled conditions (Watts et al., 2005).

## **Cation exchange capacity and sorption**

Progressive abiotic and biotic surface oxidation of charcoal results in surface proliferation of carboxyl groups and an increasing ability to sorb cations (Cheng et al., 2008a; Cheng et al., 2006), explaining high cation exchange in archaeological soils (Liang et al., 2006). Negative charge provides the possibility for reversible storage of available nitrogen (ammonium,  $\text{NH}_4^+$ ) relevant to soil-based  $\text{N}_2\text{O}$  emissions and nitrate leaching. A mechanism based on the dehydration of phosphate and charcoal has also been described for the adsorption of phosphorus (Beaton et al., 1960), which may explain the apparent impact of biochar on crop phosphorus uptake possibly aided by arbuscular mycorrhizal fungi (Lehmann and Rondon, 2006).

Charcoal has the capacity to sorb polar compounds including many environmental contaminants (Yu et al., 2006), particular PAH for which it may be the dominant sink in soils and sediments (Rhodes et al., 2008). The significance of biochar addition in removing contaminants from the environment depends on its capacity to fulfil this function relative to charcoal, the affinity (security and reversibility) of stabilisation, and the ultimate fate of both char and contaminants, and also the contaminants that it contains (Section 3.5).

## **Microbial activity**

The possibility that biochar catalyses breakdown of organic matter by providing microbial habitat alone is improbable, since microbial sustainable proliferation depends on a



replenishable source of accessible carbon substrate as well as nutrients. Provided that the majority of biochar carbon is highly stable, after an initial flush of mineralisation microbes that inhabit biochar pores will depend primarily on the indirect effects of biochar to obtain an enhanced supply of substrate. This could either be through the capture and retention of soluble organic matter otherwise lost to deeper horizons or watercourses, or through a change in loci of plant root activity. Increased plant productivity, however, should be reflected in increased exudation of carbon through roots, and the deposition of carbon from residues of above-ground growth. The complication that this adds to interpretation of field data has been highlighted by Major et al. (2010).

Many plants can form symbiotic associations with mycorrhizal fungi, whose filamentous hyphae provide an extension to plant roots which can enhance acquisition of both nutrients and water, at the expense of some metabolisable plant carbon. Although potentially limited by inoculum, soil chemical conditions and the abundance of exploitable nutrients are more likely to limit mycorrhizal proliferation in most circumstances. Reported promotion of mycorrhizal activity by biochar (Rondon et al., 2007; Yamato et al., 2006) could reflect utilisation of reversible stores of water and soluble nutrients, or exhaustible 'mining' of nutrients embedded in ash. Warnock et al. (2007) proposed a range of possible mechanisms.

## **4.2 Limitations of existing research base**

Until recently there have been no directed research programmes to strategically evaluate biochar for its function in soil. Much of the current understanding of the function of biochar rests on published data for charcoal, often in the context of natural systems and wildfire. For reasons highlighted in Chapter 3, the function of biochar in soil is strongly influenced by formation conditions, and charcoal may only provide an insight into some general principles of biochar function in soil. In addition to the problem of extrapolating from studies of charcoal, pilot- and commercial-scale pyrolysis may produce biochar that differs from the products of bench scale pyrolysis systems operating under ostensibly the same conditions. There is no existing research to evaluate char from gasification, which is likely to provide a function between that of biochar and ash from straight combustion.

There are very few pyrolysis reactors (or gasification plants) using organic feedstock operating at a commercial scale in the UK, and existing facilities may offer relatively little scope for researching biochar due to technical and logistical (as well as financial) constraints. A small number of projects exist at the planning stage, and several biomass gasification plants are under construction. However, such facilities have, and are being, designed for energy provision rather than for producing a biochar by-product with consistent properties. A relatively high degree of process control might be required to provide "bespoke biochar"; new reactors may need to provide close and possibly flexible control if use of the product in soil is contemplated.

The non-availability of specified biochar at an adequate scale has propagated considerable research effort around charcoal, as its most available analogue. Given the similar formation and chemical characteristics, charcoal in the natural environment provides a powerful tool to investigate the long term stability of biochar. However, the short term impacts of biochar may not be well represented in studies of old charcoal. This is in part because the feedstock can be quite different, and partly because the more complex composition of biochar is overlooked. Also, any labile components associated with the charcoal will have been mineralised prior to sampling.

Publication of research papers on topics related to biochar has risen rapidly since 2000. More than half of the papers assessed here have been published in or since 2007.

### 4.3 Categorisation of current literature

**Sediment or soil:** Early evidence for the stability of biochar arose from sediments studies, where charcoal is preserved under anoxic conditions in which decomposition proceeds inherently slowly (Masiello and Druffel, 1998; Masiello et al., 2002). Generally, this more established literature has been excluded here.

**Static or dynamic:** Static studies provide snapshot comparisons for a response variable at locations where a relevant soil (or other) variable differs e.g. presence or absence of vegetation burning history (Dai et al., 2005; Oros et al., 2002). In a dynamic experiment a 'treatment' is imposed, and change in response variables over a time period determined, or ideally their trajectory observed through intermediate measurement. Chronosequence studies are a variant of the latter that enable long term dynamics to be studied by using samples deemed comparable, aside from the point in history at which the (ideally singular) change or intervention occurred (Kimetu et al., 2008; Liang et al., 2009; Nguyen et al., 2008).

**Biochar or charcoal:** Natural fire contains an anoxic zone where biomass pyrolysis prevails over combustion. Natural fire yields low charcoal conversion rates in the range 0.1–5% (Forbes et al., 2006). Wildfire is typically brief and the peak temperature variable. Heating rate being rapid the conversion may be partial, superficial, or progressive and affected by vegetation moisture content. Wildfire and charcoal are significant considerations in the global carbon cycle, and now an established topic for research.

Much work on the dynamics of charcoal has been undertaken in this context, and laboratory studies have aimed to mimic wildfire carbonisation by exposing biomass to similarly brief, variable but generally low (ca. 350 °C) temperature and semi-oxic conditions, i.e. limited or partial restriction of air flow. Experiments with char produced with complete exclusion of oxygen, i.e. biochar as defined in this report, are much more limited and recent. Published research using char from commercial pyrolysis reactors rather than material produced in a laboratory-scale batch process are very scarce. Only eight studies categorised in Appendix 1 used pyrolysis char.

**Short term or long term:** The various functions of biochar listed may be manifest over different timescales and crucially the trajectory of these functions appears to be non-linear, and may not be entirely independent of other functions or the wider system (Figure 3.1). The average duration of the dynamic studies identified in Appendix 1, including those undertaken in field plots (but excluding long term chronosequences) was 11 months. Although the chronosequence approach has been employed to observe the development or demise of functions that change slowly over time (rather than emerge or decline rapidly at the start), few attempts have been made to short cut such change, other than by imposing favourable laboratory-imposed conditions.

**Gasification or fast or slow pyrolysis:** After oven drying plant biomass usually contains about 45% carbon by mass, and a few per cent mineral ash. Ash is broadly conserved, but the proportion of carbon that is retained is specific to the process. Combustion leaves trace amounts of carbon, gasification less than 10%, and pyrolysis typically 30–40% (Chapter 3). Ash includes key mineral nutrients such as phosphorus and potassium, other metals and a range of micro-nutrients concentrated by loss of total feedstock mass in the conversion process (Brewer et al., 2009). The nutrient value of the products differs markedly on a carbon-mass basis, but in terms of their value to crops will depend not only on rate of char application but on the physical accessibility of nutrients in the char to leaching, plant roots and mycorrhizal fungi. The production process and feedstock mineral content will also modify the pH of the char by-products, which tend to be moderately to highly alkaline.

**Feedstock:** Scanning electron microscopy of fresh charcoal and charcoal aged in the natural environment reveals a cellular structure resembling that of the woody feedstock from which it was derived, lignified cell walls of dead xylem cells. The structure of char from grass

and non-woody plant material is rarely reported, and similarly the structure of char produced from digested or composted materials.

**Tropical or temperate:** Under otherwise equal conditions (moisture, nutrient and substrate availability) biological activity increases with temperature. Consequently soils in the tropics tend to be depleted in organic matter and associated biological activity relative to those from temperate regions. In addition, soils that are very old have usually been subjected to extensive weathering and leaching and display low inherent fertility and are often acidic. Certain functions of biochar may be more or less conspicuous in such soils, so although all functions may be expressed at all locations, they will be more or less apparent. In field studies and controlled experiments, half of the research effort has been undertaken in regions with above 20°C mean annual air temperature, and only one-fifth in temperate zones below 10°C.

**Laboratory or field:** Laboratory conditions enable variables and functional attributes to be isolated or controlled, and the impact of climatic variation to be removed. Permutations of different factors are possible since the space and resource requirement may be relatively small and good replication is possible. The interactions between functional attributes of soil and biochar with the wider environment, such as fluctuations in rainfall and evaporation impacting leaching, soil structure and microbial community composition can only be assessed in the field. However, the rate at which processes proceed in the field is dictated by the ambient climate and cannot be manipulated. Spatial heterogeneity demands intensive sampling, whilst constraining design.

**Soil or soil with plants:** Plants provide a sink for soil nutrients, exert suction on soil pores, and secrete compounds and enzymes that mobilise nutrients and modify soil surfaces. The microbial activity that concentrates around plant roots may “prime” processes that would not otherwise occur, for example, the co-mineralisation of recalcitrant biochar and labile glucose (Hamer et al., 2004). However, the complex soil environment does not comprise such discrete components and plant-derived substrates are separated by the soil mineral matrix.

**Empirical (descriptive) or mechanistic (predictive):** Empirical studies identify statistical relationships between two or more test variables; mechanistic studies seek to understand the reason for such relationships. Mechanistic approaches should offer greater prospect for prediction of effects at other locations, being based on a fundamental understanding of the underlying process. Although technically more robust, mechanistic understanding may take time to acquire, and may still not be accurate, and both approaches require considerable validation especially where multiple variables or processes are involved (Figure 4.1).

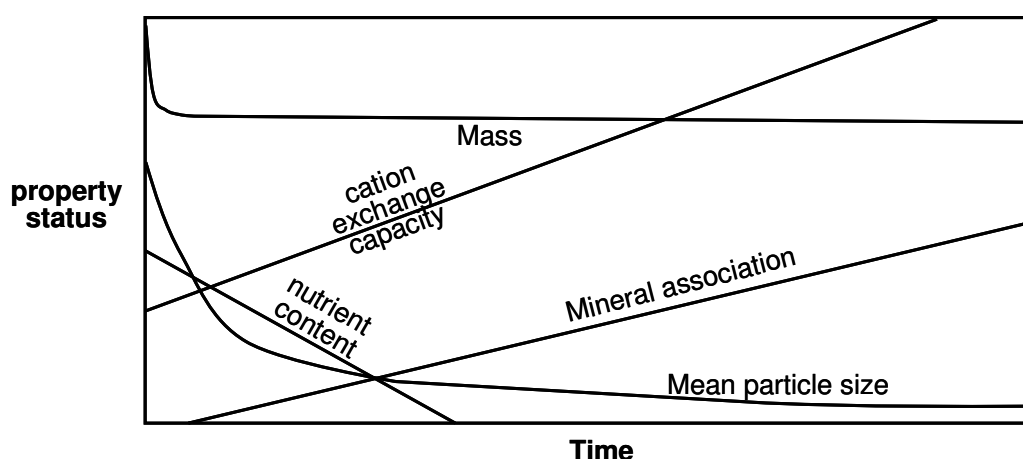


Figure 4.1: Schematic to illustrate the challenge of unravelling multiple functions of biochar whose possible trajectories strongly differ

#### 4.4 Extrapolation from studies of environmental charcoal

Given the basic similarity in formation and the relatively abundant literature, it is necessary to view biochar in the context of the existing understanding of charcoal, especially in terms of long term stability. To date, however, studies that compare char produced under a range of conditions, e.g. varying levels of oxygen exclusion, in terms of agronomy, mineralization or other parameters relevant to biochar deployment, are lacking. Until these studies have been completed the congruence in the properties of these materials remains uncertain.

**Does charcoal in soil constitute soil organic matter?** In the discrimination of more and less recalcitrant forms of organic matter in soil generally, the ratio of oxygen to carbon broadly decreases with age with progressive removal of oxygen through biological or chemical 'oxidation'. Charcoal has a characteristically low O:C ratio, while graphitic black carbon (the most stable form derived in combustion) is essentially elemental carbon. By comparison, charcoal and biochar are merely highly depleted in oxygen and hydrogen, containing groups that are strictly organic (most particularly aromatic forms), and part of the soil organic carbon pool.

**Can charcoal be distinguished from other soil organic matter?** Charcoal is particularly abundant in aromatic carbon that occupies a distinct position in the nuclear magnetic resonance spectrum for carbon ( $^{13}\text{C}$  NMR), displays a minor depletion in the abundance of the scarce carbon isotope ( $^{13}\text{C}$ ) relative to other compounds, and is characterised by certain biomarkers (so far, benzene polycarboxylic acid and levoglucosan have been most extensively evaluated). Charcoal is partially resistant to some chemical oxidants typically used to quantify total soil carbon (potassium dichromate), and both chemical and photo-oxidation have therefore been used to quantify it. However, none of these signals have proven entirely exclusive and the procedures for measurement are complex or slow. Because the functionally relevant level of stability is itself ill-defined or context-specific, the analytical separation of charcoal and 'ordinary' soil organic matter has yet to be perfected.

**What is the historic significance of charcoal in the global carbon cycle?** Models describing soil carbon in the agronomic or global change context consider a near-inert soil carbon fraction to correctly simulate response to altered climate or organic matter inputs, which being site-specific generally reflect, at least in part, contrasting abundance of charcoal in regions where wildfire is more or less frequent. The rate, extent, and completeness of conversion of biomass to charcoal in wildfire are highly variable. Nonetheless, making assumptions about such factors based on available evidence leads to estimates for a mean residence exceeding 1000 y (Lehmann et al., 2009). Charcoal is thought to account for 1–20% of organic carbon in soils, and at least 150 GtC of the global soil pool comprises charcoal or its more condensed or graphitic relatives, soot and elemental black carbon (Kuhlbusch, 1998). This implies that up to 150 Mt of carbon has annually cycled through the biosphere in the formation and degradation of charcoal-derived carbon.

**Are the impacts of biochar carbon analogous to those of soil organic matter?** Some properties of biochar, and specifically its impacts on physical soil properties, are also associated with bulk soil organic matter. It is not however, safe to assume that the mechanisms by which these are provided are identical, or that the impacts are equivalent in magnitude, direction or duration – and thus that biochar can provide a direct substitute for higher levels of other organic matter in soil. This is of practical importance since biochar is carbonaceous and thus not readily distinguished from organic matter using current techniques. This is analogous to the challenge of discriminating chalk and limestone from organic carbon in soil.

**Can impacts be predicted from ex-situ properties?** The ex-situ characteristics of organic matter and biochar are unlikely to be additive with respect to a soil's properties. For example, certain soil minerals (clays) have a high cation exchange capacity; although organic matter has higher specific exchange capacity mass for mass, binding between organic and mineral fractions shields exchange sites at the molecular-scale and reduces the

sum effect. At the moment, it is not completely clear whether interactions between char and mineral particles will occur significantly at this physical scale or primarily as discrete, disparate particles. Cation exchange capacity of biochar also appears to evolve over time, and it is likely that many other properties have a trajectory which is currently ill-defined.

#### **4.5 Evidence to address key questions around PBS**

##### **Biochar and contaminants**

In terms of human health and the food chain, the irreversibility of biochar addition is a key consideration. Existing soil amendments contain immobile components, albeit in less visible form and biochar inherits the potential risk posed by the feedstock that might otherwise be directly applied (See Chapter 6). However, the class of these compounds known to be formed in the charring process itself (polycyclic aromatic hydrocarbons, PAH) are process dependent. Without extensive evaluation of pyrolysis char it is difficult to assess the risk posed by PAH in PBS specifically, as most data available relates to charcoal.

Charcoal is generally produced at lower temperatures that might favour PAH formation, but vapours may combust rather than condense and could thus be eliminated. Levels of extractable PAH in charcoal are variable, but reported concentrations (Brown et al., 2006; Bucheli et al., 2004; Fernandes and Brooks, 2003; Rumpel et al., 2007) generally fall between those reported for urban and rural soil on mass basis (see Section 3.5). These compounds are persistent but ultimately degradable in soil (Creaser et al., 2007).

The effect of association with chars on rate of degradation of PAH, and the balance between rates of accumulation and release has not been systematically addressed. Concentrations of PAH in soils subjected to natural fire suggest, however, that degradation is in excess of sorption. The capacity of both activated and non-activated charcoal, typically as charcoal from or mimicking natural fire to adsorb PAH and other organic contaminants, has been relatively well assessed (Cornelissen et al., 2005; Zimmerman et al., 2004).

Since metals are broadly conserved in pyrolysis, the total metal content of biochar will be determined largely by the feedstock content and the yield of char. The higher the carbon content of the char, the lower will be the mass concentrations of metals. On a biochar mass basis, the metal concentrations in products from gasification where char yield is small (a few to ten percent) are likely to be up to ten-fold higher than in slow pyrolysis. Data on the availability of metals from charcoal or biochar in soil is lacking. However, the potential for pyrolytic char to remediate land contaminated by metal cations has been demonstrated (Wingate et al., 2009).

##### **Stability of biochar carbon**

About 60% of the literature evaluated in this assessment (Appendix 1) related to the stability of charcoal or to the quantification of char in soil (equally divided). Stability has been addressed both in real time observation, where sensitivity can be enhanced through isotope tracers (Bruun et al., 2008; Kuzyakov et al., 2009), or extrapolation from measurements of soils from systems routinely experiencing natural fire (Kimetu et al., 2008; Lehmann et al., 2008; Nguyen et al., 2008). In three cases the effects of biological activity enhanced by substrate addition has been investigated (Hamer et al., 2004; Kuzyakov et al., 2009; Liang et al., 2009). Only in one case has pyrolysis char been evaluated (Nguyen and Lehmann, 2009) and most often the feedstock has been wood-derived.

Inference from measurements on soils in systems subject to natural fire suggests millennial stability, and in extrapolation from controlled incubations (elevated temperature and optimal moisture) the general acceleration of mineralization (decomposition) that occurs in such systems has been noted and accounted for (Cheng et al., 2008b).

Newly formed char appears to contain a small biologically labile fraction (see below), alkaline pH (mean pH=8.5; ten studies), and nutrients available in ash from partial combustion

embedded in the residual matrix. Only in one published study is this labile fraction deliberately extracted prior to evaluation (Yanai et al., 2007). Allowing for these characteristics that may lead to non-linear carbon loss, other deficiencies in laboratory studies (simulation of natural char formation) and effects of induced changes in soil chemistry, the assumption of centennial to millennial stability does not appear unreasonable (Kuzyakov et al., 2009).

Experiments using newly formed charcoal have generally used particles <2mm diameter (with no minimum particle size), but it has been noted that the physical fate of charcoal is predominantly in fine fractions, broadly <50 µm (Brodowski et al., 2006) and that its physical diminution appears relatively rapid, presumably through physical weathering and abrasion. There appears to be substantial evidence for intimate mineral–char interaction which, it has been hypothesised, might guard against degradation; however, discrete char particles have been found to persist within free organic fractions over a period of decades (Murage et al., 2007).

The three studies available found no evidence for a role of tillage in the mineralisation of wood-derived charcoal (Brodowski et al., 2007; Kuzyakov et al., 2009; Murage et al., 2007). The single study that has explicitly examined the stability of pyrolytic char from wood and cereal straw suggested a slow and predominantly abiotic degradation which has been convincingly demonstrated for wood charcoal in a climosequence that confirmed the sensitivity of absolute rates of degradation to temperature (Cheng et al., 2008a).

Oxidative measures of various types feature in key methods used to quantify char in soil, but typically as part of a wider continuum of black carbon that extends (at the extreme) to soot, and with the objective of retaining all charcoal, rather than identifying more and less stable sub-components. However, the potential to develop artificial aging techniques to rapidly compare and evaluate biochar stability (relative to charcoal) appears to have been rather overlooked and could be useful in seeking greater certainty on this critical matter (Lehmann et al., 2009).

### **Labile biochar fractions**

Incubation of soil with manufactured or un-aged char typically results in higher CO<sub>2</sub> evolution than from the same soil non-char amended. However, the degree of excess declines over time in a strongly non-linear fashion in the short-term (Bruun et al., 2008; Nguyen and Lehmann, 2009). This suggests a ‘priming’ of decomposition of carbon, either of that already in the soil, or of carbon in the added char. Priming of existing soil carbon could be a consequence of the modification of the soil chemical environment (see below), while loss of carbon from biochar can result from the mineralisation of a labile char fraction. These patterns also suggest that priming is complex and that extrapolation of short-term decay rates will be unreliable; such rates are not consistent with the age of charcoal found in archaeological soils such as the *terra preta*. The parameters that govern the balance between labile and stable components are not yet fully understood.

### **Priming of soil carbon or biochar loss**

The potential for biochar, in the form of synthetic charcoal, to cause or accelerate the decomposition of pre-existing soil organic matter (priming) has been reported in medium-term study of litter layers in the boreal zone (Wardle et al., 2008). The loss of litter carbon was measured over a period of 10 y, but almost all the loss occurred prior to the first annual sampling. The litter into which charcoal was introduced was likely to be acidic and nutrient constrained, in which case the decomposition response is expected.

In Canada, and with the benefit of a carbon isotope trace, information on priming in tilled arable soil was obtained on a 65 y timeframe. This indicated that the MRT for particulate organic matter in soil increased by a factor of 2.5 at sites where charcoal derived from historic natural fire was present (Murage et al., 2007). Another study, also with a carbon isotope trace, suggested slower and less complete utilisation (high stabilisation) of organic

material added to soils from a tropical environment containing aged charcoal (Liang et al., 2010).

A single laboratory study (Hamer et al., 2004) showed an approximate doubling of charcoal degradation rates (charcoal priming) with the addition of glucose to soil, a compound often used as a simple analogue for the labile carbon exuded into soil by living plant roots. The initial rates of loss were still low – especially for higher temperature char created from wood and for an experiment conducted under optimal conditions in sand matrix – 0.5% over 60 d, which is a smaller proportion of charcoal carbon that might reside in a labile charcoal component. Quantitative extrapolation of such laboratory studies to the priming that might be likely to occur in the field, particularly give contrasting levels of microbial and plant root activity is difficult.

It has been noted that if priming of soil organic matter is a permanent function of charcoal, the amount of non-charcoal carbon present under equilibrium field conditions must be lower than in charcoal-free soils (Woolf, 2009). Available data does not support this, and the Amazonian *terra preta* are enriched in organic matter relative to the surrounding soils, as well as containing large amounts of aged charcoal. Due to climatic influences, the Amazonian soils are rather low in organic matter naturally. The likelihood of an analogous accumulation in UK soils amended with biochar is not certain given higher background soil carbon mineralization rates.

### **Biochar and soil nutrient dynamics**

Reported increases in crop yield with charcoal addition have precipitated a number of plot-scale field trials to evaluate impacts on soil fertility, mainly through crop grain or biomass yield, usually with some measure of nutrient uptake. Reviewing 19 relevant articles in the literature, none of the reported studies have been undertaken in temperate zones. As such, caution should be adopted in directly transferring knowledge gained from tropical environments to the UK context.

In the tropical environment the impacts have generally been positive, though most often in combination with fertiliser nitrogen. Less than one-third of these studies have used char application rates of less than 15 tC ha<sup>-1</sup>, however, and only three used pyrolytic char.

Substituting chemical fertiliser for the nutrients added into the soil as biochar has not resulted in the same increase of crop productivity as provided by biochar addition. In two cases where the effect of pH modification was controlled for by liming, the effect of char was still superior. This suggests that char might impact crop growth through its impacts on soil physical properties and / or on mediation of nutrient exchange between soil and plant.

In classic studies of *terra preta* fourth-season maize yields were much higher in plots amended with char and fertiliser than the non-fertilised and non-char amended control (Steiner et al., 2007). However, it is strictly incorrect to say that the effect of the treatments was to increase yield since the yields for all treatments displayed post-clearance decline, the control yields were ultimately very low.

Limited evidence under tropical soil conditions suggest that the addition of fresh charcoal can reduce nitrogen leaching loss. Soils with higher and long-established charcoal content had enhanced nutrient status but leached extra added nitrogen (Lehmann et al., 2003). There is a relatively large amount of consistent evidence for the partial surface oxidation of char by chemical and biological processes in soil, and proliferation of carboxyl groups (Lehmann et al., 2005). It appears that this is reflected in the cation exchange capacity of aged charcoal and charcoal-rich soils, but not shown in new char. Plot scale experiments indicate that the uptake of other nutrients may be enhanced by charcoal, in particular phosphorus as ash in charcoal may be more available than phosphate in the soil.

Since biochar has a high carbon-to-nitrogen ratio, it is likely that rapid mineralisation of a labile carbon fraction could – by immobilisation – contribute to a draw on soil mineral

nitrogen, in addition to an effect of ammonium sorption, and potentially reduce crop nitrogen supply. Evidence for this effect is relatively abundant and consistent in the literature, but the effect depends on the status of indigenous soil mineral nitrogen and these studies have been undertaken exclusively in the tropics.

Immobilisation tends to enhance soil nitrogen supply to the crop in the longer term, since microbial proliferation builds a reservoir of mineralisable nitrogen. In field studies of charcoal or biochar extending beyond a single season this effect may be observed, where second- or subsequent-season (but not first-season) are elevated relative to non-amended controls.

### **Biochar and emission of nitrous oxide and methane from soil**

A single peer-reviewed study reports suppression of nitrous oxide emission from soil from charcoal (Yanai et al., 2007); however, in the light of the importance of N<sub>2</sub>O emissions in UK agriculture, and emerging evidence reported in recent studies, the effect warrants further attention. A plot-scale experiment using char from the commercial pyrolysis of maize straw biochar under temperate conditions has been initiated in the USA. Results from planted fields in Columbia showing a large positive effect are unpublished (Rondon et al., 2005), as are three studies showing conflicting outcomes in laboratory studies using soils from Australia (Rogovska et al., 2008; Rogovska et al., 2009) and New Zealand (Clough et al., 2008). Laboratory studies used high rates of application (Spokas et al., 2009; Yanai et al., 2007), single soils (Condrón et al., 2009), or single types of charcoal, with no results for pyrolysis biochar.

Nitrous oxide is emitted mainly by specific groups of bacteria which under anaerobic conditions reduce nitrate rather than oxygen (nitrate to N<sub>2</sub>O via nitrite and nitric oxide). Emission of N<sub>2</sub>O at low rates may also occur under aerobic conditions, from the activity of chemotrophic bacteria converting mineralised organic nitrogen (ammonium) to nitrate. Higher soil organic matter increases nitrification, but the application of nitrogen fertiliser has a greater immediate impact on soil nitrate concentrations and hence N<sub>2</sub>O emission.

Proposed mechanisms for biochar suppression of N<sub>2</sub>O revolve around modification of soil water dynamics, e.g. drawing soil solution and dissolved nitrate into inaccessible pores (small pores saturating first) and maintaining aerobicity in inhabited pore space; increase of soil pH which under anaerobic conditions favours completion of nitrate reduction to N<sub>2</sub> from N<sub>2</sub>O; or the adsorption of ammonium and its protection from nitrification and denitrification (Clough et al., 2008; Condrón et al., 2009; Yanai et al., 2007).

The effect of water addition cannot be completely evaluated under constant conditions, but Yanai et al. (2007) found suppression was reversed when water-filled pore space was increased from partial to near-complete saturation. In the same study (Yanai et al., 2007) the addition of combustion ash to the soil, separately from charcoal, did not suppress emission. Simultaneous monitoring of N<sub>2</sub> is required to confirm N<sub>2</sub>O reduction. In conference proceedings, Nitrate has also been reported to accumulate where N<sub>2</sub>O is suppressed (Van Zwieten et al., 2009).

### **Mobility of char**

Biochar and charcoal fines have a low bulk density of approximately 300 kg m<sup>-3</sup> against a typical soil bulk density of 1300 kg m<sup>-3</sup>. Particles may be very fine in size and in addition surfaces may be hydrophobic (DeLuca and Aplet, 2008). Collectively these characteristics indicate a higher potential for lateral transfer in water than for other soil components (Rumpel et al., 2006) and applied at a high rate in tropical environments subjected to frequent intense rainfall, erosion of charcoal off-site has been measured in proportions up to 25% in two years (Major et al., 2010), and most of the 66% loss calculated by Nguyen et al. (2008) in 30 y after surface deposition was attributed to erosion.

Negligible longer term losses (Nguyen et al., 2008) and low rates of movement apparent for natural charcoal in a temperate environment (Murage et al., 2007) suggests a rapid decline



in hydrophobicity, physical breakdown, and development of association with mineral particles (Brodowski et al., 2005a; Glaser et al., 2000; Spycher et al., 1983). The ‘anchoring’ of particles within the soil matrix at depth may be critical in limiting erosion. The apparent combustion of fire-derived char in dry regions where material remains at the surface between fires (Czimczik et al., 2005; Ohlson et al., 2009) emphasises the role of incorporation into deeper soil in ensuring longevity in the natural environment, and that in more biologically active soils this must therefore occur. However, measured rates of transport into subsoil appear to be slow (Major et al., 2010).

Meanwhile, studies of the global cycle of the ‘black carbon’ have established the existence of significant flux from land to ocean at a macro-scale (Crutzen and Andreae, 1990; Masiello and Druffel, 1998; Seiler and Crutzen, 1980). Little literature has addressed the process of transport of char through the environment, although it has been noted that PAH is high in organic matter dissolved in alkali extracts after natural fire (Kaal et al., 2008b).

### **Char, soil water dynamics and irrigation**

In large quantities wood-derived charcoal modifies soil physical properties. It has a low inherent bulk density of 0.3–0.5 t m<sup>-3</sup>, which is one-third to one-fifth that of typical UK arable soil. Depending on particle size distribution of the char relative to that of the soil and the extent to which added char may locate within existing pores, higher experimental rates of application could directly reduce soil bulk density and increase soil volume. This affects water holding capacity and water filled pore space, but declining hydrophobicity and the effects of weathering on particle size will determine the duration of this effect. In the experimental context, water holding capacity is measurably increased by adding fresh charcoal and must be considered in the design of laboratory soil incubations (Liang et al., 2009). Studies of amended soils can be adjusted for either equal gravimetric water content, or to equal tension (depending on the hypothesis). Water storage could be of critical value, yet the factors that determine the efficacy of char in this context have not been clarified.

Published evidence (Bird et al., 2008) for the effect of biochar on pore size distribution, however, is remarkably scarce. Some assessments have been made, and the problem appears to be in the level of replication required to demonstrate significant effects using methods best used in comparison of different soils. One study (Gaskin et al., 2007) has reported water holding capacity of soils amended at low, medium and high rates with pyrolytic char; one study has focused solely on pore size characteristics of charcoal and pyrolytic char (Bird et al., 2008); and one has measured the impact of charcoal residues on water holding capacity at old kiln sites (Oguntunde et al., 2008).

### **Summary**

The evidence for the function of biochar in soil is based largely on evidence from studies of charcoal, and predominantly in the tropical environment. Triangulation of existing knowledge with systematic studies of biochar produced using relevant technology and feedstocks relevant to viable UK systems is needed, and techniques to rapidly assess long term stability.

## 5 APPLICATION TO SOIL

*Jason Cook and Saran Sohi*

The collection and incorporation of biochar into agricultural soils is a logistical and technological challenge that has not been explored in great detail, and is in need of innovation. Key stages in this “application” of biochar are: (i) preparation for application in terms of particle size, density and water content, etc., (ii) transportation from storage to the soil surface, and (iii) its physical incorporation into the top and deeper soil.

The existing literature concerning techniques for the addition of biochar into different systems is scarce to date. Very little experimental or developmental field work has been done, particularly in relation to the use of biochar in commercial farming operations. This section of the report outlines a range of practical techniques for applying biochar and the factors to be considered depending on the agricultural system concerned.

### 5.1 Relevant factors

The following factors influence the appropriate methods and techniques for the application of biochar to soil:

- a) The physical properties of the biochar, namely its specific gravity, bulk (effective) density, particle size (as a mechanical consideration and in terms of a health issue, i.e. the dust fraction)
- b) The physical constraints of the cropping system to which biochar is applied, e.g. field scale row crops versus raised bed horticulture or soft fruits, tillage regime and phases in a mixed rotation.

In reality, the mechanical equipment available to the farmer and its cost-structure will also impact on the techniques that can be employed by a particular enterprise. By integrating application into the normal agricultural timetable, e.g. immediately before a ploughing, harrowing, disking or drilling operation in arable systems, the incorporation incurs fewer additional costs.

### 5.2 Methods of application

Particle size is a key consideration in determining the equipment suitable for application of biochar to soil, and to control the potential for exposure to dust. Biochar from fast pyrolysis is inherently dusty (particle size 100  $\mu\text{m}$ ), and some applications would require agglomeration. Conversely, experience with charcoal fines suggests that coarse products from slow pyrolysis of resistant materials (woody biomass such as arboricultural arisings) could present a significant challenge in terms of preparing particles of a consistent size, probably best dealt with at site of production.

The requirement for consistency of biochar particle size is currently unclear, though it is likely that commercial PBS would necessitate greater uniformity. One possibility already explored is pelleting, and brittle pellets appear to break-up fairly readily in soil. Although this would add to the costs of biochar production, technologies for preparing materials to a consistent size, using grinders and rollers, etc, are well-established. Handling of biochar during transportation and application needs to be properly managed, and application and period immediately after is viewed as bearing the greatest risk for run-off and wind erosion. A key consideration is avoidance of nuisance and human exposure to risk from dust, etc.

Experimentation with charcoal and biochar at the plot scale has relied on mainly quantitatively precise application methods (e.g. hand-spreading) that do not inform appropriate practice at field-scale. Depending on the volumes handled, the nature and precision of pre-treatment (such as grinding or adjustment of moisture content) may not be

practical at the farm scale. Since most work to date using charcoal fines, there is also limited experience with handling pyrolysis char.

Conventional application of fertiliser involves broadcasting, pneumatic and liquid systems. Injection technologies developed for slurry allow insertion of slurry at depths of 5–10cm, and similar approaches could be used for biochar. By these methods and using existing machinery, biochar addition could be best facilitated using the following techniques: uniform topsoil mixing, incorporation with other mediums (manure, composts, liquid manures and slurries), deep banded in rows, topdressing, specific site application and potentially addition to animal feed (Van Zwieten et al., 2009).

The challenge of spreading fine texture biochar from fast pyrolysis using conventional equipment has been documented in a practical demonstration to arable land in Canada using an agricultural spreader designed to apply lime to a swath of approximately 10 m width. Dust emissions during the application were a potential nuisance with 25% char lost from the target application area even in calm weather conditions (BlueLeaf, 2009).

Field-scale work using a 1.2 t fertilizer spreader to apply coarse charcoal fines to arable land in Scotland did not pose such issues, indicating that disking or harrowing can satisfactorily incorporate biochar in tilled systems with minimal potential for surface erosion by wind and water, at least on level land (Figure 5.1).<sup>3</sup> The fines used in this demonstration had been pre-treated by the addition of water to overcome this, albeit at the expense of increased haulage mass. The effect of such treatments must be taken into account in the refinement of estimated transport and spreading costs, and associated life-cycle carbon emissions.



Figure 5.1: Spreading charcoal fines using a fertiliser spreader

It is not documented in published or grey literature whether biochar has been applied to grassland, though footage of successful straightforward application of biochar (from poultry litter) to grassland using a muck spreader has been publicised<sup>4</sup>. Whilst the combination of biochar and management of slurries in livestock systems has been discussed in the research context, liquid application of biochar does not appear to have been tested. In this scenario, addition of porous biochar to predominantly aqueous slurry might be applied at low marginal costs, with some possible handling and odour related benefits over slurry alone.

In the case of the incorporation of biochar into grassland soils, grass sward should be effective in trapping airborne particles if they arise. Non-permanent grasslands which are reseeded (typically every 4–5 y) would allow for biochar integration with planned management activities. Biochar could be applied to the surface of permanent grasslands as is the case for other applications, for example, of fertilisers. Incorporation into soil is expected to be slow compared to mechanically incorporated char, and cattle would need to be prevented from grazing for perhaps the same period as post-application of other slurry.

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<sup>3</sup> Cook J, University of Edinburgh

<sup>4</sup> Publicity material on the website of the International Biochar Initiative

In intensive horticultural systems, where the crop is grown in bags, pre-mixing of biochar and soil is conceivable. Where crops are grown in rows such as many root vegetables, there is clear potential for deep banded application of biochar as seed potatoes, for example, are planted. Mechanical application of biochar in forest or woodland would be practically limited to the window between clear felling and planting. The potential to combine the application of biochar with establishment of energy grasses or coppice crops has been recognised, and its use in these systems is the subject of ongoing UK research (McNamara, 2009).

### 5.3 Technical constraints

Larger lime spreaders have a capacity of about 30 m<sup>3</sup>, which equates to approximately 12 t biochar. This suggests that up to 2.5 loads ha<sup>-1</sup> for a 30 t ha<sup>-1</sup> rate of application. Many enterprises would bear the cost of such application as a contracted operation, as for routine liming which is a similarly occasional practice. It is indeed possible, that to some extent, biochar application may substitute for liming, offsetting part of an existing cost.

Based on existing experimentation with charcoal fines, the incorporation of biochar into cultivated soils should be relatively straightforward, with simple disking removing significant potential for wind erosion or surface run-off. However, incorporation of biochar quite soon after application is likely to be necessary to minimise potential problems.

### 5.4 Economic Constraints

Several regimes for biochar deployment can be envisaged: e.g. an initial application at a high rate, followed by regular (not necessarily annual) applications in order to maintain shorter-term effects (e.g. up to 30 t ha<sup>-1</sup> initially, 5 t ha<sup>-1</sup> thereafter, e.g. every 5 y). An alternative would be annual low-rate applications that resulted in a gradual building of biochar soil concentrations until appreciable benefits are attained (e.g. 1–10 t ha yr<sup>-1</sup>).

The return on the former strategy might be more rapid, but over a smaller area with a greater financial outlay, and potentially greater logistical challenges; intensive trafficking on the soil also presents risks for soil structure. The latter may provide slower accrual of soil benefits, but the up-front costs are less, and existing farm machinery could be used for deployment of biochar, possibly on a more *ad hoc* basis.

In reality, the availability and price of biochar, and the hours committed to its application, will determine the amount of material applied in a year, and this may be spread thickly or thinly. There may be logistical advantages of one over the other in terms of distance travelled, and the desire to evaluate crop response on treated areas will likely favour thick application. The logic of targeting 'problem' areas will favour a high rate of application, although the risks of multiple machinery passes during application may mitigate this through compaction.

Several different models for production and distribution of biochar can also be envisaged. Small-scale systems based on one or a few farms would source biomass, and distribute biochar, locally, utilising existing machinery. A larger-scale PBS would likely envisage sub-contractors who would apply the biochar onto a farmer's fields and incorporate into the soil, and also arrange for collection of the residues for charring. Economies of scale of logistics, transportation and storage capabilities would be the key driver for large-scale PBS.

### 5.5 Outlook

The collection, storage and incorporation of biochar into agricultural soils present logistical and technological challenges. Most of the methods discussed are well understood as they have been integral parts of agricultural practice for some time. The development of machinery for large-scale contractor-delivered application could require technical innovation, and might emerge over time, and in the interim there might be scope for relatively simple modification or retro-fitting of existing machinery.

## 6 REGULATION<sup>5</sup>

*Simon Shackley and Colin Cunningham*

There are a number of areas of regulation that are potentially relevant for a pyrolysis-biochar system (PBS). In terms of regulating biochar as a product, the control of soil amendments varies greatly depending upon whether the amendment is regarded as a waste or not; and, if so, whether it is exempted from Environmental Permitting. It is important, therefore, to establish whether the biochar is a waste or not and whether it could be used under a Waste Management Licence exemption.

Regulation of the production of biochar depends on the scale of the plant, technology used and the feedstock being processed. If the material that is being pyrolysed is considered to be a waste, the provisions of the Waste Incineration Directive (WID) may then apply to the process. If certain categories of food waste were used as a feedstock, animal by-products regulations would also apply. Farmers will be concerned about meeting the requirements of farm assurance schemes or standards, and also with potential concerns from supermarkets; effective regulatory systems will allow such concerns to be managed.

The regulatory regime in the UK is complex, and most of this chapter relates to regulation in England and Wales only, with a brief mention of Scottish regulation towards the end. Regulation of biochar is a highly specialist, cross-cutting topic. Biochar developers, and researchers wishing to undertake field trials, are strongly advised to contact the relevant regulatory organisation for detailed advice (Environment Agency in England and Wales, Scottish Environmental Protection Agency in Scotland, and the Northern Ireland Environment Agency in Northern Ireland). The complexity and ambiguity of the legal framework in the EU as it applies to biochar has recently been analysed by Van den bergh (2009) providing a more specialist treatment of some of the issues addressed in this Chapter.

### 6.1 Is biochar a waste?

Depending on what is done with the biomass, and whether it is discarded or required to be discarded, will determine if it is a waste or not. More specifically, the identity of the biochar as a waste will depend upon: a) the identity of the material from which the biochar is produced; and b) the thermochemical process by which the biochar is produced. A starting point is that any material that is generated through the thermochemical conversion of a waste material is itself likely to be a waste. If the input material is not a waste, whether or not the biochar is a waste depends upon whether the biochar is intentionally discarded or not. Article 1(1)(a) of Directive 2006/12/EC on Waste defines waste as: 'any substance or object in the categories set out in Annex 1 which the holder discards or intends or is required to discard'. The Environment Agency has further clarified that: "anything which is discarded or otherwise dealt with as if it were waste, shall be presumed to be waste unless the contrary is proved" (Van den bergh, 2009).

The distinction between biochar as a product or as a production residue is critical in deciding whether biochar is classified as a waste. Biochar is a product if it is the result of a technical choice of the manufacturer to deliberately produce it. Van den bergh (2009) comments that: "Although there are reasonable arguments that biochar may develop as a product in the future, it appears at the moment that biochar constitutes a production residue since the primary aim of the pyrolysis process is often to generate bio-energy rather than to produce a specific type of biochar." A material that is subject to a recovery operation does not necessarily constitute waste. In at least one case, the determination of waste depended

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<sup>5</sup> Jonathan Atkinson and Matthew Davies of the Environment Agency, and Peter Olsen of SEPA, are thanked for their help in writing this chapter.

upon whether the holder intended to discard the material; hence, the definition of waste may depend upon the intention of the holder (Nash, 2009). In practice, it has been very difficult to demonstrate that a discarded material is not a waste, as discussed in more detail below.

## 6.2 Virgin- and non-virgin biomass resources

In this report virgin biomass is defined as that derived from whole plants and trees or from the processing of virgin biomass (where that does not involve chemical or biological transformation, amendment or treatment). Biochar produced from non-virgin biomass resources, e.g. construction and demolition waste (CDW), municipal solid waste (MSW), refuse-derived fuels (RDF), slurries, bedding matter, manures, sewage and paper sludge would be regarded as wastes. Biochar produced from virgin biomass resources (e.g. wood chips, straw, coconut shells, peanut shells and rice husks) would only be regarded as a waste if they were intentionally discarded. If the biochar is being produced to supply a market, and is not being discarded, it is not a waste by this definition. This might conceivably apply to the intentional production of biochar for agricultural application from virgin biomass resources utilising dedicated pyrolysis plants; however, only when a regulator is faced with a specific proposal could such a matter be decided.

Article 5 of the **revised EU Waste Framework Directive** (WFD) (Directive 2008/98/EC) allows for a material to be defined as a non-waste by-product where: (i) use of the substance or object is certain; (ii) the substance or object can be used directly without any further processing other than normal industrial practice; (iii) the substance or object is produced as an integral part of a production process; and (iv) further use is lawful.

Van den bergh (2009) notes that the four criteria under Article 5 are accumulative and interpreted narrowly. With regards to the first point (certainty of use), Van den bergh (2009) writes: “If the storage of biochar exceeds the normal storage that a specific type of soil can store, the storage of biochar is likely to be a dumping operation which makes the superfluous biochar waste. It should also be noted that the characteristics of the soil should meet the characteristics of the biochar and that if these do not meet or vary significantly, the storage of biochar is likely to be an act of discarding”. It is unclear how ‘normal storage’ would be defined here, in terms of what is stored (soil organic matter, soil carbon, etc.), how it may be defined against a historic baseline, and how the characteristics of biochar and soils would be matched (which characteristics, and how to measure these).

Regarding the second point (direct use without further processing other than normal industrial), the European courts have ruled in one case that: “if an additional recovery process is required before further use, even if such subsequent use is certain, this is evidence that the material is a waste until the process has been completed” (ibid.). In similar vein, UK Circular 11/94 states that the requirement for a specialised recovery operation is a reasonable indication that a substance has been discarded as a waste”. Consequently it appears as if “a recovery process is not a normal industrial practice. ... the biochar cycle entails different stages of recovery .. and ... the pyrolysis process is likely to constitute a ‘recovery operation’. Biochar can consequently not be a non-waste by-product in the EU” (Van den bergh, 2009).

Turning to the third criterion, production as an integral part of a production process: “It appears that there are reasonable indications that biochar will not be an integral part of the biomass energy production in the pyrolysis process since biochar leaves the pyrolysis plant in order to undergo a further processing, i.e. underground storage, and at least somebody – the producer – has discarded it” (Van den bergh, 2009). In summary, it looks unlikely that biochar could be defined as a non-waste by-product under existing EU law.

Article 6 of the WFD provides criteria for establishing when a material considered to be a waste ceases to be a waste. Such a material must have gone through a recovery process and the reclassified material must comply with four conditions: (i) the substance or object is commonly used for specific purposes; (ii) a market or demand exists for such a substance or

object; (iii) the substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and (iv) the use of the substance or object will not lead to overall adverse environmental or human health impacts. Biochar would not easily qualify at present under Article 6 since it is not currently commonly used and there is no existing market and there is insufficient knowledge of the technical requirements for specific purposes. Complete recovery is required for a waste to become a non-waste substance. Under one interpretation, material can only cease to be waste if it is: “chemically and physically identical to the original material” (Van den bergh, 2009). This is not feasible in the case of biochar, however, because of the thermochemical conversion the feedstock undergoes during pyrolysis. More analysis of the interpretation of Article 6 of the WFD with respect to biochar can be found in Van den bergh (2009). The precise interpretation of the definitions of wastes, non-wastes and by-products has yet to clearly emerge, especially in the context of biochar. Past experience suggests, however, that making an end of waste case is difficult (Olsen, 2009).

### 6.3 Regulation of pyrolysis as an industrial process

There are three types of permits for biochar production facilities under the Pollution Prevention Control (PPC) regulations (SI2000/1973, as amended by SI2001/503)

- (1) Over 50 MW electricity generation scale: authorisation directly by the Secretary of State (or equivalent in Scotland);
- (2) Between 3 MW and 50 MW electricity, subject to Part A1 permit, authorised by the Environment Agency (England & Wales), SEPA (Scotland), NIEA (Northern Ireland);
- (3) Under 3 MW electricity capacity, subject to Part A2 or a Part B permit, administered by the Local Authority.<sup>6</sup> Activities involving pyrolysis and carbonisation are covered by the description given in Section 1.2 A(1)(j) of Schedule 1 of the PPC Regulations<sup>7</sup>.

Thermochemical processing of a waste may also be regulated under the terms of the Waste Incineration Directive (WID) (Directive 2000/76/EC). The WID imposes much tighter controls on emission limits of a range of pollutants than if the facility is regarded as a power plant. Some wastes are exempt from full WID requirements, however. This includes vegetable wastes from agriculture and forestry and other categories of bio-waste.<sup>8</sup> Hence, pyrolysis of virgin biomass resources may not fall under the provisions of the WID; whilst pyrolysis of non-virgin biomass resources probably would fall under its provisions.

The WID is applicable to any facility which thermally processes non-exempt wastes, whether it be via gasification or pyrolysis. Operators can, however, be exempt from the WID, even for wastes, provided that: “the purpose is the manufacture of products with no resulting release of combustion gases. Therefore, if gasification or pyrolysis plant produces a number of products, one or more of which are subsequently burnt, then the WID applies to the whole plant. In cases where the products are burnt away from the gasification or pyrolysis plant

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<sup>6</sup> A plant with a capacity of one tonne or more per hour will be regulated under Part A2. A plant with a capacity between 50 kg and 1 t h<sup>-1</sup> is regulated under Part B. Incineration of all hazardous wastes are regulated under Part A.

<sup>7</sup> Paragraph (j) specifically excludes activities making charcoal with the phrase “otherwise than with a view to making charcoal”. In a similar manner, the activity description given in Section 5.5 A(1)(a) of Schedule 1 of the PPC Regulations also specifically excludes activities making charcoal with the phrase “other than charcoal”.

<sup>8</sup> Namely, vegetable wastes from food processing (if the heat is recovered), fibrous vegetable waste from pulp making (provided this occurs on site of waste generation and heat is recovered), and wood waste (with exception of that which has been treated with halogenated organic compounds, heavy metals or other preservatives or coatings). (SI 3538, Environment Agency Position Statement 005, 2008).

(remote units), the WID will apply both to the plants initially producing, as well as subsequently using, these products” (Defra, 2009c). To clarify: “Pyrolysis and gasification plants that dispose of all their products and residues without incineration (for example by landfill or use as raw materials in other processes) would not be covered by the WID” (Defra, 2009c).

In reality, it is unlikely that there would be no combustion of the bio-liquids or syngas from a pyrolysis or gasification plant, since this is likely necessary for obtaining a sensible energy balance and economic case for such a plant. Therefore, it is unlikely in reality that pyrolysis or gasification of wastes would be exempt from the WID.

The WID imposes inter alia a limit of 3% organic carbon in ash or a limit of 5% Loss on Ignition for the ash. The original purpose of this requirement (along with a limit on Carbon Monoxide emissions) was as a measure of the 'completeness of combustion'. Whilst such a measure is reasonable for a combustion plant, its application to substoichiometric processes such as gasification and pyrolysis is arguably inappropriate and presents a significant technical challenge. This is a particular issue if the intention is to produce biochar which, by definition, has a high carbon content.

Where syngas and bio-oils are produced from a WID-regulated process, the co-combustion of these by-products in a separate power plant would also be a WID-regulated process. The control of NO<sub>x</sub>, CO and volatile organic compounds (VOCs) from gas engines and gas turbines can be difficult, and the removal of CO emissions from flue gas requires expensive catalytic converters or thermal oxidisers (Anon, 2004). Similar considerations of air quality issues apply to biochar production as to any process capable of producing particulate matter including PM<sub>10</sub>s.

**Small-scale pyrolysis of biochar**, e.g. on a farm, might be regulated through a Part B permit for emissions to air.<sup>9</sup> There are provisions for exempting waste combustion from requiring a waste disposal permit, though this depends on the scale and types of waste being combusted (paragraphs 3 and 5, Schedule 3, SI.3538). There is the possibility of excluding experimental plants from the requirements of the WID where they are being used for R&D to improve upon the incineration process. However, this only applies where less than 50 t y<sup>-1</sup> waste are treated.

#### **6.4 Regulation of biochar application to soil**

If the biochar is deemed to be a waste, then biochar cannot be applied to soils under the terms of the Environmental Protection Act 1990, unless a permit has been granted. The detailed regulations are set out in The Environmental Permitting (England and Wales) Regulations 2007 (SI 3538). If biochar is not a waste, then it can be applied to soils without a permit, though the Environment Agency still has regulatory powers under its pollution prevention role to step-in and stop a polluting activity. In the case of biochar, since there is no specific legislation directed at protection of soils, an alternative legislative mandate would be employed for the purpose (e.g. the Water Resources Act 1991 where there is an adverse risk identified to surface or ground water). In the case of wastes, the relevant objectives of the Waste Framework Directive to avoid risks to the air, water, soils, animals and plants, must not be breached. This provides the regulator with a wide-ranging power to prevent a polluting activity that arises from an inappropriate waste application.

#### **Nitrogen and Nitrate Vulnerable Zones**

Given the anticipated biological recalcitrance of biochar and the predominance of the carbon over nutrient elements, the trajectory of nutrient release from biochar is likely to be different

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<sup>9</sup> If the activity consists of manufacturing charcoal from wood it may not require a permit under Part A or Part B, though an operator should contact the Local Authority about this matter. In this report, biochar has been defined so as to exclude charcoal and charcoal fines.



compared to that from fertiliser, ash, manure, or crop residues. However, since Nitrate Vulnerable Zone (NVZ) regulations are based on total content (addition of nitrogen exceeding 250 kg is not permitted) application of biochar at 10 t ha<sup>-1</sup> (and much less when produced from manures) would breach NVZ limits if the ratio of carbon to nitrogen in biochar was 40:1 or lower, and at more realistic higher ratios (e.g. 80 or 200:1) it would still seriously limit the application of other nutrient sources. As noted in Chapter 4, charcoal can immobilise nitrogen at least in the short-term, which would pose further constraint through the additional crop demand for nitrogen. Hence, the amount of biochar that could be added (without or without a permit) could be limited in NVZs and the regulations may need to be looked at again with respect to available and non-available nitrogen in biochar.

### **Biochar is not an Exempted Substance under Environmental Permitting Regulations**

It is not necessary to obtain a permit for an exempt waste operation, but the activity still needs to be registered with the Environment Agency. There are two general areas of exemption. One concerns waste for the benefit of land, including addition to agricultural land (paragraph 7, Part 1 of Schedule 3); the other to land reclamation or improvement (paragraph 9, Part 1 of Schedule 3). The detailed tables under both paragraphs 7 and 9 in SI.3538 of exempted kinds and sources of waste do not include biochar. In addition, biochar is not an exempted substance under the Environment Agency Regulatory Position Statement (MWRP, 2008). Therefore, it would be necessary for an applicant to obtain a permit to apply biochar to agricultural soils or for land reclamation or improvement. If biochar *were* an exempted waste, it would still be necessary to demonstrate that it has benefits to agriculture or results in ecological improvement. Providing evidence for the agricultural or ecological improvement benefits of biochar is important in establishing a case for its streamlined regulation; there is insufficient research in the UK context to demonstrate this case at the current time.

### **6.5 Biochar application and movement from site of application**

A permit or exemption applies to application at a defined spatial location, and thus movement of biochar beyond site boundaries could infringe permit or exemption conditions. Transport of biochar into surface water courses could represent pollution of controlled water and measures such as the method and timing of application will need consideration. Similarly, migration of wind-blown biochar would need to be minimised. As noted above, the Environment Agency has a general pollution prevention duty and power to protect the environment and to act upon cases of detriment to amenity (e.g. under the EPA 1990 and WFD). It could use this power to respond to unforeseen and potentially adverse environmental impacts of biochar (such as excessive dust, or water pollution). Control of the timing and conditions of biochar application will be important in the prevention of pollution. Well-developed protocols exist with respect to applying slurries and sludges to different types of land (e.g. with respect to grazing and cropping of arable and grassland). The Safe Sludge Matrix (ADAS, 2001) is a good model for regulators in developing protocols and best practice for applying biochar.

### **6.6 Health and safety issues**

Pyrolysis or other biochar production methods should not raise any unique health and safety issues and the Health and Safety Executive (HSE) does not anticipate that expanded use of such technologies requires much change to regulatory practices (HSE, 2006). However, there are several potential issues that need to be evaluated. For example, some types of biochar may be at risk of accidental ignition and therefore care needs to be taken in how they are stored and transported (Major, 2009). Under certain conditions, and if the feedstock has a high silica content, pyrolysis might result in the formation of crystalline particles. Inhalation of crystalline silica is associated with silicosis and relevant precautions would be required to minimise exposure. Consideration of human health impacts from inhalation of

small particulates would also be required during handling, transport and application (Collison et al., 2009).

## 6.7 Possible contaminants in biochar

Polycyclic aromatic hydrocarbons (PAH) are by-products of fuel-burning and occur in oils, tars and coal. They are of concern because some compounds have been shown to be carcinogenic, mutagenic and/or teratogenic (Lerda, 2009). A range of charcoal and biochar samples have been investigated with respect to the USEPA's list of 16 PAH; benzopyrene is of particular concern. From current evidence, it appears that biochar produced from virgin biomass resources contain lower concentrations of these PAH than typical urban soils in the UK. Higher levels of PAH have been measured in biochar produced from MSW, suggesting that processed and amended materials such as wastes may be problematic sources of biochar (Jones, 2009). There is currently no clear consensus on which technique(s) to use in assessing the PAH concentration of biochar.

Some biomass feedstocks contain high levels of metals and (some of) these are likely to remain in the biochar. If pyrolysis of biosolids increased the availability of heavy metals such as cadmium, copper and zinc (Chan and Xu, 2009) this would be of concern and limit application of such biochar material. A number of charcoal and biochar samples from virgin biomass resources have been tested for metal concentrations at UKBRC, including from sycamore, rice husks and rubber tree. The detectable metal concentrations were determined to be lower than the acceptable limits as set out for composts in PAS100 and in The Sludge (Use in Agriculture) Regulations (1989), S.I. 1263. However, even compost meeting the PAS100 standard must comply with application and testing requirements as there is the potential for accumulation of potentially toxic elements in soil. In the case of a biochar sample produced from a non-virgin woody feedstock, content for some metals (including zinc, chromium, copper and mercury) were found slightly above PAS100 permissible levels, though PAH levels were similar to those found in charcoal from virgin woody feedstock, and lower than levels in carbonised rice husks.

A number of existing regulatory frameworks, protocols and codes of good practice provide useful ways forward with respect to biochar. The Code of Practice for the Agricultural Use of Sewage Sludge (1989) considers metal concentrations in both the waste and the receiving soils and only application to a 'ceiling' level (in  $\text{kg ha}^{-1} \text{y}^{-1}$ , or over a longer time-horizon) is countenanced. The Quality Protocol for the Production and Use of Quality Compost from Source-Segregated Biodegradable Waste (WRAP & Environment Agency) evaluates not only metal contaminants in the compost and in the receiving soil but also physical materials. The MBT compost-like outputs (CLOs) code-of-practice currently under development by the Environment Agency is considering a range of physical, chemical and biological properties, including total nutrients, readily available N, organic C, organic matter, C:N ratio, stability, potentially toxic metals and metalloids, organic pollutants (polychlorinated biphenyls, dioxins and furans, PAH), and microbiological properties. This analytical suite could provide a useful and precautionary set of methods and indicators for consideration of biochar.

The Environment Agency is also developing a more systematic approach to risk assessment through the development of Soil Screening Values (SSVs), defined as: "concentrations of chemical substances found in soils below which there are not expected to be any adverse effects on wildlife such as birds, mammals, plants and soil invertebrates, or on the microbial function of soils" (Merrington et al., 2008). SSVs are at an early stage of development and elements for which values are available include cadmium, chromium, zinc, copper, lead and nickel. The limits are generally more demanding than for the above-mentioned Codes of Practice and PAS 100. A value is also provided for benzo(a)pyrene, toluene and few other organic substances. If the concentration of a chemical is found to be above the SSV, a further investigation should be undertaken to examine whether there are any ecological risks.

## **6.8 Food safety and assurance schemes**

A potential barrier to biochar use in the agricultural sector relates to issues of traceability and food safety. There are no anticipated adverse impacts to food crops from biochar use and utilisation of agricultural wastes would contribute to low-carbon food chains. Quality assurance schemes such as Scottish Quality Cereals and the Assured Produce Scheme (APS) would likely produce best practice guidance on biochar production and use for producers taking into account different feedstocks and application rates. Consideration will also need to be given to potential issues related to subsidy e.g. through the Single Payment Scheme (SPS).

## **6.9 Implications of existing regulation for biochar deployment**

From a regulatory perspective, biochar is more likely to be developed and used if the following issues are borne in mind.

### **Use virgin biomass resources and technologies which avoid the requirements of the Waste Incineration Directive**

Meeting the requirements of the WID would render the technology prohibitively expensive. An Environment Agency position statement states that where used as a fuel "...wood not contaminated with halogenated organic compounds or heavy metals (resulting from treatment with wood preservatives or coating) are excluded from the WID requirements" (Environment Agency, 2008a).

### **Use materials and technologies which avoid classifying biochar as a waste**

Avoiding the 'waste' tag would help deployment of biochar within agriculture since it would not then require an Environmental Permit or exemption. There are provisions under the Waste Framework Directive for re-classifying waste as a non-waste or for defining a by-product. In reality, there are numerous regulatory and legal issues and challenges which need to be addressed in making such a case for biochar.

### **Where biochar is classified as a waste, develop a Standard Rule**

At the present time it is likely that much biochar production would be classified as a waste. This does not imply that biochar could not be utilised, but rather that it would need to be regulated through obtaining an Environmental Permit. The uncertainty associated with this regulatory process, and the potentially high cost, could be off-putting to a developer. One way forward is through the creation of a Standard Rule, which is provided for under Chapter 4 of the Environmental Permitting (England and Wales) Regulations 2007. Standard Rules allow a standard permit to be provided, which simplifies and streamlines the regulatory process for waste materials to be approved for application. The Environment Agency is currently consulting on the replacement of some existing exemptions with Standard Permits. Hence, the general direction of policy in England and Wales is towards formalisation of (at least some of) the exempted materials.

Standard permits for waste materials require an assessment of the agricultural benefits to land (up to 50 ha). Value is deemed to be recovered from applied wastes through nutrient recovery (e.g. nitrogen and phosphorus), soil conditioning benefits (e.g. enhanced organic carbon content), and replacement of chemical inputs (e.g. lime, chemical fertilisers). Once application is deemed to be recovery, not disposal, the Environment Agency then assess the risks to water, air, soils, plants and animals under the Waste Framework Directive's Relevant Objectives. Provided the application does not breach the objectives of the WFD with respect to avoiding environmental harm, the permit can be granted.

## **6.10 Development of a biochar standard or protocol**

A single standard for biochar similar to PAS100 for compost could be developed, also drawing upon the MBT CLO analytical suite currently under development by the

Environment Agency. As well as providing limits for allowable concentrations of metals and organic compounds, the standard would require controls on input materials, processes and extends to labelling. There may be benefits to developing a wider quality protocol (as produced for compost) as some biochar will be made from waste materials and such protocols give clarity on when the material has been fully recovered and is no longer waste.

### **6.11 Development of research applications of biochar**

In England and Wales, researchers can submit a proposal to the Environment Agency's Low Risk Panel where their intention is to undertake experimental trials using biochar. The Agency has issued a Regulatory Position Statement that sets out the conditions under which the Environment Agency will consider allowing experimental trials to go ahead without requiring an Environmental Permit, or an exemption from a permit (Environment Agency, 2008). This mechanism may be appropriate for undertaking biochar field trials, although the Environment Agency will need to undertake an assessment of appropriateness on a case-by-case basis.

### **6.12 Regulation in Scotland**

Scotland does not have environmental permitting and waste spread on land would be regulated under Schedule 3 of the Waste Management Regulation 1994 as amended ([http://www.sepa.org.uk/waste/waste\\_regulation/application\\_forms/exempt\\_activities.aspx](http://www.sepa.org.uk/waste/waste_regulation/application_forms/exempt_activities.aspx)). The controls under Regulation 17 relate to certain conditions being met in order for the activity to be exempt, which includes the requirement that the activity must not endanger human health or harm the environment by: presenting a risk to water, air, soil, plants or animals; causing nuisance through noise or odours; or adversely affecting the countryside or places of special interest.

SEPA has provided criteria for evaluating agricultural benefits from applying wastes to land which include: a) assessment of N, P and other plant nutrients in the waste relative to that in the soil; b) effect of organic matter addition on water retention, porosity, stability, tilth and workability; c) assessment of the pH of the waste and of the soil; and d) effect of the waste on levelling uneven land. Meanwhile for ecological improvement, regard is to be had for the maintenance and support of otherwise degraded habitats, the creation of new habitats and restoration of an old habitat.

The distinction between Part A and B of Pollution Prevention Control exists in Scotland. A pyrolysis plant with a capacity of less than 50 kg h<sup>-1</sup> feed for non-hazardous waste would be exempt. For plants 50–1000 kg h<sup>-1</sup>, Part B applies. For all hazardous waste facilities (of any size), and for non-hazardous waste facilities of over 1 t h<sup>-1</sup> feed, Part A will apply. These are generic conditions only; the precise nature of the permit would rest with the local licensing team which would consider all aspects of the installation.

### **6.13 Summary**

Despite the potentially relatively low risks posed by most types of biochar to human health or the environment, the current situation lacks clarity and would benefit from a position statement agreed by all UK regulators. It is complicated by the need to consider regulation of the production and also of a variety of potential end uses for biochar. These need to be proportional to any risks to human health and the environment and there will need to be distinctions made between potentially lower-risk biochar from virgin biomass sources and that from non-virgin biomass (waste) derived biochar. More information is required on the properties and behaviours of different chars to better understand potential risks and allow appropriate levels of regulation. The quality protocol approach used for wood, recovered aggregates, compost and other lower-risk materials could provide an excellent starting point for this. Consideration should also be given to suppliers' quality schemes for crops, and livestock fed on crops and grassland where biochar has been applied. A supportive

regulatory framework will give confidence to producers and buyers and ensure there are no barriers to widespread biochar use (assuming that biochar can be shown to be beneficial and without adverse risks). Another potential avenue for regulation would be to develop a matrix governing application of biochar to agricultural land similar to that used for treated sewage sludge.

## 7 MONITORING, VERIFICATION, ACCOUNTING AND REPORTING

*Saran Sohi, Sarah Carter and Simon Shackley*

Monitoring, verification, accounting and reporting (MVAR) is necessary in order to ensure that: a) the claimed-for properties of biochar are realised (and / or better understood); b) what is claimed to have happened does actually happen and is properly accounted for; c) there are no adverse impacts arising from biochar utilisation; and d) the impact of biochar on other indicators is properly understood. The research and development community will need to undertake monitoring in order to further knowledge and provide information on techniques that can be employed more widely. The stability, fate and impacts of biochar will need to be monitored at long-term experimental and benchmark sites. A key objective will be to validate the predicted trajectories for stability and other properties predicted from laboratory and controlled environment studies. If predictability for such trajectories can be established, the intensity and precision of deployment monitoring required for biochar carbon verification and accounting could be relatively low, or rest primarily on verification of application of a specified, certified, product rather than its actual presence in the soil. Developers and regulators will need to develop MVAR capabilities that are accurate, cost-effective, practical, and accord with best practice.

### 7.1 Techniques to determine the black carbon content of soil

Despite an extensive and coordinated effort in a ring-trial (Hammes et al., 2007), no strong consensus on a universal, practical method for quantification of biochar in soil has emerged. In part, this is because there has been a desire to discriminate black carbon in all its forms from non-pyrogenic carbon, i.e. by the origin of the material, rather than according to their stability in soil. As a consequence, some methods seek to include fractions of pyrogenic carbon whose chemical composition and stability overlaps with the more stable (also carbonaceous) components of heavily transformed soil organic matter. Different quantification approaches operate at different levels of precision. Some methods are correlative or proximate approaches typically based on spectroscopic data. Others are oxidative approaches that seek a gravimetric quantification based on progressive oxidative removal. Finally, there are methods that seek to quantify supposedly universal molecular markers for pyrogenesis, rather than the entire pyrogenic product.

Biochar is chemically complex and difficult to distinguish from historic and naturally present forms of black carbon present in soils including charcoal, coal and bituminous coal in areas around coal seams and carboniferous sediments (Glaser and Knorr, 2008). Key current techniques for estimation of char in soil are summarised in Table 7.1. The techniques vary in their ability to accurately discriminate black carbon quantity and type in soil, and many are inconsistent (Simpson and Hatcher, 2004a), with different results emerging from the same soil samples and feedstocks (Manning and Lopez-Capel, 2009). Most experimental work has been done on developing methods; these methods have not been used widely in dynamic studies.

In the selection and development of methodologies for *deployment* monitoring, a compromise in precision, cost and frequency must be made. In general, deployment monitoring strategies should be low cost and reproducible, use readily available technology, and not require a high level of expertise for consistent application at diverse sites. High frequency monitoring using field-based spectroscopic methods could meet these requirements, and therefore help to reduce project cost. Comparative accuracy is required at the project stage, rather than the quantitative accuracy demanded for research purposes. Site-specific sensitivity is also less important if site-specific reference land is available. However, as yet there is no agreement on the most appropriate techniques for deployment monitoring of biochar.

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- 1 Determination of solvent-extractable aromatic compounds as benzene polycarboxylic acids (Brodoweki et al, 2005) or other biomarkers (e.g. Elias et al, 2001)
  - 2 Chemo-thermal oxidation at 375 °C followed by elemental analysis of the residue (Gustafsson et al, 1997; Gélinas et al, 2001; Gustafsson et al, 2001)
  - 3 Chemical oxidation using acid dichromate (Song et al, 2002) or sodium hypochlorite followed by elemental analysis of the residue by <sup>13</sup>C nuclear magnetic resonance (NMR) analysis (Simpson and Hatcher, 2004a, 2004b)
  - 4 Thermal/optical laser transmittance or reflectance (a method used for airborne particulates; Huang et al, 2006)
  - 5 UV-photo-oxidation of the sample followed by <sup>13</sup>C NMR analysis of the residue (Skjemstad et al, 1996, 1999).
  - 6 Thermogravimetric analysis of the sample under flowing He<sub>80</sub>O<sub>20</sub> (Lopez-Capel et al, 2005; Manning et al, 2008)
- 

Table 7.1: Key methods for quantifying biochar in soil  
Source: Manning and Lopez-Capel (2009)

## 7.2 Monitoring the stability of biochar

The viability of biochar as a means of carbon abatement relies greatly upon its stability (see Chapter 8). Benchmarked sites provide a means to validate and refine (but not develop) predictions of longevity for diverse environmental contexts – land-use type, soil organic matter content, soil texture, crop rotation, soil tillage, rainfall, and temperature regime – but not permutations for different levels of each factor. Benchmark sites can also be used to evaluate laboratory quantification methods, and for cross-referencing with emerging field applicable tests.

## 7.3 Routine soil monitoring

As noted in Chapter 4, impacts to soil arising from the addition of biochar may differ qualitatively, quantitatively and temporally from those associated with other organic carbon, in part according to their comparative level of stability. A large addition of biochar could potentially double the carbon content of many UK soils. Routine measurement techniques do not discriminate biochar soil organic matter, and monitoring locations receiving periodic addition of biochar are likely to show an increase that could mask an underlying decline in soil organic matter content. In an Australian example, charcoal from prescribed annual burning of sugarcane resulted in an increase in soil carbon, but an underlying decrease in soil organic matter compared to the prior land use (Skjemstad et al., 1999).

The National Soils Inventory<sup>10</sup> for England and Wales in its second partial re-sampling measures pH, soil organic carbon and carbon to nitrogen ratio; Natural England's five-yearly Countryside Survey<sup>11</sup> measures an extended range of variables that encompass biodiversity, but at a smaller number of sites. Similar soil surveys are conducted in Scotland by the Macaulay Land Use Research Institute. If the objective of monitoring is to establish the general trend in microbially available organic matter, analytical techniques discriminating atypical levels of black carbon would be required. If biochar use became widespread, however, it would be possible to resolve the issue by reference to a national record of biochar application, or a requirement to prevent biochar application at these sites (or at least to require appropriate monitoring of black carbon). This suggests that part of any regulatory system for biochar would require farmers and land-owners to maintain a record of biochar application to identified land-areas.

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<sup>10</sup> <http://www.landis.org.uk/data/nsi.cfm>

<sup>11</sup> [http://www.countrysidesurvey.org.uk/work\\_packages\\_4.html](http://www.countrysidesurvey.org.uk/work_packages_4.html)),

## 7.4 Monitoring for incorporation in the UK Greenhouse Gas Inventory

Biochar production and use has potential implications for three of the six Kyoto greenhouse gases, namely: CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> (UNFCCC, 2008). The UK National Inventory Report (NIR) is submitted as a voluntary submission to the United Nation's Framework Convention on Climate Change (UNFCCC). The inventory is compiled in accordance with the Inventory Reporting Guidelines agreed by the UNFCCC Conference of Parties at its eighth session (COP8), and set out in document FCCC/CP/2002/8 (Jackson et al., 2008).<sup>12</sup> The inventory is updated annually with the capacity to incorporate new methodologies where required (Jackson et al., 2008). However, any change to the NIR has to comply with the UNFCCC reporting guidelines on annual inventories.<sup>13</sup>

The UNFCCC uses a three-tiered approach in constructing a NIR: tier 1 (generic activity data), tier 2 (technology specific emission factor) and tier 3 (detailed and nationally-specific). There is an increase in complexity and accuracy in the data required in going from tier 1 to tier 3. A combination can be used where data, or resources required to gather data, are not available (Eggleston et al., 2006). The Intergovernmental Panel on Climate Change (IPCC) has provided guidance on quantifying NIR uncertainties and these can be large (up to 20%) for non-CO<sub>2</sub> gases (IPCC, 2001).

Inclusion of biochar in the NIR would require some changes to existing methods and data collection; however, some of the direct and indirect effects of biochar do not require a separate approach or methods from those already in place. Table 7.2 summarises the areas of the inventory which PBS would have an effect upon were biochar to be included in the NIR. For emissions related to energy, transport, fertilisers and waste management, there would be no need to change existing methods or data collection, which would capture changes in greenhouse gas fluxes due to PBS. Under the regulations for Agriculture, Forestry and Other Land Use (AFOLU), existing land-use would be reported under 3B1a (forests), 3B2a (cropland) and 3B3a (grassland) (Eggleston et al., 2006), whilst changes in land-use, and consequent GHG fluxes, would also be reported. The detail of the land-use regulations distinguishes between the following carbon equivalent stocks: above-ground biomass, dead organic matter and soil carbon and non-CO<sub>2</sub> emissions from crop residues (Eggleston et al., 2006).

A new category would be required in the NIR to account for stabilised carbon in the biochar. It would also be necessary to have a method for accounting for changes in flux of CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> due to the presence of biochar. The key category principles for NIR propose that tier 1 is appropriate for non-key sources, meaning sources that are not large or where the trend is not rapidly changing. At the current time, biochar is not a recognised source (of abatement) and hence a tier 1 approach could be appropriate until such time as biochar becomes more widely and rapidly deployed. The method for constructing a tier 1 approach for biochar is not yet available due to scientific uncertainties regarding the properties of biochar and its interaction with the receiving soil. As the R&D community continues to develop better ways of characterising biochar with respect to indicators such as the CSF, MRT and the impacts on soil organic matter, it should be possible to define specifications for biochar which would allow a tier 1, 2 or 3 method to be adopted.

A tier 1 approach might simply account for the stabilised carbon in the biochar over a defined project timescale. Biochar producers, importers and exporters would be required to submit a 'stabilised carbon return', which would contain information on the quantity of stabilised aromatic carbon imported, produced or exported, according to standards or specifications. The NIR would record such stabilised carbon as a new category within the inventory.

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<sup>12</sup> <http://www.ghgi.org.uk/> This is the UK Greenhouse Gas Inventory, 1990 to 2007.

<sup>13</sup> FCCC/CP/2002/8 and Decision 18



Energy (including transport) (CRF sector 1)	Savings from avoided emissions due to energy generation and any transport fuel changes. Under current practice, pyrolysis of biomass would be regarded as a 'carbon neutral process'. It would not therefore be necessary to include the CO <sub>2</sub> emissions from pyrolysis, or from the subsequent use of bio-oil and syngas derived from pyrolysis, in the energy sector part of the inventory. Change in transport requirements would be accounted for in changed use of fuels at the national level and would not, therefore, be separately accounted for.
Industrial Processes (CRF sector 2)	Emissions from the pyrolysis process are already accounted for through fuel and materials consumption.
Agriculture (CRF sector 4)	Fertiliser, feedstock production and avoided degradation of the feedstock, or burning of feedstock. Any reduction in fertiliser use through use of biochar would be accounted for in the reduced consumption of fertiliser in the national accounts. Hence, it is already accounted. The same applies to any change in the diesel fuel used to drive farming equipment, machinery and vehicles.
LUCF (Land Use Change and Forestry) (CRF sector 5)	Land conversion for dedicated biochar crops from other land-use types are included
Waste (CRF sector 6)	Diverting feedstocks out of waste streams will alter this sector, for example diverted organic waste from landfill will potentially lead to reduced methane emissions from landfill.
<b>Future considerations for integrating biochar into the UK GHGI</b>	
LUCF (Land Use Change and Forestry) (CRF sector 5)	Carbon stored in the biochar, added to soil Stable carbon in the biochar added to soil
Agriculture (CRF sector 4)	Biochar and its interaction in the soil; reduced nitrous oxides and methane.

Table 7.2: Components of the UK greenhouse gas inventory relevant to biochar  
Note: Categories are from Jackson et al. (2008)

## 7.5 Timeframe for analysis of biochar carbon abatement

An important policy question concerns the appropriate time-horizon for evaluating the carbon abatement potential of biochar. If the time-horizon is 100 y, then carbon abatement from biochar will appear much higher than if the time-horizon is, say, 500 y, because some of the recalcitrant carbon will probably have mineralised to CO<sub>2</sub> between year 100 and year 500. There is, in other words a seepage of recalcitrant carbon to atmospheric CO<sub>2</sub> on a centurial to millennial timescale. Perhaps the key uncertainty for biochar as a form of long-term carbon storage is uncertainty over the precise value of this seepage rate. For some forms of carbon mitigation, a 100 y timeframe or even less is commonly regarded as appropriate for climate policy analysis, and GWPs for comparing different greenhouse gases are typically calculated on a 100 y timeframe. Where carbon or carbon dioxide is being stored, however, and there is a risk of some of that carbon or CO<sub>2</sub> seeping back into the atmosphere, then it has been argued (Shackley and Gough, 2006) that a multi-centurial time-scale may be more appropriate than 100 y given model results indicating that the CO<sub>2</sub> concentration in the atmosphere remains high even when emissions have been radically reduced (Solomon et al., 2009). In other words, if a large percentage of the stored carbon returns to atmosphere within 100 y, then CO<sub>2</sub> could be being added at a time when greenhouse gas concentrations are already at a dangerous level – simply making the problem of climate change worse within the next century.

A similar debate has taken place within the context of CO<sub>2</sub> Capture and Storage (CCS). The IPCC Special Report on CCS provided a judgement that: "...the fraction retained in appropriately selected and managed geological reservoirs is very likely [probability between

90 and 99%] to exceed 99% over 100 years and is likely [probability between 66 and 90%] to exceed 99% over 1000 years” (IPCC, 2005). This represents an annual seepage rate of between 0.01 and 0.001% per annum, or 100% loss over 10,000 to 100,000 y. Note that these numbers do not attempt to provide an appropriate or acceptable measure of seepage, but rather approach it from the perspective of what is probable given judicious selection of sites and best practice. It is not necessarily the case that biochar should aim to achieve the same seepage rate as this, therefore, but it does strongly indicate the need for more debate, clarity and methodological development on this vital issue.

## **7.6 Regulatory monitoring**

Monitoring would probably be undertaken of activities involving biochar by EA, SEPA and NIEA in fulfilment of statutory pollution prevention responsibilities. This may include monitoring of: feedstocks, production, handling, transport and application, total nitrogen and phosphorus content, silicates content, PAH and metal contaminants, wind- and water-borne erosion from the application site and potential environmental sinks (water systems, sediments, etc.). As discussed in Chapter 6, the use of standard rules, specifications, quality protocols, and the like, will reduce the required monitoring intensity.

Establishing the contaminant or non-nitrogen nutrient content of soils or soil amendments depends for either conceptual or practical purposes on “available” rather than total content. Most analytical techniques require a liquid sample and depend on partial solubilisation, either by leaching (“extraction”) with salts or solvents, dissolution with acids or alkali, or prior ashing. With the exception of elemental contaminants (metals), this may result in artefacts through modification of the target compounds. Char has a resilient aromatic structure that results in low yields of extractable PAH, and a challenging analytical matrix that remains resistant to hydrofluoric acid used to dissolve soil minerals. The apparent contaminant content may be enhanced by “accelerated extraction”, but whilst falling short of providing true content, it exceeds that which could conceivably become available in the soil. It is likely that for widespread application of biochar, analytical protocols that draw on experience from other regulatory areas, such as sewage sludge, will need to be established.

## **7.7 Monitoring for carbon credits**

The requirement and rigour of methodologies proposed to determine carbon credits differ according to the markets in which credits might be traded (Voluntary, Clean Development Mechanism, etc.). This report is not the appropriate place for a detailed analysis of the issues surrounding inclusion of biochar into carbon markets, a topic that is currently being intensively debated in response to a proposed methodology for biochar under the Voluntary Carbon Standard (VCS) (Carbon Gold, 2009). This methodology proposed that the stability of biochar can be assessed as a function of the volatile to fixed carbon ratio: namely, if biochar contains less than 50% volatile carbon the total mass of biochar can be considered to be inert. This assumption has been strongly criticised and is not based upon any good scientific evidence.

Central to acquiring any carbon credit is clear establishment of the baseline against which the project is to be compared. A project also has to demonstrate ‘additionality’ – the carbon credit should make a project economically-viable and carbon credits should generally not be allocated to projects that are already financially-viable.

### **Credit on biochar transfer**

Most simply, a credit for the stable carbon fraction of biochar could be issued at point of sale or application. Limited monitoring would be required, specifically for the amount of biochar added to the soil. Unless a CSF has been directly established for the biochar in question, a conservative (generic) CSF would be applied to calculate saleable credit. The simplicity renders a low transaction cost, excluding complexity (e.g. conferred by soil type and soil processes) whilst excluding indirect or incidental CO<sub>2</sub>eq gain. It may also be possible to

define a laboratory-based “threshold” assurance system in which products with a minimum proportion exceeding a critical stability level would receive certification. The threshold would be carefully defined to ensure long-term stability, even under conditions that are relatively favourable to degradation (Lehmann et al., 2009). No additional monitoring would be required for biochar that has been certified, with carbon markets insuring against the residual uncertainty.

Simply accounting for the amount of biochar added to the soil, however, may be insufficient assurance given the scale of the existing scientific uncertainties. Furthermore, the possibility of biochar eroding-off site cannot be precluded (though it should still remain as stabilised carbon in receptor sinks). There is also a risk that biochar may be diverted for combustion in some circumstances. To verify incorporation of biochar into soil, or to assess the amount of biochar carbon in a soil, an analytical technique that can discriminate biochar from the soil matrix and other soil carbon, and quantify the biochar component, is likely to be required.

### **Credit on soil management change**

In some voluntary carbon markets, carbon credits can, in principle, be assigned for a net change in soil carbon associated with a permanent change in management. This might be extended to include the addition of biochar. Since some of the changes in soil organic matter evolve over time, while the amount of biochar added to soil over a given time period would be recorded, the credit could be based on the measured change in total stabilised soil carbon that emerges, or on the basis of a change that is predicted using a system underpinned by a model that deals with underlying changes in soil organic matter at a high resolution, including the dynamics and interactions of biochar. The system would accommodate emerging empirical understanding of the impacts of biochar, e.g. on the emissions of methane and nitrous oxide from amended soils, as well as on the CSF (Gaunt and Cowie, 2009).

### **Credit on direct soil monitoring**

Net reduction of GHG emissions can be directly assessed as the difference between “with” and “without” biochar management (Carbon Gold, 2009). This approach has been adopted in a proposed Voluntary Carbon Standard (VCS) for biochar. This undoubtedly provides a thorough and direct assessment for overall CO<sub>2</sub>eq gain, but is intensive in measurement and administrative terms. The proposed VCS methodology suggests that the percentage composition of the biochar should be analysed a minimum of four times a year using standard test methods, with pyrolysed material considered inert if the ratio of volatile to fixed carbon is less than 50% (Carbon Gold, 2009).

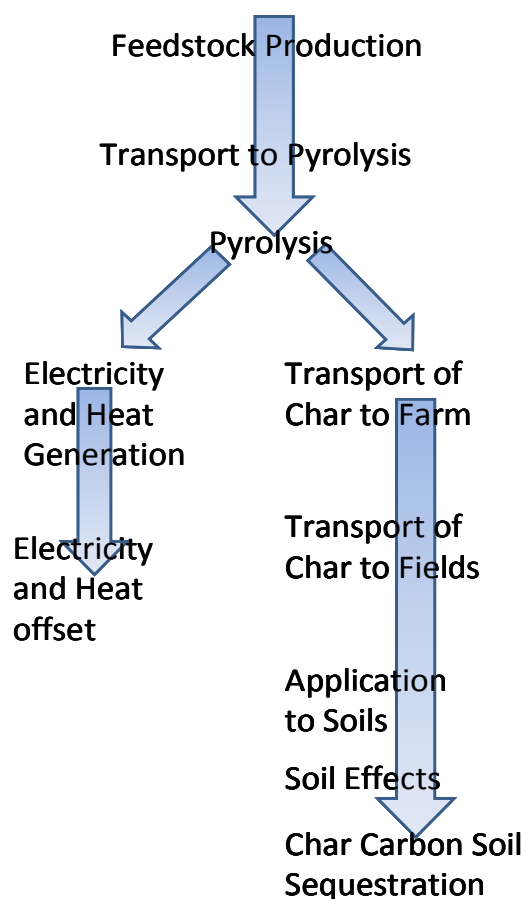
## 8 LIFE CYCLE ASSESSMENT

*Jim Hammond, Rodrigo Ibarrola, Simon Shackley, Saran Sohi, Peter Brownsort and Patricia Thornley<sup>14</sup>*

The focus of this chapter is the carbon abatement (CA) and carbon abatement efficiency (CAE) of PBS. The main units used as measures of abatement are kg CO<sub>2</sub> t<sup>-1</sup> o.d. feedstock; kg CO<sub>2</sub> MWh<sup>-1</sup> electricity and/or heat delivered, and kg CO<sub>2</sub> ha<sup>-1</sup> land. A schematic for LCA methodology is shown Figure 8.1, and in more detail in Figure 8.2. A detailed list of the technical assumptions is available at: [www.biochar.org.uk](http://www.biochar.org.uk).

The CA and CAE of major feedstocks outlined in three supply scenarios (Table 8.1) are examined. The LCA approach is attributional rather than consequential LCA (Brander et al., 2008), with the exception of the fossil-fuel offset through renewably-sourced electricity and heat, where the usual convention of including offsets in calculating CA has been followed. The analysis for virgin feedstocks assumes that 30 t ha<sup>-1</sup> biochar is applied to agricultural soil in the first year, and that this is supplemented with 5 t ha<sup>-1</sup> biochar each subsequent 5 y. The time horizon used is 15–20 y.

### Life Cycle Stages



**Methods:** The LCA tool is built from three different components.

A) For the greenhouse gas emissions associated with the production, transportation and distribution of biomass to the factory gate, BEAT2 was used, a bioenergy LCA tool developed by the EA, AEAT and Northern Energy Associates (AEA, 2008). A separately developed Excel-based LCA tool developed for the EPSRC Supergen consortium was also used. Information on feedstocks was derived primarily from Supergen and other sources, although modified for the special circumstances of biochar.

B) The slow pyrolysis plant was modelled separately, based upon an extensive literature review (Chapter 3). Carbon and energy balances were calculated for a range of technologies and operating assumptions.

C) The biochar to soils element was modelled using estimates in the literature and by expert elicitation.

Figure 8.1: Overview of Life Cycle Assessment stages modelled

<sup>14</sup> Contributors: Jim Hammond (virgin biomass resources), Rodrigo Ibarrola (non-virgin biomass resources), Peter Brownsort (pyrolysis model), Simon Shackley (integration and writing), Patricia Thornley (advice, feedstocks) and Saran Sohi (soil model input). The detailed analyses are in Hammond (2009), Ibarrola (2009) and Brownsort (2009)

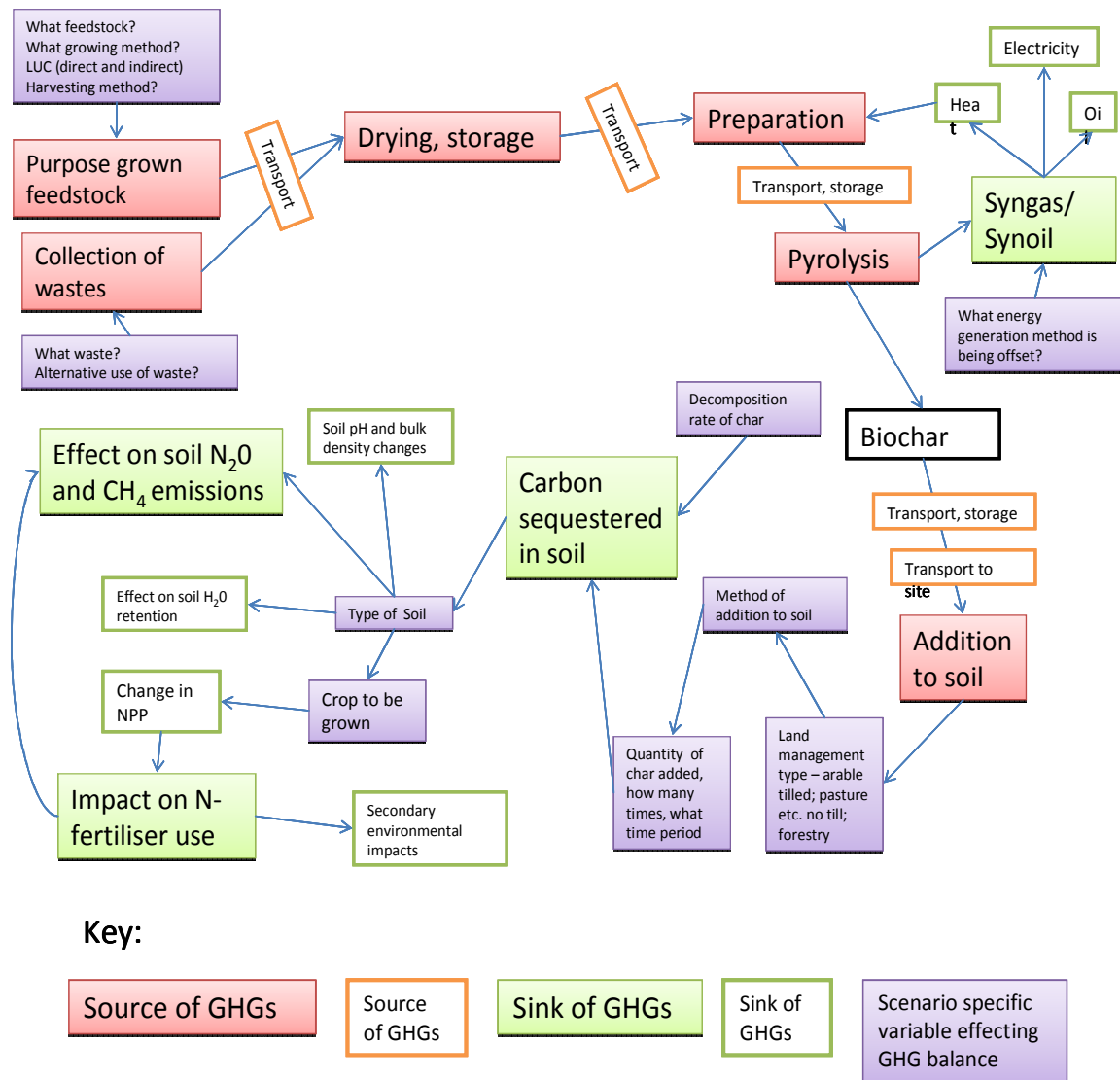


Figure 8.2: Detailed outline of Life Cycle Assessment stages modelled

### 8.1 Scenarios for available feedstock, biochar supply and technology scale

The resource pyramid approach (Bradshaw et al., 2007) was used to distinguish between ‘theoretical available resources’ (i.e. the total amount currently accessible), ‘realistic available resources’ (which applies a first level of pragmatic judgement to limit the supply), and ‘viable available resources’ (which applies a second level of pragmatic judgement to further limit supply, taking particular account of likely or possible other demands in the market place). Three different biomass supply scenarios of viable available resources were developed to reflect the high level of uncertainty over availability given uncertain demand and supply factors. These are: lower supply, higher supply and very high supply of feedstocks available for pyrolysis. A wide range of virgin and non-virgin biomass feedstocks have been included in the scenarios, though not all potential feedstocks are included. For example, only one imported feedstock has been included, and not all types of organic municipal and industrial waste. A further proviso is that the scenarios are based upon *existing or likely future* biomass feedstocks as assessed by the team and drawing upon the Supergen assessment of Thornley et al. (2009b); large-scale expansion of forestry has not therefore been accounted for.

Feedstock	Theoretical available biomass resource for bioenergy (t yr <sup>-1</sup> o.d.)	Realistic available biomass resource for PBS (t yr <sup>-1</sup> o.d.)	Viable available resource assumed available for pyrolysis			
			Lower resource (%)	Higher resource (%)	High resource (%)	High resource (t yr <sup>-1</sup> o.d.)
<i>Virgin biomass resources</i>						
Wheat straw	6,300,000	4,725,000	25	75	100	4,725,000
Small scale		413,438				1,653,750
Large scale		767,812				307,1250
Barley straw	2,400,000	1,800,000	25	75	100	1,800,000
Small scale		157,500				630,000
Large scale		29250				1170000
Oil seed rape and other cereal straw	3,150,000	2,362,500	25	75	100	2,362,500
Small scale		206,719				826,875
Large scale		38,390				1535625
Forestry residues	880,000	800,000	25	75	75	600,000
Arboricultural arisings	341,000	341,000	25	75	100	341,000
Sawmill co-product	1,606,000	86,000	25	75	100	86,000
Wood pellets	4,107,505	4,107,505	10			0
Miscanthus, switchgrass & short rotation coppice - agricultural land	2,012,500	2,012,500	25	75	100	2,012,500
Reed canary grass	50,000	50,000	25	75	100	50,000
Short rotation forestry - contaminated or public land	210,000	210,000	25	50	75	157,500
<b>Total virgin biomass resource</b>	<b>21,057,005</b>	<b>16,494,505</b>				<b>12,134,500</b>
<i>Non-virgin biomass resources</i>						
Construction and demolition wood waste	5,040,000	2,520,000	0	50	75	1,890,000
Commercial and industrial wood waste	4,481,000	2,240,500	0	50	75	1,680,375
Municipal solid waste - wood	1,065,000	798,750	0	50	75	599,063
Mechanical and biological treatment (MBT) waste	6,250,000	6,250,000	0	50	75	4,687,500
Green and food waste	3,600,000	3,600,000	0	50	75	2,700,000
Sewage sludge	1,509,000	1,509,000	0	50	100	1,509,000
Commercial and industrial animal and vegetable waste	540,000	405,000	0	50	75	303,750
Poultry litter	4,276,000	2,138,000	0	50	75	1,603,500
<b>Total non-virgin biomass resource</b>	<b>26,761,000</b>	<b>19,461,250</b>				<b>14,973,188</b>
minus MBT and poultry waste	16,235,000	11,073,250				8,682,188
<b>Total virgin and non-virgin biomass resource (including MBT and poultry waste)</b>	<b>47,818,005</b>	<b>35,955,755</b>				<b>27,107,688</b>
<b>Total virgin and non-virgin biomass resource (excluding MBT and poultry waste)</b>	<b>37,292,005</b>	<b>27,567,755</b>				<b>20,816,688</b>

Table 8.1: UK Biomass Resource Availability Scenarios Used for Generating Three Supply Scenarios Used in the LCA and Economic Analysis. Sources: team discussions; (Copeland and Turley, 2008; Hammond, 2009; Ibarrola, 2009; Thornley et al., 2009b). Note that all Miscanthus goes to medium- and large-scale pyrolysis units; SRC, RCG and switch grass resources are allocated between small- and medium / large-scale pyrolysis units on the following approximate proportions (30%, 23% and 25% to small scale for lower, higher and very high scenarios respectively). Poultry litter and MBT waste have not been included in the evaluation of the quantities of biochar available.

As will be explained in Chapter 9, three representative pyrolysis units (PUs) have been selected here: small scale (processing 2000 t y<sup>-1</sup>), medium-scale (16,000 t y<sup>-1</sup>) and large-scale (185,000 t y<sup>-1</sup>). For the purposes of the LCA, the small-scale PU has been modelled differently from large-scale PU. This is in respect of the efficiency of energy conversion of the oil and syngas, energy recovery from heat and the transportation and storage implications. Hence, the LCA findings for the small- and large-scale PUs are different (indicated as ‘small’ or ‘large’ in the figures in this Chapter). The medium-scale unit has not been explicitly modelled.

## 8.2 CO<sub>2</sub> abatement using virgin biomass feedstocks

Unless otherwise stated, all results show CA relative to an average carbon emission factor for UK grid electricity generated in 2008. Figure 8.3 shows CA ranges from 1.0–1.4 t CO<sub>2</sub> t<sup>-1</sup> o.d. feedstock. Systems which utilise wood residue feedstocks have the highest CAE, closely followed by purpose-grown woody feedstocks. Small-scale straw-based systems have a 15–30% lower CAE than wood residues, partly because of scale-factors (as shown by the higher CAE of straw-based systems at larger pyrolysis unit scale); the rest of the difference is explained by higher inputs for straw-based systems versus wood residues. The values for straw compare well with other estimates in the literature for corn stover (-1.11 t CO<sub>2</sub>eq t<sup>-1</sup> o.d.) (McCarl et al., 2009) and for wheat straw (-1.06 t CO<sub>2</sub>eq t<sup>-1</sup> o.d.) (Gaunt and Cowie, 2009).

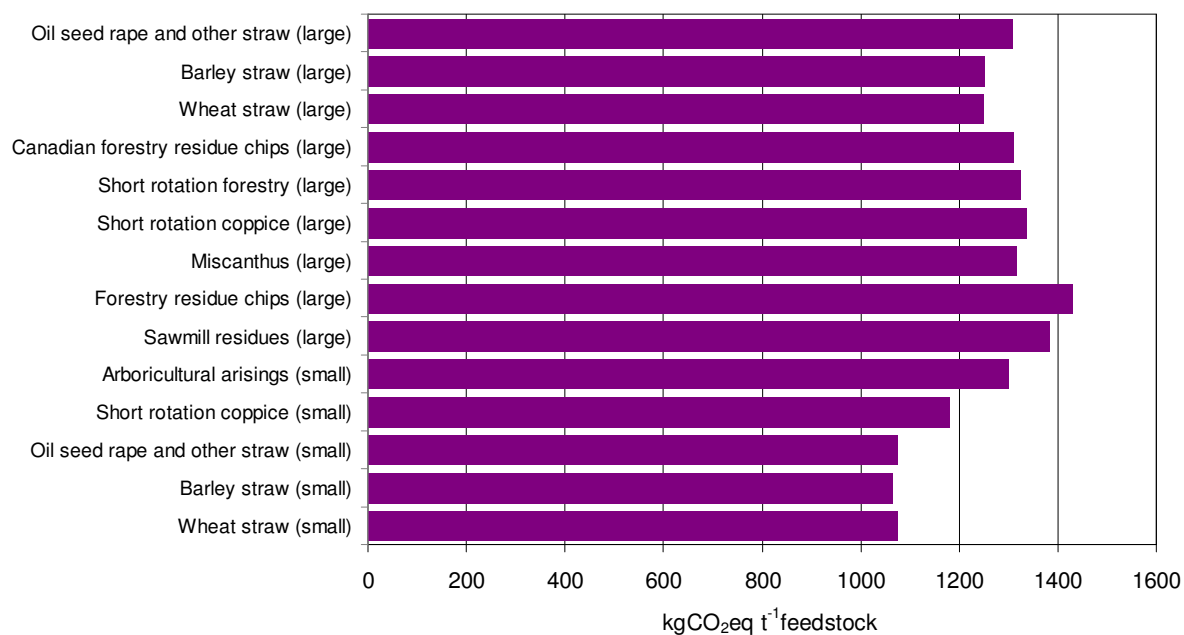


Figure 8.3: CO<sub>2</sub>eq abatement for virgin biomass feedstocks

## 8.3 Greenhouse gas emissions of virgin biomass feedstock production

With respect to feedstock production, not including the transport from production location, for arable crops (wheat, barley, oil seed rape) there is an emission of approximately 90 kg CO<sub>2</sub>eq t<sup>-1</sup> o.d.<sup>15</sup>; and for SRC the value ranges from 30–70 kg CO<sub>2</sub>eq t<sup>-1</sup> o.d.. For UK-sourced forestry residues the values are low or slightly negative due to avoided CH<sub>4</sub> emissions; for dedicated wood supplies that are chipped e.g. small round wood, short rotation forestry, arboricultural arisings and sawmill residues, GHG emissions are lower (ca. 7–30 kg CO<sub>2</sub>eq t<sup>-1</sup> o.d.) due to the low inputs required, provided that fossil fuels are not

<sup>15</sup> Where residues are used as the feedstock, a proportion of the total GHG emissions entailed in their production is allocated to the residue, given by the economic value of the residue relative to the main product.

used in the drying process. For the imported Canadian forestry residues, the production emissions are about 70 kg CO<sub>2</sub>eq t<sup>-1</sup>o.d. (chipped) and 130 kg CO<sub>2</sub>eq t<sup>-1</sup>o.d. (pellets) of which approximately 100 kg CO<sub>2</sub>eq t<sup>-1</sup>o.d. is due to the transport by ship<sup>16</sup>. For Miscanthus, emissions are just over 20 kg CO<sub>2</sub>eq t<sup>-1</sup>o.d., the low-value being explained by no requirement for fertiliser or sewage sludge additions.

#### 8.4 Life-cycle stage contributions to carbon abatement

The largest contribution to CA is from stabilised carbon in biochar, accounting for approximately 40–50% of total CA (Figure 8.4).

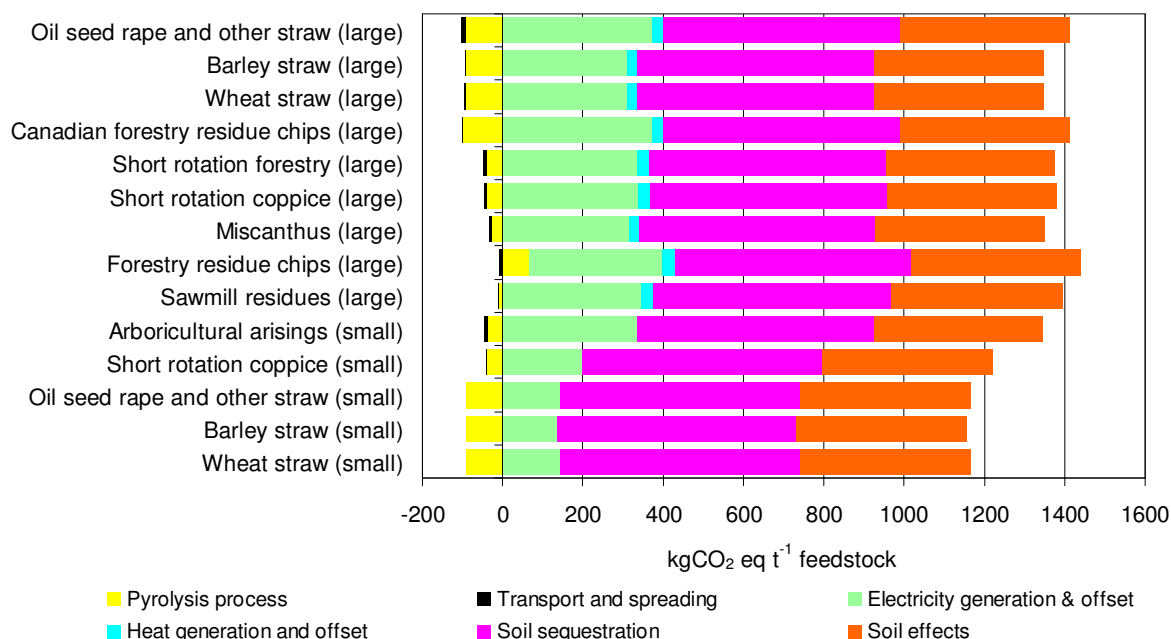


Figure 8.4: Life Cycle stage contributions to carbon abatement using virgin biomass feedstocks

The next largest contribution is from the indirect impacts of biochar in the soil, all of which are currently uncertain: lower crop fertiliser requirement, lower soil N<sub>2</sub>O emissions, increased SOC. These account for 25–40% of CA (the proportion changing with the size of other CA categories). The final major CA category is fossil-fuel offsets from renewable electricity generation, 10–25% of total CA. Similar information is presented in Figure 8.5 in which the life cycle stages of the lower resource supply scenario are broken-down to illustrate CO<sub>2</sub> emitting and abating stages.

#### 8.5 CO<sub>2</sub> equivalent emissions per unit delivered energy

Carbon abatement is 1500–2000 kg CO<sub>2</sub>eq MWh<sup>-1</sup> (1.5–2.0 kg kWh<sup>-1</sup>) for large systems (Figure 8.6). This compares to average electricity grid emissions of 0.56 kg CO<sub>2</sub> kWh<sup>-1</sup> in 2006, and a long-term marginal value of 0.43 kg CO<sub>2</sub> kWh<sup>-1</sup> (Defra, 2009). For comparison, modern bioenergy systems (combustion with grate or fluidised bed, gasification) produce *emissions* from between 0.03–0.07 kg CO<sub>2</sub> kWh<sup>-1</sup> (Thornley, 2009), or from 0.05–0.30 kg CO<sub>2</sub> kWh<sup>-1</sup> according to the Environment Agency (2009). Whilst PBS appears to offer far better CA MWh<sup>-1</sup> than conventional bioelectricity, this is a somewhat misleading finding. Much of the CA from PBS results from stabilised carbon in the biochar and from indirect soil effects (rather than from offset fossil fuel emissions), whilst the denominator - electricity generation per unit biomass - is lower than for conventional bioelectricity due to

<sup>16</sup> There are methane emissions avoided with use of forestry residues; therefore, although 100 kg CO<sub>2</sub>eq t<sup>-1</sup> o.d. is attributed to ship transport, the total emissions for Canadian forestry residue chips is 70 kg CO<sub>2</sub>eq t<sup>-1</sup> o.d.



lower efficiency. Thus, the CA per unit electricity is high, but electrical efficiency is low. The effect is pronounced in the case of the small systems which have very low electrical efficiency (ca. 7%)., Since the CA is relatively constant, with a smaller denominator the CAE increases relative to the large system.

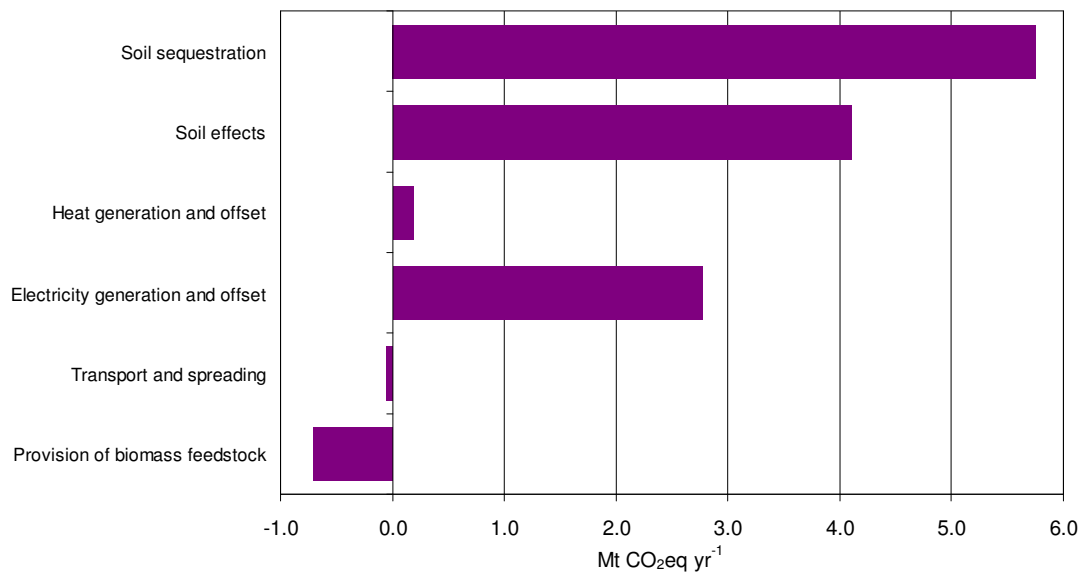


Figure 8.5: CO<sub>2</sub>eq abatement by life-cycle stage for lower biomass supply scenario

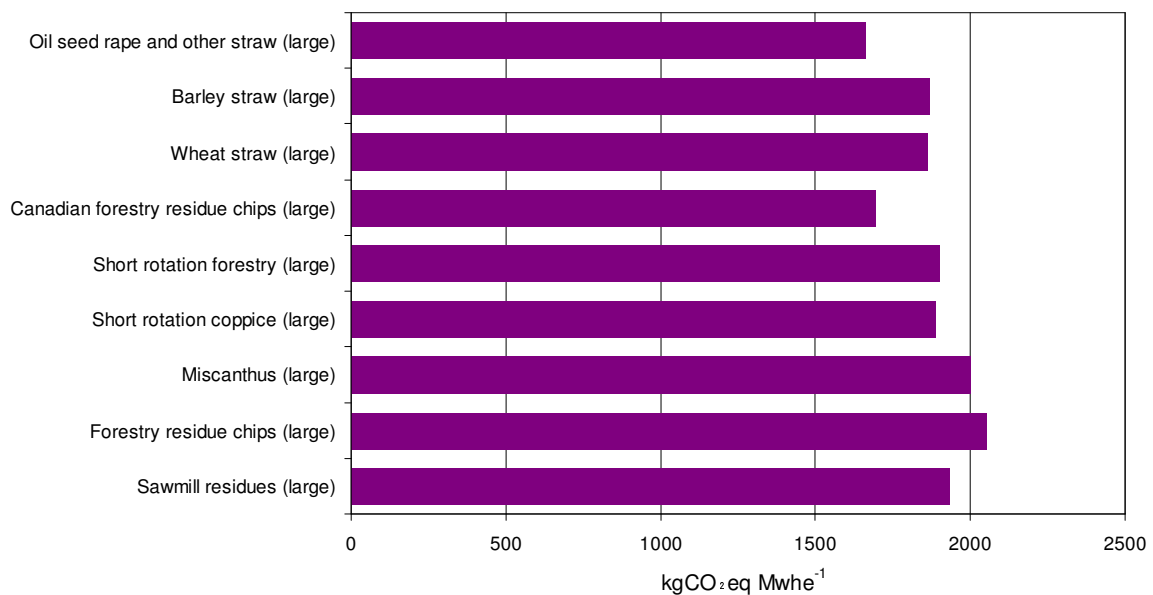


Figure 8.6: CO<sub>2</sub>eq emissions per MWh electricity delivered from virgin biomass feedstocks

### 8.6 CO<sub>2</sub> equivalent emissions per hectare

On an area basis CA ranges from zero to nearly 30 t CO<sub>2</sub>eq ha<sup>-1</sup> y<sup>-1</sup> depending on PBS feedstock (Figure 8.7). Waste feedstocks such as arboricultural arisings are the most efficient in terms of land use as they do not require any additional land use change and do not interfere with crop production systems; moreover, they are commonly disposed of as wastes and hence PBS incurs less emissions through additional transport, handling and storage stages.

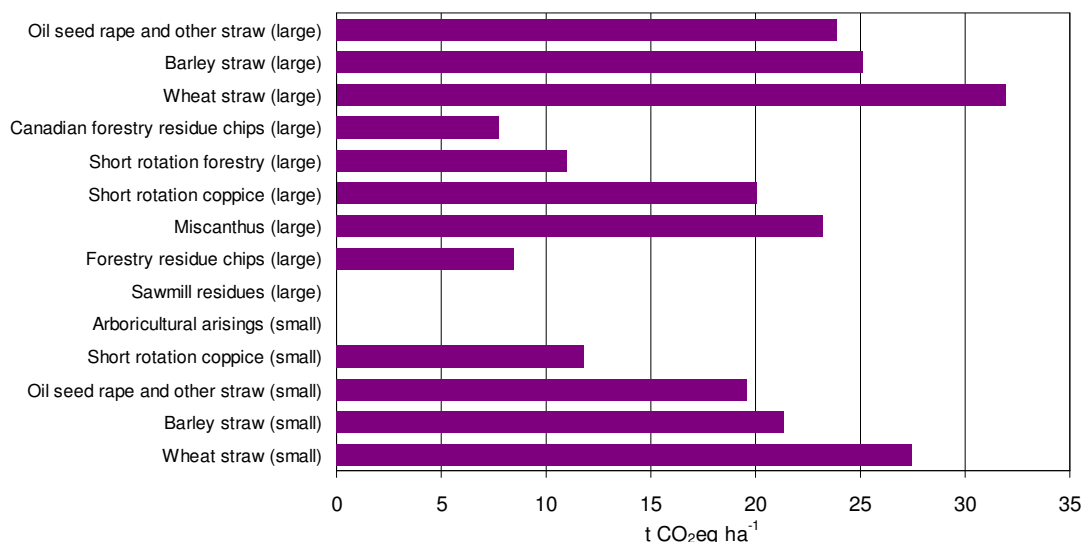


Figure 8.7: Annual CO<sub>2</sub>eq abatement per hectare

Note: No value is given for sawmill residues or arboricultural arisings since the plants are not grown specifically for pyrolysable residues

### 8.7 Potential CO<sub>2</sub> abatement using non-virgin biomass feedstocks

Using the local authority area of Glasgow and the Clyde Valley as a case study, PBS was assessed by LCA for five non-virgin feedstock streams: commercial and industrial (C&I) waste wood, garden and green waste, sewage sludge, food waste, and anaerobic digestion (AD) digestate (Ibarrola, 2009). Selecting a specific geographic area allowed more precise LCA, but extrapolation of the findings to other local authorities has to be done with care. The kg CO<sub>2</sub>eq t<sup>-1</sup> o.d. are shown in Table 8.2. The results for PBS are shown relative to landfill and AD as alternative options<sup>17</sup>, and both fast pyrolysis and slow pyrolysis are modelled assuming 35% and 10% biochar yield respectively. Calculated CAE ranges from 0.65 to over 2.00 t CO<sub>2</sub>eq t<sup>-1</sup> encompassing, but also extending, the range for virgin biomass feedstocks. A high CSF (1.0) has been assumed for non-virgin biomass, compared to a value of 0.68 for virgin biomass. The CSF value in the case of non-virgin biomass feedstocks is very uncertain and likely to be highly variable depending on feedstock type and processing. Rather than arbitrarily selecting a value, we therefore chose to simply use a value of 1.0. This will over-estimate the CA of non-virgin biomass feedstocks to some extent (by about a fifth if the CSF were in reality 0.7 over 100 years).

PBS outperforms landfill and AD because it results in greater carbon stabilisation and more efficiently converts biomass to electricity, therefore displacing more fossil fuel CO<sub>2</sub> emissions. Wood waste (construction and demolition, plus commercial and industrial), garden and green waste, and food waste have greater CAE than sewage sludge or AD digestate. This is because of the higher calorific value of the former, and the higher stabilised carbon content of their biochar product. Fast pyrolysis tends to produce more CA than slow pyrolysis: the greater energy efficiency of fast pyrolysis proves more important to the overall CA than the higher biochar yield of slow pyrolysis.

Gaunt and Cowie (2009) present a similar figure for CA of green waste compared to conventional landfill with CH<sub>4</sub> recovery (1.0–1.2 t CO<sub>2</sub>eq t<sup>-1</sup> o.d. feedstock). The Australian and New Zealand Biochar Researchers Network has recently presented more results for a range of non-virgin biomass feedstocks including poultry litter, paper sludge and green waste: the CA is between 1.4 and just over 2.0 t CO<sub>2</sub>eq t<sup>-1</sup> o.d. feedstock, the somewhat

<sup>17</sup> To calculate the absolute CA for PBS, add the CA for landfill or AD to the value shown in the table for the PBS.

higher values being explained by the larger avoided CH<sub>4</sub> emissions due to less CH<sub>4</sub> recovery than is typical for the UK case (Joseph et al., 2009).

Case Scenario	Abatement efficiency (kg CO <sub>2</sub> eq t <sup>-1</sup> o.d. feedstock)
<i>Construction and demolition / industrial and commercial waste wood</i>	
Landfills	110
Pyrolysis (10% biochar yield, biochar as fuel consumption)	4217
Pyrolysis (35% biochar yield, biochar as fuel consumption)	3578
Pyrolysis (10% biochar yield, biochar as fertilizer)	2207
Pyrolysis (35% biochar yield, as fertilizer)	1619
<i>Garden and green waste</i>	
Landfills	107
AD (replacing landfills)	346
Pyrolysis (10% biochar yield, replacing landfills)	1441
Pyrolysis (35% biochar yield, replacing landfills)	1067
Pyrolysis (10% biochar yield, replacing anaerobic digestion)	1276
Pyrolysis (35% biochar yield, replacing anaerobic digestion)	902
<i>Sewage sludge</i>	
Landfills	26
AD (replacing landfills)	12
Pyrolysis (10% biochar yield, replacing landfills)	910
Pyrolysis (35% biochar yield, replacing landfills)	648
Pyrolysis (10% biochar yield, replacing anaerobic digestion)	918
Pyrolysis (35% biochar yield, replacing anaerobic digestion)	657
<i>Food waste</i>	
Landfills	83
AD (replacing landfills)	-4
Pyrolysis (10% biochar yield, replacing landfills)	1622
Pyrolysis (35% biochar yield, replacing landfills)	1147
Pyrolysis (10% biochar yield, replacing anaerobic digestion)	1665
Pyrolysis (35% biochar yield, replacing anaerobic digestion)	1189
<i>Anaerobic digestion (digestate)</i>	
Pyrolysis (10% biochar yield)	110
Pyrolysis (35% biochar yield)	79

Table 8.2: CO<sub>2</sub>eq abatement for five waste feedstock streams

Figure 8.8 indicates that the largest contribution to CA for both fast and slow pyrolysis in the case of wood, food and green wastes is carbon stabilised in biochar (50–70%, excluding digestate case) - higher than for virgin biomass feedstocks. The second largest contribution comes from offset GHG emissions from fossil-fuel emissions (20–40%).

There are large uncertainties associated with the LCA work presented here. Many assumptions have had to be made, and the overall outcome is quite sensitive to some of these (such as the way that heat is provided for biomass drying, the implied yield of the biomass production, and the way that the by-product co-allocation is calculated). Also, biomass production systems vary in space and with time, making a calculation using a single number problematic. For the non-virgin waste feedstocks, considerable uncertainties occur with respect to the management of individual landfill sites (e.g. the biodegradable fraction, oxidation factors, CH<sub>4</sub> recovery, etc.) making comparison of PBS to existing options difficult.

## 8.8 Potential CO<sub>2</sub> abatement using virgin biomass resources

Three viable resource scenarios have been used to estimate CO<sub>2</sub>eq abatement for lower, higher and very high virgin biomass supply scenarios, extrapolating nationally using the results for individual virgin biomass feedstocks shown in Figure 8.4. In these calculations the contribution of imported wood residue from Canada converted into wood chips was kept

constant across scenarios. The results are shown in Table 8.3, which indicate that the carbon abatement potential arising from virgin biomass feedstocks in the UK is between 3.5–11.0 Mt CO<sub>2</sub>eq y<sup>-1</sup> (Table 8.3).

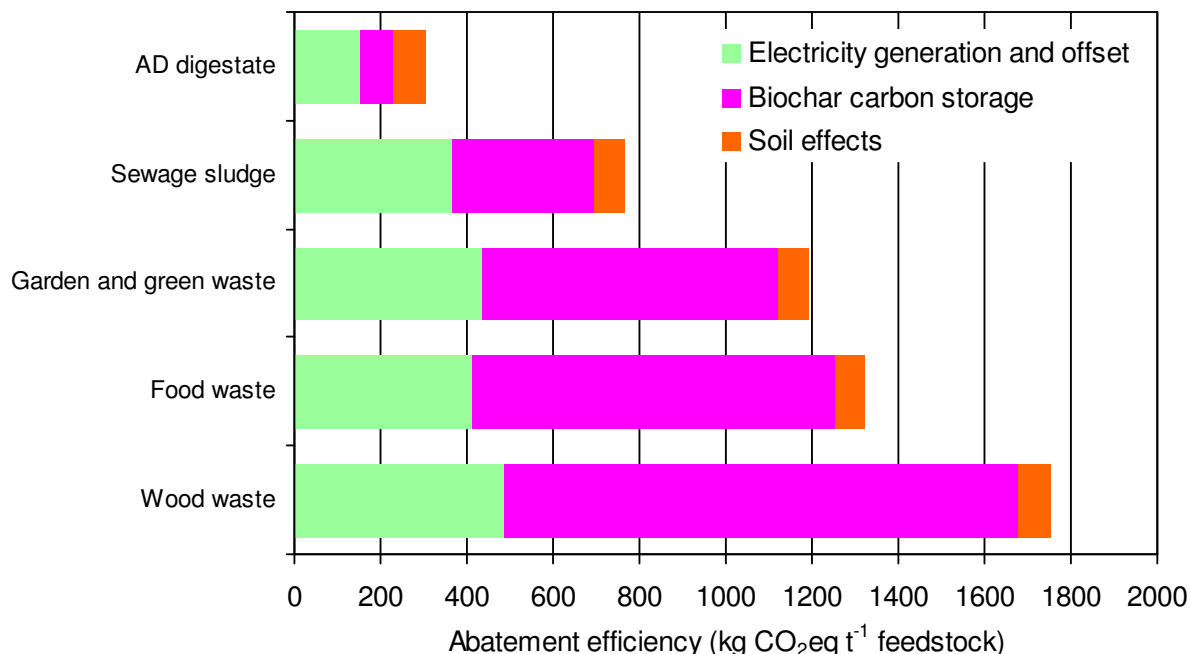


Figure 8.8: The relative contribution of life-cycle stages to CO<sub>2</sub>eq abatement for a range of waste streams and waste management options

Scenario	Total assumed viable feedstock (Mt y <sup>-1</sup> o.d.)	Total abatement (Mt CO <sub>2</sub> eq. y <sup>-1</sup> )	Total abatement (Mt Ceq. y <sup>-1</sup> )
Lower resource	3.10	3.59	0.98
Higher resource	9.24	8.77	2.41
Very high resource	12.13	11.15	3.07

Table 8.3: CO<sub>2</sub>eq abatement from biochar production in the UK under three scenarios of viable available virgin biomass resource

Note: Assumes slow pyrolysis and a CSF of 0.68. Stabilised carbon calculated over 100 yr time horizon; baseline for fossil fuel offsets is 2008 average grid electricity. In the majority of cases, no comparative baseline for the treatment of the biomass resource has been included, i.e. except in the case of forestry residues, no account has been made of the fate of the carbon in the biomass if pyrolysis to biochar had not been used. Provided that carbon does not convert to CH<sub>4</sub>, it is appropriate not to include the carbon in the non-pyrolysis baseline, but treat as a carbon neutral cycle.

Use of imported biomass for biochar production would increase the overall amount of CA achieved if it resulted in an increase in available feedstock, though it would have to be demonstrated that it makes more sense to move the biomass, rather than process it into biochar in the country of origin (or use for some other purpose). The reason that some PBS applications have little impact on overall CA is due primarily to the relatively small feedstock volumes available for producing biochar. This can be seen in Figure 8.9 which tracks feedstock volumes and CO<sub>2</sub> (equivalent) abatement of each. There is a very strong relationship between feedstock quantity and biochar carbon abatement, which reflects the assumed constant yield of biochar, and an assumed CSF, for all feedstock types. In reality it is likely that yield and CSF, as well as the indirect properties of biochar in the soil, will vary between (and even within) feedstocks. Some feedstocks have a somewhat greater CAE than others – e.g. Miscanthus, Canadian residue imports, sawmill residues - than the straw-

based feedstocks. This is likely to be a consequence of the lower emissions associated with stages of the life-cycle, in particular production of the biomass.

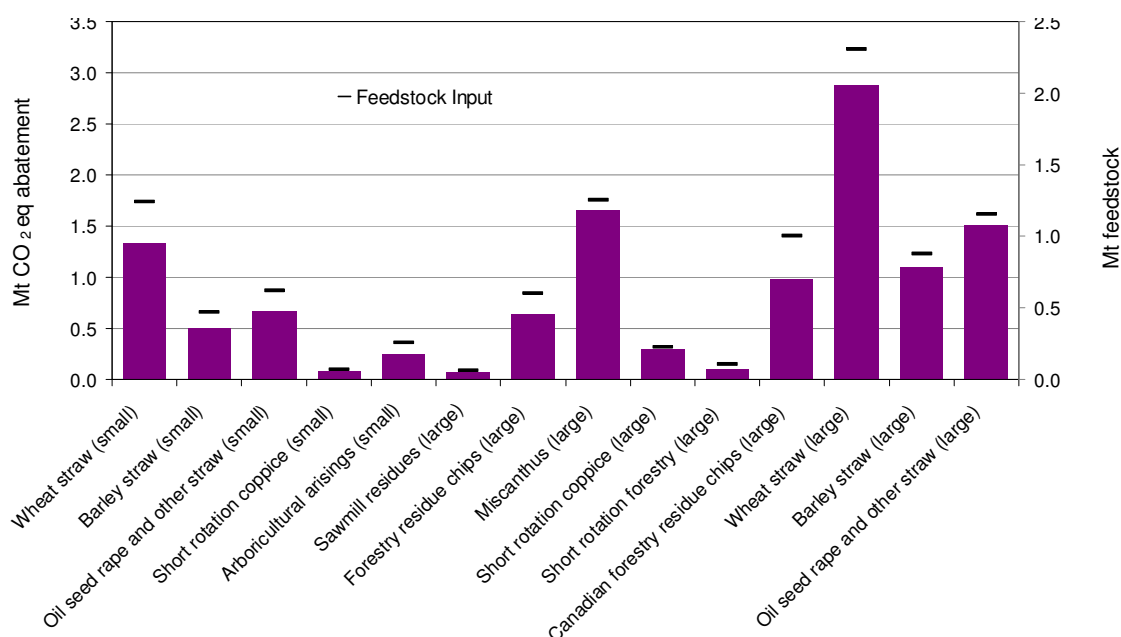


Figure 8.9: Quantity of virgin biomass feedstock and CO<sub>2</sub>eq abatement arising from PBS

## 8.9 Potential CO<sub>2</sub> abatement using non-virgin biomass resources

Calculated national CO<sub>2</sub>eq abatement values for non-virgin biomass resources are shown in Table 8.4, derived using abatement factors presented in Table 8.2. The CAE of biochar from non-virgin biomass waste is somewhat higher than that from virgin biomass resources

Scenario	Total assumed viable feedstock (Mt y <sup>-1</sup> o.d.)	Total abatement (Mt CO <sub>2</sub> eq. y <sup>-1</sup> )	Total abatement (Mt Ceq. y <sup>-1</sup> )	Abatement assuming 50% utilisation (Mt CO <sub>2</sub> eq y <sup>-1</sup> )
Lower resource	0.00	0.00	0.00	0.00
Higher resource	5.54	7.16	1.95	0.98
Very high resource	8.31	10.74	2.92	1.46

Table 8.4: CO<sub>2</sub>eq abatement from biochar production in the UK under three scenarios of viable available non-virgin biomass resource.

Notes: Based upon slow pyrolysis with a CSF of 1.0 and data for one city-region (Glasgow and the Clyde Valley) (Ibarrola, 2009). If fast pyrolysis is used instead, the abatement is 9.75–14.63 Mt CO<sub>2</sub> y<sup>-1</sup> (higher and very high supply). Calculations are relative to landfill-based waste management systems (which are, overall, a net carbon abatement strategy). This is an appropriate baseline to use given some conversion of carbon to methane in the non-pyrolysis baseline and reasonably good knowledge of waste management practices. The table does not currently include all categories of waste (e.g. MBT, poultry litter – both large sources of waste)

This is largely due to the assumed CSF of 1.0 for non-virgin feedstocks, though in reality we expect a quite wide range of values for the CSF less than 1.0. It is also partly due to the lower or non-existent GHG emissions associated with biomass production. Non-virgin biomass wastes have to be collected, transported and processed whether PBS is used or not; in the case of virgin biomass resources, this is generally not the case, with some exceptions, e.g. arboricultural arisings and sawmill residues; and GHG-emitting practices are used in the production of dedicated feedstocks. Note that for the purposes of calculating how much agricultural land could be treated with non-virgin biomass-derived biochar, it was

assumed that only 50% available non-virgin biomass feedstock would be suitable for agricultural-grade biochar due to regulatory controls. This would potentially reduce carbon abatement from non-virgin biomass resources, though other applications of biochar are possible, including building or structural material, or storage in landfill or disused mines, etc.

### 8.10 Sensitivity analysis

The outcome of the LCA is sensitive to assumed decay rate of the biochar, expressed as mean residence time (MRT). If the MRT is below 500 y, there is a reduction in the CAE which begins to look concerning. This partly depends on the time horizon over which an analysis is undertaken. Over the 100-year horizon evaluation, there is no important reduction in CAE unless the MRT reduces to about 400 y. At a longer time-horizon evaluation of 200 or 500 y, the MRT value at which the CAE begins to decrease significantly is 500–700 y.

The CA values reported here will vary depending on the baseline against which they are calculated. The 2008 average electricity grid carbon emission factor (CEF) has been used here ( $0.501 \text{ kgCO}_2 \text{ kWh}^{-1}$ ). If the offsets from avoided fossil fuel emissions were not included, the CA would clearly be lower, as shown in Figure 8.10. Also shown is the implied CEF for the electricity grid in 2030 which would be needed for the UK to be on track to meeting its long-term carbon reduction targets. It can be seen that the choice of baseline has an impact on the absolute CA at the kt scale. Conventional bioenergy systems have CEFs that are, in most cases, larger than the implied 2030 CEFs (Environment Agency, 2009), suggesting that such electricity generation technologies would not be sustainable in the long-term. On the other hand, Figure 8.10 shows that all PBS still abate  $\text{CO}_2$  emissions relative to the 2030 CEF, since emissions savings do not arise from offsetting other fossil fuels used in electricity generation so much as from the carbon stabilised, and the indirect effects of biochar in soil.

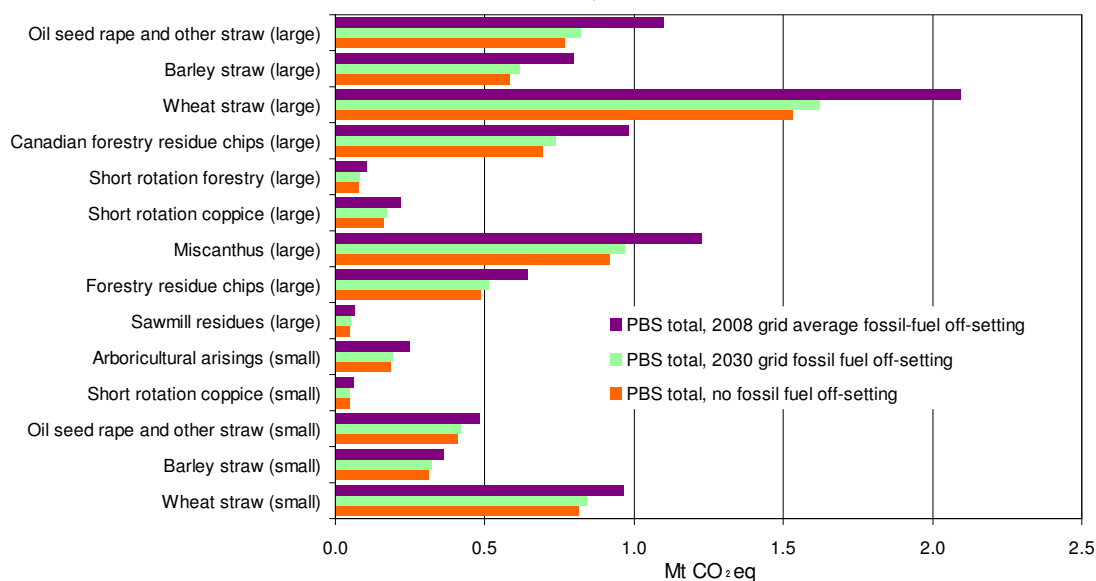


Figure 8.10:  $\text{CO}_2\text{eq}$  abatement by feedstock relative to three baselines for higher resource supply  
 Note: Grid electricity carbon emission factor (CEF) used is for 2008; offset fossil fuel emissions not included; Implied CEF for the UK electricity grid in 2030 (assuming current government targets met)

### 8.11 Electricity generation from pyrolysis–biochar systems versus combustion

Figure 8.11 shows that biomass combustion stands to produce much more electricity than PBS – more than twice as much. The electrical efficiency of PBS systems modelled range from 6–15%, whilst the electrical efficiency of combustion here is assumed to be 33%. Electrical efficiency in dedicated bio-energy plant in the UK is typically below 30%, so our assumption is conservative. In systems co-firing biomass with coal, however, efficiency can be significantly higher in new plant (up to 42%): average UK coal plant efficiency is 33%. Including thermal energy, the PBS systems are 12–22% efficient. If more generous

assumptions for heat availability are made (e.g. if it is assumed that 50% of the heat generated is useful and made use of), the overall conversion efficiency may rise to 15–30%. It is anticipated that a programme of innovation improving the overall energy efficiency of PBS will evolve with the prospect or practice of biochar deployment.

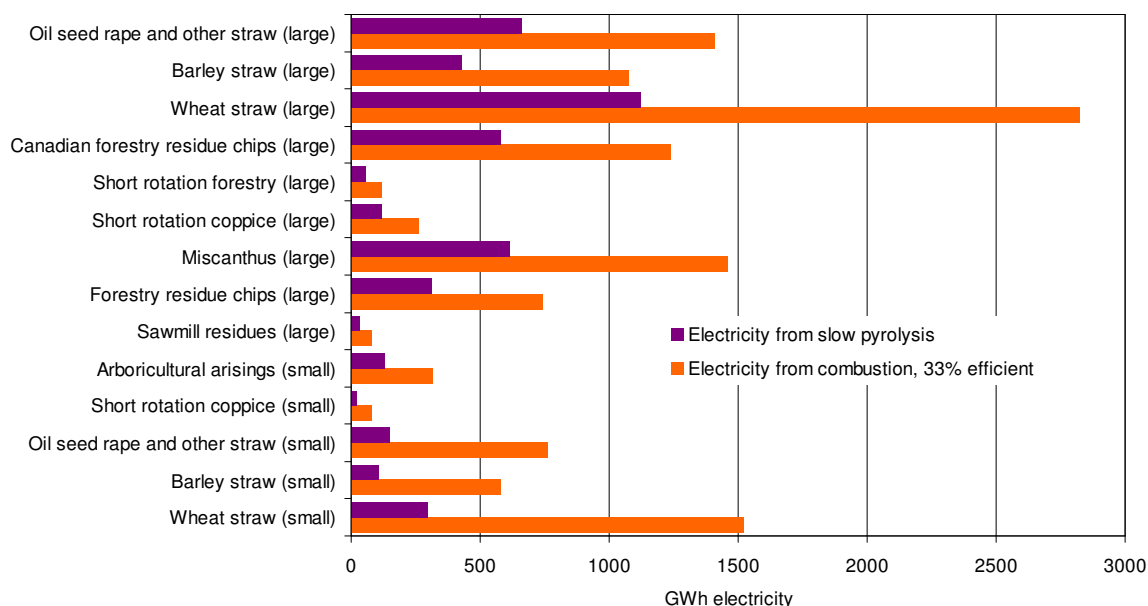


Figure 8.11: Electricity generated on basis of potentially available virgin biomass feedstock

PBS appears to offer greater CA than combustion at ca. 30% efficiency, even without inclusion of indirect soil effects, though such indirect effects are necessary to compete with combustion at an efficiency over 40%. If grid average of 80 kg CO<sub>2</sub>eq MWh<sup>-1</sup> is attained by 2030, and assuming biomass is still available as a resource, biomass combustion offers almost no benefit (Bates et al., 2009), but PBS still offers CA benefits, i.e. it has net negative CO<sub>2</sub>eq MWh<sup>-1</sup> emissions (Figure 8.6). The PBS option raises the question of whether it is electricity generation or GHG abatement that is most desired. At present, the incentives structure is focused upon renewable electricity generation, and there is no mechanism for rewarding stabilised carbon abatement in the soil. If carbon equivalent abatement is the primary policy driver, inclusion of stabilised carbon in biochar and its indirect impacts on soil GHG fluxes, would be given some value alongside renewable electricity generation.

## 9 ECONOMIC ANALYSIS

*Simon Shackley, John Gaunt, Saran Sohi and Jason Cook*

The economic assessment of biochar should consider the total costs and benefits of developing, implementing and managing PBS. A simple framework is presented in Table 9.1. Information on many of these costs and benefits is currently not available because dominant technological designs and management systems for biochar production and application are not yet developed.

Total costs: Cost of producing , delivering and applying biochar			Total benefits: Value of biochar			
Biochar Production	Transportation & storage	Application	Energy production	Agricultural gains	Carbon storage	Diffuse pollution abatement
Feedstock	Equipment	Equipment	Electricity value	Yield gain	C abatement	Reduced nitrate run off
Transport	Labour	Labour	Heat value	Quality		
Utilities	New covered storage facilities	Monitoring, verification, reporting		Reduced fertiliser		
Maintenance & operation				Soil workability		
Labour				Water retention		
Capital costs						
Gate fee						

Table 9.1: Summary of costs and benefits associated with pyrolysis-biochar systems (assuming that the biochar does not contain contaminants)

One attempt to undertake a full Cost Benefit Analysis (CBA) for biochar in the context of the US mid-west was undertaken by McCarl et al. (2009). This is for a 70,000 t y<sup>-1</sup> plant, costing \$24 million (£14.5 million), with a 20 y life time and a discount rate of 12%. McCarl et al. conclude that slow and fast pyrolysis of maize residue for biochar production and energy by-products is not profitable. The Net Present Value (NPV) for fast pyrolysis is -\$45 t<sup>-1</sup> feedstock and -\$70 t<sup>-1</sup> feedstock for slow pyrolysis. There is a risk in putting too much credence on quantitative net present values in a situation of such high uncertainty, and as noted in Chapter 4, many of the possible benefits of biochar are speculative at the current time, in the UK context. It is also understood that the data for the slow pyrolysis operation in this study were inferred, not derived from a pilot plant. Given that 1 t feedstock converted to biochar results in approximately 1 t CO<sub>2</sub>eq abatement (Chapter 8), and removing the \$4 t CO<sub>2</sub>eq abatement value assumed by McCarl, et al. (2009), the carbon abatement cost is therefore \$49 to \$74 t<sup>-1</sup> CO<sub>2</sub>. This is similar to the abatement costs commonly reported for many renewable energy technologies and for CO<sub>2</sub> capture and storage (CCS), though cheaper options for carbon abatement currently exist in the UK.

The financial benefits to agriculture of biochar application to soil are insufficiently understood, in the UK context or globally. This leads to reluctance to undertake a full CBA. Some existing studies have attempted to do this, but have needed to assume the benefits of biochar in terms of elevated crop yield. For example, Gaunt and Cowie (2009) explore three scenarios (low, medium, high) to represent soil responses to a biochar addition at 5 t ha<sup>-1</sup>. McCarl et al. (2009) assume a 5% increase in crop yield from a 5 t ha<sup>-1</sup> biochar addition, as well as a reduction in lime and nutrient requirements. Collison et al. (2009) assume that an unspecified level of biochar application would result in a 5% increase in feed wheat and potato yields, a 3% uplift in quality, a 10% reduction in fertiliser use and a 5% reduction in cultivation costs in the East of England region.<sup>18</sup> The overall effect was a reduction in the total variable costs in the case of biochar addition and a significant increase in per hectare profitability (£143 ha<sup>-1</sup> for feed wheat, £545 ha<sup>-1</sup> for potatoes). Making these

<sup>18</sup> An increase in costs for grading and sundries in the case of potatoes with biochar addition is also included here.



kinds of assumptions is necessary if the agronomic value of biochar is being sought, or if a full CBA is being attempted. There is a significant uncertainty in the net present value of biochar, and over 40–60% of the agronomic value of biochar in the above studies arises from impacts other than crop yield (for example, from changes in quality and reduced fertiliser application), and the factors included in different studies are not consistent (e.g. the impact on crop quality is included in Collison et al. (2009), but not in McCarl et al. (2009).

A further complication with undertaking a CBA from a societal perspective, is that transfer payments from one firm in the economy to another should be excluded, such as revenue streams that are in effect a cost (including as a lost revenue) to another firm. This would apply to revenue from tipping fees, avoided landfill tax and payment of ROCs. A more limited approach than full CBA is to estimate the cost of producing, transporting and applying biochar to the field and then working backwards to what the break-even selling point (BESP) would be per tonne of biochar. The BESP is a production cost for a tonne of biochar; hence the accumulative agronomic and soil benefits of biochar plus any carbon storage benefits that could be claimed need to exceed BESP for a biochar strategy to be financially viable.

## 9.1 Feedstock

A recent report from NNFCC (Mortimer et al., 2009) has provided estimates of bioenergy feedstock costs and feedstock transportation costs (see Table 9.2). Transportation from the feedstock production site to the pyrolysis unit is assumed to occur in a single stage for small-scale operations, or in two stages (with an intermediate storage facility on field or side of road or in an existing waste handling facility) for large-scale operations. The data on feedstock and transportation costs is largely derived from (Mortimer et al., 2009) and represents state-of-the-art assumptions, practice and understanding.

## 9.2 Storage and transport from pyrolysis unit to farm

Once the biomass has been pyrolysed, it needs to be taken from the pyrolysis unit to a storage unit either on the farm, or in a dedicated storage facility. If biochar is to be widely deployed, large-scale storage facilities are necessary. Virgin biomass resources will be available intermittently throughout the year, e.g. at harvest times in summer – autumn, although some energy crops, e.g. Miscanthus, are harvested in the spring. Some non-virgin biomass resources will be more consistently available throughout the year, though the availability of others such as arboricultural arisings and green waste will be skewed towards the growing season. Opportunities for biochar application to soils will also be skewed towards certain times of the year, e.g. spring and autumn, when crops are not growing and fields are suitable for coping with tractors and implements. The availability of biochar in adequate quantities at the appropriate time would inevitably require large storage capabilities. Such storage facilities might be already available on farm, or could be constructed on-farm for relatively small quantities of biochar, e.g. from a small-scale pyrolysis unit (processing under 2000 t y<sup>-1</sup> feedstock). For medium-scale (2000–25,000 t y<sup>-1</sup> feedstock) and large-scale (>25,000 t y<sup>-1</sup> feedstock) pyrolysis, it is assumed that biochar deployment will be contracted-out and storage will occur in specially constructed units at a cost of £130 m<sup>2</sup> over 10 y. The annualised cost is £25 t<sup>-1</sup> biochar.<sup>19</sup> 85 very large (200 x 100 x 5 m) storage facilities would be required at the UK scale for the lower supply scenario; and 293 and 393 such units under the higher and very high supply feedstock scenarios respectively. A lower-cost storage option was considered, storing biochar at the margin of fields in appropriate flexible containment. This would cut out the need for lengthy indoor storage periods. A nominal value of £1 t<sup>-1</sup> was selected for this approach, though the extent to which this approach might be achievable and practicable is as yet unknown.

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<sup>19</sup> Further analysis suggests that the cost of storage can be brought down to approximately £15 per tonne by assuming optimal use of the available storage area. This would lower biochar production costs by £10 per tonne and reduce the number of storage facilities required.

Feedstock	Default price (£ t <sup>-1</sup> o.d.)	Gate fee for wastes / cost of alternative management option (£ t <sup>-1</sup> )	Net cost for feedstock (£ t <sup>-1</sup> )	Transport- ation costs (£ t <sup>-1</sup> km <sup>-1</sup> )	Total costs of processed feedstocks at pyrolysis unit (£ t <sup>-1</sup> )	Costs of transporting biochar from pyrolysis unit to farm (£ t <sup>-1</sup> )	Storage costs of biochar at the farm or at a dedicated storage facility (£ t <sup>-1</sup> ) <sup>4</sup>	Total costs feedstock provision + transport to farm assuming existing storage available (£ t <sup>-1</sup> )	Total costs feedstock provision + transport to farm assuming dedicated storage (£ t <sup>-1</sup> )
Barley straw bales – small-scale pyrolysis	42	4 <sup>3</sup>	47	3.60	50.6	0.0	7 or 25	54.3	57.6
Barley straw bales – large-scale pyrolysis	42	4	47	0.14	52.6	6.9	7 or 25	63.2	66.5
ORS straw – small-scale pyrolysis	42	5 <sup>3</sup>	48	3.60	51.6	0.0	7 or 25	55.3	58.6
ORS straw – large-scale pyrolysis				0.14	53.6	6.9	7 or 25	64.2	67.5
Short rotation coppice (chips) - small-scale pyrolysis	64	-	64	0.15	69.1	3.7	7 or 25	76.5	79.8
Short rotation coppice (chips) – large-scale pyrolysis <sup>1</sup>				0.21	70.0	7.3	7 or 25	81.1	84.3
Miscanthus (chips)	64	-	64	0.39	79.6	19.1	7 or 25	102.4	105.7
Miscanthus (bales)	45	-	45	0.14	50.6	6.9	7 or 25	61.2	64.5
Sawmill residues	57 <sup>2</sup>	15	42		39.2	0.0	7 or 25	42.9	46.2
Forestry residues (chips)	57	-	57	0.21	65.4	10.3	7 or 25	79.4	82.7
Arboricultural arisings				0.21	17.0	0.0	7 or 25	20.7	24.0
Short rotation forestry (chips) <sup>1</sup>	64	-	64	0.21	74.5	10.3	7 or 25	88.5	91.8
Imported Canadian forestry (chips)	90	-	90	0.21	91.1	10.3	7 or 25	102.1	108.3
Wheat straw bales – small-scale pyrolysis				3.60	49.6	0.0	7 or 25	53.3	56.6
Wheat straw bales – large-scale pyrolysis	42	3 <sup>3</sup>	46	0.14	51.6	6.9	7 or 25	62.2	65.5
Construction & demolition (C&D) waste wood <sup>2</sup>	57 <sup>2</sup>	25	32	0.22	36.4	5.0 <sup>5</sup>	7 or 25	40.1	43.4
Industrial & commercial (I&C) waste wood <sup>2</sup>	57 <sup>2</sup>	25	32	0.22	36.4	5.0	7 or 25	40.1	43.4
Municipal solid waste (MSW) wood <sup>2</sup>	57 <sup>2</sup>	25	32	0.22	36.4	5.0	7 or 25	40.1	43.4
Green and food waste		22	-22	0.22	-17.6	5.0	7 or 25	-13.9	-10.6
Sewage sludge		22	-22	0.22	-17.6	5.0	7 or 25	-13.9	-10.6
Commercial & industrial animal & vegetable waste		45	-45	0.22	-40.6	5.0	7 or 25	-36.9	-33.6

**Table 9.2: Costs of Producing and Delivering Biomass Feedstocks for Processing at a Pyrolysis Unit** Sources: (Mortimer et al., 2009), Appendix B and C. The detailed assumptions for each feedstock are presented in that report on pages 69-73; assumptions about transportation are presented on pages 10-11 and 74-79. Gate fee data for wastes from (Ibarrola, 2009; Levy et al., 2006). Notes: 1) Values for SRC and SRF in (Mortimer et al., 2009) assume bulk drying with electric fans; all other feedstocks assume natural drying. Values for Miscanthus chips have substituted with the most similar feedstock to SRC & SRF since electrical drying would not be credible within a PBS. 2) This value inferred from (Mortimer et al.) from the value for a range of wood waste sources chipped and dried naturally. 3) This accounts for the cost of straw cutting on a harvester (approximately £1/t (Copeland and Turley, 2008)) required under the alternative of direct incorporation of straw, but also of the loss of nutrients through pyrolysis (assuming that 45% of N remains and 90% of P and K remain post-pyrolysis) (ibid. and Masek, 2009). 4) Storage costs are calculated from the figure of £130 per meter squared floor space for construction of dedicated facilities (Cook, pers.com.). This is similar to the value in Nix's (Nix, 2008) for construction of on-farm storage space (fully enclosed building with concrete floor and rainwater drainage). The annualised storage cost per tonne is calculated using a Capital Recovery Factor of 0.149 (8% interest rate, 10 year project). If existing storage facilities are available on the farm, they are costed at 35p per tonne per week (the cost of grain storage in (Nix, 2008)), assuming that the biochar is stored on average for 20 weeks. 5) For the non-virgin waste feedstocks, it is assumed that some transportation is required in the baseline case (e.g. from disposal point to landfill site). An estimate of this transportation distance from the transport from pyrolysis unit to the farm has been deducted, which is why the non-virgin waste feedstocks incur no additional transport requirement in this phase.

### 9.3 Capital costs of the pyrolysis plant

Plant accounts for a large part of total cost. There is a wide variation in the specific capital costs for bioenergy systems, with smaller plants costing substantially more per unit of installed capacity than large plants, but advanced technologies not necessarily costing significantly more than conventional ones (Thornley et al., 2009a). There are three reasons for this. Firstly, biomass feedstocks are bulkier and require larger storage areas and handling facilities than fossil fuels. These costs commonly constitute 20% of the overall capital costs, this proportion remaining constant regardless of the technology.

Secondly, bioenergy systems require significant engineering design input and this does not scale with capacity. Thirdly, many of the component parts (especially steam plant) are optimised for larger-scale utilisation and so procuring small-sized components costs proportionally more than in the case of a larger-sized component.

**Existing specific capital cost estimates of bioenergy plant** can be used to provide an estimate of what a slow pyrolysis unit might cost. The costs of two such systems are illustrated in Table 9.3.

Plant analogy	Wood gasification (power only)	Wood combustion (power only)
Installed capacity (MWeq)	2	25
Specific investment costs (£ kWeq <sup>-1</sup> )	2400	1100
Feedstock rate at 30% moisture (kg s <sup>-1</sup> )	0.64	7.19
Cost (£m kg s <sup>-1</sup> installed capacity)	7.5	0.003824
	Pyrolysis unit in place of downdraft gasifier	Pyrolysis unit in place of combustion chamber.
Major design differences for pyrolysis	Addition of conveyors, augers, separation equipment, and storage silos for biochar (replacing existing ash discharge unit)	Addition of conveyors, augers, separation equipment, and storage silos for biochar (replacing existing ash discharge unit)
	Smaller rated engine for reduced gas throughput	Possible: Smaller rated engine replacing boiler and steam turbine
Remarks on costs	Material requirements similar; design costs higher.	Material requirements similar; higher control and design costs
Direction of cost changes for pyrolysis- biochar unit	There might be small reduction in costs compared to gasification unit, though unlikely to be more than -20%.	There might be a small increase in costs compared to combustion due to additional handling, design and control costs. Again unlikely to exceed +20%.

Table 9.3: Specific capital costs of bioenergy plant that is analogous to pyrolysis plant  
Note: Specific capital costs of 250 kW gasifier with engine using woodchips assumed £2300 kWh<sup>-1</sup>

There is a large difference in the specific capital costs of the two cases, due more to the difference in scale than to the differences in technology. As with bioenergy systems in general, there are strong economic drivers towards implementation of larger-scale technological systems. Some analyses of costs and recent policy incentives (e.g. new ROC values) suggest that a better return on investment will derive from larger, more-centralised units, than from smaller-scale units (Thornley et al., 2009a). The indicative numbers in Table 9.3 broadly agree with other numbers in the literature, e.g. McCarl et al. (2009) uses a value of \$1896 kWh<sup>-1</sup> (c. £1185 per kWh) for a 12.5 MWeq pyrolysis facility.

## 9.4 The overall cost of biochar delivered to the farm

The overall per tonne cost has been calculated using the data in Table 9.2 on the costs of delivering feedstocks to a pyrolysis unit, transporting biochar to a storage facility and then to the farm. The costs of transporting biochar from the farm depot and applying and incorporating it into fields was calculated at approximately £7 t<sup>-1</sup>). These data were entered into a spreadsheet model of a medium-scale (16,000 t yr<sup>-1</sup> feedstock) pyrolysis unit, using the capital and feedstock costs provided in Tables 9.1 and 9.2. A list of the detailed technical assumptions behind the analysis is available at: [www.biochar.org](http://www.biochar.org). The spreadsheet model can also be made available by contacting one of the editors. The spreadsheet was adapted to explore the situation for a small (2000 t yr<sup>-1</sup> feedstock throughput), medium (16,000 t yr<sup>-1</sup> feedstock throughput) and a large (185,000 t yr<sup>-1</sup> feedstock throughput) facility. The results are shown in Table 9.4. The cost of production is calculated by subtracting revenue from the total costs over a ten year period and then dividing that number by the quantity of biochar produced over that period. In other words, the loss made by the PBS is distributed across the quantity of biochar produced, giving a break-even selling point value. The numbers in Table 9.4 therefore represent the minimum price that would have to be charged per tonne of biochar generated in order for the operation to at least break-even. Note that where a profit is made by the operation, it is not possible to ascribe a cost to biochar production in the same way as where a loss is made. In that case the PBS is already profitable, and the biochar by-product is essentially free. For this reason a cost of zero has been applied for those situations where PBS is profitable. In future work, it may in these cases be preferable to ascribe a cost to biochar based upon the relative value of all the by-products.

	Total cost of biochar production: feedstock production to field deployment (£ t <sup>-1</sup> biochar)		
	On-farm storage	Dedicated storage	Innovative field-margin storage
Small-scale farm-based pyrolysis facilities (c. 2000 t yr <sup>-1</sup> o.d. feedstock)			
Average feedstock	291	not relevant	276
Low-cost straw (£10 t <sup>-1</sup> )	211	not relevant	194
Medium-scale pyrolysis facilities (c. 16,000 t yr <sup>-1</sup> o.d. feedstock)			
Very high feedstock resource scenario	311	358	304
Higher feedstock resource scenario	334	379	318
Lower feedstock resource scenario	397	430	380
Food waste	68	117	52
Green waste & sewage sludge	131	181	115
Arboricultural arisings (higher resource)	220	275	210
Low-cost straw (£10 t <sup>-1</sup> )	261	304	214
Wood waste	280	329	263
Large-scale pyrolysis facilities (c. 185,000 t yr <sup>-1</sup> o.d. feedstock)			
Very high feedstock resource scenario	206	280	181
Higher feedstock resource scenario	170	246	158
Lower feedstock resource scenario	309	363	282
Green waste & sewage sludge	0	0	0
Food waste	0	0	0
Arboricultural arisings (higher resource)	47	112	4
Low-cost straw (£10 t <sup>-1</sup> )	78	156	11
Wood waste	118	199	91
Low-cost straw (£20 t <sup>-1</sup> )	123	204	96

Table 9.4: Total cost of biochar production from feedstock provision to soil application

Notes: Use of all the virgin biomass resources is assumed in each scenario and, in addition, 50% of the non-virgin biomass resources for each scenario. The three feedstock supply scenarios imply different quantities of each feedstock type. The proportion and cost of each feedstock type in each scenario was calculated to come up with an 'average' cost for one tonne of feedstock for each feedstock supply scenario. The cost of producing 1 t biochar from the cheaper virgin and non-virgin biomass feedstocks was also calculated

Depending on the assumptions used, biochar may cost up to £430 t<sup>-1</sup> delivered and spread on fields. There are potentially attractive opportunities for producing biochar in terms of cheaper virgin feedstocks, such as arboricultural arisings. Under scenarios where green waste or food waste is used as a non-virgin feedstock, biochar can be produced as a product at no cost. By using these, instead of more expensive wood or straw feedstocks, it is possible to reduce the costs per tonne of biochar produced in a medium-scale unit by 25–35%. The cost reduction is even greater for biochar produced from arboricultural arisings in a large-scale unit: namely, from 80 to nearly 100% as shown in Table 9.4.

Some lower-cost straw options have also been explored, since there can be a wide temporal and spatial variation in the price of straw feedstocks. For example, whilst wheat and barley straw prices have been £30–60 t<sup>-1</sup> during much of 2008 and 2009, in 2007 the price of wheat straw was more typically in the range £20–30 t<sup>-1</sup>, and £30–50 t<sup>-1</sup> for barley straw (Defra, 2009). It can be seen that at a price of £10 t<sup>-1</sup> the costs of producing biochar from straw comes down significantly – especially at the large-scale production unit.

**The breakdown of the costs** is shown in Table 9.5. The greatest costs are those for borrowing capital, feedstock and operation. Costs are also compared for PBS using small-, medium- and large-scale production systems Figure 9.1. Small-scale on-farm biochar production benefits from lower transport cost, large-scale production from much lower capital costs. Figure 9.2 shows a corresponding costs breakdown for three non-virgin biomass waste streams: wood, green waste, sewage sludge and food (vegetable and animal) waste. The feedstock costs are low except for waste wood, whilst avoided gate fees provide an important revenue stream. Transport costs are also low because PBS introduces few additional transport requirements, beyond transport needs already accounted for in waste management.

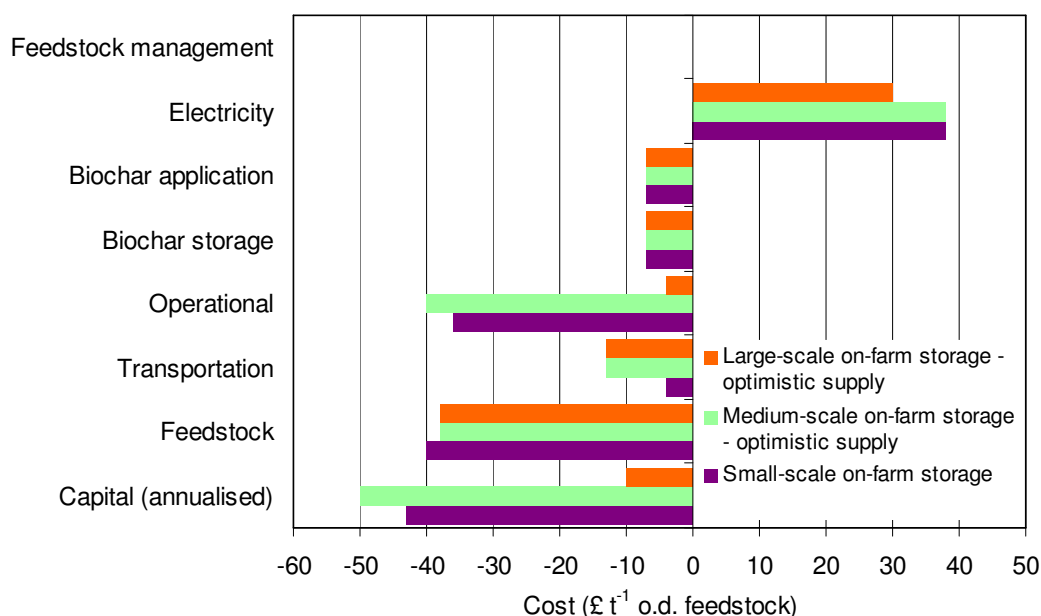


Figure 9.1: Breakdown of pyrolysis—biochar system costs at three different production scale

The ability to raise additional revenue through avoided gate fees, the low or non-existent feedstock costs, and the low transport costs all help to explain why the use of non-virgin biomass waste resources provides a much more favourable economic outlook for a PBS. On the other hand, pyrolysis of such materials will probably pose greater risks and more difficulty in addressing regulatory questions and issues. Use of such materials might also encounter scepticism and resistance from some farmers and land-owners. The most attractive option is perhaps to use virgin feedstocks that are also relatively low cost, such as arboricultural arisings. At prices of less than £20 t<sup>-1</sup>, straw also looks to be an attractive option, especially if storage costs can be minimised.

Feedstock	Costs in pounds per tonne of feedstock (£ t <sup>-1</sup> )					Revenue (£ t <sup>-1</sup> feedstock)		
	Annualised capital	Feedstock purchase	Transport	Operational	Biochar storage	Field application	Electricity	Tipping fee
small-scale on-farm storage - optimistic supply	-43	-40	-4	-36	-7.0	-7.0	38	0
small-scale innovative field-margin storage - optimistic supply	-43	-40	-4	-36	-1.0	-7.0	38	0
medium-scale on-farm storage - optimistic supply	-50	-38	-13	-40	-7.0	-7.0	38	0
medium-scale dedicated storage - optimistic supply	-50	-38	-13	-40	-25.0	-7.0	38	0
medium-scale innovative storage - optimistic supply	-50	-38	-13	-40	-1.0	-7.0	38	0
large-scale on-farm storage - optimistic supply	-10	-38	-13	-4	-7.0	-7.0	30	0
large-scale dedicated storage - optimistic supply	-10	-38	-13	-4	-25.0	-7.0	30	0
large-scale innovative storage - optimistic supply	-10	-38	-13	-4	-1.0	-7.0	30	0
medium-scale on-farm storage - waste wood	-50	-29	-4	-40	-7.0	-7.0	38	0
medium-scale on-farm storage - green & sewerage waste	-50	0	-4	-40	-7.0	-7.0	38	22
medium-scale on-farm storage - food waste	-50	0	-4	-40	-7.0	-7.0	38	45
large-scale on-farm storage - waste wood	-10	-29	-4	-4	-7.0	-7.0	30	0
large-scale on-farm storage - green & sewerage waste	-10	-29	-4	-4	-7.0	-7.0	30	22
large-scale on-farm storage - food waste	-10	-29	-4	-4	-7.0	-7.0	30	45

Table 9.5: Breakdown of the costs of a range of different pyrolysis-biochar systems in the UK

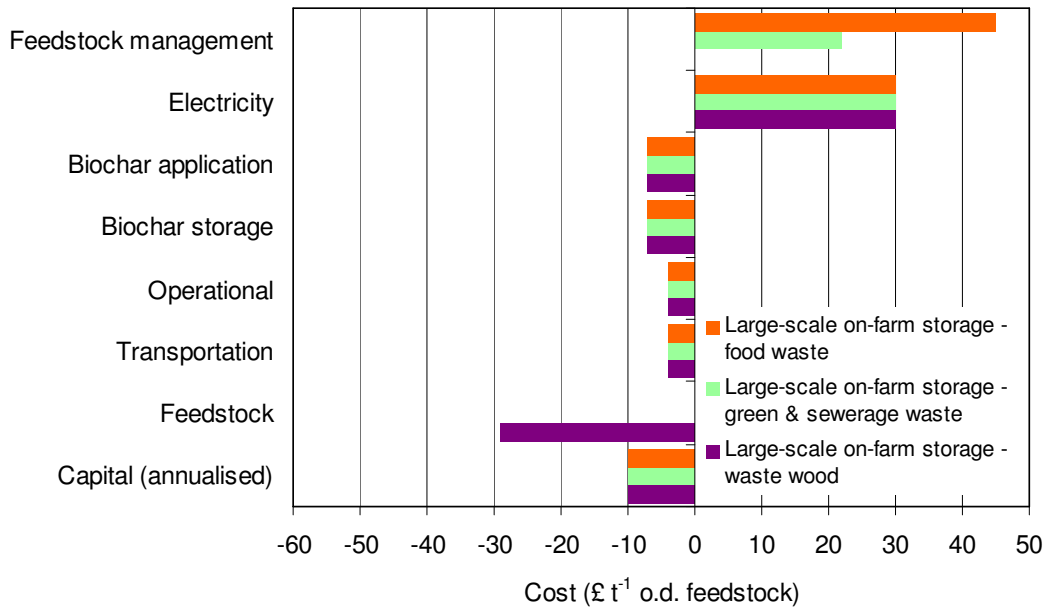


Figure 9.2: Breakdown of pyrolysis—biochar system costs for non-virgin biomass resources: wood waste, green and sewage waste, and food waste

## 10 SURVEY RESULTS

*Sarah Carter, Kirsten Sims, Simon Shackley and Saran Sohi*

An online survey, using a standard design,<sup>20</sup> was distributed to individuals (and online networks) who are working on, or have a knowledge of, biochar and related issues. The sample is not random since individuals and organisations involved in biochar R&D and policy were approached deliberately. In total 145 useable responses were received, of which 118 were complete. Individual responses were requested, whilst recognising that opinions will usually be shaped by the organisation in which that person works. Some organisations chose to submit a combined response on behalf of the organisation.

The participants were asked to indicate how much time they spent working directly or indirectly on biochar (Figure 10.1). It can be seen that most respondents (ca. 60%) worked on biochar for less than a third of their time. Only 19% worked on biochar for more than 70% of their time. Many respondents had expertise in related issues, and 55% (n=145) spent >10% of their time working on either soils, bioenergy, agronomy or project development / carbon markets. Respondents were from a total of 21 different countries in Europe, Africa, Asia, Australasia and North America. The majority were from the UK, however (58%). Very few respondents considered that they had very high levels of expertise on biochar.

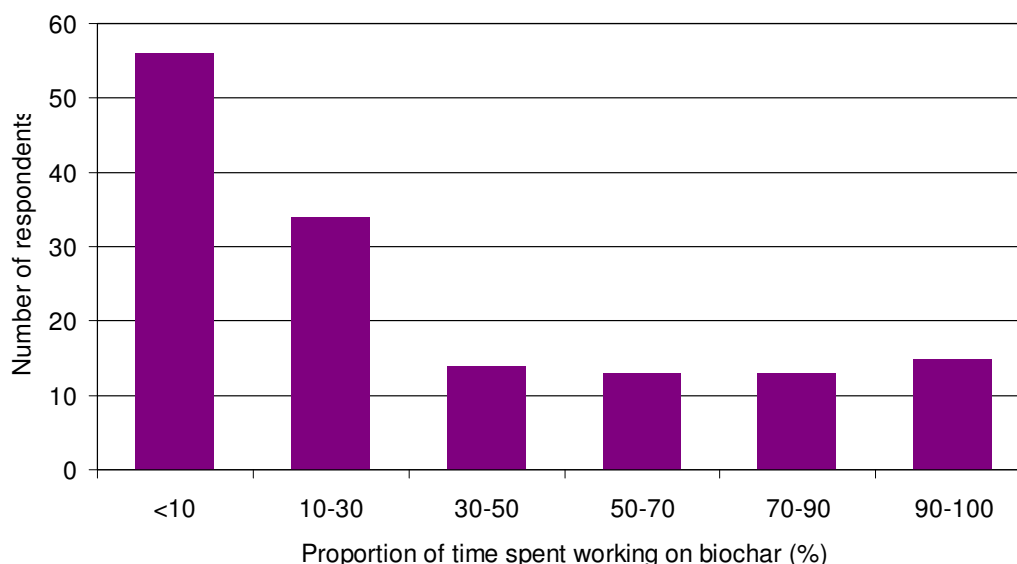


Figure 10.1: How much time is spent on average on issues directly or indirectly concerned with biochar?

### 10.1 Global abatement potential and achievement

Respondents were asked to predict how much carbon abatement from the use of biochar – in a sustainable way – is credible by 2010, 2020 and 2030. The results in Figure 10.2 to Figure 10.4 show the general trend in expected growth in the use of biochar over the next 20–40 years. This was expected to be slow initially (Figure 10.2): in 2010, 17% of the sample predicted that no carbon would be abated using biochar, whereas by 2020 no-one selected this option of zero abatement potential. By 2030, over 50% of respondents estimate that more than 500 MtC could be abated globally through biochar deployment. Perceptions of biochar carbon abatement by 2050 varied by several orders of magnitude: 8% of respondents thought that <100 MtC could be abated, while 3% thought that >6000 MtC (i.e.

<sup>20</sup> Bristol Online Survey Tool: [www.survey.bris.ac.uk/](http://www.survey.bris.ac.uk/)



6 Gt) was possible. There is considerable uncertainty in estimating the long-term prospects for biochar, just over a third of the sample responding 'don't know' (or using the option to make a general comment). This uncertainty increased somewhat for the longer-term scenario.

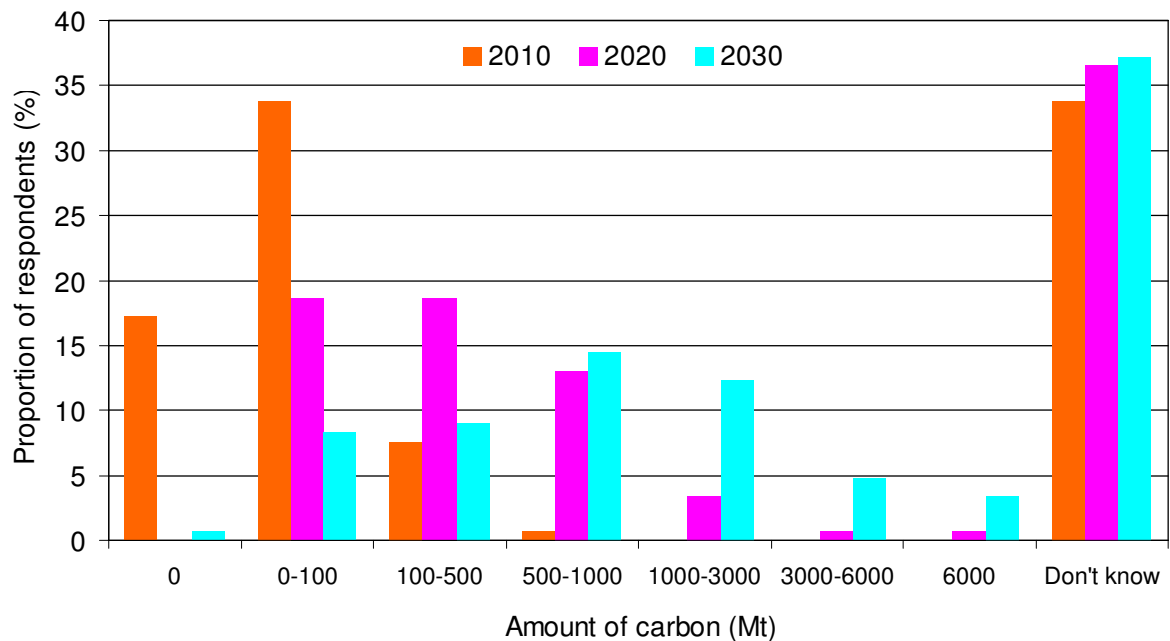


Figure 10.2: Globally, how much carbon abatement from use of biochar – in a sustainable way – do you think is credible by 2010, 2020 and 2030?

Data from UK respondents on whether they thought that the potential for biochar would be likely to be greatest in the developing or developed countries was analysed. Figure 10.3 illustrates that they expected the most potential will be in developed countries in the next two decades, but that by 2050 the developing countries hold greater potential. There was, however, a large increase in uncertainty, from 17% 'don't knows' (n=84) for predictions over the next 10–20 years to 31% 'don't knows' for predictions in 40+ years (n=84).

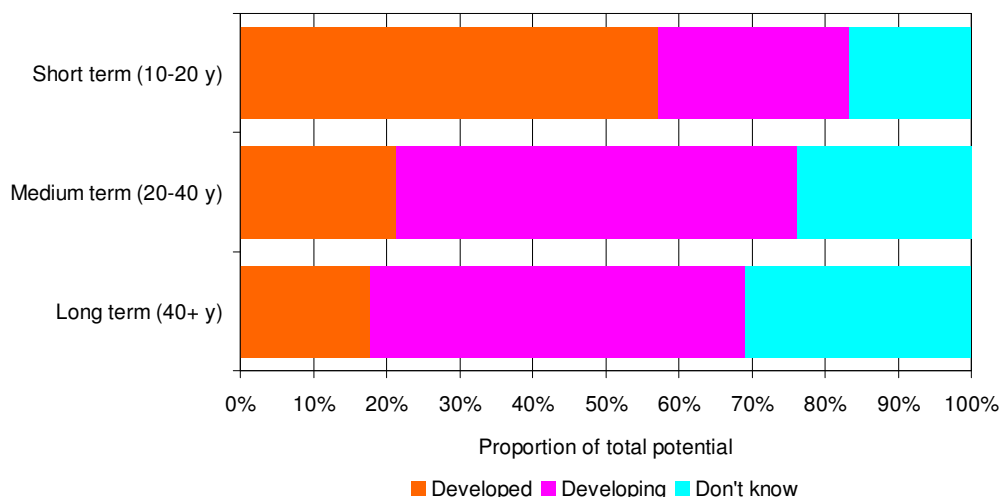


Figure 10.3: Overall, where do you feel there is most potential for biochar uptake?

Data was also analysed from the UK respondents about the potential in Europe in 2020 and 2050 (Figure 10.4). The potential for deployment being 'very high', 'high' or 'moderate' was expected by 63% (n=76) of respondents by 2020 and by 79% (n=75) of respondents by 2050.

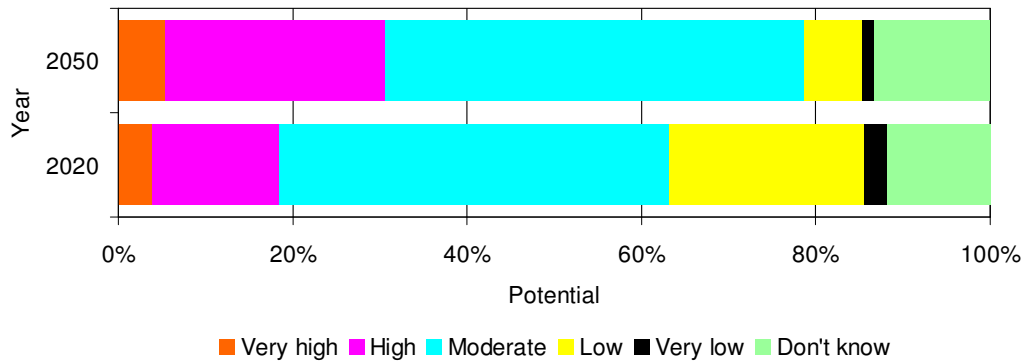


Figure 10.4: The potential for biochar deployment in Europe by 2020 and 2050

## 10.2 Carbon abatement in the UK

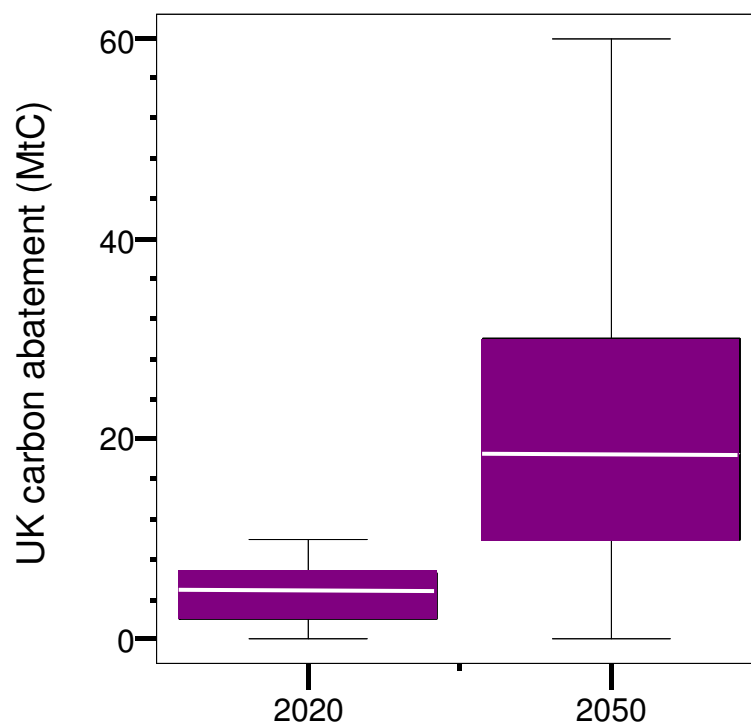


Figure 10.5: How important in terms of carbon reduction potential do you think biochar will be in achieving deep carbon abatement in the UK by 2020 and 2050?

Figure 10.5 and Table 10.1 show the response to the question of how much carbon abatement can be achieved from biochar deployment in the UK by 2020 and 2050. The box plot shows the minimum value, the median (q2), the lower quartile (q1; 25% below the median), the upper quartile (q3; 25% above the median) and the maximum value. Any outliers are included, but outliers more than three times the inter quartile range (IQR) or three box plot lengths from the mean) have been removed from this figure. Reductions are relative to 1990 emissions of 212 MtCeq. By 2020, a reduction of 82 MtC is needed to meet a 40% reduction target. By 2050, a reduction of 170 MtC is needed for 80% reduction. It can be seen that respondents expect larger reductions from biochar in 2050 than in 2020.

	tC reduced by 2020 (n=23)	% of 2020 emissions reduction target abated	MtC reduced by 2050 (n = 23)	% of 2050 emissions reduction target abated
Min	0	0	0	0
q1	3	4	10	6
q2	5	6	20	14
q3	10	12	30	17
Max	200	244	800	470

Table 10.1: Carbon which can be abated annually from UK biochar deployment by 2020 and 2050

If the biochar carbon abatement expected by the mid 50% (or IQR) of the group was achieved this would constitute 4–12% of the 40% reduction needed by 2020, and 6–17% of the 80% by 2050 reduction. The respondents' estimate for 2020 of between 4–12 Mt C yr<sup>-1</sup> abatement compares with LCA results in Chapter 8 that provide a figure of between 1–6 Mt carbon abatement. Respondents may, therefore, be somewhat over-optimistic on the availability of feedstock for biochar production in the UK: on the other hand, respondents were addressing this issue with respect to 2020 rather than today or the short-term (which is the focus of the LCA assessment). Even though the majority of the responses were quite compact, which suggests a consensus for the majority, there were still disparate views. Some respondents suggested that no abatement is possible, whilst others suggested that biochar alone could more than exceed the abatement target for 2020 and 2050.

### 10.3 UK feedstock potential

Potential feedstocks for the UK scenario were considered and the results presented in Figure 10.6 for UK respondents.

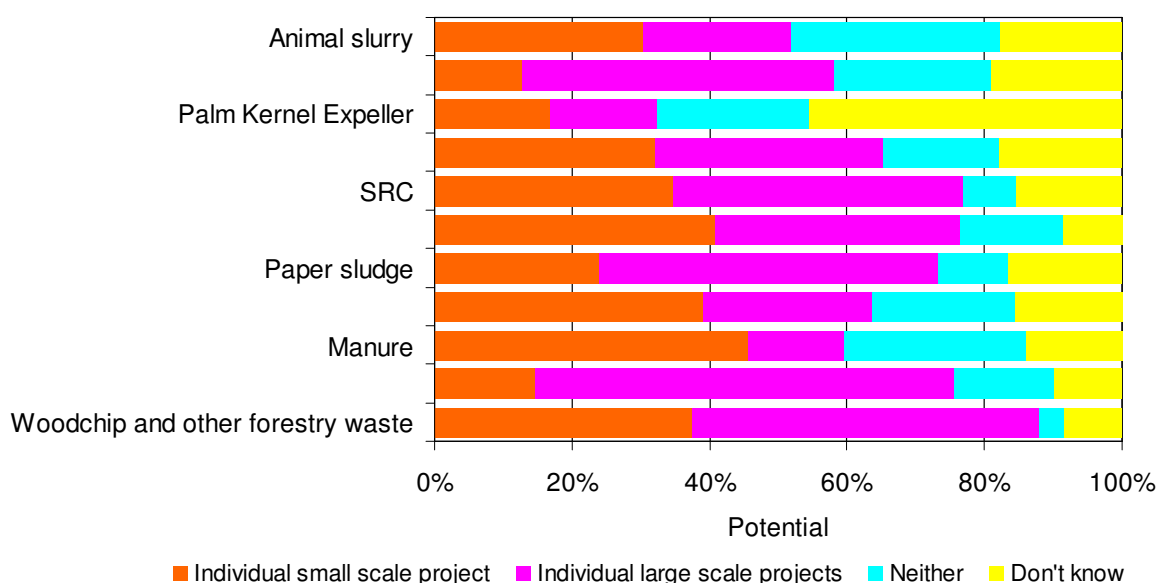


Figure 10.6: At present what feedstocks do you expect to have the most potential for biochar production in the UK? Small scale = individual projects involving <math>10 \text{ t yr}^{-1}</math> biochar, large scale = Individual projects involving >math>10 \text{ t yr}^{-1}</math> biochar).<sup>21</sup>

<sup>21</sup> The definition of small- and large-scale PBS differs from those used in Chapters 8 and 9; thinking on PBS has evolved during the course of the work but makes it difficult to interpret responses to this question in the context of other aspects of the report.

Woodchip, municipal organic waste, paper sludge, arable crop residue and SRC were considered to have the most potential. A range of scales were expected, with the greatest potential for small scale projects being for manure (45.6%, n=79) and arable crop residues (40.7%, n=81), while the greatest potential for large scale projects was from feedstocks already collected in large centralised facilities (e.g. MSW, woodchip, sewage sludge) and from dedicated biomass crops (e.g. SRC).

#### 10.4 Mean residence time in soil

Respondents were asked to estimate the likely mean residence time (MRT) of biochar (Table 10.2, Figure 10.7). Maximum and minimum residence times were also requested.

	Maximum residence time	Mean residence time	Minimum residence time
minimum	100	20	1
q1	1900	500	43
median	5000	1000	100
q3	10,000	1600	391
maximum	1,000,000,000	10000	7000

Table 10.2: Estimates of the mean residence time of biochar in soil

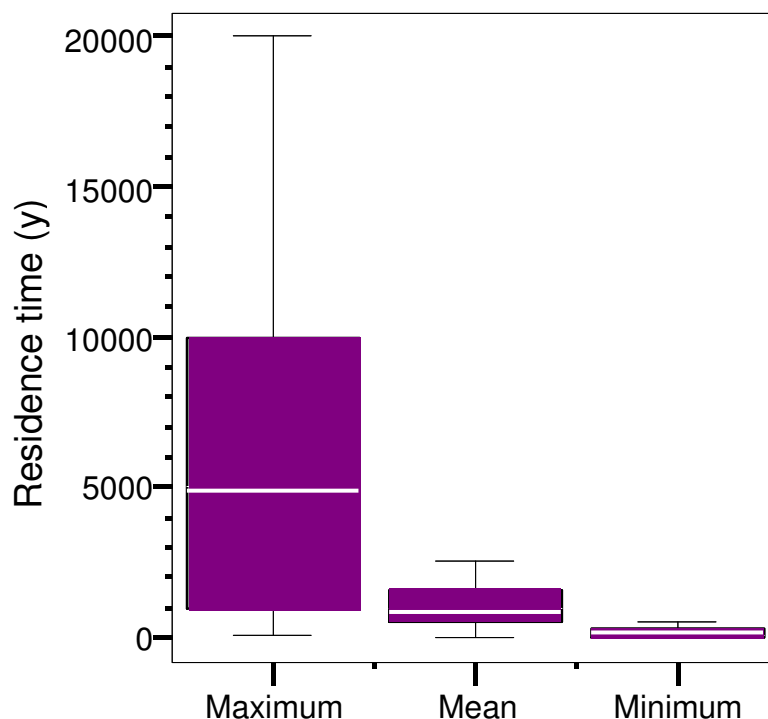


Figure 10.7: Estimates for the mean residence time of biochar in soil

Nearly half of the sample (47%) suggests that there is not enough evidence available at present to estimate the mean residence time of biochar (n=137; Figure 10.8). Less than one fifth of the sample believed that there is sufficient information to address the question of the MRT. This level of uncertainty is very important given that the carbon equivalent abatement from biochar (and its cost) is highly sensitive to the assumed MRT of biochar (see Chapter 8). Furthermore, many of the respondents do not consider that they possess the specialist knowledge to answer the question concerning MRT: between 37 and 44% of respondents

selected “don’t know”.<sup>22</sup> Only 6% of the sample felt that they had sufficient knowledge to answer the question. And there were only five respondents who thought that there is enough evidence *and* that they personally had enough knowledge to estimate the MRT.

Response	No. respondents	%	n
In my opinion, there is not enough evidence available to answer this	64	46.7	137
In my opinion, there is sufficient evidence available to answer this	24	17.5	137
I feel I do not have enough knowledge of this subject to answer this question accurately	46	33.8	137
I feel I have sufficient knowledge of this subject to answer this questions accurately	8	5.8	137
Other	42	30.7	137

Table 10.3: The state of knowledge surrounding estimation of mean residence time of biochar in soil

Data from those who responded “In my opinion, there is sufficient evidence available to answer this” were selected; the data show reasonable consensus (Figure 10.8; Table 9.4).

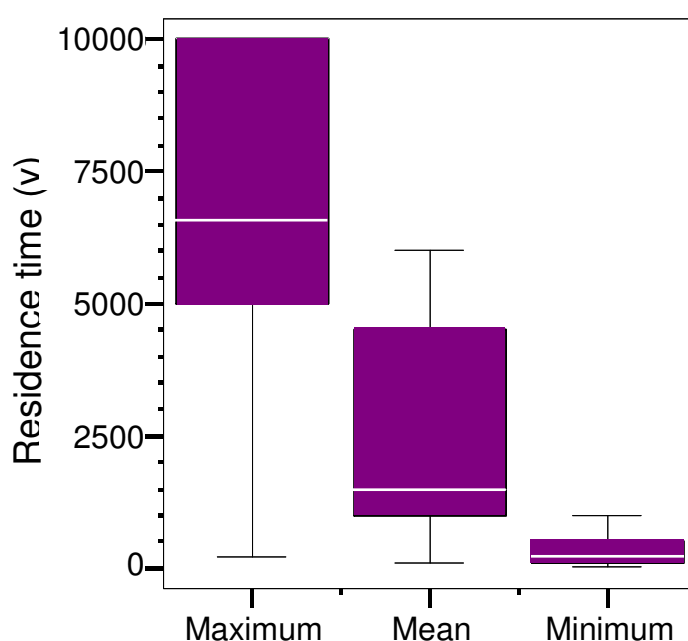


Figure 10.8: Estimates from those who feel that there is sufficient evidence to predict mean residence time of biochar in soil

	Maximum residence time	Mean residence time	Minimum residence time
minimum	200	100	20
q1	500	1000	100
median	10000	1500	200
q3	10000	4500	500

Table 10.4: Estimates from those who feel there is sufficient evidence to predict the mean residence time of biochar in soil

22

	No. of respondents	% of respondents	n
Mean residence time: 'Don't know'	53	38.7	137
Maximum residence time: 'Don't know'	58	42.3	137
Minimum residence time: 'Don't know'	60	43.8	137

As a carbon abatement strategy, this report proposes that PBS must abate carbon on at least a centennial time-scale. Some of the lower estimates of the MRT would render the PBS approach as a less desirable option for CA, though it may still be desirable from the perspective of agronomy and sustainable soils. Several respondents held a different perspective and commented that exact knowledge of the MRT is not necessary:

a) “Every measure decelerating the carbon cycle slows climate change; an exact knowledge of MRT is less important”

b) “It is long enough to be important in C sequestration. The exact time is not that important”

## 10.5 Public opinion

UK based respondents (n=71) were asked whether there may be any negative public opinion regarding biochar application. In the UK context, Figure 10.9 shows that possible impacts on land use / food prices is the major cause of concern, with 66% of respondents suggesting a significant likely concern in the UK. Potential concerns at the global scale relate predominantly to land-use change, biodiversity loss and large-scale plantations.

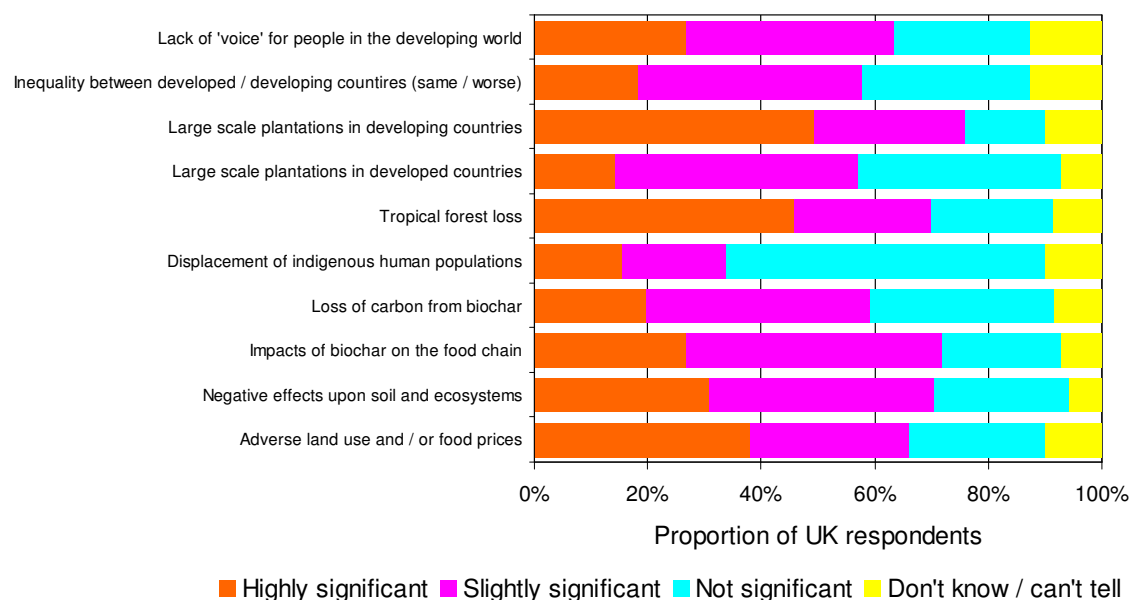


Figure 10.9: What do you think may cause a negative public opinion of biochar in the UK?

## 10.6 Barriers

Figure 10.10 shows that UK respondents expected the major barriers to biochar deployment in developing countries were: ‘Lack of knowledge and understanding of the impacts of biochar in soil (78.9%, n=71); ‘Lack of financial or policy incentives’ (73.2%, n=71), and ‘Proves difficult / impossible to monitor and verify deployment of biochar’ (71.8%, n=71).

Lack of financial / policy incentives were a particularly significant barrier, and this is reflected in the respondents views of the future carbon emission policy frameworks which are likely to emerge in Figure 10.11 (i.e. >50% selected options a, b or c – relatively low targets).

The difference in those who anticipate a tough global emissions accord (options d and e, n=38) and those who were more pessimistic about the framework which will emerge over the next few years are shown in Figure 10.12 with respect to anticipated global carbon abatement from the use of biochar (options a and b, n=31). Those who are the most confident in achieving a tougher climate policy framework (options d and e) tend to regard the contribution of biochar to CA as being greater.

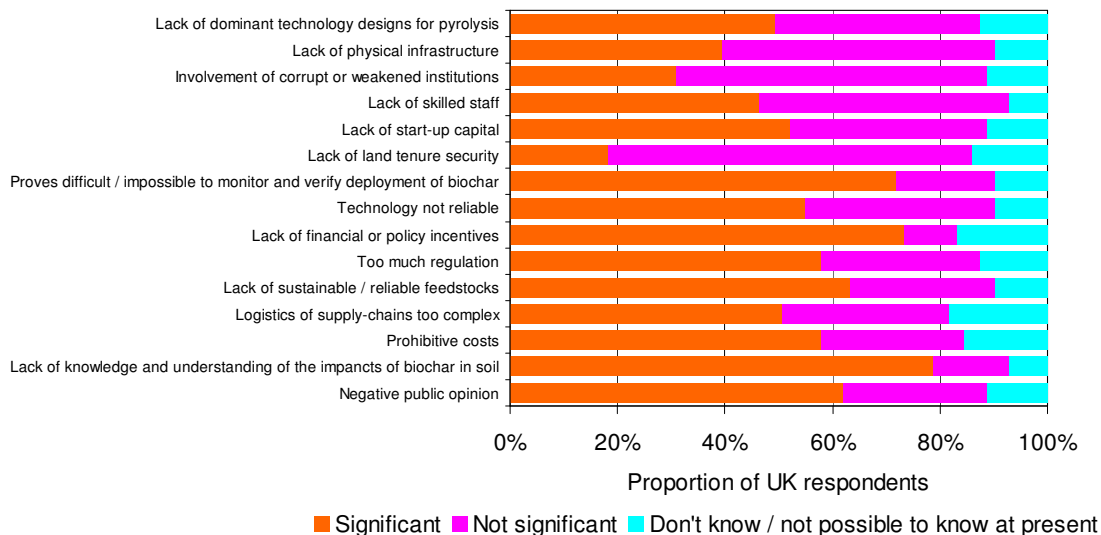


Figure 10.10: What barriers do you think are potentially going to reduce the uptake of biochar as a carbon storage tool in developing countries? (Significant = 'Highly significant' or 'Slightly significant', Not significant – 'Probably not significant' or 'Definitely not significant')

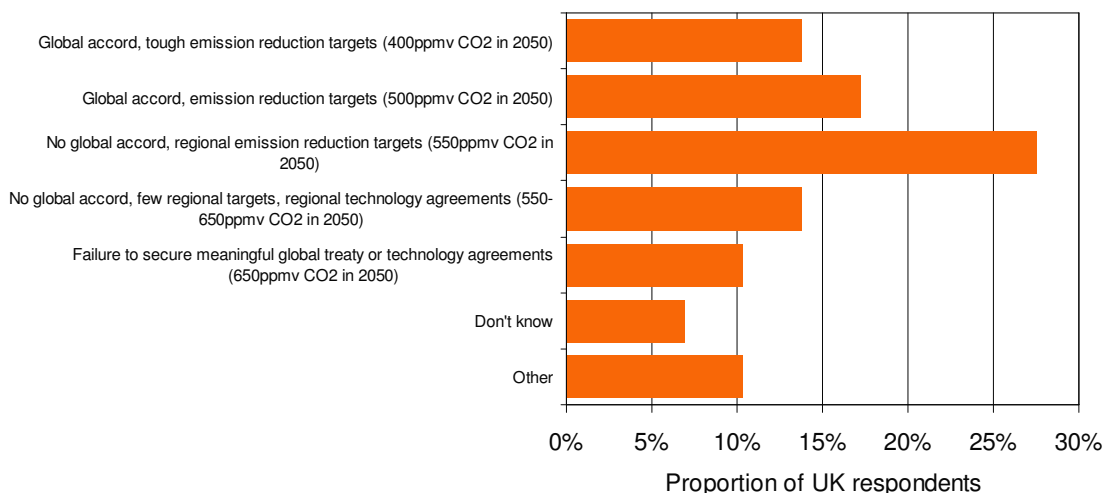


Figure 10.11: What climate policy framework do you think will emerge over the next few years?

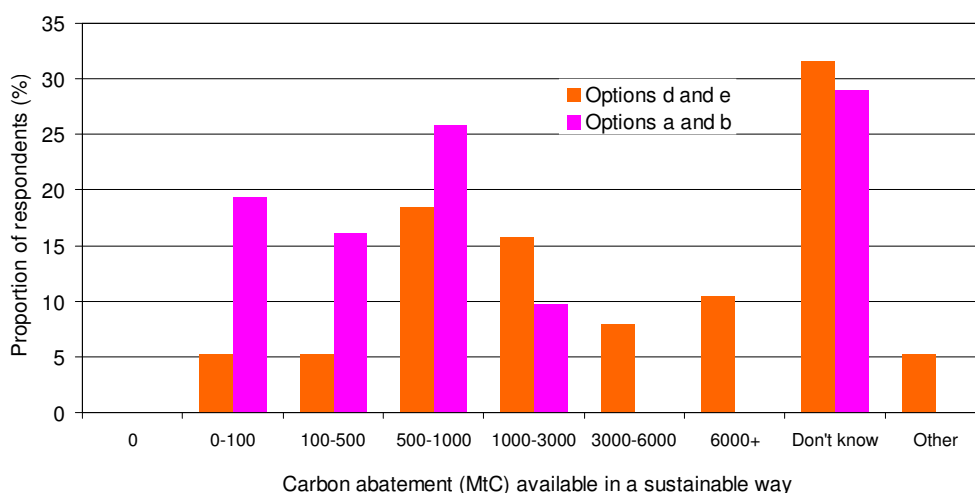


Figure 10.12: Globally, how much carbon abatement from use of biochar in a sustainable way do you think is credible by 2030?

## 10.7 Potential impacts of biochar on GHG fluxes in soil

Respondents were asked about two scenarios for adding biochar to a well-managed arable crop in typical UK conditions: i) a single application of 30 t ha<sup>-1</sup>; and ii) a single application of 30 t ha<sup>-1</sup> followed-up by repeat applications at the rate of 30 t ha<sup>-1</sup> y<sup>-1</sup> for the next 10 y. Only those who considered themselves to have more expertise have been used in this analysis.<sup>23</sup>

Figure 10.13 shows that about half of the respondents thought that there would be an increase in crop yield in the year of a biochar application, and 40% an increase 5 y after a one-off application. However, about 10% thought crop yields might decrease following an 30 t ha<sup>-1</sup> application. A high level of uncertainty was expressed; the 25% of the sample selecting 'don't know / not enough information' for the scenario with a one-off application increased to nearly 50% for the tenth year of repeat application (the second scenario). This likely reflects the general lack of experimental field data for the longer-term impacts on soil.

Respondents were also reasonably confident that biochar would improve water retention in silty and sandy soils (60%), virtually no-one expressing the view that there it would decrease (Figure 10.20). Opinion was split with respect to the impact of biochar on water retention in clayey soils, some respondents believing that water retention would be increased, others that it would be decreased (Figure 10.21). Uncertainty dominated the response to many other questions on the indirect impacts of biochar, although positive effects were more frequently expected. Level of uncertainty was higher for longer periods of biochar addition.

Regarding the impact on bio-availability of fertilisers (Figure 10.14) 'don't know / not enough information' was the most common response (40–60%). There was a perception that bio-availability would improve as the time biochar had been in the soil increased, and likewise for the impact of biochar on field operations (Figure 10.15). Figure 10.17 [should be Figure 10.18] shows that about 40% of respondents expected soil organic matter to increase with biochar addition, and less than 10% considering that it would decrease. Figure 10.19 indicates a more mixed view about the impact of removing 75% of arable straw and returning it to the soil as biochar. However the survey was limited in not defining a baseline and in not asking respondents to explain why they considered repeat biochar applications would result in more soil organic matter,. The respondents may have interpreted some of the questions in this section in a different way to how has been intended. For example, opinion on methane emissions avoided by diversion of decomposing plant residues (Figure 10.17) is hard to interpret, as logically ongoing diversion should avoid CH<sub>4</sub> emission.

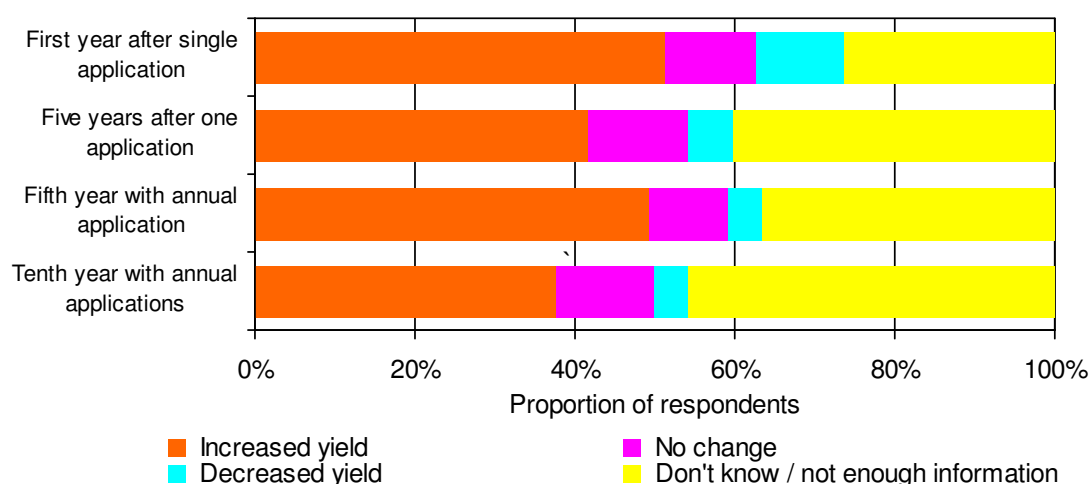


Figure 10.13: What are the impacts of biochar on crop yield?

<sup>23</sup> Respondents who rated their level of expertise in answering the questions in this section as 'very high', 'high' or 'medium' were included. Those who rated their expertise as 'low', 'very low' or 'no expertise' were not included.



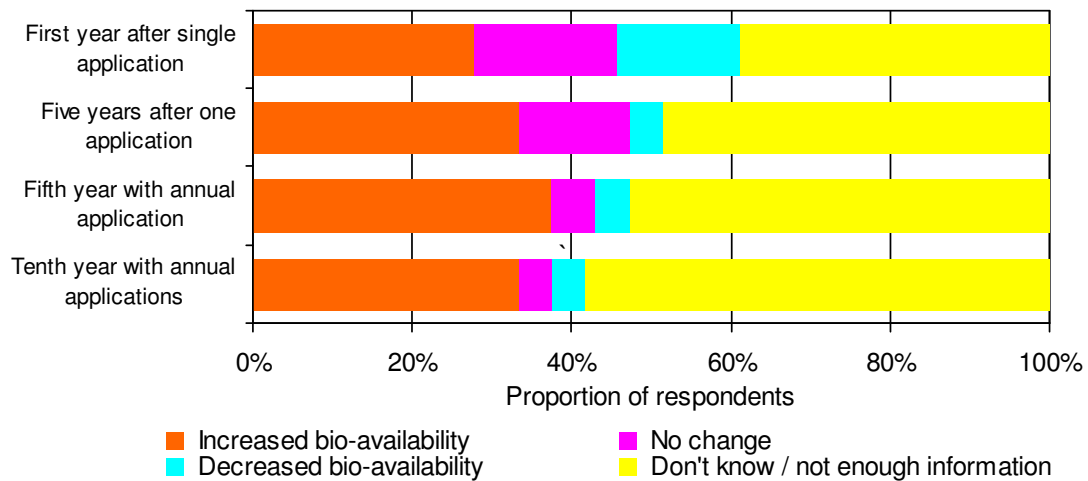


Figure 10.14: What are the impacts of biochar on fertiliser addition?

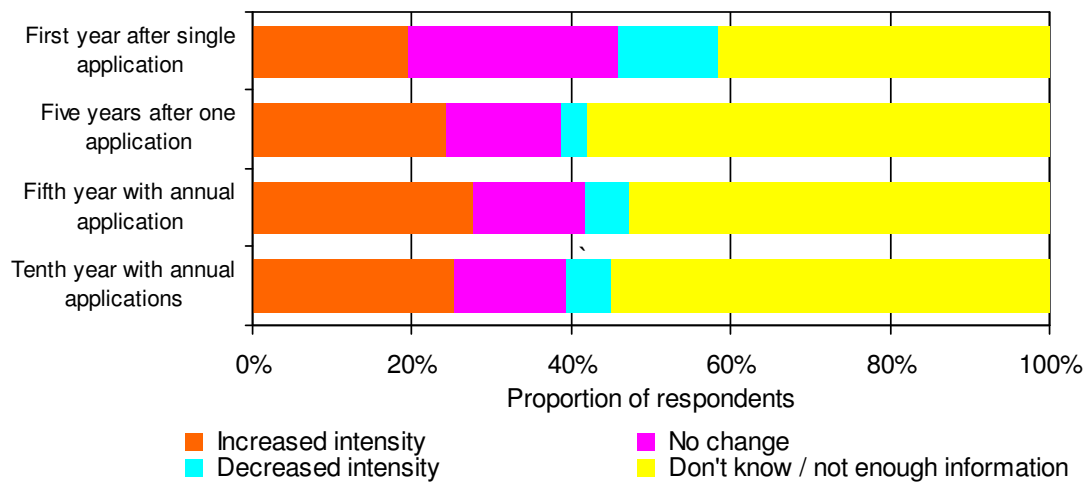


Figure 10.15: What are the impacts of biochar on field operations?

Note: Fuel intensity is the quantity of diesel per hectare used by agricultural machinery

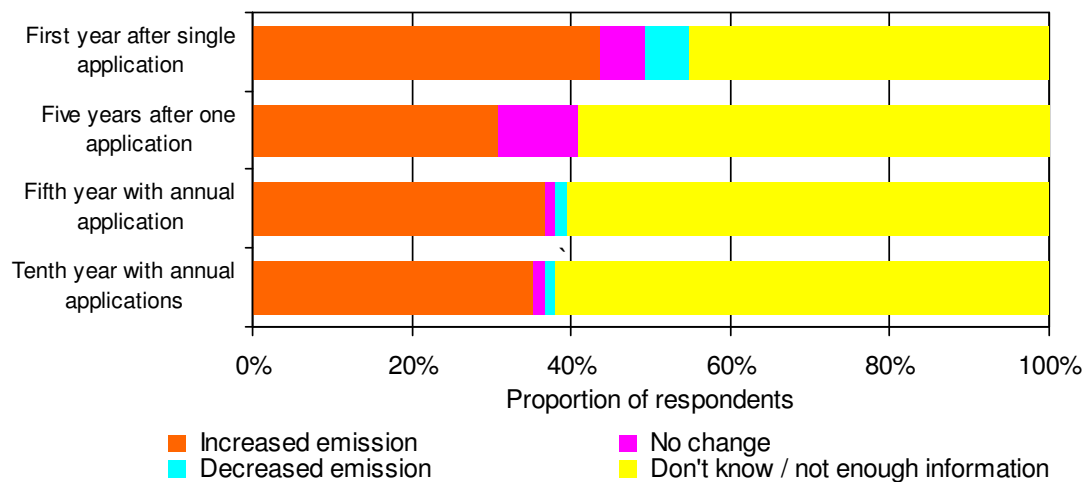


Figure 10.16: What are the impacts of biochar on nitrous oxide emissions from soil to atmosphere?

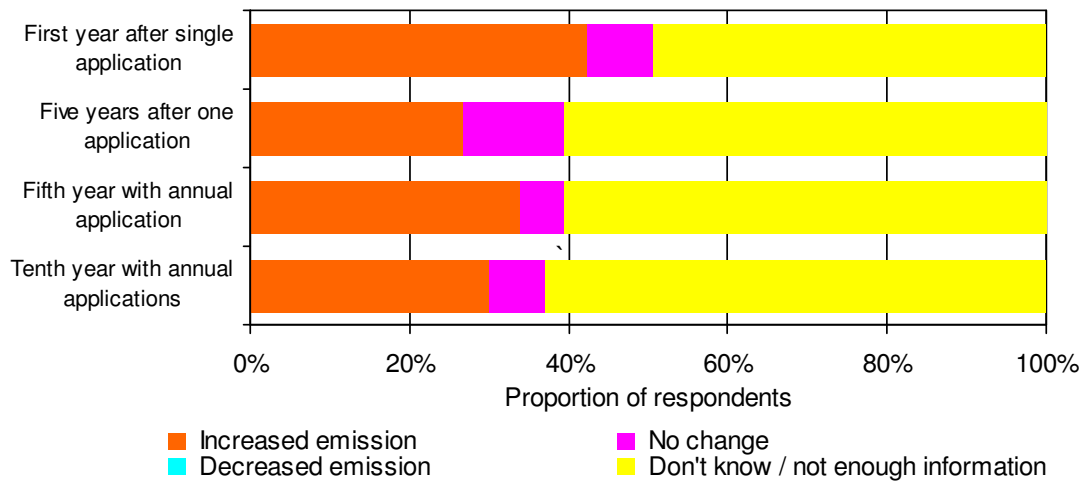


Figure 10.17: What are the impacts of biochar on methane emissions through reduced organic waste made available for anaerobic respiration where crop residues are used to produce char?

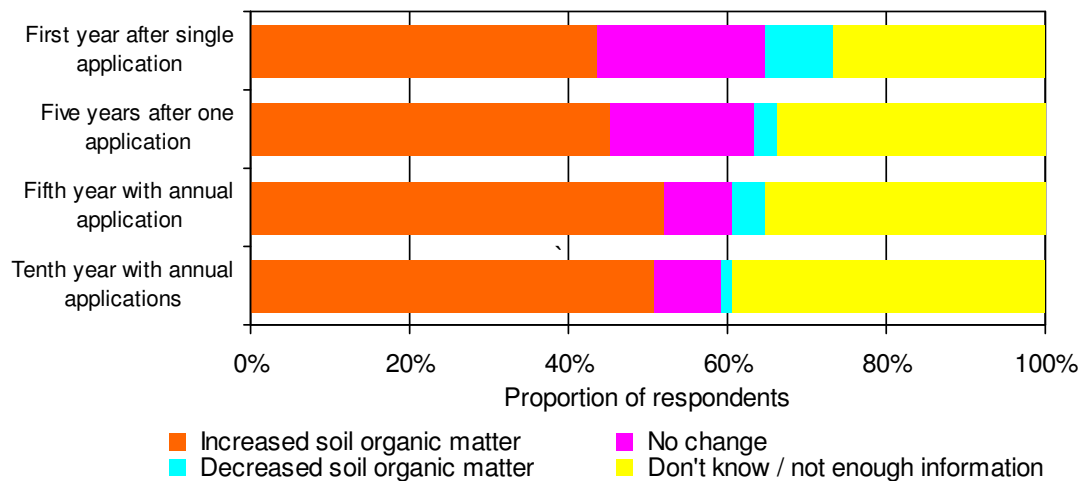


Figure 10.18: Assuming that soil organic matter (SOM) is in equilibrium, what would be the impact of biochar on the existing SOM?

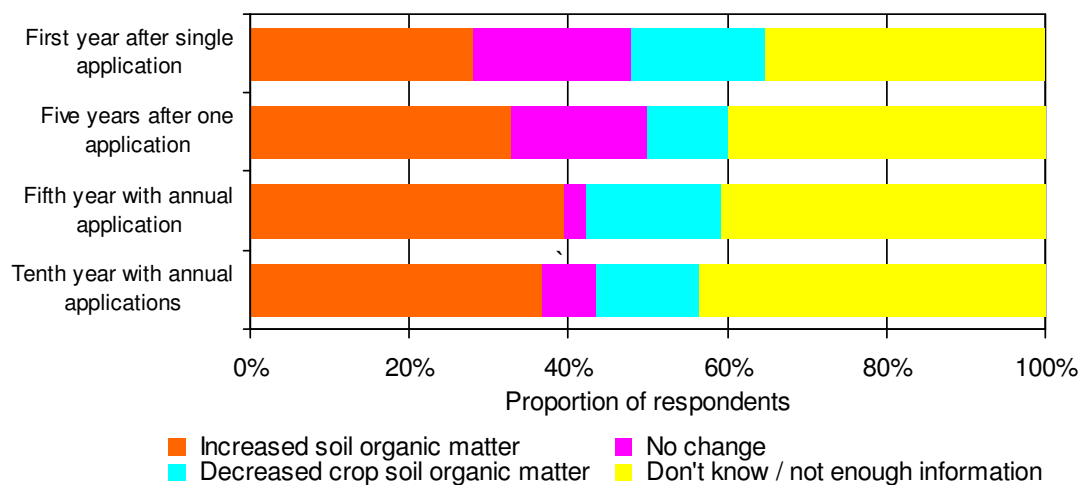


Figure 10.19: What are the impacts of biochar on SOM under the following scenarios on arable land in a closed system where 75% of residues are used to produce char for each application?

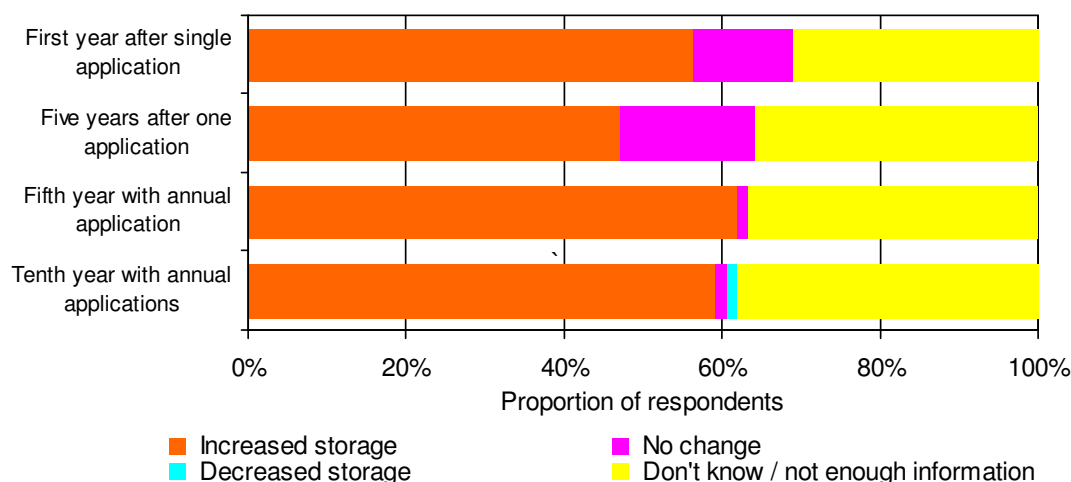


Figure 10.20: What are the water storage properties of biochar in a sandy or silty soil?

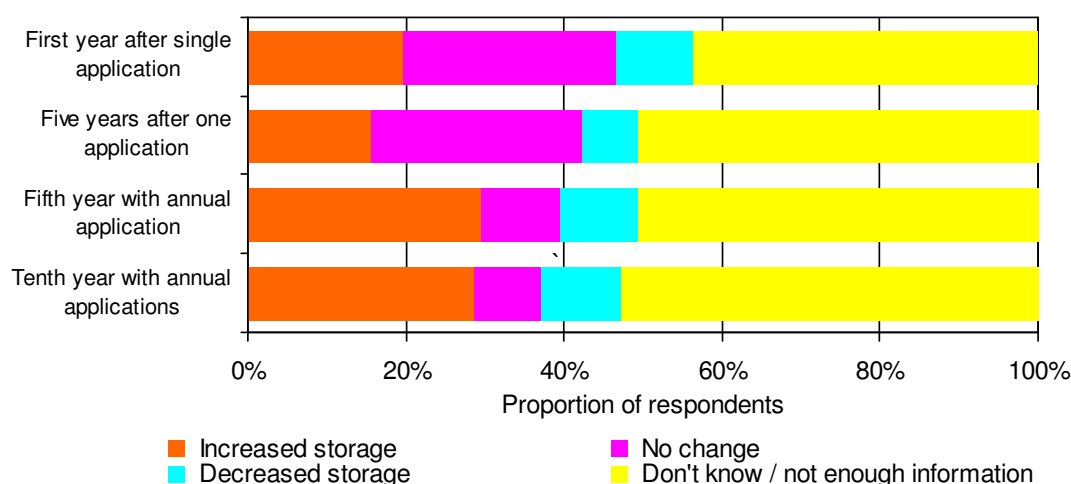


Figure 10.21: What are the water storage properties of biochar in a clayey soil?

## 10.8 The risks of the loss of carbon from biochar

Responses from those who considered themselves to have more expertise were analysed for the potential risks cited for biochar being ineffective in CA due to loss of carbon (Figure 10.22)<sup>24</sup>. Rapid loss of carbon in the highly labile biochar fraction was the main risk identified, followed by hypothesised ‘priming’ of SOM loss. The most common response was ‘minimal’ to the five risks listed, except for the labile carbon fraction. In comparison to some of the other questions, respondents were relatively certain about these issues with 17% suggesting that not enough was known about some of these issues (‘Seepage 2’, n = 87).

## 10.9 Production factors

The production method can have an effect on the physical and chemical properties of biochar according to the respondents (n = 47) who considered themselves to have expertise in this area.<sup>25</sup> There appeared to be a reasonably high level of certainty and consensus (Figure 10.23) on the importance of residence time, temperature, production method and feedstock. There was less consensus regarding the influence of pressure and particle size.

<sup>24</sup> Respondents who rated their level of expertise in answering the questions in this section as ‘very high’, ‘high’ or ‘medium’ were included. Those who rated their expertise as ‘low’, ‘very low’ or ‘no expertise’ were not included.

<sup>25</sup> Respondents who rated their level of expertise in answering the questions in this section as ‘very high’, ‘high’ or ‘medium’ were included. Those who rated their expertise as ‘low’, ‘very low’ or ‘no expertise’ were not included.

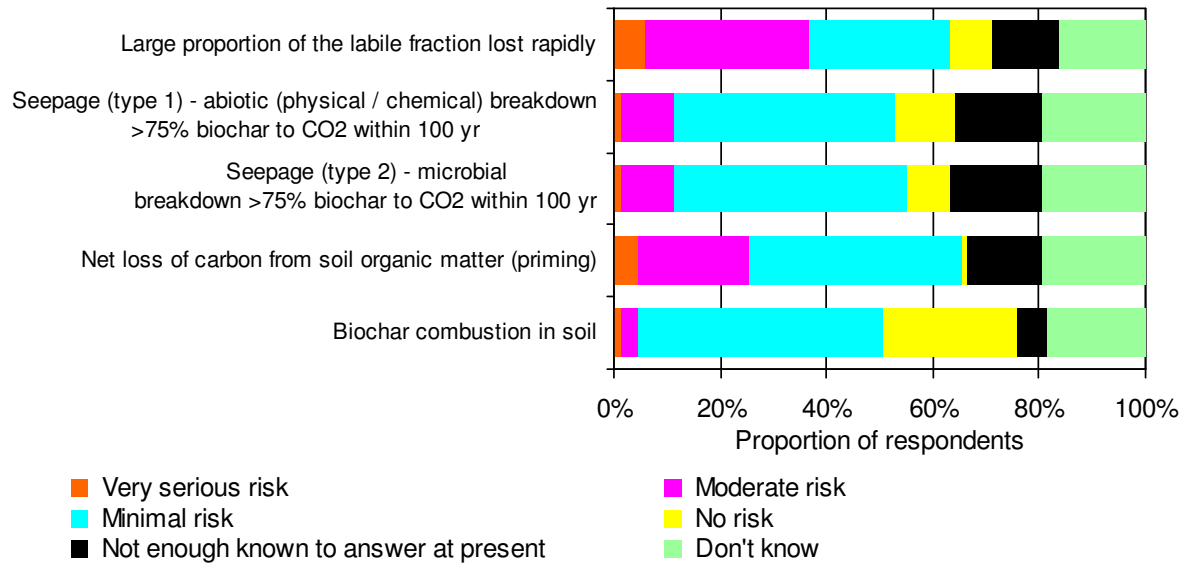


Figure 10.22: What are the potential risks of biochar not being effective in terms of the loss of carbon in the biochar?

Respondents also listed a number of other factors which would lead to a significant or slight variation in the properties of the resultant biochar, including: the status of the feedstock (moisture content, lignin content, granularity, age, residuals on the surface and micronutrient content); the environment within the pyrolysis unit (amount of steam, gas flow, oxygen content, catalysts used, etc.); technology required to meet emissions targets; the heating and cooling rates and the method for cooling the biochar.

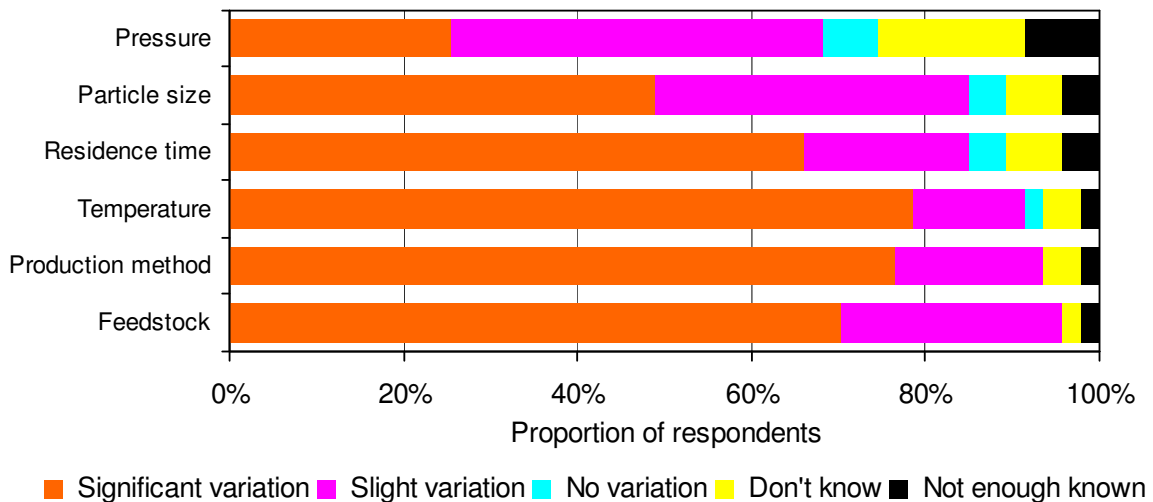


Figure 10.23: What factors are most likely to influence, and to what extent, the properties which biochar has?

### 10.10 Knowledge base

Respondents were asked to assess their expertise in each section of the survey (Figure 10.24). Those with a self-professed 'very high', 'high' or 'moderate' level of expertise constituted between 39% (n = 118) and 70% (n=124) of the sample. The wider impacts of biochar, e.g. on sustainable development, is an area where the respondents had less expertise relative to the other categories.

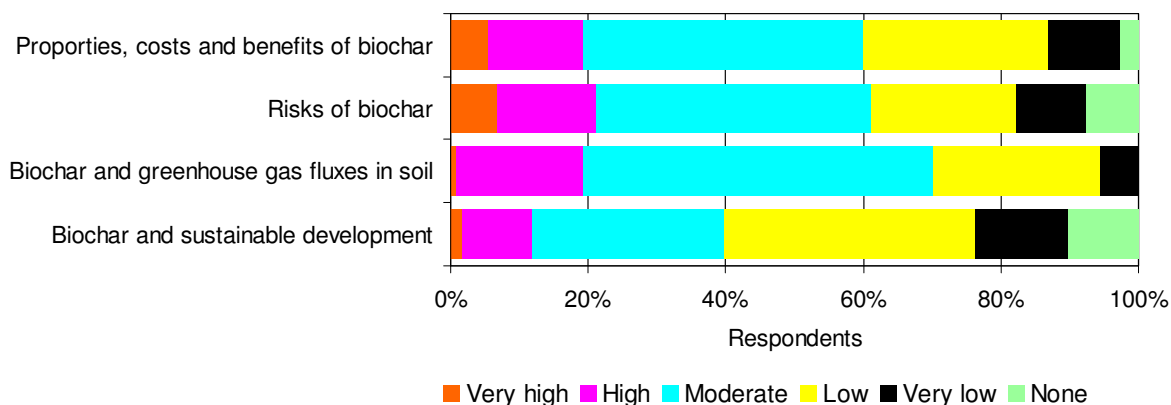


Figure 10.24: The level of expertise which the respondents felt they had after completing each section of the questionnaire

We asked respondents about their sources of information on biochar (Figure 10.25). Peer-reviewed journals form the basis of many of the opinions in the survey; however other sources, including the International Biochar Initiative (IBI) website, are also used by respondents. It is also interesting to note that, in addition to acknowledged scientific experts, in particular Professor Johannes Lehmann of Cornell University, environmental campaigners and environmental scientist ‘celebrities’ such as George Monbiot and James Lovelock have also been widely read on the topic of biochar.

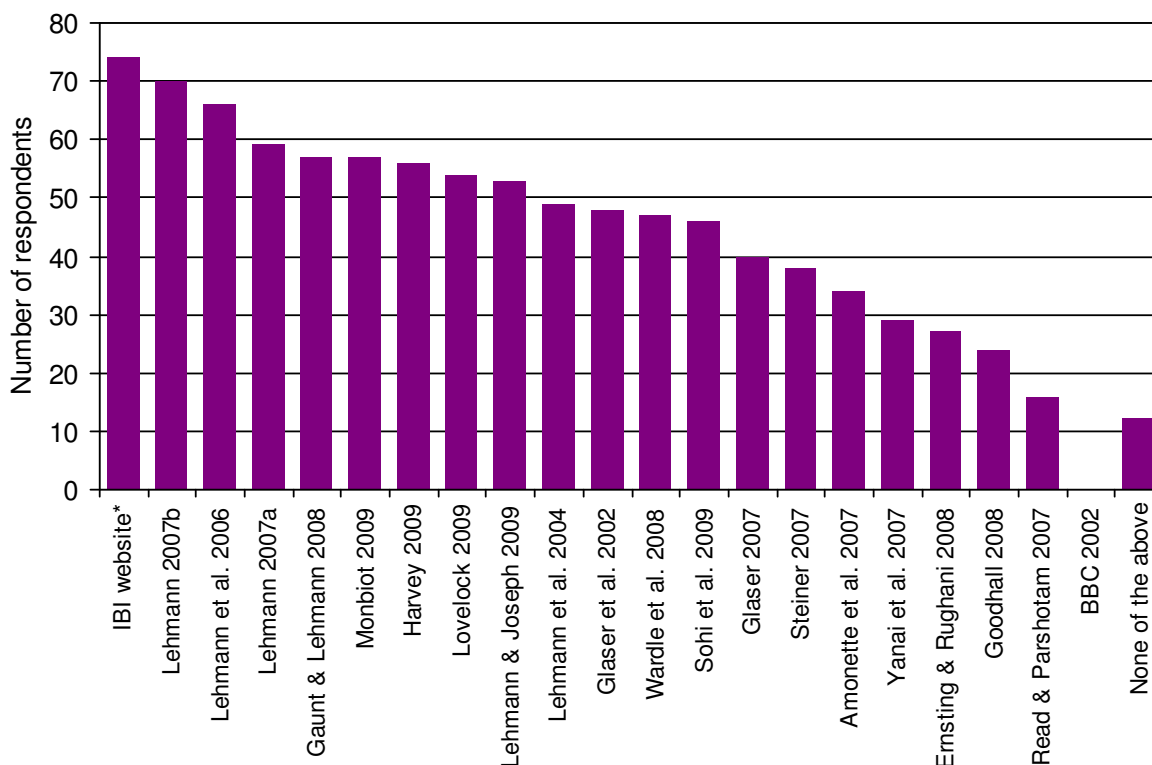


Figure 10.25: Which of the following have you read or watched?

\* International Biochar Initiative (www.biochar-international.org)

## 11 DEPLOYING BIOCHAR IN THE UNITED KINGDOM

This review has highlighted the many uncertainties which still surround the potential benefits and risks of biochar. Clearly, further research is required to address more convincingly some of these important questions. Furthermore, biochar will need to be fully appraised and assessed alongside, and using similar quality and risk assessment protocol and criteria to, other soil amendments such as composts from green waste and food wastes, anaerobic digestate and sewage sludge, etc.

If the balance of emerging evidence suggests that biochar is both safe and likely to display important benefits predicted by some climate and soil scientists, then detailed questions about how it may be efficiently deployed will come to the forefront. Pending the outcome of research efforts to establish its relevance this topic is briefly scoped in the UK context, and drawing on the findings of earlier chapters.

### 11.1 Biochar has a high carbon abatement efficiency relative to other bioenergy options

It is demonstrated in Chapter 8 that pyrolysis-biochar systems (PBS) could be highly beneficial in carbon abatement efficiency terms. The PBS configurations explored here tend to have a higher CAE than that offered by alternative uses of the same biomass in energy generation. Expressed in terms of the weight of biomass, PBS increases the carbon equivalent saving by ca. 60–80% compared with combustion. In terms of power production, carbon equivalent emissions are avoided per unit electricity generated, compared with a small emission associated with conventional bioelectricity generation. Expressed as carbon emissions avoided per hectare, PBS performs well against other bioenergy options. The low end of the PBS range in terms of avoided CO<sub>2</sub>eq ha<sup>-1</sup> y<sup>-1</sup> is the top end of the range of UK bioenergy options, those employing the most efficient conversion technologies such as gasification and combined heat and power. For less efficient bioenergy conversion technologies (such as straight combustion), the CO<sub>2</sub>eq ha<sup>-1</sup> y<sup>-1</sup> avoided emissions are well below those of an equivalent-sized PBS operation – by five to ten times.

### 11.2 Is biochar carbon negative?

It has been claimed that biochar is unique in being ‘carbon negative’. From the LCA undertaken here, the PBS are not carbon negative in a mass balance sense. The carbon content of the feedstock is between 43–50%; hence it would be necessary for the carbon equivalent abatement to be more than 1.58–1.84 tCO<sub>2</sub>eq t<sup>-1</sup> o.d. for the PBS to be carbon negative; whereas the abatement of the systems examined here is 1.0–1.4 t CO<sub>2</sub>eq t<sup>-1</sup> o.d.. The PBS would be carbon negative if the carbon content of the biomass feedstock were ignored, which is the current convention in the bioenergy field. However, this convention assumes that there is an inevitable replacement of any removed biomass with biomass that has exactly the same carbon uptake as that removed. A better approach would be to account for carbon fluxes over a given land-area dedicated to a bioenergy or other crop over the lifetime of the project and to subtract from that the overall CO<sub>2</sub> equivalent emissions arising from the biomass conversion, whilst adding the fixed carbon stabilised in the biochar. This would take account of greenhouse fluxes associated with land-conversion at the beginning and end of the project, as well as yield and process changes.

### 11.3 The agronomic and other soil benefits of biochar are credible but not well established in the UK context

In the UK context the key potential benefits that biochar might offer beyond carbon sequestration are the mitigation of trace gas emissions from soil, pH modulation, improvement of nitrogen use efficiency, and on irrigated land and certain sandy soils in low rainfall areas, improved water use efficiency. As outlined in Chapter 4 these are conceivable or probable effects that remain to be demonstrated. Improvement of soil quality, enhanced

soil organic matter dynamics and associated soil structural improvement are uncertain, but would be of key significance given the established value of organic matter to agricultural enterprises. There is also uncertainty regarding potential risks and it will be necessary to demonstrate that these are minimal and manageable.

#### **11.4 The logistics of producing, storing, transporting and applying biochar in agricultural systems requires much more innovation**

There is very little practical experience at the present time of organising and managing the production, distribution, storage and application of biochar onto land. If the quantities of biochar to be applied in any one year are in the order of a few tonnes per hectare, it is likely that existing storage facilities and equipment (e.g. lime spreaders, muck spreaders) would be adequate. If large quantities of biochar are to be used - in the order of tens of tonnes per hectare - then large dedicated storage facilities are likely to be required. The storage issue is exacerbated by the lag that is likely between the availability of suitable biomass supplies (mostly in late summer and autumn for virgin biomass feedstock) and the time period when biochar can be safely added to soils (mostly spring and early autumn). Transporting large amounts of feedstock from the source to a pyrolysis unit (PU), then from the unit to a storage facility and, finally, back to a point of application will be expensive, result in CO<sub>2</sub> emissions from diesel and increase traffic levels on roads, which is generally unpopular, especially in rural areas. Transporting 3 Mt of biomass to produce 1 Mt biochar would involve about 220,000 lorry journeys (assuming the lorry has a capacity to convey 23 Mt biochar, and assuming that biochar can all be back-transported in the truck that has delivered the biomass). In some locales, this transport requirement may become a problem for PBS. Dedicated storage facilities for biochar are an expensive option, whether on- or off-farm, and innovation will be needed on alternative ways of storing biochar safely and effectively, for example in appropriate containers at the field margin. Furthermore, for large-scale deployment, it is likely that a specialised contractor would provide large-scale biochar addition as an out-sourced service to a farmer, hence benefiting from more efficient economies of scale and access to specialised application machinery. The ideal solution to storage and transport issues is if the spatial and temporal separation between collection of the feedstock and the production of biochar can be minimised.

#### **11.5 Biochar is, currently, an expensive way of abating carbon, but the costs would likely come down with investment**

If biochar costs £100 t<sup>-1</sup>, and assuming a CSF of 0.65, the cost of abating one tonne of carbon in biochar is about £150, or £42 t<sup>-1</sup> CO<sub>2</sub>. The theoretical market value of CO<sub>2</sub> in the EU ETS is €40 t<sup>-1</sup>CO<sub>2</sub>, so biochar at £100 t<sup>-1</sup> begins to look credible and competitive with CO<sub>2</sub> capture and geological storage (CCS) and off-shore renewables. On the other hand, the current market value of a tonne of CO<sub>2</sub> on the EU Emissions Trading Scheme (EU ETS) is ca. €13 (November 2009); hence, there is, at present, a large disparity between the carbon abatement cost through use of biochar and the market price of carbon on the EU ETS. Clearly, at the current time, many PBS produce far more expensive biochar than this, though some systems also produce much cheaper or even 'free' biochar (though producers might begin to charge for feedstocks for which they currently pay a tipping fee, if biochar becomes a product with an economic value). It is also likely that learning effects will bring down the costs of producing biochar if companies begin to invest R&D resources into the technology and logistics of transporting, storing and applying biochar to soils. The feedstock costs is one of the key issues, however, and that is unlikely to decrease rapidly in the UK, though there may be opportunities for long-term contracts at relatively low feedstock cost where high variability in market prices occurs (e.g. for straw). The CSF is an area of uncertainty, and it may be possible through judicious engineering of biochar to significantly increase the CSF. If the CSF is 0.95, for example, then the cost of abating a tonne of CO<sub>2</sub> (produced at £100 per tonne) would reduce to £29. A key finding from the study is that efficiency in terms of carbon abatement does not readily translate into efficiency in economic terms. *Note, however, that*

*no agronomic or soil benefits have been included in this analysis.* If such benefits occur, and can be reliably estimated and included, then clearly the value of biochar will increase; and the carbon abatement cost could be lower than €30-40 t<sup>-1</sup>CO<sub>2</sub> – this is important given that many experts are not confident that the carbon price on the EU ETS will increase to this level in the near future.

### 11.6 How does biochar abatement compare to abatement from other parts of the agricultural, forestry and land-use sectors?

Moran et al. (2008) undertook a study of marginal abatement costs (MACs) for the Committee on Climate Change (CCC) in which the Central Feasible Potential abatement from agriculture, land-use, land-use change and forestry (ALULUCF) by 2022 was approximately 11 MtCO<sub>2</sub>eq (with maximum technical potential of 24 Mt CO<sub>2</sub>eq). This was relative to 2005 emissions from these sectors of 45 Mt CO<sub>2</sub>eq. ADAS recently revised these numbers downward to 5.2 MtCO<sub>2</sub>eq for a carbon price of £40 tCO<sub>2</sub>eq (ADAS, 2009). Meanwhile, in its 2009 Low Carbon Transition Plan, DECC has proposed that agriculture should reduce its GHG emissions by 6% by 2020, which is approximately 3.0 MtCO<sub>2</sub>eq (DECC, 2009). Biochar potentially offers a way in which abatement from ALULUCF could be enhanced (though that part of the biochar CA from fossil fuel offsets would not be included as arising from ALULUCF mitigation; rather, it would be accounted for via reduced fossil fuel consumption in the energy sector).

### 11.7 How much biochar could be produced in the UK and how much carbon abatement would this constitute?

A preliminary estimate is that the virgin and non-virgin biomass resources combined give the following levels of CO<sub>2</sub>eq y<sup>-1</sup> abatement in the UK (Table 11.1).

Feedstock availability	Abatement per annum (Mt CO <sub>2</sub> eq)		Biochar produced per annum ('000 t)			Applied land area ('000 ha)	
	CO <sub>2</sub>	C	Virgin biomass resources	Non- virgin biomass resources	Total available for use on land	Scenario 30/1: 30 t ha <sup>-1</sup> first year, then 1 t ha <sup>-1</sup> (20 y horizon)	Scenario 10/1: 10 t ha <sup>-1</sup> first year, then 1 t ha <sup>-1</sup> (20 y horizon)
Lower resource	3.590	0.980	1019	0	1019	416	703
Higher resource	15.915	4.340	2547	1934	3514	1434	2423
High resource	21.867	5.960	3267	2902	4718	1926	3254

Table 11.1: Preliminary and provisional estimate of annual biochar production and carbon abatement using three scenarios for virgin biomass feedstock and the resulting land-use implications

### 11.8 Can biochar from a non-virgin biomass resource be used on agricultural land?

Some non-virgin biomass resources would generate biochar that may be suitable for agricultural land. Some, in a non-pyrolised form, are already used as an amendment on agricultural land, e.g. sewage sludge, composted green waste and food waste and poultry litter. Conversion of 50% of the non-virgin biomass identified in the feedstock table (which already excludes many types of waste material) into biochar was assumed, and passing regulatory requirements for incorporation into soils. This amounts to 2.77 Mt feedstock (approximately 1 Mt biochar) under the high resource scenario and 4.34 Mt (approximately 1.5 Mt biochar) under the very high resource scenario.

### 11.9 How much land could be treated with biochar?

The percentage of different types of land that could be treated with biochar is shown in Table 11.2 under the three different scenarios, assuming a one-off 30 t ha<sup>-1</sup> application. It can be



seen that all potatoes and horticultural land could be treated under all three scenarios within just over 5 y. The choice would then be to apply biochar to arable land or grassland or to a mixture of both. There is sufficient arable land to utilise all biochar produced under all scenarios for 32 y to over 130 y (in the low supply scenario). Grassland has even more capacity and could provide storage for 45–210 y biochar production at the same application rate. Table 11.2 illustrates the point that land availability is unlikely to be a constraint to the use of biochar (assuming the demand for deployment exists); availability of biochar and of feedstock from which to produce biochar, as well as the cost, are likely to be much more important constraints on deployment. An important constraint on where biochar is deployed arises from the need not to deplete soils too rapidly of essential nutrients. Continuous removal of straw for pyrolysis for example, with biochar applied to horticultural soils for economic reasons, could result in the loss of nitrogen, phosphorus, potassium and other nutrients that would have to be replaced through chemical input. Assuming straw was previously not removed for a different purpose, SOC would also gradually decrease with the lower returns to the soil and necessitate additions from other sources (such as compost) to maintain aspects of soil performance that relate to soil organic matter content.

Crop type	Current cropped area ( ha) <sup>1</sup>	Years of biochar application at 30 t ha <sup>-1</sup>		
		Lower biochar supply scenario	Higher biochar supply scenario	High biochar supply scenario
Potatoes	144,000	4	1	1
Horticulture	170,000	4-9	1-3	1-2
Cereals	3,274,000	9-106	3-31	3-24
Other arable	1,152,000	107-134	32-42	25-32
Grassland < 5 y	1,141,000	or: 9.5-34	or: 3-13	or: 3-10
Grassland > 5 y	6,036,000	then: 35-212	then: 14-66	then: 11-49
Total all types	11,917,000	351	102	76

Table 11.2: The number of years to deploy biochar at 30 t ha<sup>-1</sup> for different agricultural systems and three biochar supply scenarios. Source: Chapter 7, <https://statistics.defra.gov.uk/esg/quick/agri.asp>

### 11.10 When would pyrolysis-biochar systems be available?

Given the need to establish biomass infrastructure and supply chains and to develop appropriate pyrolysis technologies, it is difficult to envisage that biochar could be produced on the scale implied by the higher and high resource scenarios before 2020. The biochar production scenarios assume that a mixture of large-, medium- and small-scale units would be employed and an estimate of the number of units that might be necessary is shown in Table 11.3, assuming that between 22 and 27% of the available feedstock goes to small-scale units and the rest to medium- and large-scale units.

Biochar production scenario	No. units by unit size (annual feedstock throughput)		
	Small scale (< 2000 t y <sup>-1</sup> )	Medium scale (2000-25,000 t y <sup>-1</sup> )	Large scale (25,000-100,000 t y <sup>-1</sup> )
Lower resource	1100	33	8
Higher resource	5300	110	23
High resource	7500	251	29

Table 11.3: Estimate of the number of pyrolysis units, of different feedstock processing capacities, that would be required to produce the volumes of biochar envisaged under three biomass supply scenarios

### **11.11 Supporting the front-runners: a credible strategy for initiating biochar deployment in the UK**

Biomass resources in the UK are increasingly sought for a range of uses, including combustion, gasification, pyrolysis, composting and anaerobic digestion; hence, 'spare' biomass is likely to become increasingly scarce. Plans are already underway for more straw and wood combustion plants, biomass gasification facilities and AD plants. Under the new banding system of the Renewables Obligation, these units will attract either 1.5 or 2.0 Renewable Obligation Certificates (ROCs)  $\text{MWh}^{-1}$ ; by contrast, biomass co-firing will only attract 0.5 ROCs  $\text{MWh}^{-1}$ , and landfill gas only 0.25 ROCs  $\text{MWh}^{-1}$ . Most of these plans are well ahead of PBS, which is still at the R&D stage. A few PBS 'front-runners' could be identified quickly and implemented, so as to promote rapid learning and bring down carbon abatement costs associated with PBS. A potential front-runner is arboricultural arisings with a carbon abatement cost ( $\text{t CO}_2\text{eq}$ ) of £2–£46 (if produced at a large-scale, though an additional feedstock would be required to support the requisite feedstock rate), or £88–£115  $\text{t CO}_2\text{eq}$  (if produced on a small or medium-scale). While potentially less desirable from a regulatory perspective, non-virgin feedstocks are more attractive than most virgin feedstocks from an economic perspective. The slow or intermediate pyrolysis of sewage sludge is an obvious front-runner here (carbon abatement cost of £48–£76  $\text{t}^{-1} \text{CO}_2\text{eq}$ ) and is already attracting research and commercial interest.

## 12 RESEARCH NEEDS

Biochar is a complex, multi-functional material that requires improved mechanistic knowledge and understanding – of its production, properties, impacts, interactions, costs and benefits. Without this mechanistic process understanding, it is difficult if not impossible to predict and assess accurately the benefits of biochar for either greenhouse gas abatement or for addition to the soil even with evidence from individual field trials.

### **Pilot production research facilities for biochar and bespoke biochar**

**What is the need?** A range of technologies can be used that produce biochar as a by-product – not only slow, intermediate and fast thermal pyrolysis, but also microwave-induced pyrolysis, hydrothermal carbonisation and gasification. A strategic approach to producing, testing and comparing biochar samples from these different technologies, under specific reproducible conditions, would improve the evidence base. Facilities are needed to serve the UK community researching biochar, focusing current and future effort away from charcoal and toward biochar, produced from designated feedstocks under highly specified process conditions.

**Why?** The engineering and technological challenges are intimately related to the bespoke biochar concept – namely engineering biochar with specific and controlled properties, designed for particular purposes (e.g. carbon abatement, short- and long-term agronomic gain, waste management and pollution control, energy production, etc.) and contexts of application (soil types, agricultural systems, other land-uses, etc.).

**When?** The need is urgent if biochar is to have a role in tackling climate change in the next several decades, and necessary for any future soils application of biochar.

**Resource implications:** The resources required are reasonably large, but not large compared to much technology-development since biochar can be produced at small-scales using relatively straightforward equipment.

**How well advanced is existing research?** There is currently limited activity or capacity anywhere in the world for technological evaluation of biochar production. Through judicious investment, the UK could be amongst the leaders here.

**Ability to address key questions:** Once equipment is in place, it should be relatively straightforward to address the key questions which arise, though some issues will inevitably take time to answer.

### **Examples of key questions to address:**

*Recipes for producing bespoke biochar with specific properties and functions* – acquiring the technological know-how to produce biochar with defined properties based upon a process understanding of production conditions.

*Better understanding of the carbon and energy balance of alternative biochar production technologies* – as yet there is little consistent and high-quality data on pilot- and commercial-scale pyrolysis (especially slow and intermediate) without which any evaluation of biochar is impaired.

*Better understanding of the superlabile, labile and stabilised components of biochar* – better knowledge of what influences the Carbon Stability Factor for biochar is required, along with the effects in soil and field of labile versus stable carbon.

### **The predictability and certainty of the impacts of biochar**

**What is the need?** If biochar is to be a commercial proposition, it will be necessary for reliable predictive knowledge of its impacts in particular soil and agronomic contexts to be well established (just as is the case for chemical fertilisers or pesticides). There is also need for a practical and scaleable method by which the stable component of biochar can be

established experimentally through acceleration of initial degradation, as well as for examining the change that occurs soon after incorporation in soil.

**Why?** Only if the user is confident of positive and cost-effective benefits of biochar, when applied at particular rates, will a biochar market emerge. If the purpose is solely carbon storage, then the key issue will be long-term stability of the biochar.

**When?** For the purposes of carbon storage, urgent knowledge of long-term stability will be necessary. Predictive knowledge of soil and plant impacts is necessary for development of a market for biochar addition to land.

**Resource implications:** The resources required are moderate but progress is being held back by lack of samples and equipment.

**How well advanced is existing research?** Evidence for the stability of charcoal in agriculture and the wider environment has been inferred in detailed studies in the USA and Australia. Work on the definition and stability of biochar is ongoing by established research groups, and has been initiated in the UK, and elsewhere. Work on soil and plant effects is well-established internationally (especially in the USA, Australia, Brazil and Japan). However, this research is still in its infancy with no systematic effort, and although more organised networks appear to be evolving, the opportunity exists for UK expertise to contribute a focused and deterministic approach.

**Ability to address key questions:** In principle, it should be possible to address the stability question relatively quickly. Addressing the soil and plant effects will be more complex and time-consuming because of variability and complexity.

**Examples of key questions to address:**

**These questions / topics can be addressed / answered fairly quickly.**

*Short- and long-term effects* – separating out the long-term and short-term effects of biochar by comparing the functions of fresh and artificially aged material

*Available nutrients and contaminants* – agreement on a methodology to quantify "available" nutrients and contaminants in a biochar matrix.

*Deployment equipment and appliances* – Develop modifications of existing agricultural equipment and implements so as to develop effective and efficient ways of storing and deploying biochar in realistic farm-based scenarios.

*Biochar in grassland systems* – the potential to reduce methane emissions from cattle, biochar as a slurry additive for odour control, etc.

*Methodologies for evaluating the migration of biochar by movement through the soil profile, wind-erosion, water-erosion, etc.* – necessary for regulation and carbon accounting.

*Low-cost monitoring of biochar* – Investigation of field spectroscopy and remote sensing for the low-cost monitoring of biochar added to soil.

**These questions / topics are more difficult, complex and/or simply time-consuming and will take longer to address or answer**

*Nitrous oxide suppression* – examination of the mechanism by which biochar at least under certain conditions, can suppress nitrous oxide emission from soil

*Field experimentation and trials strategy* – Field experiments and trials that encompass diverse rotations and systems (arable, horticulture and grassland) and including feedstocks derived from (*inter alia*) agricultural residues.

*The value of biochar-based soil management* – Compare the likely value of biochar-based soil management against the return that has been established for active use of other organic resources in management of soil.

*Biochar for the control of diffuse pollution* – More research on the ability of biochar to reduce leaching from land (e.g. using buffer ditch experiments) or from other sources (e.g. waterways, road surfaces).

## **Wider biochar sustainability Issues**

**What is the need?** What are the wider impacts of biochar as a system, potentially deployed at different scales and in different spatio-temporal and socio-economic contexts? How can the biochar system be made sustainable?

**Why?** Pyrolysis biochar systems (PBS), or variants thereof, only make sense if they meet minimum sustainability requirements (standard) and avoid incurring adverse environmental, social or economic impacts. Sustainability appraisal methods can be utilised to ensure that biochar at a system level ‘adds-up’

**When?** It is important to understand system level impacts as these help direct more basic research and development, by identifying key sensitivities. It is necessary to evaluate system-level effects prior to real-deployment to understand knock-on effects and potential problems.

**Resource Implications:** The resources required are small compared to the technological and basic scientific research and development required because equipment and experimental costs are typically lower.

**How well advanced is existing research?** Although the UK has strong capabilities to deliver on sustainability and systems research, activity in the USA is currently ahead.

**Ability to Address Key Questions:** Rapid progress can be made once resource is available, though accuracy and precision is dependent upon the availability of new data from technological and natural scientific R&D.

### **Examples of Key Questions to Address:**

*Better Life Cycle Assessments of pyrolysis-biochar systems* – improved data across the whole PBS supply-chain (from feedstock to field) and alternative biochar-producing systems.

*Better Techno-Economic Cost Modelling*, using more accurate data and with an improved representation of the key processes and stages, including production, distribution, storage and deployment.

*Better comparative analyses of biochar versus other resource-use options* – need for explicit and transparent comparisons using best-available data of the most effective way of using and managing limited biomass resources for, e.g., bio-energy generation, carbon / greenhouse gas abatement, sustainable soils and waste management, and sustainable agri-food systems.

*Assessment of land-use implications of biochar deployment* – how biochar might influence the competitive advantage of different crops and the knock-on impacts on land-use decisions, supply and demand.

## BIBLIOGRAPHY

- ADAS (2001). The Safe Sludge Matrix, 3rd Edition. ADAS, BRC, Water UK.
- ADAS (2009). Analysis of Policy Instruments for Reducing Greenhouse Gas Emissions from Agriculture, Forestry and Land Management, Rep. No. RMP/5142. ADAS UK Ltd., Wolverhampton
- AEA (2008). BEAT<sub>2</sub> (Biomass Environmental Assessment Tool): User Guide, Rep. No. Issue Number 3. AEA Technology and North Energy, Harwell, UK
- Amonette, J., Lehmann, J., and Joseph, S. (2007). Terrestrial carbon sequestration with biochar: A preliminary assessment of its global potential. American Geophysical Union, Fall Meeting, San Francisco, 10-14 December
- Anon (2004). The Viability of Advanced Thermal Treatment of MSW in the UK. Fichtner Consulting Engineers Ltd., Stockport, UK
- Antal, M. J., and Gronli, M. (2003). The art, science, and technology of charcoal production. *Industrial & Engineering Chemistry Research* **42**, 1619-1640
- Asai, H., Samson, B. K., Stephan, H. M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T., and Horie, T. (2009). Biochar amendment techniques for upland rice production in northern Laos. *Field Crops Research* **111**, 81-84
- Ascough, P. L., Bird, M. I., Brock, F., Higham, T. F. G., Meredith, W., Snape, C. E., and Vane, C. H. (2009). Hydropyrolysis as a new tool for radiocarbon pretreatment and the quantification of black carbon. *Quaternary Geochronology* **4**, 140-147
- Baldock, J. A., and Smernik, R. J. (2002). Chemical composition and bioavailability of thermally altered *Pinus resinosa* (Red pine) wood. *Organic Geochemistry* **33**, 1093-1109
- Bates, J., Edberg, O., and Nuttall, C. (2009). Minimising Greenhouse Gas Emissions from Biomass Energy Generation. Environment Agency, Bristol
- BBC (2002). The Secret of El Dorado. 'Horizon' television documentary
- Beaton, J. D., Peterson, H. B., and Bauer, N. (1960). Some aspects of phosphate adsorption by charcoal. *Soil Science Society of America Proceedings* **24**, 340-346
- Bird, M. I., Ascough, P. L., Young, I. M., Wood, C. V., and Scott, A. C. (2008). X-ray microtomographic imaging of charcoal. *Journal of Archaeological Science* **35**, 2698-2706
- Blackwell, P., Shea, S., Storer, P., Solaiman, Z., Kerkmans, M., and Stanley, I. (2007). Improving wheat production with deep banded oil mallee charcoal in Western Australia. First Asia Pacific Biochar Conference, Terrigal, Australia, 30 April-2 May
- BlueLeaf (2009). Preliminary Evaluation of Biochar in a Commercial Farming Operation in Canada, Drummondville, Quebec
- Bradshaw, J., Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen, H. P., and Mathiassen, O. M. (2007). CO<sub>2</sub> storage capacity estimation: issues and development of standards. *International Journal of Greenhouse Gas Control* **1** 62-68.
- Brander, M., Tipper, R., Hutchison, C., and Davis, G. (2008). Consequential and Attributional Approaches to LCA: a Guide to Policy Makers with Specific Reference to Greenhouse Gas LCA of Biofuels. Ecometrica, Edinburgh

- Brewer, C. E., Schmidt-Rohr, K., Satrio, J. A., and Brown, R. C. (2009). Characterization of biochar from fast pyrolysis and gasification systems. *Environmental Progress & Sustainable Energy* **28**, 386-396
- Brodowski, S., Amelung, W., Haumaier, L., Abetz, C., and Zech, W. (2005a). Morphological and chemical properties of black carbon in physical soil fractions as revealed by scanning electron microscopy and energy-dispersive X-ray spectroscopy. *Geoderma* **128**, 116-129
- Brodowski, S., Amelung, W., Haumaier, L., and Zech, W. (2007). Black carbon contribution to stable humus in German arable soils. *Geoderma* **139**, 220-228
- Brodowski, S., John, B., Flessa, H., and Amelung, W. (2006). Aggregate-occluded black carbon in soil. *European Journal of Soil Science* **57**, 539-546
- Brodowski, S., Rodionov, A., Haumaier, L., Glaser, B., and Amelung, W. (2005b). Revised black carbon assessment using benzene polycarboxylic acids. *Organic Geochemistry* **36**, 1299-1310
- Brown, R. A., Kercher, A. K., Nguyen, T. H., Nagle, D. C., and Ball, W. P. (2006). Production and characterization of synthetic wood chars for use as surrogates for natural sorbents. *Organic Geochemistry* **37**, 321-333
- Brownsort, P. (2009). Biomass Pyrolysis Processes: Performance Parameters and their Influence on Biochar System Benefits. MSc thesis, University of Edinburgh.
- Bruun, S., Jensen, E. S., and Jensen, L. S. (2008). Microbial mineralization and assimilation of black carbon: Dependency on degree of thermal alteration. *Organic Geochemistry* **39**, 839-845
- Bucheli, T. D., Blum, F., Desaulles, A., and Gustafsson, Ö. (2004). Polycyclic aromatic hydrocarbons, black carbon, and molecular markers in soils of Switzerland. *Chemosphere* **56**, 1061-1076
- Campbell, C. D., Cameron, C. M., Bastias, B. A., Chen, C., and Cairney, J. W. G. (2008). Long term repeated burning in a wet sclerophyll forest reduces fungal and bacterial biomass and responses to carbon substrates. *Soil Biology and Biochemistry* **40**, 2246-2252
- Carbon Gold (2009). VCS: General Methodology for Quantifying the Greenhouse Gas Emission Reductions from the Production and Incorporation into Soil of Biochar in Agricultural and Forest Management Systems. Carbon Gold, London
- Chan, K., and Xu, Z. (2009). Biochar: nutrient properties and their enhancement *In Biochar for Environmental Management: Science and Technology* (J. Lehmann and S. Joseph, eds.), pp. 67-84. Earthscan, London
- Chan, K. Y., Van Zwieten, L., Meszaros, I., Downie, A., and Joseph, S. (2007). Agronomic values of greenwaste biochar as a soil amendment. *Australian Journal of Soil Research* **45**, 629-634
- Chan, K. Y., Van Zwieten, L., Meszaros, I., Downie, A., and Joseph, S. (2008). Using poultry litter biochars as soil amendments. *Australian Journal of Soil Research* **46**, 437-444
- Cheng, C. H., Lehmann, J., and Engelhard, M. H. (2008a). Natural oxidation of black carbon in soils: Changes in molecular form and surface charge along a climosequence. *Geochimica et Cosmochimica Acta* **72**, 1598-1610
- Cheng, C. H., Lehmann, J., Thies, J. E., and Burton, S. D. (2008b). Stability of black carbon in soils across a climatic gradient. *Journal of Geophysical Research - Biogeosciences* **113**, 2027

- Cheng, C. H., Lehmann, J., Thies, J. E., Burton, S. D., and Engelhard, M. H. (2006). Oxidation of black carbon by biotic and abiotic processes. *Organic Geochemistry* **37**, 1477-1488
- Cherubini, F., Bird, N., Cowie, A., Jungmeier, G., Schlamadinger, B., and Woess-Gallasch, S. (2009). Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations *Resources, Conservation and Recycling* **53**, 434-447
- Clough, A., and Skjemstad, J. O. (2000). Physical and chemical protection of soil organic carbon in three agricultural soils with different contents of calcium carbonate. *Australian Journal of Soil Research* **38**, 1005-1016
- Clough, T. J., Ray, J. L., Sherlock, R. R., Condon, L. M., Callaghan, M. O., and Buckthought, L. E. (2008). Nitrous Oxide-Novel Mitigation Methodologies: Objective 2 – Biochar effects on urinary-N N<sub>2</sub>O emissions. Report to Ministry of Agriculture and Forestry, Lincoln University, Lincoln, New Zealand
- Collison, M., Collison, L., Sakrabani, R., Tofield, B., and Wallage, Z. (2009). Biochar and Carbon Sequestration: A Regional Perspective. Low Carbon Innovation Centre, UEA, Norwich
- Condon, L., Clough, T. J., Ray, J., Sherlock, R., and O'Callaghan, M. (2009). Biochar effects on nitrous oxide emissions from a pasture soil. Asia Pacific Biochar Conference, Gold Coast, Australia 17-20 May.
- Copeland, J., and Turley, D. (2008). National and Regional Supply / Demand Balance for Agricultural Straw in Great Britain. National Non-Food Crops Centre, York
- Cornelissen, G., Gustafsson, O., Bucheli, T. D., Jonker, M. T. O., Koelmans, A. A., and Van Noort, P. C. M. (2005). Extensive sorption of organic compounds to black carbon, coal, and kerogen in sediments and soils: Mechanisms and consequences for distribution, bioaccumulation, and biodegradation. *Environmental Science & Technology* **39**, 6881-6895.
- Cowie, A. (2009). Personal email communication with P. Brownsort concerning slow pyrolysis, June 2009.
- Creaser, C. S., Wood, M. D., Alcock, R., Copplestone, D., Crook, P. J., and Barraclough, D. (2007). UK soil and herbage pollutant survey: Environmental concentrations of polycyclic aromatic hydrocarbons in UK soil and herbage, Rep. No. 9. Environment Agency, Bristol
- Crutzen, P. J., and Andreae, M. O. (1990). Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles. *Science* **250**, 1669-1678
- Czimczik, C. I., Preston, C. M., Schmidt, M. W. I., Werner, R. A., and Schulze, E. D. (2002). Effects of charring on mass, organic carbon, and stable carbon isotope composition of wood. *Organic Geochemistry* **33**, 1207-1223
- Czimczik, C. I., Schmidt, M. W. I., and Schulze, E. D. (2005). Effects of increasing fire frequency on black carbon and organic matter in Podzols of Siberian Scots pine forests. *European Journal of Soil Science* **56**, 417-428
- Dai, X., Boutton, T. W., Glaser, B., Ansley, R. J., and Zech, W. (2005). Black carbon in a temperate mixed-grass savanna. *Soil Biology & Biochemistry* **37**, 1879-1881
- Das, K. C., Garcia-Perez, M., Bibens, B., and Melear, N. (2008). Slow pyrolysis of poultry litter and pine woody biomass: Impact of chars and bio-oils on microbial growth. *Journal of Environmental Science and Health: Part A* **43**, 714-724



- Day, D., Evans, R. J., Lee, J. W., and Reicosky, D. (2005). Economical CO<sub>2</sub>, SO<sub>x</sub>, and NO<sub>x</sub> capture from fossil-fuel utilization with combined renewable hydrogen production and large-scale carbon sequestration. *Energy* **30**, 2558-2579
- DECC (2009). Low Carbon Transition Plan: National Strategy for Climate and Energy. HM Government, London
- Defra (2008). Guidelines to Defra's Greenhouse Gas Conversion Factors for Company Reporting. Defra, London
- Defra (2009a). 2009 Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting. Defra, London
- Defra (2009b). Average prices of hay and straw in England and Wales (weekly) 2000-date <https://statistics.defra.gov.uk/esg/publications/amr/default.asp>
- Defra (2009c). Environmental Permitting. Environmental Permitting Guidance: the Directive on the Incineration of Waste for the Environmental Permitting (England and Wales) Regulations 2007. Updated October 2009 Version 2.0, Defra, London
- DeLuca, T. H., and Aplet, G. H. (2008). Charcoal and carbon storage in forest soils of the Rocky Mountain West. *Frontiers in Ecology and the Environment* **6**, 18-24
- Downie, A. (2009). Personal email communication with P. Brownsort concerning slow pyrolysis, July 2009
- Downie, A., Klatt, P., and Munroe, P. (2007). Slow pyrolysis: Australian demonstration plant successful on multi-feedstocks. Bioenergy, Jyvaskyla, Finland, 3-6 September.
- Dynamotive Energy Systems Corporation (1999). BioTherm™ - a system for continuous quality, fast pyrolysis biooil. Fourth Biomass Conference of the Americas, Oakland, Canada, 29 August - 2 September
- Eggleston, H. S., Buendia, L., Miwa, K., Ngara, T., and Tanabe, K. (2006). IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme, Geneva.
- Elias, V. O., Simoneit, B. R. T., Cordeiro, R. C., and Turcq, B. (2001). Evaluating levoglucosan as an indicator of biomass burning in Carajas, Amazonia: A comparison to the charcoal record. *Geochimica et Cosmochimica Acta*. **65**, 267-272.
- Environment Agency (2008a). The Environmental Regulation of Wood: Position Statement. Environment Agency
- Environment Agency (2008b). Regulating Trials of Waste Management Activities, Position Statement MWRP004
- Environment Agency (2009). Minimising Greenhouse Gas Emissions from Biomass Energy Generation . Environment Agency, Bristol
- Ernsting, A., and Rughani, D. (2008). Climate Geo-engineering with 'carbon negative' bioenergy: Climate saviour or climate endgame? Biofuelwatch, London
- Fernandes, M. B., and Brooks, P. (2003). Characterization of carbonaceous combustion residues: II. Nonpolar organic compounds. *Chemosphere* **53**, 447-458
- Fernandes, M. B., Skjemstad, J. O., Johnson, B. B., Wells, J. D., and Brooks, P. (2003). Characterization of carbonaceous combustion residues: I. Morphological, elemental and spectroscopic features. *Chemosphere* **51**, 785-795

- Forbes, M. S., Raison, R. J., and Skjemstad, J. O. (2006). Formation, transformation and transport of black carbon (charcoal) in terrestrial and aquatic ecosystems. *Science of the Total Environment* **370**, 190-206
- Froese, K. L., and Hutzinger, O. (1996a). Polychlorinated benzene and polychlorinated phenol in heterogeneous combustion reactions of ethylene and ethane. *Environmental Science & Technology* **30**, 1009-1013
- Froese, K. L., and Hutzinger, O. (1996b). Polychlorinated benzene, phenol, dibenzo-p-dioxin, and dibenzofuran in heterogeneous combustion reactions of acetylene. *Environmental Science & Technology* **30**, 998-1008
- Gaskin, J. W., Speir, A., Morris, L. M., Ogden, L., Harris, K., Lee, D., and Das, K. C. (2007). Potential for pyrolysis char to affect soil moisture and nutrient status of loamy sand soil. *In Georgia Water Resources Conference, University of Georgia*
- Gaunt, J., and Cowie, A. (2009). Biochar, greenhouse gas accounting and emissions trading. *In Biochar for Environmental Management* (J. Lehmann and S. Joseph, eds.), pp. 317-340. Earthscan, London
- Gaunt, J. L., and Lehmann, J. (2008). Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. *Environmental Science & Technology* **42**, 4152-4158
- Gaur, S., and Reed, T. B. (1995). *An Atlas of Thermal Data for Biomass and other Fuels*. NREL, Colorado
- Gélinas, Y., Prentice, K. M., Baldock, J. A., and Hedges, J. I. (2001). An improved thermal oxidation method for the quantification of soot/graphitic black carbon in sediments and soils. *Environmental Science and Technology* **35**, 3519-3525
- Glaser, B. (2007). Prehistorically modified soils of central Amazonia: A model of sustainable agriculture in the 21st Century. *Philosophical Transactions of the Royal Society* **362**, 187-196
- Glaser, B., Balashov, E., Haumaier, L., Guggenberger, G., and Zech, W. (2000). Black carbon in density fractions of anthropogenic soils of the Brazilian Amazon region. *Organic Geochemistry* **31**, 669-678
- Glaser, B., and Knorr, K. H. (2008). Isotopic evidence for condensed aromatics from non-pyrolytic sources in soils - implications for current methods for quantifying soil black carbon. *Rapid Communications in Mass Spectrometry* **22**, 935-942
- Glaser, B., Lehmann, J., and Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal – a review. *Biology and Fertility of Soils* **35**, 219-230
- Goodhall, C. (2008). *Ten Technologies to Save the Planet, Green Profile, London*
- Grace, J. (2004). Understanding and managing the carbon cycle. *Journal of Ecology* **92**, 189-202
- Guggenberger, G., Rodionov, A., Shibistova, O., Grabe, M., Kasansky, O. A., Fuchs, H., Mikheyeva, N., Zrazhevskaya, G., and Flessa, H. (2008). Storage and mobility of black carbon in permafrost soils of the forest tundra ecotone in northern Siberia. *Global Change Biology* **14**, 1367-1381
- Gustafsson, O., Bucheli, T. D., Kukulska, Z., Andersson, M., Largeau, C., Rouzaud, J.-N., Reddy, C. M., and Eglinton, T. I. (2001). Evaluation of a protocol for the quantification of black carbon in sediments. *Global Biogeochemical Cycles* **15**, 881-890

- Gustafsson, O., Haghseta, F., Chan., C., Macfarlane, J., and Gschwend, P. M. (1997). Quantification of the dilute sedimentary soot phase: implications for PAH speciation and bioavailability. *Environmental Science and Technology* **31**, 203–209
- Hamer, U., Marschner, B., Brodowski, S., and Amelung, W. (2004). Interactive priming of black carbon and glucose mineralisation. *Organic Geochemistry* **35**, 823-830
- Hammes, K., Schmidt, M. W. I., Smernik, R. J., Currie, L. A., Ball, W. P., Nguyen, T. H., Louchouart, P., Houel, S., Gustafsson, O., Elmquist, M., Cornelissen, G., Skjemstad, J. O., Masiello, C. A., Song, J., Peng, P., Mitra, S., Dunn, J. C., Hatcher, P. G., Hockaday, W. C., Smith, D. M., Hartkopf-Froder, C., Bohmer, A., Luer, B., Huebert, B. J., Amelung, W., Brodowski, S., Huang, L., Zhang, W., Gschwend, P. M., Flores-Cervantes, D. X., Largeau, C., Rouzaud, J. N., Rumpel, C., Guggenberger, G., Kaiser, K., Rodionov, A., Gonzalez-Vila, F. J., Gonzalez-Perez, J. A., Rosa, J. M. d. I., Manning, D. A. C., Lopez-Capel, E., and Ding, L. (2007). Comparison of quantification methods to measure fire-derived (black/elemental) carbon in soils and sediments using reference materials from soil, water, sediment and the atmosphere. *Global Biogeochemical Cycles* **21**, 1-18
- Hammes, K., Smernik, R. J., Skjemstad, J. O., and Schmidt, M. W. I. (2008). Characterisation and evaluation of reference materials for black carbon analysis using elemental composition, colour, BET surface area and C NMR spectroscopy. *Applied Geochemistry* **23** 2113–2122
- Hammond, J. (2009). The Best Use of Biomass? Greenhouse Gas Life Cycle Analysis of Predicted Pyrolysis Biochar Systems MSc, University of Edinburgh
- Harvey, F. (2009). Black is the New Green. *In* The Financial Times, London
- Helsen, L., Van den Bulck, E., Van den Broeck, K., and Vandecasteele, C. (1997). Low-temperature pyrolysis of CCA-treated wood waste: Chemical determination and statistical analysis of metal input and output; mass balances. *Waste Management* **17**, 79-86
- Hockaday, W. C., Grannas, A. M., Kim, S., and Hatcher, P. G. (2006). Direct molecular evidence for the degradation and mobility of black carbon in soils from ultrahigh-resolution mass spectral analysis of dissolved organic matter from a fire-impacted forest soil. *Organic Geochemistry* **37**, 501-510
- Hornung, A. (2008). Fast, intermediate or slow pyrolysis for fuels production, power generation from various biomasses or as pre-conditioning unit for gasifiers. Vol. 2009
- Hornung, A., Apfelbacher, W., Koch, W., Linek, A., Sagi, S., Schoner, J., Stohr, J., Seifert, H., Tumiatti, V., and Lenzi, F. (2006). Thermo-chemical conversion of straw - Haloclean intermediate pyrolysis. 17th International Symposium on Analytical and Applied Pyrolysis, Budapest, Hungary 21-26 May
- Hornung, U., D., S., Hornung, A., Tumiatti, V., and Seifert, H. (2009). Sequential pyrolysis and catalytic low temperature reforming of wheat straw. *Journal of Applied and Analytical Pyrolysis* **85**, 145-150
- Houghton, J. T., Meira Filho, L. G., Lim, B., Tre´anton, K., Mamaty, I., Bonduki, Y., Griggs, D. J., and Callander, B. A., eds. (1997). Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, Hadley Centre Meteorological Office, Exeter
- HSE (2006). The Health and Safety Risks and Regulatory Strategy Related to Energy Developments: An Expert Report by the Health and Safety Executive Contributing to the Government's Energy Review, 2006. Health and Safety Executive. London

- Huang, L., Brook, J. R., Zhang, W., Li, S. M., Graham, L., Ernst, D., Chiculescu, A., and Lu, g. (2006). Stable isotope measurements of carbon fractions (OC/EC) in airborne particulate: A new dimension for source characterization and apportionment. *Atmospheric Environment* **40**, 2690–2705
- Hwang, I. H., Nakajima, D., Matsuto, T., and Sugimoto, T. (2008). Improving the quality of waste-derived char by removing ash. *Waste Management* **28**, 424-434
- Ibarrola, R. (2009). Pyrolysis for Waste Treatment: A Life Cycle Assessment of Biodegradable Waste, Bioenergy Generation and Biochar Production in Glasgow and Clyde Valley, University of Edinburgh
- IPCC (2001). Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. IPCC, Geneva
- IPCC (2005). Carbon Dioxide Capture and Storage: Summary for Policymakers. IPCC, Geneva
- IPCC (2007). Summary for Policymakers. *In* Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller, eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Jackson, J., Choudrie, S., Thistlethwaite, G., Passant, N., Murrells, T., Watterson, J., Mobbs, D., Cardenas, L., Thomson, A., Leech, A., Li, Y., Manning, A., Walker, C., Brophy, N., Sneddon, S., Pierce, M., Thomas, J., and Brown, K. (2008). UK Greenhouse Gas Inventory, 1990 to 2006. National Air Emissions Inventory, AEA Technology, Harwell
- Janik, L. J., Skjemstad, J. O., Shepherd, K. D., and Spouncer, L. R. (2007). The prediction of soil carbon fractions using mid-infrared-partial least square analysis. *Australian Journal of Soil Research* **45**, 73-81
- Janik, L. J., Taylor, J. A., and Skjemstad, J. O. (1998). Non-living soil organic matter: what do we know about it? *Australian Journal of Experimental Agriculture* **38**, 667–680
- Jones, M. (2009). PAH content of biochar samples. Data presented at UKBRC MSc Colloquium, Newcastle, 29 July
- Joseph, S., Munroe, P., van Zweiten, L., Cowie, A., Krull, E., Singh, B., and Downie, A. (2009). Biochar for Soil Fertility and Carbon Sequestration: A Review of Current Understanding. Australia and New Zealand Biochar Researchers Network
- Kaal, J., Baldock, J. A., Buurman, P., Nierop, K. G. J., Pontevedra-Pombal, X., and Martínez-Cortizas, A. (2007). Evaluating pyrolysis-GC/MS and <sup>13</sup>C CPMAS NMR in conjunction with a molecular mixing model of the Penido Vello peat deposit, NW Spain. *Organic Geochemistry* **38**, 1097-1111
- Kaal, J., Brodowski, S., Baldock, J. A., Nierop, K. G. J., and Cortizas, A. M. (2008a). Characterisation of aged black carbon using pyrolysis-GC/MS, thermally assisted hydrolysis and methylation (THM), direct and cross-polarisation <sup>13</sup>C nuclear magnetic resonance (DP/CP NMR) and the benzenepolycarboxylic acid (BPCA) method. *Organic Geochemistry* **39**, 1415-1426
- Kaal, J., Martínez-Cortizas, A., Nierop, K. G. J., and Buurman, P. (2008b). A detailed pyrolysis-GC/MS analysis of a black carbon-rich acidic colluvial soil (Atlantic ranker) from NW Spain. *Applied Geochemistry* **23**, 2395-2405
- Kimetu, J. M., Lehmann, J., Ngoze, S. O., Mugendi, D. N., Kinyangi, J. M., Riha, S., Verchot, L., Recha, J. W., and Pell, A. N. (2008). Reversibility of soil productivity decline with

- organic matter of differing quality along a degradation gradient. *Ecosystems* **11**, 726-739
- Knicker, H., Hilscher, A., González-Vila, F. J., and Almendros, G. (2008). A new conceptual model for the structural properties of char produced during vegetation fires. *Organic Geochemistry* **39**, 935-939
- Knicker, H., Muffler, P., and Hilscher, A. (2007). How useful is chemical oxidation with dichromate for the determination of Black Carbon in fire-affected soils? *Geoderma* **142**, 178-196
- Knicker, H., and Skjemstad, J. O. (2000). Nature of organic carbon and nitrogen in physically protected organic matter of some Australian soils as revealed by solid-state <sup>13</sup>C and <sup>15</sup>N NMR spectroscopy. *Australian Journal of Soil Research* **38**, 113-128
- Krull, E. (2009). Personal email communication with S. Sohi concerning retrofit of Australian agricultural equipment for deployment of biochar, November 2009
- Krull, E. S., Skjemstad, J. O., Graetz, D., Grice, K., Dunning, W., Cook, G., and Parr, J. F. (2003). <sup>13</sup>C-depleted charcoal from C4 grasses and the role of occluded carbon in phytoliths. *Organic Geochemistry* **34**, 1337-1352
- Kuhlbusch, T. A. J. (1998). Black carbon and the carbon cycle. *Science* **280**, 1903-1904
- Kuo, L. J., Herbert, B. E., and Louchouart, P. (2008). Can levoglucosan be used to characterize and quantify char/charcoal black carbon in environmental media? *Organic Geochemistry* **39**, 1466-1478
- Kurosaki, F., Koyanaka, H., Hata, T., and Imamura, Y. (2007). Macroporous carbon prepared by flash heating of sawdust. *Carbon* **45**, 671-673
- Kuzyakov, Y., Subbotina, I., Chen, H., Bogomolova, I., and Xu, X. (2009). Black carbon decomposition and incorporation into soil microbial biomass estimated by <sup>14</sup>C labeling. *Soil Biology and Biochemistry* **41**, 210-219
- Ladha, J. K., Pathak, H., Krupnik, T. J., Six, J., and van Kessel, C. (2005). Efficiency of fertiliser nitrogen in cereal production: retrospects and prospects *Advances in Agronomy* **87**, 85-156
- Lehmann, C. J., and Rondon, M. (2006). Bio-char soil management on highly-weathered soils in the tropics. *In Biological Approaches to Sustainable Soil Systems* (N. T. Uphoff, ed.), pp. 517-530. CRC Press, Boca Raton
- Lehmann, C. J., and Sohi, S. P. (2008). Comment on Fire-derived charcoal causes loss of forest humus. *Science* **321**, 1295c
- Lehmann, J. (2007a). Bio-energy in the black. *Frontiers in Ecology and the Environment* **5**, 381-387
- Lehmann, J. (2007b). A handful of carbon. *Nature* **447**, 143-144
- Lehmann, J., Czimczic, C., Laird, D., and Sohi, S. (2009). Stability of Biochar in Soil. *In Biochar for Environmental Management* (J. Lehmann and S. Joseph, eds.), pp. 317-340. Earthscan London
- Lehmann, J., da Silva Jr, J. P., Steiner, C., Nehls, T., Zech, W., and Glaser, B. (2003a). Nutrient availability and leaching in an archaeological Anthrosol and a Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant & Soil* **249**, 343-357

- Lehmann, J., Gaunt, J., and Rondon, M. (2006). Bio-char sequestration in terrestrial ecosystems - a review. *Mitigation and adaptation strategies for global change* **11**, 403-427
- Lehmann, J., and Joseph, S., eds. (2009). *Biochar for Environmental Management: Science and Technology*. Earthscan, London
- Lehmann, J., Kern, D. C., Glaser, B., and Woods, W. I., eds. (2003b). *Amazonian Dark Earths: origin, properties, management*. Kluwer Academic Publishers, Dordrecht, Netherlands
- Lehmann, J., Liang, B. Q., Solomon, D., Lerotic, M., Luizao, F., Kinyangi, J., Schafer, T., Wirick, S., and Jacobsen, C. (2005). Near-edge X-ray absorption fine structure (NEXAFS) spectroscopy for mapping nano-scale distribution of organic carbon forms in soil: Application to black carbon particles. *Global Biogeochemical Cycles* **19**, GB1013
- Lehmann, J., Skjemstad, J., Sohi, S., Carter, J., Barson, M., Falloon, P., Coleman, K., Woodbury, P., and Krull, E. (2008). Australian climate-carbon cycle feedback reduced by soil black carbon. *Nature Geoscience* **1**, 832-835
- Leifeld, J. (2008). Biased <sup>14</sup>C-derived organic carbon turnover estimates following black carbon input to soil: an exploration with RothC. *Biogeochemistry* **88**, 205-211
- Lerda, D. (2009). Polycyclic Aromatic Hydrocarbons (PAHs) Factsheet Rep. No. JRC 50087. Joint Research Centre Geel, Belgium
- Levy, S., Blandford, N., and Mayhead, G. (2006). *Of Chips and Logs: Making the Most of Arboricultural Arisings in the Mersey Belt*. Red Rose Forest and Mersey Forest Report to Forestry Commission North West England Conservancy
- Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., Skjemstad, J. O., Thies, J., Luizao, F. J., Petersen, J., and Neves, E. G. (2006). Black carbon increases cation exchange capacity in soils. *Soil Science Society of America Journal* **70**, 1719-1730
- Liang, B., Lehmann, J., Solomon, D., Sohi, S., Thies, J. E., Skjemstad, J. O., Luizãod, F. J., Engelharde, M. H., Nevesf, E. G., and Wirick, S. (2009a). Stability of biomass-derived black carbon in soils. *Geochimica et Cosmochimica Acta* **72**, 6069-6078
- Liang, B., Lehmann, L., Sohi, S. P., Thies, J. E., O'Neill, B., Trujillo, L., Gaunt, J., Solomon, D., Grossman, J., Neves, E., and Luizãod, F. J. (2010). Black carbon affects the cycling of non-black carbon in soil. *Organic Geochemistry* **41**, 206-213
- Lievens, C., Carleer, R., Cornelissen, T., and Yperman, J. (2009). Fast pyrolysis of heavy metal contaminated willow: Influence of the plant part. *Fuel* **88**, 1417-1425
- Lopez-Capel, E., Sohi, S. P., Gaunt, J. L., and Manning, D. A. C. (2005). Use of thermogravimetry-differential scanning calorimetry to characterize modelable soil organic matter fractions. *Soil Science Society of America Journal* **69**, 136-140
- Lovelock, J. (2009). One last chance to save mankind. *New Scientist*, 23 January 2009
- Major, J. (2009). *A Guide to Conducting Biochar Trials*, Rep. No. Ver. 1.1. International Biochar Initiative
- Major, J., Lehmann, J., Rondon, M., and Goodale, C. (2010). Fate of soil-applied black carbon: downward migration, leaching and soil respiration. *Global Change Biology* **16**, 1366-1379

- Manning, D., and Lopez-Capel, E. (2009). Test procedures for determining the quantity of biochar within soils. *In Biochar for Environmental Management* (J. Lehmann and S. Joseph, eds.), pp. 317-340. Earthscan, London
- Manning, D. A. C., Lopez-Capel, E., White, M. L., and Barker, S. (2008). Carbon isotope determination for separate components of heterogenous materials using coupled thermogravimetric analysis/isotope ratio mass spectrometry. *Rapid Communications in Mass Spectrometry* **22**, 1187-1195
- Mašek, O. (2007). Studies on Pyrolytic Gasification of Low-rank Solid Fuels in the Presence of Steam, Hokkaido University, Sapporo, Japan
- Masiello, C. A. (2004). New directions in black carbon organic geochemistry. *Marine Chemistry* **92**, 201-213
- Masiello, C. A., and Druffel, E. R. M. (1998). Black carbon in deep-sea sediments *Science* **280**, 1911-1913
- Masiello, C. A., Druffel, E. R. M., and Currie, L. A. (2002). Radiocarbon measurements of black carbon in aerosols and ocean sediments. *Geochimica et Cosmochimica Acta* **66**, 1025-1036
- McCarl, B., Peacocke, C., Chrisman, R., Kung, C.-C., and Sands, R. (2009). Economics of biochar production, utilisation and emissions. *In Biochar for Environmental Management* (J. Lehmann and S. Joseph, eds.), pp. 341-357 Earthscan, London
- McGrath, T., Sharma, R., and Hajaligol, M. (2001). An experimental investigation into the formation of polycyclic-aromatic hydrocarbons (PAH) from pyrolysis of biomass materials. *Fuel* **80**, 1787-1797
- McGrath, T. E., Chan, W. G., and Hajaligol, M. R. (2003). Low temperature mechanism for the formation of polycyclic aromatic hydrocarbons from the pyrolysis of cellulose. *Journal of Analytical and Applied Pyrolysis* **66**, 51-70
- McGrath, T. E., Wooten, J. B., Geoffrey Chan, W., and Hajaligol, M. R. (2007). Formation of polycyclic aromatic hydrocarbons from tobacco: The link between low temperature residual solid (char) and PAH formation. *Food and Chemical Toxicology* **45**, 1039-1050
- McNamara, N. (2009). Personal verbal communication with S. Sohi concerning new PhD research using biochar in miscanthus field plots, June 2009
- Merrington, G., Crane, M., Ashton, D., and Benstead, R. (2008). Guidance on the Use of Soil Screening Values in Ecological Risk Assessment Rep. No. Science report SCO70009/SR2b, Environment Agency, Bristol
- Michel, K., Terhoeven-Urselmans, T., Nitschke, R., Steffan, P., and Ludwig, B. (2009). Use of near- and mid-infrared spectroscopy to distinguish carbon and nitrogen originating from char and forest-floor material in soils. *Journal of Plant Nutrition and Soil Science* **172**, 63-70
- Milne, T. A., Evans, R. J., and Abatzoglou, N. (1998). Biomass Gasifier Tars: Their Nature, Formation, and Conversion, Rep. No. NREL/TP-570-25357. National Renewable Energy Laboratory, Golden
- Monbiot, G. (2009). Woodchips with everything. It's the Atkins Plan of the low carbon world. *The Guardian*, 24 March 2009
- Moran, D., MacLeod, M., Wall, E., Eorya, V., Pajotb, G., Matthews, R., McVittiea, A., Barnesa, A., and Rees, B. (2008). UK Marginal Abatement Cost Curves for the Agriculture and Land Use, Land-Use Change and Forestry Sectors out to 2022, with

Qualitative Analysis of Options to 2050. Final Report to the Committee on Climate Change. SAC Commercial Ltd., Edinburgh

- Mortimer, N., Evans, A., Shaw, V., and Hunter, A. (2009). Life Cycle and Techno-Economic Assessment of the North East Biomass to Liquids Project Rep. No. NNFCC Project 08/016. National Non-Food Crops Centre, York.
- Murage, E. W., Voroney, P., and Beyaert, R. P. (2007). Turnover of carbon in the free light fraction with and without charcoal as determined using the  $^{13}\text{C}$  natural abundance method. *Geoderma* **138**, 133-143
- MWRP (2008). Spreading Waste to Agricultural Land (R. P. Statement, ed.). Environment Agency, Bristol
- Nash, L. (2009). The revised Directive on Waste: resolving legislative tensions in waste management? *Journal of Environmental Law* **21**, 139-149
- Nguyen, B. T., and Lehmann, J. (2009). Black carbon decomposition under varying water regimes. *Organic Geochemistry* **40**, 846–853
- Nguyen, B. T., Lehmann, J., Kinyangi, J., Smernik, R., Riha, S. J., and Engelhard, M. H. (2008). Long-term black carbon dynamics in cultivated soil. *Biogeochemistry* **89**, 295-308
- Nix, J. (2008). The John Nix Farm Management Pocketbook, 39th Ed. The Andersons Centre, Melton Mowbray
- Oguntunde, P. G., Abiodun, B. J., Ajayi, A. E., and van de Giesen, N. (2008). Effects of charcoal production on soil physical properties in Ghana. *Journal of Plant Nutrition and Soil Science* **171**, 591-596
- Oguntunde, P. G., Fosu, M., Ajayi, A. E., and van de Giesen, N. (2004). Effects of charcoal production on maize yield, chemical properties and texture of soil. *Biology and Fertility of Soils* **39**, 295-299
- Ohlson, M., Dahlberg, B., Økland, T., Brown, K., and Halvorsen, R. (2009). The charcoal carbon pool in boreal forest soils. *Nature Geoscience* **2**, 692-695
- Olsen, P. (2009). Personal email communication with S. Shackley, September 2009
- OPSI (2004). The Biofuel (Labelling) Regulations 2004. Defra, London
- Oros, D. R., Mazurek, M. A., Baham, J. E., and Simoneit, B. R. T. (2002). Organic tracers from wild fire residues in soils and rain/river wash-out. *Water, Air, and Soil Pollution* **137**, 203-233
- Pignatello, J. J., Kwon, S., and Lu, Y. (2006). Effect of natural organic substances on the surface and adsorptive properties of environmental black carbon (char): Attenuation of surface activity by humic and fulvic Acids. *Environmental Science & Technology* **40**, 7757-7763
- Prentice, I. C., Farquhar, G. D., Fasham, M. J. R., Goulden, M. L., Heimann, M., Jaramillo, V. J., Khashgi, H. S., Quéré, C. L., Scholes, R. J., and Wallace, D. W. R. (2001). The Carbon Cycle and Atmospheric Carbon Dioxide. In *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell and C. A. Johnson, eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA
- Read, P., and Parshotam, A. (2007). Holistic greenhouse gas management strategy. Victoria University of Wellington, Wellington, New Zealand.



- Redlein, D., and Kingston, A. (2007). The Potential Role of Agrichar in the Commercialization of Dynamotive's Fast Pyrolysis Process. First Asia Pacific Biochar Conference, Terrigal, Australia, 30 April-2 May
- Rhodes, A. H., Carlin, A., and Semple, K. T. (2008). Impact of black carbon in the extraction and mineralization of phenanthrene in soil. *Environmental Science & Technology* **42**, 740-745
- Rogovska, N., Fleming, P., Laird, D., and Cruse, R. (2008). Greenhouse gas emissions from soils as affected by addition of biochar. Joint Annual Meeting of ASA, CSSA and SSSA, Houston, USA
- Rogovska, N., Fleming, P., Laird, D., Cruse, R., and Parkin, T. (2009). Greenhouse gas emissions from soils as affected by addition of biochar. North American Biochar Conference, 9-12 August, Boulder, Colorado, USA
- Rondon, M., Ramirez, J. A., and Lehmann, J. (2005). Charcoal additions reduce net emissions of greenhouse gases to the atmosphere. *Proceedings of the 3rd USDA Symposium on Greenhouse Gases and Carbon Sequestration, Baltimore, USA, March 21-24*
- Rondon, M. A., Lehmann, J., Ramirez, J., and Hurtado, M. (2007). Biological nitrogen fixation by common beans (*Phaseolus vulgaris* L.) increases with bio-char additions. *Biology and Fertility of Soils* **43**, 699-708
- Rouquérol, J., Avnir, D., Fairbridge, C. W., Everett, D. H., Haynes, J. H., Pericone, N., Ramsay, J. D. F., Sing, K. S. W., and Unger, K. K. (1994). Recommendations for the characterization of porous solids. *Pure and Applied Chemistry* **66**, 1739-1758
- Rumpel, C., Alexis, M., Chabbi, A., Chaplot, V., Rasse, D. P., Valentin, C., and Mariotti, A. (2006). Black carbon contribution to soil organic matter composition in tropical sloping land under slash and burn agriculture. *Geoderma* **130**, 35-46
- Rumpel, C., González-Pérez, J. A., Bardoux, G., Largeau, C., Gonzalez-Vila, F. J., and Valentin, C. (2007). Composition and reactivity of morphologically distinct charred materials left after slash-and-burn practices in agricultural tropical soils. *Organic Geochemistry* **38**, 911-920
- Ryu, C., Sharifi, V. N., and Swithenbank, J. (2007). Waste pyrolysis and generation of storable char. *International Journal of Energy Research* **31**, 177-191
- Schmidt, M. W. I., and Noack, A. G. (2000). Black carbon in soils and sediments: Analysis, distribution, implications, and current challenges. *Global Biogeochemical Cycles* **14**, 777-793
- Seifritz, W. (1993). Should we store carbon in charcoal? *International Journal of Hydrogen Energy* **18**, 405-407
- Seiler, W., and Crutzen, P. J. (1980). Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. *Climatic Change* **2**, 207-247
- Shackley, S., and Gough, C. (2006). Conclusions and Recommendations. In *Carbon Capture and its Storage: An Integrated Assessment* (S. Shackley and C. Gough, eds.), pp. 281-303. Ashgate, Aldershot
- Shindo, H., Honna, T., Yamamoto, S., and Honma, H. (2004). Contribution of charred plant fragments to soil organic carbon in Japanese volcanic ash soils containing black humic acids. *Organic Geochemistry* **35**, 235-241

- Simpson, M. J., and Hatcher, P. G. (2004a). Determination of black carbon in natural organic matter by chemical oxidation and solid-state  $^{13}\text{C}$  nuclear magnetic resonance spectroscopy. *Organic Geochemistry* **35**, 923-935
- Simpson, M. J., and Hatcher, P. G. (2004b). Overestimates of black carbon in soils and sediments. *Naturwissenschaften* **91**, 436-440
- Skjemstad, J. O., Clarke, P., Taylor, J. A., Oades, J. M., and McClure, S. G. (1996). The chemistry and nature of protected carbon in soil. *Australian Journal of Soil Research* **34**, 251-271
- Skjemstad, J. O., Taylor, J. A., Janik, L. J., and Marvanek, S. P. (1999a). Soil organic carbon dynamics under long-term sugarcane monoculture. *Australian Journal of Soil Research* **37**, 151-164
- Skjemstad, J. O., Taylor, J. A., and Smernik, R. J. (1999b). Estimation of charcoal (char) in soils. *Communications in Soil Science and Plant Analysis* **30**, 2283-2298
- Smernik, R. J., Baldock, J. A., Oades, J. M., and Whittaker, A. K. (2002). Determination of T1 $\rho$  relaxation rates in charred and uncharred wood and consequences for NMR quantitation. *Solid State Nuclear Magnetic Resonance* **22**, 50-70
- Smernik, R. J., and Oades, J. M. (2000). The use of spin counting for determining quantitation in solid state  $^{13}\text{C}$  NMR spectra of natural organic matter: 2. HF-treated soil fractions. *Geoderma* **96**, 159-171
- Smernik, R. J., Skjemstad, J. O., and Oades, J. M. (2000). Virtual fractionation of charcoal from soil organic matter using solid state  $^{13}\text{C}$  NMR spectral editing. *Australian Journal of Soil Research* **38**, 665-683
- Sohi, S., Lopez-Capel, E., Krull, E., and Bol, R. (2009). Biochar, climate change and soil: A review to guide future research., CSIRO Land and Water Science Report Rep. No. 05/09, Geln Osmond, Australia.
- Solomon, S., Plattner, G.-K., Knutti, R., and Friedlingstein, P. (2009). Irreversible climate change due to carbon dioxide emissions. *Proceedings of the National Academy of Sciences* **106** 1704-1709
- Song, J., Peng, P., and Huang, W. (2002). Black carbon and kerogen in soils and sediments: I. Quantification and characterization. *Environmental Science and Technology* **36**, 3960-3967
- Spokas, K. A., Koskinen, W. C., Baker, J. M., and Reicosky, D. C. (2009). Impacts of woodchip biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil. *Chemosphere* **77**, 574-581
- Spycher, G., Soilins, P., and Rose, S. (1983). Carbon and nitrogen in the light fraction of a forest soil: Vertical distribution and seasonal patterns. *Soil Science* **135**, 79-87
- Steinbeiss, S., Gleixner, G., and Antonietti, M. (2009). Effect of biochar amendment on soil carbon balance and soil microbial activity. *Soil Biology and Biochemistry* **41**, 1301-1310
- Steiner, C., Das, K. C., Garcia, M., Forster, B., and Zech, W. (2008a). Charcoal and smoke extract stimulate the soil microbial community in a highly weathered xanthic Ferralsol. *Pedobiologia* **51**, 359-356
- Steiner, C., Glaser, B., Teixeira, W. G., Lehmann, J., Blum, W. E. H., and Zech, W. (2008b). Nitrogen retention and plant uptake on a highly weathered central Amazonian ferralsol amended with compost and charcoal. *Journal of Plant Nutrition and Soil Science* **171**, 893-899

- Steiner, C., Teixeira, W., Lehmann, J., and Zech, W. (2003). Microbial response to charcoal amendments of highly weathered soils and Amazonian Dark Earths in Central Amazonia – preliminary results. *In Amazonian dark earths: origin, properties, management* (J. Lehmann, D. C. Kern, B. Glaser and W. I. Woods, eds.). Kluwer Academic Publishers, Dordrecht
- Steiner, C., Teixeira, W. G., Lehmann, J., Nehls, T., Macedo, J. L. V., Blum, W. E. H., and Zech, W. (2007). Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant and Soil* **291**, 275-290
- Tagoe, S. O., Horiuchi, T., and Matsui, T. (2008). Effects of carbonized and dried chicken manures on the growth, yield, and N content of soybean. *Plant & Soil* **306**, 211-220
- Thornley, P. (2009). Personal verbal communication with S. Shackley, September 2009
- Thornley, P., Brammer, J., Rogers, J., Huang, Y., and Rezvani, S. (2009a). Making Bioelectricity Economic in the UK. 17th Biomass Conference, Hamburg, 29<sup>th</sup> June - 3 July
- Thornley, P., Upham, P., and Tomei, J. (2009b). Sustainability Constraints on UK Bioenergy Development *Energy Policy* **37**, 5623–5635
- UNFCCC (2007). Glossary of CDM terms. UNFCCC, Bonn, Germany
- UNFCCC (2008). Kyoto protocol reference manual on accounting of emissions and assigned amount. UNFCCC, Bonn, Germany
- UNFCCC (2009). Glossary of climate change acronyms [http://unfccc.int/essential\\_background/glossary/items/3666.php](http://unfccc.int/essential_background/glossary/items/3666.php) (accessed Dec. 2009). UNFCCC, Bonn, Germany
- Van den bergh, C. (2009). Biochar and waste law: a comparative analysis. *European Energy and Environmental Law Review*, 243-253
- Van Zwieten, L., Kimber, S., Morris, S., Chan, K. Y., Downie, A., Rust, J., Joseph, S., and Cowie, A. (2010). Effects of biochar from slow pyrolysis of papermill waste on agronomic performance and soil fertility. *Plant and Soil* **327**, 235-246
- Van Zwieten, L., Singh, B. P., Joseph, S., Kimber, S., Cowie, A., and Chan, K. Y. (2009). Biochar and emissions of non-CO<sub>2</sub> greenhouse gases from soil. *In Biochar for Environmental Management Science and Technology* (J. Lehmann and S. Joseph, eds.), pp. 227-250. Earthscan Publishers, London
- Vassilev, S. V., and Braekman-Danheux, C. (1999). Characterization of refuse-derived char from municipal solid waste: 2. Occurrence, abundance and source of trace elements. *Fuel Processing Technology* **59**, 135-161
- Vassilev, S. V., Braekman-Danheux, C., and Laurent, P. (1999). Characterization of refuse-derived char from municipal solid waste: 1. Phase-mineral and chemical composition. *Fuel Processing Technology* **59**, 95-134
- Vitousek, P. M., Ehrlich, P. R., Ehrlich, A. H., and Matson, P. A. (1986). Human appropriation of the products of photosynthesis. *BioScience* **36**, 368-373
- Wardle, D. A., Nilsson, M.-C., and Zackrisson, O. (2008). Fire-derived charcoal causes loss of forest humus. *Science* **320**, 629
- Warnock, D. D., Lehmann, J., Kuyper, T. W., and Rillig, M. C. (2007). Mycorrhizal responses to biochar in soil – concepts and mechanisms. *Plant & Soil* **300**, 9-20

- Warren, G. P., Robinson, J. S., and Someus, E. (2009). Dissolution of phosphorus from animal bone char in 12 soils. *Nutrient Cycling in Agroecosystems* **84**, 167-178
- Watts, C. W., Whalley, R. W., Brookes, P. C., Devonshire, B. J., and Whitmore, A. P. (2005). Biological and physical processes that mediate micro-aggregation of clays. *Soil Science* **170**, 573-583
- West, T. O., and McBride, A. C. (2005). The contribution of agricultural lime to carbon dioxide emissions in the United States: dissolution, transport, and net emissions. *Agriculture, Ecosystems and Environment* **108**, 145-154
- Wingate, J. R., De Leij, F. A. A. M., and Hutchings, T. (2009). Method of forming ion exchange charcoal. Patent no. GB2451509A, UK Intellectual Property Office, London, United Kingdom
- Woolf, D. (2009). Personal verbal communication with S. Sohi concerning recent meta-analysis of global soil carbon and soil black carbon data, September 2009
- Yamato, M., Okimori, Y., Wibowo, I. F., Anshori, S., and Ogawa, M. (2006). Effects of the application of charred bark of *Acacia mangium* on the yield of maize, cowpea and peanut, and soil chemical properties in South Sumatra, Indonesia. *Soil Science and Plant Nutrition* **52**, 489 - 495
- Yanai, Y., Toyota, K., and Okazaki, M. (2007). Effects of charcoal addition on N<sub>2</sub>O emissions from soil resulting from rewetting air-dried soil in short-term laboratory experiments. *Soil Science and Plant Nutrition* **53**, 181-188
- Yedla, S., and Dikshit, A. K. (2008). Removal of endosulfan from water using wood charcoal-adsorption and desorption. *Journal of Environmental Engineering* **134**, 102-109
- Young, A. (1804). Paring and Burning. In *The Farmers Calendar* (. ed.), pp. 171-182. Richard Phillips, London
- Yu, X.-Y., Ying, G.-G., and Kookana, R. S. (2006). Sorption and desorption behaviors of diuron in soils amended with charcoal. *Journal of Agricultural and Food Chemistry* **54**, 8545–8550
- Zhurinsh, A., Zandersons, J., and Dobeles, G. (2005). Slow pyrolysis studies for utilization of impregnated waste timber materials. *Journal of Analytical and Applied Pyrolysis* **74**, 439-444
- Zimmerman, J. R., Ghosh, U., Millward, R. N., Bridges, T. S., and Luthy, R. G. (2004). Addition of carbon sorbents to reduce PCB and PAH bioavailability in marine sediments: Physicochemical tests. *Environmental Science & Technology* **38**, 5458-5464