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Biochar in growing media: A sustainability and feasibility assessment

A project commissioned for the Sustainable Growing Media Task Force

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Glossary

Biochar: Biochar is the porous, carbonaceous solid produced in the thermo-chemical conversion of biomass under oxygen-depleted conditions and which has physiochemical properties suitable for safe and long-term storage of carbon in the environment and, potentially, soil improvement. See also *pyrolysis*.

Char: For the purpose of this report char is the solid, possibly composite co-product of pyrolysis in general, including a wider range of thermal processing technologies such as gasification. See also *biochar* and *charcoal*.

Charcoal: A The primary solid fuel product created from biomass, generally wood.

Pyrolysis: Decomposition of organic compounds induced by heating, but in the absence of combustion (often achieved by exclusion of oxygen / air).

Pyrolysis-Biochar System (PBS): An integrated system comprising a specific combination of biomass and pyrolysis conversion technology, bio-energy capture (where applicable), extending to the infrastructure required for transport, storage and use of feedstock and/or biochar product.

Peat replacement: Complete or partial substitution of peat in a growing medium that has comprised – or currently comprises – only peat, or a mixture of peat and other constituents.

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Executive Summary

Biochar is a carbon-rich solid product created by heating of biomass with restricted oxygen / air supply (pyrolysis). Biochar is rich in conserved carbon but highly resistant to decomposition. It is analogous to charcoal but does not have to be made from wood. It should be produced in a continuous or otherwise controlled process, with energy recovery where possible.

This report focuses on the potential for using biochar in growing media, as a partial replacement for peat or to enhance reduced-peat mixes. Since experience with a wider range of biochar is limited, this report also draws on relevant work with charcoal, where appropriate.

Starting materials and pyrolysis parameters largely determine the multiple functional properties exhibited by biochar. Specific, predictable and positive effects on growing media should be possible, but biochar is not currently produced in the UK on a notable scale.

The carbon abatement possible using biochar could incentivise investment and production; development of biochar standards and classes would assist in uptake and product innovation.

- Biochar has a diverse range of properties relevant to growing media, each related in some way to the production process and selected feedstock – physical, chemical and biological. In growing media a different property or mix of properties will be desirable for each application, making specific production processes linked to specific sources of feedstock critical;

- Handled and visually assessed, size-graded biochar of various types displayed physical properties of appeal to users, formulators and retailers of peat-based and peat-replacement growing media. Positive perceptions revolved around colour and shape, size and integrity, density (inferred porosity) and 'flow'. These important properties favour simple substitution for physical and/or visual enhancement of other peat replacement ingredients, though extent of volume substitution is dependent on particle size distribution as well as bulk density;

- Functional improvement of peat-replacement products could also be achieved by selecting or manipulating biochar for particular chemical and biological effects. This requires design and research and could include modification of biochar, use of biochar as a base for a compound ingredient or additive. Slow release of mineral nutrients or ash, provision of active (sorbent) surfaces, volatile disease-suppressant compounds, sites for microbial activity as well as precise physical properties could be provided;

- Although sustainable and potentially beneficial to woodland habitat management, UK charcoal is too expensive to provide an ingredient to peat-free growing media, mainly due to the labour intensive nature of batch processing and basic technology (~15% yield, no co-products); pollution of air and soil would be unacceptable at large scale. Waste fines command a lower price but account for only 20% of the 3000 t yr^{-1} annual production;

- Imported charcoal is poorly specified and can be variable and inflexible in terms of feedstock mix and production conditions; it may not provide the ultimate source of biochar for growing media. Charcoal does, however, have recognition, perceptible properties and certainty as well as immediacy of supply. Charcoal could be adopted in growing media, but only to the extent that it is financially viable as a straight substitute and thus as a premium ingredient for most markets; if adopted more widely UK imports of 55,000 t yr^{-1} would increase dramatically;

- Brazil has pioneered clean, efficient kilns for large-scale production of charcoal for smelting from dedicated plantation forests. Several initiatives have highlighted the potential for charcoal production to benefit the local economy in developing countries, with attention to sustainable feedstock and cleaner production. Without proper investment, however, charcoal production is generally inefficient, polluting, and presents hazards associated with dust and tar. Expanding Forest Stewardship Council 'chain of custody' for approved charcoal mitigates use of unsustainable feedstock;

- Defining a 'standard' for biochar used in growing media would accelerate uptake of biochar in growing media (assuming its availability). Defining biochar functional properties linked to feedstock, pyrolysis parameters could lead to biochar classification, and use of biochar with specific, predictable properties. Investment in systems that integrate biomass re-use, continuous processing and energy recovery in biochar production could result;

- Forest waste (non-processed biomass) could prove viable as a source of biochar as an enhancing ingredient to growing media by combining continuous production with energy capture at the required scale. There is limited demonstration of relevant production technology in the UK, but expanding use elsewhere in Europe. The composition of biochar from bark may diverge from that of charcoal (higher mineral content); biochar from crop straw (also ashy) is likely to prove too expensive;

- Biochar could be available at a low price from the pyrolysis of pre-digested sewage sludge (processed biomass), integrated into a system that links sludge treatment to continuous pyrolysis with energy recovery and power generation. Pyrolysis would be regulated under Waste Incineration Directive and stabilisation of toxic metals would need to be confirmed, as well as the absence of contaminants from pre-cursors in feedstock;

- Pyrolysis could provide a means to recycle growing media into biochar, generating energy and a sterile ingredient for new mix, offsetting cost of investment in pyrolysis equipment. Activated carbon from other industries (post use) could provide another source of biochar from re-use and recycling of existing materials.

Section 1: Introduction

The Government has published its ambition to eliminate the use of peat in horticulture by 2030 (HM Government 2011). The Sustainable Growing Media Task Force (SGMTF) was established to explore barriers to further peat reduction and to assist in the transition to sustainable growing media. One of the activities undertaken by the SGMTF is the examination of alternative growing media ingredients. Peat-free and reduced-peat growing media will contain a mix of peat alternatives. Until recently, biochar had not been considered as a potential ingredient of such products.

Biochar is the porous, carbonaceous solid produced in the thermo-chemical conversion of biomass under oxygen-depleted conditions and which has physiochemical properties suitable for safe and long-term storage of carbon in the environment and, potentially, soil improvement.

Biochar is a form of charcoal, but does not have to be made from wood and – being produced under a very controlled process – could provide precise and predictable effects in growing media and soil.

This project was commissioned to consult with the industry on the feasibility (utility and economics) of using biochar as a peat replacement. Not all types of biochar are the same in their visual, physical and functional properties. They are also associated with different production costs and logistical challenges. Consequently, different types of biochar will be more and less acceptable in growing media. This report seeks to understand the opportunities and challenges associated with the adoption of biochar in horticulture.

The project also assesses the implications of widespread adoption of biochar for sustainable exploitation of biomass resources and impacts on the environment (largely independent of its relevance to carbon cycling).

Overall, the project sought to weigh the benefits of including biochar in a strategy for decreasing the peat content of growing media against the costs and sustainability of providing biochar relative to other ingredients.

Section 2: Background

2.1. Biochar

Biochar is a form of charcoal manufactured under carefully controlled conditions. It is created by heating organic materials to temperatures of up to 800°C in the absence or severe restriction of air (pyrolysis). The product is a sterile material that is resistant to biological breakdown. The precise conditions and configuration of equipment used in the conversion process (as well as the feedstock) has been found to affect the behaviour of biochar in soil – so it should be possible to select biochar to provide functional properties that match an intended use.

In horticultural growing media biochar could be a minor ingredient or major constituent. The visual differences between fresh biochar made using different starting materials (feedstock) are instructive *Figure 2.1*. However, the properties of any biochar can be modified through treatment of feedstock or by manipulation after manufacture. This could provide specific functions that moderate, complement or enhance the behaviour of other peat-replacement ingredients.

Figure 2.1: Biochar resembles the feedstock from which it is made; it can be made from a variety of materials such as – left to right – wood pellets, rice husk, wood chip, Miscanthus straw

Extrapolating from (i) explanations of results of laboratory, glasshouse and field experiments with biochar in mineral (Biederman and Harpole 2011; Jeffery et al. 2011) and (ii) information acquired in discussions with users and developers of biochar products, several properties relevant to horticultural growing media are commonly exhibited by different types of biochar (at least over the short-term):

- Macro-porosity that enhances holding and release of water
- Low bulk density and resistance to compression and shrinkage
- Biochar particles that resist fragmentation
- Can be manufactured in different particle sizes

- Internal structures can promote microbial activity
- Surface reactivity can mediate interactions with nutrients
- Positive interaction with root growth and function.

Some properties that are less useful or that may prove problematic have also been observed – notably the potential for biochar to elevate salt level and pH and precipitate some immobilisation of ammonium N. Biochar can also exhibit short-term hydrophobicity (Kinney et al. 2012).

The inclusion of biochar in horticultural media for amateur and professional growers has been tested and marketed in various countries internationally. The processes for manufacturing and upgrading biochar could hold significant know-how, intellectual property and patents as specialists emerge in this field. Active sharing of information is apparent among amateur gardeners and users of biochar, who are motivated in part by the capacity of biochar to sequester carbon into soil, but also citing some of the benefits above.

Commercial activity around the development of biochar for use in growing media may explain the limited published evidence for its utility in this context and also support its viability. Academic articles concerning biochar (about 200 per year) have focused almost exclusively on its use in agriculture and mainly in broad-acre crops.

Manufacture of biochar (pyrolysis) can create bioenergy co-products (gases suitable for combustion and power generation). Created from clean biomass in a bioenergy facility the break-even cost of biochar production in the UK has been estimated at £20–80 m^{-3}, assuming a bulk density of 0.2 t m^{-3} (based on Shackley et al. 2011). The corresponding cost of biochar created from waste-derived material would be considerably lower (Ibarrola et al. 2011).

Critics have challenged the value of making and using biochar for carbon sequestration and have particular concerns around the environmental and social sustainability of providing feedstock and/or making biochar, especially when these are imported from overseas at lower cost. Taking charcoal production as an example, the potential for negative impacts on ecology and environment are well recognised. Charcoal production is still synonymous with the depletion of forest resources and air pollution.

If biochar were to be adopted widely in horticulture as an alternative to the environmentally damaging usage of peat, the extent of these risks and impacts must be understood and controlled. The types of biochar that could be used in horticulture are assessed against a sustainability matrix and flowchart as part of this project.

Section 3: Feasibility

The four aspects of feasibility identified in this project were:

1. Functional – What can it do, is it reliable and does it enhance the combined product?
2. Logistical – How can biochar be brought together with other elements and ingredients?
3. Technological – How soon could a sufficient supply of biochar be assured?
4. Economic – How much will it cost to produce and/or buy?

The potential to combine biochar and other peat-replacement ingredients is a general consideration connecting these.

Discussion of feasibility in this report revolves around issues identified with Key Informants and Stakeholders within the project (Appendices 3 &5, 4 &6 respectively). Pre-existing awareness and interest in biochar was universal and perceptions and comments drawing on knowledge and commercial experience were instrumental in shaping questions addressed around the utility and function of biochar.

The general absence of research directed toward the use and function of biochar in growing media specifically, was highlighted by many respondents. In this report reference is made to the available scientific literature, in the context of properties and functions considered relevant but not proven in soil-free horticulture.

3.1. Introduction

The competitive price (low cost) of peat is one barrier to the development and use of replacement ingredients. However, there is also inertia to be overcome that is associated partly with the familiarity and predictability of peat, but also the supply chain. Investment in the production and amalgamation of replacement materials requires confidence in both their performance and their future availability in the necessary volume.

The break-even cost of biochar reflects the lifetime cost of producing biochar (including capital investment), before factoring profit. This is useful as it allows different requirements for profit to be considered, for example within an integrated business as opposed to a standalone producer supplying an ingredient. The projected break-even costs presented in the briefing document for Key Informants and Stakeholders were based on UK production of biochar from non-transformed (virgin) UK biomass (Shackley et al. 2011). Biochar made from transformed (non-virgin) UK biomass would be considerably cheaper (Ibarrola et al. 2011). Made from imported biomass (generally wood and other non-transformed biomass resources), biochar might have a higher or lower break-even price, depending on the country of origin.

Ingredients that, as minor constituents, enhance the performance of a mix, such as improving the feasibility and appeal of peat-free products, should sustain a higher break even cost. This is an aspect of material properties and function that, in the context of biochar, is discussed in Section 3.2.

Commercial suppliers of biochar to UK horticulture are currently limited to two small companies: *Carbon Gold* and *Oxford Biochar Company*. Both market a product that contains mainly or only biochar as a soil improver. *Carbon Gold* also market a peat-free compost mix (*GroChar*), in which other ingredients include proprietary coir, seaweed and worm casts. *Carbon Gold* started trialling *GroChar* with professional growers in the organic sector during 2012 (Carbon Gold 2012).

Bringing down the cost of biochar production will not ensure that biochar made from wood is either UK sourced or imported as sustainably produced (e.g. FSC-certified) charcoal. Charcoal is the most available form of biochar currently, but also that for which sustainability is a concern.

Although a break-even cost of biochar production that undercuts charcoal prices could increase its use in growing media the material might have to be unsuitable for use as a fuel, else the charcoal market would prove a more lucrative outlet.

3.1.1. Biochar produced in the UK from non-transformed biomass

The break-even cost of producing biochar from non-transformed (virgin) biomass is unlikely to be less than £100 t^{-1} or approx.. £20 m^{-3} (Shackley et al. 2011). This figure also assumes that biochar production is integrated with energy capture and electricity generation, accessing ROCs from capture of residual energy for power generation. It is a scalable scenario optimal for carbon abatement in the context for that analysis, which sees biochar destined to arable land.

Some elements of this figure include costs of storage and deployment into agricultural soil, which would not be relevant to its use in growing media. In assessing the economic case for the use of biochar in growing media, the cost of transporting and processing biochar (and co-ingredients) is a factor. This would be determined in part by the location of processing, mixing and final distribution of a formulated product.

Since biochar produced from biomass gasification processes geared more to energy capture may not provide properties optimal for horticultural growing media (see Section 3.2), there would be a need for projects where tailored biochar is the main product with heat / energy as a co-product.

Trade-off between capital and operating costs and other activities might affect the most appropriate configuration of pyrolysis technologies, notably between batch production and continuous flow, and the fate / use of energy products and waste heat.

3.1.2. Biochar produced in the UK from transformed (waste) biomass

The breakdown of biochar production costs establishes the purchase of virgin biomass feedstock as the principal component (capital cost of pyrolysis technology the second). The estimated costs for biochar from transformed (waste-derived) biomass are therefore considerably lower than for virgin biomass. Indeed, the projected break-even price for biochar produced from sewage sludge was close to zero (Ibarrola et al. 2011).

The use of waste-derived biochar for certain feedstock or particular products could also benefit the availability and sustainability of biochar production. Organic wastes may be spatially concentrated or generated at point sources, simplifying the logistics of production and potentially formulated products containing biochar (Section 4).

Pyrolysis technologies have a history of use in waste management, being used to neutralise, stabilise and homogenise problem wastes into a smaller volume of residue for landfill. Applied to homogeneous clean wastes streams, pyrolysis creates materials appealing in form and colour, as well as handling. The creation of sterile ingredients from potentially problematic waste material is aesthetically, economically and environmentally attractive.

Experimental production and tests on biochar derived from sewage sludge has been undertaken in the UK as part of a feasibility assessment (ESKTN, 2012). The stability of the resultant biochar and the mobility of its associated metals and mineral ash were assessed. The pyrolysis of sludge has been examined in a number of detailed laboratory studies (Gasco et al. 2012; Inguanzo et al. 2002).

Research has also been undertaken using biochar created from green waste, notably in Australia (Chan et al. 2007). Production of biochar from paper waste has been proven commercially in Australia by *Pacific Pyrolysis* over a number of years (van Zwieten et al. 2010b); biochar produced from similar feedstock in Europe is being tested as an ingredient of compost for agricultural use.

3.1.3. Biochar produced in the UK from imported biomass

The UK imports biomass for power generation. This resource could equally be procured for the production of biochar. Potential pitfalls of acquiring biochar have been highlighted in debate over the provision of feedstock for bioenergy production – in terms of security of supply as well as sustainability. Emerging initiatives to address the issues of sustainability of providing biomass for biochar production are discussed in Section 4.

In the consideration of available feedstock for UK production of biochar specifically, Shackley et al. (2011) only considered importation of Canadian wood chip. This emerged as a relatively costly option, relative to indigenous virgin biomass as well as non-virgin UK waste.

3.1.4. Biochar (charcoal) production and trade internationally

Current consumption of charcoal in the UK stands at approximately 50,000 t yr^{-1}, of which 5% is provided by indigenous production. The main market for charcoal is the retail sector as barbeque fuel and as a feedstock for activation, for which about 10 companies are involved (manufacturing 'activated carbon'). There appears to be an emerging market for charcoal as a renewable component of solid smokeless fuels such as *Ecoal*. A small volume has been sold as 'horticultural charcoal', traditionally used to 'sweeten' potted plants, rather than as part of a growing medium.

Statistics on charcoal production overseas are limited and at least 95% of known production is not traded cross-border. According to the most recent FAO statistics, global production exceeded 47 Mt in 2009. Based on these data, production in Africa also expanded by 29% during the preceding five years and represented the end-use for 30% of wood biomass harvest for fuel (Steierer 2011). This is in mainly in the form of lump-wood charcoal, sold into expanding urban areas. Africa has the fastest growing rates of charcoal consumption.

Of the 2 Mt yr^{-1} charcoal traded on the international market, most is destined for use as barbeque fuel. In the case of the UK, about 60% of the 50,000 t imported annually is from sources certified by the Forestry Stewardship Council (FSC). Social and ethical aspects of the trade have been considered as well. *Traidcraft* currently monitor the supply of barbeque charcoal to the *Cooperative* retail chain (see Section 3). Official statistics are lacking, but the lowest prices for charcoal for international export (ex-port) are in the range \$150–300 t^{-1}.

A recent trend in charcoal production is a return to its use or exploration in some steel production, where since the 19th century, coke has dominated. In Brazil, charcoal production in Brazil is worth USD 3bn yr^{-1} and new schemes have been based on short-rotation Eucalyptus, supported under certified emissions reduction (CER) and endorsed by FSC. The 6 Mt charcoal currently produced in this way command a market price of USD 200–500 t^{-1}. This has led to the development of modern batch production kilns with a mass yield of 200 kg m^{-3} compared to approximately 165 kg m^{-3} in traditional earthen 'beehive' kilns. The production system is being used to capture refinable condensates as by-products.

3.1.5. Integrated production systems

Although a lower break-even cost for sustainable biochar would increase its appeal in horticulture, production below the wholesale price for internationally traded charcoal could favour its sale as fuel.

Several factors could mitigate this possibility:

- Product obtainable using available feedstock and pyrolysis equipment being physically or chemically unsuitable as fuel;
- Introduction of a subsidy or carbon credits that are dependent on non-fuel use;

- Horizontal integration that adds greater total value to an existing business.

Production of biochar in the UK is most likely to emerge through a process yielding other products such as bioenergy, bio (solid) fuel and activated carbon. The production of chemicals is currently being explored in Brazil and Australia, as a modern bio-refining equivalent of the historic 'wood distillation' industry.

A flexible technology configuration that allows the balance between alternate value-streams to be adjusted is desirable, especially in de-risking investment against future changes in market conditions. Although integrating biochar production with the use of wastes and or capture of co-products diversifies revenues and could mitigate the break-even cost of biochar production, it is also liable to inflate capital costs and add technical and product complexity. It also necessitates the adoption of multiple, unproven technologies.

Modern pyrolysis equipment has emerged largely from the waste densification industry and biochar production. Pyrolysis applied to organic waste streams can also address the management of waste and create a resource and value stream.

Examples of integrated and less integrated systems for the UK are defined as 'case studies' in Section 3.4. These are then compared as part of the Sustainability Assessment in Section 4.

3.2. Functional attributes

The suitability of biochar as a constituent of growing media depends on the nature, range and versatility of its chemical and physical properties. Durability is also an important consideration, as well as predictability, certainty and consistency of these properties.

Biochar exhibits multiple properties relevant to the performance of growing media (potentially positive and negative). Pyrolysis involves a multitude of chemical reactions in the solid and vapour phase that can be manipulated to emphasise particular physical properties, surface chemistry and bulk elemental composition. Biochar properties can also be enhanced by modifying the physical and chemical properties of the feedstock, or treating biochar after production ('activation' being an example of post pyrolysis modification for other uses of char).

A key motive for including biochar (or any ingredient) in a mix is for mutual enhancement of the final product. Analysis of compatibility, combinability / synergy is therefore central to an analysis of suitability. Determining the proportion that biochar should constitute in a mix is also a compromise between function / enhancement and cost.

Most scientific research of biochar has focused on its behaviour in agricultural soils of varying texture. These soils generally exhibit low organic matter content (<10%), so the interface of biochar and organic materials is mediated by abundant mixed minerals. Research has examined the efficacy of biochar-amended organic material in the form of compost, though mainly after soil applications. Interactions of biochar and nutrients have been studied in soil (Dempster et al. 2012; van Zwieten et al. 2010a) and in mitigating eutrophication of water (Hollister et al. 2012).

The inclusion of biochar into soil-less growing media has only been reported in two published studies to date. One of these considers its combination with peat (Dumroese et al. 2011). Commercial peat-free growing media containing biochar is being taken up in the UK organic sector, using products marketed by *Carbon Gold* (Carbon Gold 2012).

Experience and knowledge gained through such activities, interpreted in conjunction with existing scientific understanding of biochar could lead to design of more or more specific mixes for use in horticulture. In this Section the salient properties of biochar are described in the context of growing media. The discussion is based on the results of direct characterisation of biochar of various types, or from the response of soils amended with them.

3.2.1. Physical attributes

Biochar from woody and organo-mineral sources or pelleted after production has high rigidity, low friability, and low compressibility as well as low bulk density. Biochar can appear and feel dry at high gravimetric water contents. Particle size can be manipulated through physical grading, although sub-size fractions could be created.

Dust

Dust could present handling issues in the formulation of growing media using biochar, as well as in biochar production. Dust includes native fine particles and particles generated through abrasion and physical disintegration of larger particles. Native dust comprises volatile particles condensed and charred on biochar surfaces during pyrolysis (a form of soot). These particles may comprise a small volumetric and mass proportion in biochar.

Partial saturation as part of a quenching (cooling) procedure post-pyrolysis may control dust issues, but increasing transport costs. Washing as part of a physical grading process or some other pre-treatment (such as leaching) would also potentially cleanse biochar of surface dust.

The nature of any formulation process will determine modification or the native friability of biochar. Packing and transportation will further affect changes in dust content between production and product use. This aspect may be more important than intrinsic dustiness of biochar in the deployment of biochar-containing mixes.

Particle size

Biochar particle size has been found to affect the rate at which mineral nutrients (generally alkaline) leach from biochar. Most research of biochar in soil has used biochar that has either not been size-graded, or whose size is defined only by maximum dimension, with no information provided on particle size distribution (especially very fine particles). Granular feedstock producing even-sized biochar a few millimetres in diameter may be optimal in growing media, depending on content and co-ingredients. The ability to manage or manipulate the particle-size distribution of biochar or to select a particle size range would be important and attractive in meeting the requirements of a particular horticultural use or mix (governing its mobility within the medium for example).

Since pyrolysis changes the hardness and brittleness of feedstock materials and the utility of undersize biochar particles, manipulation of biomass rather than grading of biochar might be preferable. Biomass such as coarse sawdust, rice husk, etc., can have quite defined native particle size that favours selection as biochar feedstock. The moderate shrinkage that is associated with pyrolysis has to be allowed for. If handling feedstock is problematic, the processing of biochar after pyrolysis may be preferable.

Grading biochar after pyrolysis has been undertaken experimentally, but the technology for achieving this economically at large scale needs to be demonstrated. Whether the biochar in question is strong, brittle, hard or soft will determine whether the equipment required for this task is the same that may be used to grade peat. Manipulating the size of a more friable biochar product is not practical due to the proliferation of dust and a discard fraction. Combining grading with washing could be used to simultaneously manipulate the chemical properties of biochar by leaching mineral ash (see Section 3.2.2).

The potential to pellet biochar – or to pyrolyse pelletized biomass – offers the potential for a more consistent or precisely specified and controllable particle size, bulk density and micro-structure. It also provides a means to deal with friable biochar, or biomass creating ordinarily friable biochar that otherwise has favourable properties and/or price.

Bulk density

Shrinkage of biomass particles during pyrolysis is small relative to the elimination of mass (preferentially hydrogen, oxygen and also carbon). This results in a primary product that is low in dry bulk density and by default, a dry product (changed by the addition of water as part of a quenching process). Depending on feedstock particle size and shape that grading may modify, bulk density may be as low as 0.1 t m^{-3}.

A portion of the air space in packed biochar resides within the particles, the remainder between particles. The effect of biochar on the dry bulk density of a horticultural mix will depend on whether biochar particles substitute for air space (increasing bulk density and water holding capacity) or for solid mass (potentially decreasing bulk density and affecting water holding capacity only through water held within biochar pores). The balance of these two effects is in turn dependent on mix ratios.

The dry bulk density of biochar is much greater than the 'skeletal' density, which excludes pore volume and is an indicator of the degree of pyrolytic conversion. In the utilisation of transformed biomass such as anaerobically digested sludge the porous macro-structure is considerably diminished and also infused with mineral material.

Pelleting of the biomass prior to pyrolysis or of the biochar product changes biochar porosity and pore connectivity. It also alters external surface area and biochar bulk density. Use of ingredients to promote pellet formation ('binders') would likely also alter the chemical properties of biochar.

Flow

Smooth surfaces and low compressibility favour a free flowing ingredient. Pelleted or otherwise denser biochar may be particularly amenable to the mechanised mixing processes involved in growing media formulation.

Friability

Friability is the most discernible property of biochar beyond particle size, shape and colour. It has implications for many handling properties – bulk density, compressibility, gradability and particle size distribution. It affects the durability of any chemical or physical property related to particle size. Higher pyrolysis temperatures create more rigid biochar, although this is fundamentally controlled by feedstock characteristics. Lignin content may be a key predictor, with more woody (higher lignin) feedstock creating more rigid biochar – charcoal density has been linked to this variable. Highest lignin contents (~40%) are found in nut shells; wood contains ~25–30%, straw ~15–20% and grasses ~10–15%. Where the biomass has higher lignin content but not desirable particle size, feedstock chipping may be preferable to the grading of a more rigid, brittle biochar product.

Abundant mineral elements in the mix change structure, creating more resilient particles from sludge, silica-rich husks, etc. It follows that softer, friable biochar arising from materials such as crop straw, could be strengthened by the inclusion of minerals in pyrolysis feedstock. Pelleting of biochar or biochar feedstock provides an alternative to relying on indigenous properties. Granular activated carbon is an established product and, post-use, the major ingredient of the advertised soil improver *Enrichar*. The physical properties were particularly appealing amongst those presented to key informants.

In existing research, pyrolysed biomass pellets were found to have low integrity after wetting. This tendency to fragment could be useful in growing media if the resultant products were predictable and of desirable composition and function, but potentially detrimental to physical properties. Different pelleting technologies or approaches, including the use of ingredients to bind biochar fragments could provide stable biochar pellets of various dimensions. The feasibility and costs associated with pelleting finely divided biochar and its impacts on function are not known.

Combined biochar–fertiliser products have been produced and marketed in China and in the UK, although scientific evidence for their functionality is not published.

Compressibility

Dry bulk density varies according to particle size and shape; products comprising finer and irregular particles may settle in transit. Individual particles are soft and brittle. While incompressible to the point of brittle fracture, subsequent fragmentation can increase bulk density. As noted above, biochar from woody feedstock is less friable; biochar from straw and similar materials is more fragile and powdery and thus compressible. Low compressibility is important in matching media volume to the capacity of the media to fill containers. The potential value of biochar in maintaining filled volume is discussed with shrink–swell, below.

Colour

Aesthetics of growing media are an important consideration and black is a desirable colour for the constituents of growing media. While maintaining a relatively even colour, dry biochar with a higher ash contents can appear grey. Smooth surfaces exhibited by some types of biochar can appear shiny. Heterogeneity in biochar from virgin biomass can be observed, especially amongst larger particles, where the diversity of morphology within the plant is reflected in components of the pyrolysis product.

Porosity and surface area

Biochar porosity is a key factor governing the interaction of biochar-containing mixes with water. It is possible that pores localise microbial activity undertaking chemical transformations. Porous biochar can be used as a mechanism for carriage of added nutrients as well as delivering indigenous minerals, or for transferring inoculants or control chemicals.

Biochar from virgin biomass contains an abundance of large pores (macro-pores >10 μm). Their relative concentration reflects the structure of the feedstock material, but their connectivity can be enhanced by higher-temperature pyrolysis. These pores could contribute to air-filled porosity in growing media, though it is worth noting that these pores can be clogged if kiln configurations favour charring of vapours during pyrolysis. Biomass that is biologically digested (e.g. products of anaerobic digestion) inherit less plant structure and in the case of organo-mineral feedstock such as sewage sludge, may be diminished further by infiltration by mineral particles.

Pyrolysis promotes the creation of new pores of a much smaller dimension (1 nm–1 μm) that are likely to remain water-filled. The proliferation of fine pores explains most of the apparent expansion in surface area when pyrolysis is undertaken at higher temperatures. Specific surface area Surface area, which generally ranges between 10–1000 $m^2 g^{-1}$, is often used to estimate pore volume of biochar. However, the use of methods based on gas adsorption to assess pores and their associated surfaces emphasise those that are too small or inaccessible to be relevant to mass flow or microbial colonisation.

Pure biochar includes inter-particle porosity that can be lost by mixing in other ingredients. Biochar with fine particle size (or a mix of sizes that includes fine particles) will exhibit high "inter-particle" porosity that may not be conferred to a growing media mix. This may explain why despite gravimetric water holding capacity of up to 400%, statistical significance of (smaller) effects of amended soil have proved difficult to demonstrate (Basso et al. 2012).

Water holding

Water filled pores hold water against gravity but can be accessed by plant roots (pores in the size range 10–1 μm). Using biochar to manipulate the content of plant-available water content of growing media has considerable potential to buffer watering and to increase shelf life. The hygroscopic nature of biochar may assist in maintaining even moisture content in a growing media mix by buffering against overwatering and under-watering.

The anecdotal evidence reported by *Carbon Gold* in grower trials suggests that the relationships between biochar and water are central to its utility in growing media. However, scientific data has not been collected to explain and purposefully exploit these effects, in particular information to relate feedstock and pyrolysis parameters to favourable water release properties.

As noted above, the porosity of biochar also needs to be carefully described in order to predict its impact in growing media once 'diluted' by other ingredients. However, the converse can also be the case. Studies of growing media produced using biochar pelleted with fresh biomass as part of a peat mix (Dumroese et al. 2011), reported gravimetric water holding capacity 70% higher than for peat only, when containing the biochar–biomass pellets at a volumetric content of 25% or 50%. Despite the positive effect of the biochar pellets on a peat mix, the water holding capacity of the pellets alone was 37% lower than for peat alone.

Pelleting changes the abundance and connectivity of the pores in pyrolysis feedstock and biochar. It also changes shape and external surface area in a way that affects its capacity to store water independently of a mix. At the current time, it is difficult to predict the specific effects of biochar on soil and growing media.

Shrink / swell

Biochar has a rigid structure and its volume affected rather little by degree of water saturation, independent of porosity. The importance of this to growing media was captured in studies of pelleted biochar where the effect on volume of wetting was avoided by inclusion of biochar pellets at 25% dry volume (Dumroese et al. 2011)

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Wettability

In the natural environment, the hydrophobicity of charcoal has been cited as a cause of erosion and slow ecosystem recovery after wildfire (DeBano 2000). Hydrophobicity has also been cited as a potentially detrimental property of biochar used to amend field soils; biochar freshly produced at lower pyrolysis temperatures having also been found to display hydrophobic properties (Kinney et al. 2012). The potential for hydrophobicity to affect the storage of water in growing media containing biochar has been noted. However, hydrophobicity could be potentially beneficial if it can mitigate risk of over-watering, occasionally a problem in media containing peat replacement materials. Experiments with biochar–biomass pellets did not decrease wettability of growing media up to 50 % content by volume mixed with peat. Wettability over about one hour was highest in a 50–50 mix (Dumroese et al. 2011).

Thermal conductivity

Charcoal has a heat capacity similar to soil and peat but much lower thermal conductivity that could provide thermal buffering. Absorbance of radiant energy is also higher on account of colour. These properties are of possible relevance to protection of nursery stock as well as green roof installations.

3.2.2. Chemical attributes

Biochar contains elements of value to crop growth, and interact with plants through direct interface with plant roots (Prendergast-Miller et al. 2013). Some types of biochar can also contain potentially toxic elements and measurable concentrations of organic contaminants (Freddo et al. 2012).

Nutrient supply

The elimination of C and (preferentially) O and H means that pyrolysis 'concentrates' mineral elements and most metals into biochar, the latter being stable at typical processing temperatures. Reconfiguration of carbon into stable aromatic (ring) structures results in a portion of these elements becoming leachable in the form of 'ash'. The physical structure of biochar controls the rate of leaching of minerals and metals into growing media (or soil). Nitrogen is volatile at pyrolysis temperatures, so biochar displays a very high C to N ratio. Any remaining nitrogen is, like the carbon, essentially unavailable.

Currently the leaching of nutrients from biochar of contrasting micro-structure as well as ash content is limited. However, simple tests to screen for this property have been developed (Angst and Sohi 2012; Wu et al. 2011).

Crop straw initially contains high concentrations of ash compared to woody materials. This means there is greater potential for nutrient loading to growing media. Pyrolysis processes that yield less biochar (e.g. higher-temperature processing, gasification) are also liable to concentrate mineral elements into a small volume of product. Potassium is most readily leached and could potentially have negative effects on growing media resulting from elevated salt concentrations (Dumroese et al. 2011) and raised pH. Higher temperature pyrolysis may decrease the relative availability of phosphorus in biochar while increasing its concentration

If well managed, the pattern of release of indigenous nutrients could be exploited in a formulated biochar product (Novak et al. 2009). If feedstock is mixed or otherwise inconsistent in composition, biochar made from low-ash materials might be favoured.

The absence of available nitrogen in biochar is useful in precisely controlling plant growth (Knicker 2010). Since biochar does not mineralise, it will also not release nitrogen over time. However, evidence for an affinity of biochar surfaces for ammonium and for biochar pores to store nitrate (Prendergast-Miller et al. 2011) could be useful. It suggests that biochar could help maintain a more even nutrient status if other ingredients are supplying nitrogen, or nitrogen is added from an external source.

Biochar formulated with added nitrogen or other nutrients have potential as a carrier for slow release nutrients. These could form the basis for a value added product, specifically for systems without online nutrient management. Such products, tailored for the needs of large-scale agricultural markets have been developed for commercialisation (e.g. *Full Circle Biochar* and trademarked products). Published research on this topic has not yet emerged, however.

Liming value

In supplying nutrient base cations biochar can also influence pH. In bulk soil, increased pH is a key mechanism by which biochar alleviates constraints to crop growth (Jeffery et al. 2011). The effect of biochar on soil pH depends on buffering capacity. It also depends on the base cation content of the biochar (for which ash content could provide an indicator) and the amount of biochar added.

Biochar has a liming value approximately one-tenth to one-third of calcium carbonate on a mass basis (van Zwieten et al. 2010b). The duration of the effect probably reflects the leaching pattern associated with the biochar, a function of particle size and physical micro-structure (Angst and Sohi 2012). In formulation, of growing media biochar and co-ingredients could be selected and matched to allow for this property. Although technically feasible, pre-leaching biochar to moderate its alkalinity could be more complicated than sourcing a different biochar.

Biochar does not always display alkalinity. Moderately acidifying properties have been reported for biochar made at low pyrolysis temperatures (under $400^{0}C$).

Potentially toxic elements

As mentioned above, pyrolysis concentrates metals present in feedstock into the biochar product by eliminating O, H and C. The content of biochar can be predicted from analysis of the starting material, if this is available, knowing the mass yield of biochar in the pyrolysis process (in which minerals and metals are conserved). However, methods have also been established to directly quantify the elemental composition of biochar if this information is not available (Enders and Lehmann 2012).

Assessment of risk from potentially toxic elements (PTEs) is generally based on total content and likely to limit the choice of biomass used to make biochar, particularly waste materials. The often low availability of PTEs in biochar that results from chemical stabilisation and adsorption is likely to be overlooked. Regardless of its own PTE content, the adsorptive properties of biochar lead to an affinity for metal contaminants already in soil. For this reason, the potential already for biochar in the remediation of contaminated land has been explored (Beesley et al. 2011; Quilliam et al. 2012). It is likely that biochar would localise contaminants present in biochar from other sources.

Persistent organic compounds

Polycyclic aromatic hydrocarbons (PAH) are toxic compounds distinguished at a molecular scale, as short sequences of interlinked carbon rings. They are associated with tar and can be created (as well as conserved) in biomass pyrolysis. They are more commonly present as the products of incomplete combustion of biomass and coal. Sixteen PAH compounds have been identified as high priority for regulation to prevent impacts on environment and health (referred to as EPA16). Aside from the inhalation of smoke and soot, ingestion or inhalation of soil dust is the main source of exposure for humans. The compounds are not readily taken up by plants. Plants also metabolise PAHs to innocuous products (Hoylman and Walton 1994) and PAHs do not bio-accumulate in the food chain (Devier and Budzinski 2007). PAHs degrade over months to decades in bulk soil but much more rapidly around plant roots (Hoylman and Walton 1994).

Understanding the presence, abundance, identity and source of polycyclic aromatic hydrocarbon (PAH) in biochar is the focus on current research activity. Data that has been presented or published has tended to find measurable concentrations of the EPA16 PAHs (Freddo et al. 2012; Sopeña et al. 2012). However, these are generally below screening limits of 1–5 mg kg^{-1} set for compost or soil in Europe (Carlon 2007), although it is not uncommon for UK soils to exceed these levels around urban areas (Cousins et al. 1997). Threshold PAH concentrations have been set for foods and (separately) food flavourings. These are two orders of magnitude lower than those for soil, but based on the concentration of a single key PAH compound (benzo-a-pyrene).

More comprehensive studies of PAH concentrations in biochar have started to emerge (Hilber et al. 2012). These reveal a relationship between PAH content and pyrolysis temperature, PAHs peaking in biochar produced at lower pyrolysis temperatures of ~450^{o}C (Hale et al. 2012; Keiluweit et al. 2012). This is perhaps due to the greater possibility of condensation of tar onto the biochar product. The role of pyrolysis technology is not yet fully understood, but sensitivity to kiln residence suggests it is important that thermal equilibrium is reached between kiln and the heated biomass (Hale et al. 2012). This can be more difficult to manage in continuous flow than batch production. When produced from waste materials with an indigenous PAH content, the concentration of PAH in biochar may be higher than in the feedstock mass for mass, suggesting that PAHs can be conserved during pyrolysis. Careful selection of feedstock reduces the possibility of problematic PAH concentrations, focusing on PAHs created in pyrolysis rather than concentrated into biochar from its feedstock. Biochar, like charcoal in the natural environment, has a high affinity for PAHs in soil and could localise contaminants in growing media (Quilliam et al. 2012).

Adsorption of agrochemicals

A few studies have examined the affinity of biochar for pre-emergence herbicides, when applied to soil at rates of up to 5% by mass: isoproturon sorbed by hardwood biochar at up to 2% soil mass (Sopeña et al. 2012), simazine (now banned in Europe) by hardwood biochar at up to 5% soil mass, and atrazine and trifluralin by wheat straw biochar up to 1% soil mass (Loganathan et al. 2009). In studies where efficacy of soil-applied herbicide was decreased by at least one-third, biochar adsorbed the chemicals and inhibited their subsequent breakdown. In the case of isoproturon, the presence of toxic breakdown products was decreased (Jones et al. 2011).

If herbicides are localised around biochar (by adsorption), the inhibition of natural breakdown could favour accumulation of toxic organic compounds (Jones et al. 2011). However, recent evidence suggests this may not be the case in soil (Jablonowski et al. 2013). The short life time of horticultural growing media makes such accumulation less of a concern aside from through disposal. Current research has not addressed effects on efficacy of insecticides and fungicides used in horticulture or considered also the biological attributes of biochar that could decrease reliance on chemical control (Elad et al. 2010; Harel et al. 2012).

Interactions with nitrogen

Decomposition of N-containing constituents can result in the release of mineral nitrogen to growing media, especially if in excess of microbial requirement (i.e. if the degrading substrate is deficient in N). In soil, biochar addition has been shown to lead to biotic and abiotic immobilisation of nitrogen in roughly equal measure. The extent and ratio of these effects depends on how biochar is produced. Biochar made at lower pyrolysis temperatures tends to contain a measurable fraction of carbon that is labile and promoting short-term immobilisation. Biochar made at higher temperatures tends to have surfaces that are more chemically active, adsorbing ammonium nitrogen from the soil solution.

Studies have linked decreased nitrate leaching in experimental situations to these processes. However, it appears that biochar affects the distribution of soluble nitrate nitrogen in soil. Higher concentrations of nitrate have been found to be maintained around plant roots when in the presence of hardwood biochar.

3.2.3. Biological attributes

Provided that thermal equilibrium has been reached between the kiln and biomass feedstock, biochar is sterile at the point of production. Storage results in rapid establishment of microbial populations with or without deliberate inoculation. Biochar can also contain a complex mix of compounds that are biologically relevant through condensation reactions. These are potential stimulants of plant growth and can affect the interaction between plants and plant pathogens and other stresses (Elad et al. 2011). The predictability and generality of these compounds and the feasibility of manipulating or even synthesising them is not yet known. It is possible that they might be tuned to particular user needs using consistent feedstock and specific pyrolysis technologies.

Pathogen interactions

Either the adsorptive properties of biochar or its trace chemical constituents (which may be short lived) have been found to inhibit infection of crops by pathogens. In the field and laboratory biochar has inhibited the *Fusarium* sp. infection of asparagus, apparently through adsorption (and subsequent degradation) of allelopathic agents associated with the infection process (Elad et al. 2011). Direct toxic effects of biochar on sensitive pathogen species has not been ruled out, possibly related to traces of tars or other chemicals that can condense from the volatile phase onto char before being 'swept' from the pyrolysis kiln.

Induced systemic resistance

The limited published work on biochar and disease resistance induced by biochar has been undertaken with horticultural crops (peppers, tomatoes and strawberries) in soil-less media comprising coconut fibre and/or peat with porous volcanic minerals (Elad et al. 2010). The concentration of biochar in growing media used in these studies (up to 3 % on a mass basis) has been sufficient to show positive effects on disease suppression. Some initial elucidation of the biological mechanisms has been undertaken using molecular techniques.

Growth promoting compounds

The discovery that short-term emissions of volatile compounds from biochar included ethylene (Spokas 2010) has increased focus on indirect growth-promoting properties (e.g. hormesis). Such effects may explain the variability in occasionally dramatic effects on early stage plant growth. There are relatively few scientific studies addressing this issue.

It is probable that biochar products with a relative higher content of labile (rapidly mineralised) organic carbon – about 1% – would be most likely to contain such compounds and display associate effects. In general terms, labile carbon is related inversely to pyrolysis temperature.

Microbial proliferation

In soil, bacteria and fungi are essential to effect the recycling of nutrients from soil organic matter and appear to be promoted by plants around plant roots, almost certainly to assist in the acquisition of nutrients and also to deflect pathogenic attack. More intimate associations occur in the colonisation of plant roots by mycorrhizal fungi, especially under nutrient poor conditions.

In soil the colonisation of biochar by bacterial cells and fungal hyphae has been visualised using electron microscopy. Since biochar is almost completely non-degradable over short timeframes, it has been suggested that surfaces and pores provided by biochar provide favourable habitat that promotes microbial proliferation driven by carbon and nutrients in soil solution. The result could be a localisation of processes potentially beneficial to the plant, around biochar particles.

However, the small biologically labile fraction of carbon present in biochar could also support short-term expansion of the microbial community and explain colonisation. This could be supported by the observation that colonisation of biochar is affected by biochar production conditions independently of its macro-porosity.

In growing media, external control over the supply of nutrients diminishes the potential significance of microbial abundance and diversity. The proliferation of microbial biomass without an indigenous supply of mineral nitrogen from biochar may create a small demand for nutrients that may need to be factored into the nutrient management regime.

Root interactions

Proliferation of pant roots around biochar has been quantified experimentally in soil (Prendergast-Miller et al. 2013), supporting abundant anecdotal evidence. Such effects may be explained as tropisms related to the acquisition of indigenous nutrients and stored water. They may also reflect the presence of trace compounds in biochar described above. The maintenance of high nitrate concentration around plant roots suggests a role for nitrogen storage and supply that is of potential relevance to crop performance (Prendergast-Miller et al. 2011). Proliferation of roots assists in creating plants amenable to successful transplanting.

3.2.4. Synthesis

The analysis and review of biochar properties is summarised in the table below, comparing subjectively with (a) peat, and (b) peat replacement ingredients. The purpose is to identify the proportion and mix that might best fit particular uses of growing media. The areas of particular uncertainty are highlighted.

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Function / property	Knowledge base	Pos/negative attribute	Extent	Universality	Consistency / control	Manipulability	Durability (*regenerable)	Predictability	Exhibition of property relative to alternative ingredients				Combinability		Use types most benefitted§	Unknowns / needs
									Peat	Bark	GWC	Coir	Possible. Incompat-ibility	Synergy		
Handing / aesthetic																
Dust	L	–	M	M	H	Y	L	–	+	+	+	+	Bark	All other	None	Size of v fine particles; toxicity; efficacy / cost of removal (washing / leaching, etc.)
Defined particle size dist.	M	+	H	H	H	Y	H/M/L*	H	+/	/	+	+	None	All	LFM / LFL	Suitability of equipment for crushing / grading / chipping feedstock
Low bulk density	M	+	H	M	H	N	H/M*	H	+	+	+	–	None	All	All	Database for biochar v. f'stock properties
Friable macro-structure	L	–	M	L	H	N	M/L*	–	/–	+	/–	/	Bark	None	LFM / GP	Database for abrasion number v f'stock properties and pyrolysis conditions
Flow	L	+	M	M	H	Y	H	H	+	+	+	+	None	All	LFM / LFL	
Incompressible particles	L	+/–	H	M	H	N	H/M/L*	M	+	/	+	+	None	Coir	LFM / LFL / GP	
Black / v dark colour	H	+	H	H	H	N	H*	H	+	+	+	+	None	None	All	Critical mixing ratios
Homogeneity	L	+	H	M	H	Y	H*	H	+/	+	+	/–	None	All	All	Data on biochar properties
Physical properties																
High stable macro porosity	L	+	H	M	M	Y	M*	M	+/–	+	+	–	None	All	LFL	Database of porosimetry data v f'stock properties
Surface area	M	+/–	M	L	M	L	M*	M	+	+	+	+	None	All	LFL / GP / ET / RMP	Database of iodine number v. f'stock properties and pyrolysis conditions
H_2O holding / release	Y	+	H	M	M	Y	M*	M	+	+	+	?	None	All	All	Water release curves derived from pressure plate studies of biochar *mixes*

Function / property	Knowledge base	Pos/negative attribute	Extent	Universality	Consistency / control	Manipulability	Durability (*regenerable)	Predictability	Exhibition of property relative to alternative ingredients				Combinability		Use types most benefitted§	Unknowns / needs
									Peat	Bark	GWC	Coir	Possible. Incompat-ibility	Synergy		
Chemical properties																
Low shrink–swell	Y	+	H	H	M	N	M*	M	+	/	+	?	None	All	All	Understand effect of biochar addition to the shrink–swell behaviour of the mix
High wettability	Y	+/–	H	M	M	Y/N	H*	M	+	+/	+/	?	None	All	All	Establish functional basis to select / manipulate biochar accentuating the property
Supply of mineral nutrients	Y	+/–	M	L	M	Y	L	L	+	+/	+/–	+/–	GWC, coir	Bark, peat	LFL / RMP	Predictors of nutrient release against total content, techniques for removing / adding controlled amount of slow release nutrient
Inherent alkalinity (liming)	Y	–	M	L	M	Y	L	L	+	+	+	/	Coir	?	None	Predictors of effect / longevity of effect of pH; potential to manipulate alkalinity (pre-treatment / pyrolysis parameters)
Measurable PTEs	Y	–	M	L	M	N	H*	L	+	+	+/	?	GWC	None	None	Availability of PTEs to solution in growing media
Detectable PAHs (POPs)	Y	–	M	L	M	N	M*	L	+/	+	+/	?	GWC	None	None	Systematic studies into the effect of pyrolysis quenching and cooling as well as temperature
Chemical adsorption	Y	+/–	M	L	M	Y	M*	L/M	/	+	+	+	None	GWC	LFL / GP / ET RMP	Database of iodine number v. feedstock properties and pyrolysis conditions
NH_4 / NO_3 storage	Y	+/–	M	L	M	Y	M*	L/M	+	+	+/–	?	None	GWC	LFL / GP / ET RMP	Database of functional test results for nitrate storage and ammonium adsorption

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Function / property	Knowledge base	Pos/negative attribute	Extent	Universality	Consistency / control	Manipulability	Durability (*regenerable)	Predictability	Exhibition of property relative to alternative ingredients				Combinability		Use types most benefitted§	Unknowns / needs
									Peat	Bark	GWC	Coir	Possible. Incompat-ibility	Synergy		
Biological properties																
Sterility (fresh)	L	+	H	M	M	N	L	H	+	+	+	−	None	None	All	
Inhibition of crop pathogens	L	+	M	L	L	Y/N	L	L/M	+	+	+/	+	None	All	All	Establish the identity and thus toxicity of active compounds, mode of action, potential use in growing media
Induced systemic resistance	L	+	M	L	L	Y/N	L	L/M	+	+	+/−	+	None	All	All	Establish the identity and thus toxicity of active compounds, mode of action, potential use in growing media
Growth promoting comp.	L	+/−	M	L	L	Y/N	L	L/M	+/−	+	+	+	None	All	LFM / GP	Establish the identity and thus toxicity of active compounds, mode of action, potential use in growing media
Microbial proliferation	M	+ /	L	M	M	Y	?	M	?	?	−	?	None	All	?	Draw on information on the reason for microbial proliferation and the
Root proliferation	M	+	H	M	M	Y	L?	L	+ /	+ /	+	?	None	All	EP	
Low mineralisation	M	+	H	H	M	Y	H	M	+/	+	+	+ /	None	All	All	

+ = higher; − = lower
H = high; M= medium; L = low
§ LFM = Loose fill modular; LFL = Loose fill liners; GP = Glue plugs; ET = *Ellepot* tubes; RMP = Retail multi-purpose

Table 1: *Summary of properties comparing biochar with peat and alternative peat replacement ingredients*

3.3. Logistical considerations

3.3.1. Spatial considerations

Substitution of biochar and other ingredients for peat could change the logic for siting facilities for the production of horticultural growing media. If the value of biochar in growing media is proven and becomes sufficiently important, the opportunity to integrate biochar production with other needs and activities can be addressed. This could decrease the cost of biochar by integrating multiple elements into one business and at the same time take control of factors introducing uncertainty or risk associated with the supply chain (including feedstock availability and supply).

In addition to processing a defined biomass waste stream into biochar as an ingredient to a range of growing media, pyrolysis at a certain scale can lend itself to the generation of electricity or at least supply of heat.

Depending on the ingredients used in growing media, the potential to recover and recycle used growing media through pyrolysis and re-grading into a new product could be considered, saving disposal costs to growers and adding to security of feedstock supply. Biological and certain chemical contaminants could be eliminated.

3.3.2. Technological innovation

Batch processing has limited scalability or potential to decrease operating costs. Although traditional batch production is specific and inflexible with respect to feedstock, the potential for clean production with capture of condensable co-products and close management of temperature and other relevant process parameter has been demonstrated.

There is limited commercial experience with new technologies for slow continuous flow pyrolysis of biomass. *BEST Energies* in Australia (now *PacPyro*) pioneered advances in this area, pyrolysing a range of biomass types but mainly (high mineral) paper sludge in a rotating horizontal tube kiln. In Europe, a continuous flow design based on cylindrical inclined kiln and internal auger screw to transmit feedstock has been deployed by *Pyreg* in multiple locations, including production of biochar from paper sludge for use in a composting business.

Rotating kilns draw on technology that has been established in other industries (including reactivation of carbon and waste densification) and thus already operational at scales considerably higher than 1 t d^{-1} throughput. If the challenges of processing diverse feedstock for biochar with a clean separation of volatile products are addressed, these technologies could provide a suitable basis for energy recovery in large scale biochar production.

Technology for biomass gasification, where energy is the main product, is better established. Gasification produces biochar as a minor product, generally enriched in ash.

3.3.3. Potential scale of biochar use

Although biochar has a distinct mix of properties relevant to growing media and can under some circumstances sustain the growth of plants alone, content exceeding 25% might compromise provision of other characteristics. Diminishing returns to product performance might occur when biochar content exceeds a somewhat lower figure.

To achieve 10% biochar content in all growing media, 0.42 M m^3 yr^{-1} biochar would be required. This would equate to 40,000–170,000 t yr^{-1} depending biochar type (bulk density). The biomass required to produce this amount of biochar would depend on the technology used to convert it. Using slow pyrolysis it could be derived from 120,000–500,000 t of dry biomass. Produced as a co-product of biomass gasification (bioenergy), as much as 1.5 Mt of biomass might be involved. These figures guide the scoping of sustainability issues in Section 4.

3.4. Economic feasibility – Deployment Scenarios

Biochar made from a diverse range of biomass could provide properties beneficial to growing media. Raw materials could include virgin and non-virgin biomass. A range of technologies could be deployed, in a range of locations at a range of scales, and with potential for creating co-products. This creates diverse possibilities, narrowed down by logistical and technological issues introduced above (Section 3.3) as well as the functional properties of biochar that are relevant in growing media (Section 3.2).

However, the availability of biochar for use in growing media will depend on matching technical considerations with economic feasibility and other policy drivers. Since a range of diverse biochar products could prove feasible once the trade-offs between price and performance are established, it is useful to develop scenarios for feasibility and sustainability assessment.

Considerations of economic availability are particularly important in the categorisation of biochar types since biochar available at low price implies waste materials as feedstock, or use of an existing waste product described as biochar. Such choices of material affect the other parameters in the assessment structure.

Representative scenarios were identified for the assessment of sustainability and economic viability of use of biochar in growing media as follows:

3.4.1. Scenario A1 / A2: *UK charcoal*

In analysis of virgin and non-virgin biomass resources potentially available for biochar production in the UK, Shackley and Sohi (2010) used an estimate of 200,000–800,000 t yr^{-1} for woody wastes and residues from woodland and forests. It was recognised that this quantitatively important supply of biomass would be attractive to an existing industry, albeit with feedstock of less convenient form and enriched in bark (which has distinct chemical composition and morphology relative to heartwood).

Currently, about 5% of the 60,000 t yr^{-1} charcoal used in the UK is produced indigenously, mainly by small scale charcoal producers using internally fired 'ring kilns' – portable metal rings placed on the ground, loaded with seasoned hardwood and lidded after a short combustion phase. These units have ~7 m^3 capacity, are vented from the kiln floor, and cleaner than less well sealed and vented (e.g. earthen) kilns. Pyrolysis over 24 h is followed by an extended (3 day) cooling phase. Such technology matches the scale and nature of current operations which are linked to seasonal thinning or clearing operations for which portability is convenient. Pyrolysis in these kilns is also suited to dense ash, beech, oak, chestnut, hazel, etc.

Carbon Gold based their initial production of *GroChar* (and related products) on a development of this model, mitigating the slow and labour-intensive production through development of a modified ring kiln technology. The larger kilns that emerged convert larger volumes of biomass more effectively and in less time (25 % mass yield in an 8 hr pyrolysis process).

A1. To achieve throughput of the smallest scale of biochar production considered in the 2010 report (2000 t yr^{-1} biochar) in batch processing, ten large kilns in continuous seasonal operation would be required. Assuming typical recovery costs for biomass recovery and chipping from woodland and plantations (£57 t^{-1}, see Table 2) biochar produced in this system is estimated to incur a break-even cost approaching £500 t^{-1} biochar. Charcoal bulk density increases with particle size, but is unlikely translate into a break-even price of less than £100 m^{-3} for use in growing media (un-pelleted).

A2. In all three scales of operation defined in the analysis of Shackley and Sohi (2010) a continuous flow process (rather than batch system) was envisaged. This saves labour costs and creates a system that is amenable to energy capture and generation of electricity from co-products, that is then eligible for Renewable Obligation Certificates (ROCs). Projected income from electricity and ROCs more than recoups the capital cost associated with the continuous system, resulting in a break-even cost (excluding on-farm storage and field application) of £270 t^{-1} (a minimum of approx.. £50 m^{-3}). The technology involved in this scenario is currently unproven, especially the channelling of pyrolysis products to the production of electricity (gas engines or micro- turbine technology).

3.4.2. Scenario B1 / B2: *Imported biochar*

The international industry associated with charcoal production was outlined in Section 3.1.4. Charcoal fines arising in charcoal fuel production are a waste material of potential value to horticulture, but liable to be variable in composition and limited volume, even at large production sites (e.g. in Brazil).

B1. Charcoal supplied in bulk from West Africa – the largest regional charcoal exporter globally – is liable to be produced in kilns with limited process control and low product yield, from tropical hardwood. This is the source of lowest price charcoal with import prices as low as USD 150–300 t^{-1}. Costs to bring the product to UK horticulture would include shipment and crushing / grading and processing / blending to increase consistency in composition.

B2. The emergence of FSC-certified charcoal should offer traceability and responsible management of land with re-planting. The current contribution of charcoal fuel production in some African economies has led to interest amongst some NGOs in formalising and regulating charcoal production. They seek to couple investment in more effective kilns with the growing of trees specifically for charcoal manufacture as well as rural fuel, creating a sustainable link between rural communities and the urban economy (Seidel 2008; wa Gathui et al. 2011).

3.4.3. Scenario C: *Integrated biochar production and retail*

Producing growing media close to the retail business provides opportunity for the use of a homogenous feedstock stream for biochar production, i.e. utilising a consistent stream of clean (non-virgin biomass) wastes. Biochar can integrate horticulture, waste management and the provision of energy (heat / electricity) for retail or commercial space.

In addition to ROCs, a gate fee for waste disposal is avoided.

3.4.4. Scenario D: *Biochar production from UK wastewater sludge*

Wastewater treatment sludge presents a major organic resource in the UK (approx. 1.5 Mt yr^{-1}) that is also considerably less contaminated with toxic metals than a decade ago. Pyrolysing pelleted sludge could convert an existing homogeneous stream of amorphous organic matter with substantial mineral content into biochar, with recovery of energy that covers some costs otherwise associated with drying wet feedstock.

3.4.5. Summary of estimated biochar costs used in scenarios

The break-even cost of biochar deployment in UK agriculture have been previously assessed in the context of UK feedstock and production (Shackley et al. 2011; Shackley and Sohi 2010). The simple economic analysis below draws on feedstock and production costs / income from these earlier analyses, assuming small scale (2000 t yr^{-1}) for Scenarios A1/A2 and medium scale for Scenarios C/D. Multiple units incurring labour costs estimated by Shackley et al. (2011). In the UK production scenarios excluding A1 (traditional technology), continuous yields energy co-products used for electricity generation and eligible for ROCs (B2, C, D).

Costs of biochar storage are omitted, assuming that any costs associated with storage of biochar borne by producers of growing media also apply to alternative ingredients. Transportation costs are only from the feedstock source to the producer, as downstream transportation costs exists from current biochar-free product. Location of production facility is assumed optimal for biochar production, but could be designed around access to co-ingredients. Costs for imported charcoal are based on a range of wholesaler prices for African export, assigning the higher price to sustainably sourced product, notionally created in modified kilns, although evidence for a differential in price (rather than availability) is lacking.

Since the net cost calculated for each scenario is the break-even cost, it represents the price to a producer of growing media producing biochar within the supply chain. The price for biochar created under the scenarios and purchased by a producer of growing media would be subject to a mark-up from the producer.

Scenario Costs (£ t^{-1} biochar)	A1 UK charcoal	A2 UK forest waste pyrolysis	B1 Imported W African charcoal	B2 Sustain-able Kenyan charcoal	C Waste wood pyrolysis at formulator/ retailer	D Sewage sludge pyrolysis
Sales of electricity	0	-114			-114	-86
Renewable obligation cert.	0	-74			-74	-56
Avoided gate fee	0	0			-75	-50
Capital cost	10	87			101	101
Feedstock (collection)	228	171			171	0
Transport (to unit)	3	15			0	0
Storage (feedstock)	21	7			0	0
Kiln start up fuel	11	11			11	11
Transport to formulator	2	0	40	40	0	7
Labour	205	41			48	48
Plant costs	1	49			60	60
Charcoal purchase			136	212		
Formulation / pelleting	0	0	0	0	0	0
Net cost (£ t^{-1})	**481**	**193**	**196**	**272**	**128**	**37**
Net cost (£ m^{-3})	**116**	**46**	**48**	**66**	**31**	**9**

Table 2: *Indicative net cost for biochar in growing media under different production scenarios*

Section 4: Sustainability Assessment

Biochar can be made from a range of virgin and non-virgin biomass resources– using a range of alternative technologies. The conversion of biomass to biochar could occur in diverse geographic locations. The range of scales of operation and the potential for creating and valorising co-products is large. Despite the infinite possibilities, economics and logistical considerations will limit feasible options for biochar production and use (Sections 3.3 and 3.4).

The fundamental issues concerning sustainability of biochar use in growing media depend on the ultimate scale of production and use. If approx. 85,000 t yr^{-1} of biochar were to replace10% of current growing media (average) in the UK, certain types might not be economically supplied indigenously. Adoption driven by performance as well as policy, potential demand for imported biochar in the EU and overseas could be considerably larger.

As well as total use, the preferred types of biochar would impact its sustainability. It is useful to categorise types of biochar in sustainability assessment by type, considering the relative availability of feedstock. Biochar available at lower cost implies processed waste feedstock, or use of an existing co-product that can be described as biochar (e.g. gasification ash).

4.1. Sustainability issues in pyrolysis–biochar systems

Biochar sits within a complex set of systems and can impact on sustainability in multiple ways. These are briefly reviewed below.

4.1.1. Carbon management

Creating biochar can stabilise carbon that would ordinarily degrade and return to the atmosphere as CO_2, This applies to a range of unprocessed biomass wastes (crop residues) as well as processed waste materials ordinarily destined for re-use or landfill. Creating biochar from harvesting dedicated for bioenergy does not have this full benefit, if energy cropping is considered carbon neutral. Substituting biochar for peat in all cases avoids the oxidation of sequestered carbon that occurs through the use and disposal of growing media. Growing media used as a feedstock for pyrolysis would result in the stabilisation (as well as sterilisation) of degradable components, prior to use or re-use in growing media or agriculture. This would extend the CO_2 abatement value beyond that of the default content of biochar in single-use.

4.1.2. Waste recycling

A portion of the mineral nutrients present in pyrolysis feedstock (in mineral or organic form) may be rendered slowly leachable through pyrolysis. Biochar could provide a mechanism by which nutrients can be recycled to plants effectively. This return may offset mined resources but in a different spatial position (or even geographic location) that that in which nutrients were acquired.

While phosphorus and potassium are largely conserved (and thus concentrated into biochar), nitrogen is volatile at pyrolysis temperatures, resulting in net loss. The fate of used growing media is relevant, since the beneficial interaction that develops between biochar and nitrogen could benefit nutrient cycling in the receiving soils over the long-term.

4.1.3. Habitat provision

Biochar production presents a competitive and potentially additional use for biomass resources.

The potential for transfer of land from farming to energy crops in one location leading to land-use change elsewhere, possibly remote, is now generally accepted (indirect land use change, ILUC). Increasing agricultural land area has direct implications for habitat loss at a global level. For horticultural demand for biochar to increase ILUC, demand would have to be additional rather than an alternative to energy-only use, and biomass crops to provide a better starting material than cheaper alternatives. Without schemes to support carbon abatement alongside schemes that promote renewable energy (such as ROCs), this is an unlikely scenario.

If the materials required are specific and derived from virgin wood, direct loss of forest cover overseas is a possibility. This is more likely if the functionality, predictability or regulatory barriers associated with use of a lower-priced waste feedstock favour it. If charcoal is being used as a source of biochar, it may already be unsustainable. Pyrolysis technologies for efficient charcoal production could increase the profitability of unsustainable charcoal systems as well as making sustainable production viable. Some forestry land is neglected and strategic management has the potential to enhance biodiversity.

Proliferation of new technologies for making biochar could legitimise charcoal production in general, even in countries where policy interventions have restricted it. Increasing charcoal production could push existing charcoal markets into increasingly unsustainable production, unless overall improvements of efficiency are possible to meet fuel as well as export demands.

Use of waste resources for biochar production diminishes the potential for energy recovery, although probably not to increase the demand for energy crops and land-use change. Managing the trade-off between lower energy production and higher carbon abatement would be critical to incentivising the co-production of energy and biochar.

4.1.4. Soil fertility

Harvesting and transporting any crop removes and transfers nutrients (such as nitrogen, phosphorus and potassium) from one area of land to a new location. Nutrient depletion is greater if the crop is large (such as a biomass crop) or if it contains a high concentration of nutrient elements (such as cereal straw). Unless replaced by fertilisers, nutrients are only slowly replaced through the slow weathering of the underlying geology or atmospheric deposition. Replacement in one location is more acceptable overall if the harvested nutrients are somehow recycled to crops elsewhere either in use or disposal. Horticultural growing media for certain applications could be designed to efficiently recycle nutrients into new crops, as mentioned above.

The feedstock selected for other types of growing media may be selected for their low content of mineral nutrients, so associated with rather low depletion in the soils of origin.

4.1.5. Pyrolysis

Production of biochar can be a clean process in which volatilised components of biomass are burned or condensed and purified. In the traditional production of charcoal volatile products (which includes at least half of the nitrogen content) would be emitted to the air as smoke and soot. Smoke contains greenhouse gases (methane and nitrous oxide) as well as acidic pollutants (oxides of nitrogen). Soot is an important contaminant in the atmosphere that can be transported long distance. Deposition of soot has been linked to accelerated polar ice melt.

Pyrolysis involves potentially explosive atmospheres and assorted physical risks. The smoke, soot and volatile compounds comprising tars and oils in uncontrolled production are potentially hazardous to health. The condensable fraction from pyrolysis contains chemicals that in large scale production can be refined, producing acetic acid and methanol amongst other compounds. However, condensing chemicals without facilities for their refining, or their uncontrolled use on crops for disease protection could present health risks. The complex mixture of compounds present in pyrolysis condensate can include tars and polycyclic aromatic hydrocarbons (PAHs).

Biochar contains soot and can be dusty when dry. The dust may contain detectable concentrations of PAHs. Dust is detrimental to lung function and provides a route into the body for contaminants. Quenching fresh biochar with water prevents ignition on immediate exposure to air, but leaches nutrient elements as well as dust. The resulting sludge is liable to be further enriched in toxic metals and compounds and present a disposal risk. Pelleting and mixing of biochar should decrease general risk from dust, provided human exposure to dust can be assured in the process of formulation.

4.1.6. Transportation

Transportation of biochar for the purpose of formulation is inevitable and could be potentially transnational. As well as the implications for greenhouse gas emissions from long-distance shipment (diminished when primarily by sea), inland transportation of a low density, incompressible material generates additional road movements.

4.1.7. Use

Risk of contamination of plants and crops by chemicals or compounds present in biochar and transmitted through growing media. Although PAHs are not actively taken up by plants, leachable metals may be.

4.1.8. Disposal

It is possible that growing media could be regenerated through pyrolysis to create new biochar. It would create new biochar from organic co-ingredients, providing a sterile ingredient for the production of new growing media, stabilising carbon and eliminating disposal costs. Energy could be recovered at the same time and nutrients (aside from nitrogen) would be recycled. Ordinarily degradable waste would be converted into a high value product for re-use.

4.2. Assessment against interim criteria of Sustainable Growing Media Task Force

This analysis was undertaken based on the criteria and scoring system that had been developed by the Task Force in May 2012. The Task Force has continued to develop their criteria and scoring system since this assessment was made. The method used here does not, therefore, represent the current criteria and scoring system.

The sustainability parameters defined by the Task Force at the time of this analysis were:

(i) Renewability,
(ii) Ethical,
(iii) Reduce-Reuse-Recycle,
(iv) Availability (within five years),
(v) Resource security, and
(vi) Water use (in production).

A decision tree defined by the Task Force at the time was used to assign a score for each of these parameters. The scale ranged from 1 to 10 in each case, with 1 indicating the highest sustainability. With the specified weightings applied this structure was used to compare the comparative sustainability of biochar used in growing media under the four scenarios (two with sub-categories) defined in Section 3.4:

Scenario A1: UK biochar (charcoal batch kiln)
Scenario A2: UK biochar (continuous production system)

Scenario B1: Imported charcoal (bulk shipment)
Scenario B2: Imported charcoal (certified)

Scenario C: Integrated biochar production and retail
Scenario D: Biochar production from UK wastewater sludge.

4.2.1. Renewability

The consideration of wastes biomass resources as completely renewable is embodied in the eligibility for Renewable Obligation Certificates (ROCs).

Scenario	A1	A2	B1	B2	C	D
Score	1		9	1	1	1
Is it a renewable resource?	Sustainably cropped UK forestry is completely renewable, though nutrient depletion could ultimately occur		Primary forest is not renewable resource if land-use changes after harvest	Sustainably cropped woodlots are completely renewable if nutrients replaced	Assuming the supply chain for packaging materials is sustainable, it is renewable	Sewage sludge contains organic materials of diverse origin
Renewable within 5 yr?	The cycle of thinning and recovery or harvest residues follows that of the forest stand. Within a certain catchment, the annual recovery of biomass is matched by growth		No	Annually harvest should match regrowth across the stand	Replanting should be matched to the supply of source material on annual basis	N/A
Renewable within 50 yr?	Yes		Reversion to forest unlikely after conversion	Yes	H	N/A

4.2.2. Ethical

Scenario	A1	A2	B1	B2	C	D
Score	1		10	4	1	1
UK employment standards	High probability of compliance with UK standards, although small scale operations hard to monitor		N/A	No	Yes	Yes
National employment standards	N/A		Probability non-compliance	Probable	N/A	N/A
Working towards national standards	N/A		Probability of non-compliance	Yes	N/A	N/A

The production of biochar in open charcoal kilns (B1) present health risks from inhalation of smoke and persistent contact with dust as well as physical risks. Workers are vulnerable to exploitation running relatively simple technology. Modified kilns (A & B2) present lesser risks of a similar nature. Continuous systems (A2, C & D) are closed systems that reduce potential for exposure to contaminants. Pyrolysis gases are toxic and explosive, so systems have to be properly designed and health and safety rules implemented.

4.2.3. Reduce–re-use–recycle

<u>Re-used waste</u>

Waste organic resources such as sewage sludge (D) can be considered completely renewable, as is the case for gases derived from anaerobic digestion in the context of ROCs. Some pre-processing is required before pyrolysis, including de-watering. A consistent stream of untreated waste wood (C) offers a low cost alternative to virgin wood resources.

Scenario	A1	A2	B1	B2	C	D
Score	10	5	10	8	2	2
Re-used waste	No	No	No		Yes, with clean processing	Yes, with significant processing (drying, pelleting)
Virgin co-product	No	Energy co-product	No		N/A	N/A
Waste in production	Airborne volatiles plus >10% charcoal fines	No	Airborne volatiles plus >10% charcoal fines	Lower airborne volatiles may make use of charcoal fines in crops	All co-products used	All co-products used

<u>Virgin co-products</u>

Controlled pyrolysis systems provide for the capture of energy through combustion of volatile oils and gases. Alternatively oils and aqueous liquids can be condensed. Use as fuel is still at a research level; extraction of valuable low-volume products such as food flavouring is established.

<u>Waste in production</u>

Fines are generated in batch production of wood charcoal (A1, B1 & B2) and amount to 10–15% of production. In principle fines are suitable for use as biochar in horticultural growing media, not least since graded fine materials may be desired. However, handling and long distance transportation of fines would be problematic. Fines may have properties that are distinct from those of a parent lump wood charcoal fraction. The fines could be productively used as biochar in agriculture, potentially. In continuous pyrolysis systems (envisaged in A2, C & D) feedstock rather than product might be pelleted or granulated to achieve a desirable dimension if product. In this way fines and wastes should be eliminated.

Fugitive emissions from traditional charcoal manufacture (B1) are injurious to health, containing soot and volatile oils and tars in the form of smoke. These pollutants as well as greenhouse gases produced in pyrolysis can be controlled with improved kilns (A1 & B2) as well as through continuous processing technologies (A2, C & D).

4.2.4. Availability within five years

<u>Timeframe</u>

Five years is a short time frame – only existing proven technologies can be deployed. Charcoal traditionally produced is available on the international market (B1 & B2) and can carry certification of sustainable production. There are a range of clean kiln designs (relevant to A1 and B2) being tested internationally. There is good probability that reliable models will be being manufactured within five years. Commercial production systems can currently produce a few m^3

biochar per day but are modular. Options for energy recovery at such scale (A2) are at an early stage and unlikely to be proven within five years. In large facilities where there may be a use for renewable heat or power utilising energy products from pyrolysis (C). Examples of pyrolysis units at this scale that are tuned to biochar production are lacking. Very large scale processing of sewage sludge using slow pyrolysis (D) has been demonstrated in Japan, but the accessibility of such relevant technology in the UK is not known. Systems to monitor sustainability and traceability of biochar production internationally would take at least five years to implement.

Scenario	A1	A2	B1	B2	C	D
Score	9	9	2	9	9	6
Scale: will 50,000 m^3 yr^{-1} (or 325,000, 650,000, 1.3m, 4m m^3) be available?	Yes - current production is ~15,000 m^3	Yes – 10 units within 5 yr – pyrolysis technology exists, linking in power generation less certain	Yes – market currently supplies 250m m^3 globally; most from the region	Monitoring and certification schemes will take time to implement	Many very large facilities could process the 5m m^3 potentially available, but not on the timeframe	One large facility could invest in large scale unit to supply more than 36,500 m^3 per year
Potentially a sole ingredient	No	No	No	No	No	No

<u>Composition</u>

Optimal and minimum effective contents for biochar of different types in different growing media products will be established by R&D. However, based on current knowledge it appears that biochar should be an enhancing rather than sole or dominant ingredient. An exception could be biochar made from a feedstock of high mineral content (such as sewage sludge), where the content could be higher if processing conditions are selected to limit the mobility of ash.

4.2.5. Resource security

Scenario	A1	A2	B1	B2	C	D
Score	1	1	4	4	1	1
Local, UK or Europe?	Local		International		Local	
Stable	N/A		Yes		N/A	

The probability of intense future competition for UK biomass resources, including organic wastes, has been much discussed. A more favourable balance between biomass productivity and use in other countries offers potential for biochar production overseas, or the import of biomass for pyrolysis in the UK. Biomass and biochar could be sourced from a range of countries overseas, mitigating concerns around security of supply. However, economic assessments of biochar assume feedstock is supplied at current prices and subsidies continue at current levels.

4.2.6. Water use in production

Use of water in biochar production is typically limited to the quenching (cooling) of freshly produced biochar, or in the control of dust.

Scenario	A1	A2	B1	B2	C	D
Score	2	1	3	3	1	1
Water use	Minimal	No	Some	Some	No	No

Quenching water is liable to become contaminated with biochar dust. Disposal of resulting sludge could present some risk to water courses.

4.3. Current and future tools to guide sustainable use of biochar

- At the international level the Forest Stewardship Council (FSC) uses record keeping on chain of custody to assure sustainability of wood harvesting and charcoal production;
- The International Biochar Initiative (IBI) has issued "standardized product definition and product testing guidelines" to assist on clarity on biochar material properties; parallel "biochar sustainability guidelines" are under development and expected in mid-2013;
- A consortium of biochar producers in Austria, Switzerland and Germany have also engaged with researchers to create a European Biochar Certificate (EBC). This option documentation provides declaration of biochar properties and some aspects of sustainability;
- In the UK level a risk assessment framework for biochar production is under development. This is led by the UK Biochar Research Centre (UKBRC) and guided by a steering group that includes stakeholder such as Environment Agency, SEPA, WRAP, etc. This project is considering sustainability standards for biomass used in UK biochar production, including indirect land use change impacts.

The definitions of sustainable biomass, developed for the Department for Energy and Climate Change (DECC), are a relevant reference point.

Section 5: State of current knowledge

Key Informants and Stakeholders interviewed broadly perceived the role for biochar in peat-replacement as credible. Those engaged in face-to-face meetings and representative biochar materials tended to yield more positive responses than Stakeholders interviewed remotely.

Participants focused on basic physical properties, with less interest in claims of functions related to more elaborate chemical and biological mechanisms. As well as anticipated future competition for biomass resources the availability and likely cost of biochar were a concern..

The greatest desire was to see conclusive research-based evidence for the specific application of biochar to growing media. This reflected: (a) a high pre-existing awareness of biochar, and (b) recognition that research has so far focused on use of biochar in soil and particularly soil sin tropical regions.

5.1. Priorities for research and development

Current evidence for the potentially important effects of biochar are poorly communicated. The evidence that exists resides mainly in scientific literature and arises from situations with a poor contextual relevance to growing media.

Evidence for an understanding for the nature and predictability for the various functional properties of biochar is required. This would enable biochar materials made in different ways to be short-listed for their combinability and for prototype growing media to emerge for a range of different uses and markets.

The potential to integrate such demonstration of biochar materials into a wider integrated demonstration of technology, feedstock and waste / energy requirements could then be communicated alongside the practical demonstration of growing media themselves.

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Appendix 1: Background to the Project

Background to the Industry

The industry relevant to this report segments as follows:

(i) Companies that produce peat and/or formulate peat-containing growing media
(ii) Discerning professional users of growing media, and
(iii) Retailers of growing media to the amateur market.

Amateur gardeners account for 75% of all peat in growing media sold in the UK and are present a price-sensitive market. However, infiltration of the amateur market by products that are peat-free (or contain peat-replacements) has been relatively rapid. The Defra project SP8019 categorised professional users of horticultural growing media by their share of the market (in 2007) as follows:

Hardy nursery stock including container grown trees, shrubs and perennials (43%)

- Bedding and patio plants (25%)
- Vegetable plant propagation* (7%)
- Casing layers on mushrooms (6%)
- Pot bulbs and bulb forcing (6%)
- Pot plants (6%)
- Soft fruit - mainly strawberry (4%)
- Glasshouse salad crops including pot herbs (1%)
- Cut flower propagation* (1%)

The work undertaken in SP8019 considered alternatives to peat replacement in terms of the availability. The project did not consider biochar.

Peat-products considered in the project

Interviews covered biochar as a peat-replacement ingredient in:

- <u>Loose fill modular propagation trays</u> use a fine peat mix with little/no nutrient 'charge'
- <u>Loose fill liners</u> use a coarse mix that may have nutrients tailored to the needs of the crop*
- <u>Compressed peat blocks</u> are the primary product used for germination, typically produced on site using pre-mixed media typically containing 80% peat
- <u>Glue plugs</u> are compressed blocks typically using non-peat constituents such as coir, bound with bio-degradable glues

- Ellepot tubes (sausage type) comprise a paper tube filled with a peat medium beneficial to the growth of young seedlings/cuttings (a root system may strike 3-4 days earlier)
- Retail multipurpose compost is general purpose and blended with peat (or a replacement)
- Garden soil derived from beet washings is retailed with peat included to decrease density and ease in-store handling.

Biochar samples used with Key Informants

Physical samples of biochar were used in discussions held as part of this project, in terms of the acceptability and utility of biochar of different types in different uses. These were selected from the University of Edinburgh (UK Biochar Research Centre, UKBRC) sample archive.

Powdery and amorphous materials were avoided – the focus was on granular materials of contrasting dimension, density and bulk density. The selected samples had generally been previously assessed for their biologically labile carbon content, i.e. in the short term promote microbial activity and immobilise N (biochar is not generally a source of available N). They have also been compared for their material stability (longevity) and physical integrity (propensity to fragment).

The feedstock for these materials included waste biomass (that would be available at a lower price) as well as more expensive virgin biomass resources (which could also be economically or environmentally unsustainable). These included biochar derived from sewage sludge, which contains a higher metal content (of lower bioavailability) than present in its feedstock. Post-use activated carbon from water purification was also included.

One sample derived from virgin biomass was manually size-graded to illustrate how evenness of particle size can be managed and manipulated to meet specific needs in horticulture.

A description of each sample with an indication of their respective properties / characteristics is provided in Table A2.1.

Key informant interviews

Seven Key Informants were interviewed by Carbon Consulting (John Gaunt) and ADAS Horticulture (John Atwood) 20th to 23rd March 2012. The Key Informants are listed against the nature of their business and the horticultural growing media that they use, in Table A3.1.

Each one-hour interview have been summarised according to five topics covered: pre-existing awareness of biochar, thoughts on the physical characteristics of biochar, on its chemical characteristics, on the physical samples presented – and on the extent and nature of the opportunities for adoption. The interviews are reported in Table A4.1.

Stakeholder engagement

A Stakeholder group was selected to represent a wider group with direct or indirect interest in the development of biochar-containing growing media. They were initially selected against the following categories: advisors, providers of technology (for making biochar), potential providers of biochar feedstock, researchers, and environment and sustainability NGOs.

Twenty four stakeholders listed in Table A5.1 were interviewed by telephone by the Environmental Sustainability Knowledge Transfer Network as part of the project, between 30th April and 15th May 2012.

The Stakeholder groupings are summarised below:

- Manufacturers / formulators of growing media
- Professional growers (edibles)
- Professional growers (other)
- Retailers of growing media (to amateur market)
- Ag/horticultural advisors
- Biochar producers
- Feedstock suppliers
- Trade body
- Researchers
- Government
- NGOs

Drawing on the themes that emerged out of the preceding Key Informant interviews discussion topics were expanded to include:

1. Prior awareness/knowledge – own and that of contacts in the industry / sector
2. Possibilities and barriers associated with the use of biochar in growing media
3. Integration into the growing media business / industry
4. Marketing opportunities arising from the use of biochar in growing media.

The Stakeholder interviews are reported in Table A6.1.

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Appendix 2: Details of biochar samples used in Key Informant interviews

Feedstock	Manu-facture	Temp.	Form	Physical stability	Material stability	Labile content	Nutrient loading	Ash content	Status
Mixed deciduous wood	Batch kiln	Not known	Particulate (size graded)	High					Virgin biomass
Mixed softwood	Continuous flow (pilot)	700°C	Pellets	Good	Medium	Very low			Virgin biomass
Mixed softwood	Continuous flow (pilot)	400°C	Pellets	Good		High			Virgin biomass
Rice husk	Continuous flow (small)	650°C	Native granular						Virgin biomass
Miscanthus straw (chopped)	Commercial continuous flow	550°C nom.	Native chunky	Medium	Medium	Very low	High		Virgin biomass
"	"	"	Particulate – coarse	"	"	"			"
"	"	"	Particulate – medium	"	"	"			"
"	"	"	Particulate – fine	"	"	"			"
Bio-solids	Continuous flow	550°C	Granular	Good	Medium	Medium	Very low	High	Digested sewage sludge
Woody biomass	Continuous flow	High	Granular	High					Post-use activate carbon

Table A2.1: Comparative properties of biochar samples used with Key Informants to this project

Appendix 3: Profile of Key Informants interviewed in the project

	Summary of business	Horticultural media used or sold
1.	Nursery business Specialises in hardy plants, supplying directly to independent retail garden centre outlets. 95% of 30,000 m^2 growing area is covered and uses capillary, sand bed irrigation. Business sees environmental issues as a differentiator (ISO 14001 environmental management standard). The nursery has installed rainwater harvesting and under-pond water recovery to meet irrigation needs; photovoltaics provide 30-50% of energy requirements. Look to make further gains in addressing energy use for heating and pesticides. Decisions are driven by economics and business philosophy first.	Loose fill liners using peat and peat replacement media with three mixes: 1. Ericaceous mix 2. A 30% wood fibre mix blended with peat including a long duration controlled release fertiliser 3. A 30% wood fibre mix blended with peat including a long duration controlled release fertiliser 4. Peat based propagation media and Elle plugs
2.	Retailer One of the UK's major retailers with a significant share of the UK multipurpose retail compost. Committed to the replacement of peat in their products. Sell peat replacement products at the same price as products containing peat – at parity to the consumer yet with an on cost to the retailer. Have streamlined bag size and range (60 & 125 L). Use two suppliers	Multi-purpose compost both peat and peat replacement Peat product uses a 50:50 mix Peat replacement product could contain a mixture of bark, coir wood fibre and green compost Top soil reformulated to be a Peat Free product in 2013
3.	Horticultural Advisor Background in horticulture industry, most recently as part of the Bristol Community Forest project. Works for Soil Association (organic).	Not really clear with direct experience of coir media, biochar and organic certified growing media.
4.	Gardening journalist Background in horticultural research.	Wide range of research experience including introducing coir into UK horticultural production.

5.	Producer of peat replacement products 60% of products are wood-based specialty mulch products. 40% are peat-free. Products use two primary feedstock – mixed conifer (spruce, Douglas fir, some larch) and pine. In addition fine composted product is produced with nitrogen added during compost.	A range of wood based peat free media for commercial and retail horticulture applications. Products also include
6.	Nursery A leading commercial propagator in organic. Producing organic vegetables and plants, selling both directly online and to independent garden centres. Uses bio-energy on-site for heat with a 900 kW boiler and plan to install a further 900 kW boiler in the near future.	A peat based compost Peat based material containing 20% compost products sourced from Germany is used to form blocks. Peat free organic material for online retail.
7.	Major producer of packaged growing media Sells to the retail market with about 35% of UK market share for retail growing media, including 25% own brand and 10% produced for retailer branded.	Product lines range from 50% peat to 100% peat free. Has been steadily reducing peat content. Other ingredients used are bark, wood fibre (own production), coir and green waste. Peat free mix uses all of these.

Table A3.1: Profile of Key Informants interviewed in the project

Appendix 4: Reports from Key Informant interviews

i) Pre-existing awareness

	Prior knowledge of biochar		Follow up requested / planned
1.	No		Keen to assess formulated products and to establish competitive advantage as an early entrant
2.	Yes	Met Carbon Gold at Glee industry show. Discussions in the Task Force.	Interested to see more information and to explore potential opportunity for integration of biochar production as part of their vision for "circular economy". Would be interested to explore potential to use business by-products as feedstock for a bioenergy and biochar production facility utilising their regional distribution centres.
3.	Yes	Use of Carbon Gold products in Bristol Community Garden and some germination trials with Carbon Gold Compost vs. Coir compost. Observed good germination with earlier emergence compared to coir based compost. Had not tested products against peat containing media. Had some experience of incorporating biochar in soil, but was to early to make any observations. He had inconsistent results which appeared to be due to factors unrelated to soil. Was interested in developing an integrated agroforestry growing system that would integrate biochar production.	Interested to have further information. Drew attention to Soil Association events where it would be helpful to have presentations on biochar and soil carbon. Carbon Gold will be trialling / promoting their products with 20 growers in 2012.
4.	Yes	Carbon Gold's PR person seeking advertising. Answers 2,500 letters from readers annually and has received a number (approx. 7) asking about Carbon Gold product (*GroChar*) but not general enquiries about biochar	Interested to receive information on biochar that could be used to inform responses to readers

	Prior knowledge of biochar		Follow up requested / planned
5.	Yes	Has purchased Charcoal for customers – not presented to them by the customer as biochar rather needed to create a unique growing environment – orchid plants in a non-favourable environment. Had a number of customers who believe that charcoal makes their compost "sweet" and is interested to follow up	Evidence basis important. Keen to access biochar for trials and product development purposes. Currently concerned about price
6.	Yes	First introduced by Mark Kibblewhite and subsequently by Carbon Gold. Have grown using Carbon Gold compost with promising results – germinated OK. Despite claims would not consider it trial – no replication, controls etc., but promising first exposure	Interested to get involved in research and highlighted that the scale of their operation, provided a good opportunity to undertake product development and testing trials that may be more difficult to integrate in a larger facility.
7.	Yes	First aware three years ago when a predecessor to Carbon Gold appeared on the market. Has investigated a little but sketchy on details. Was unaware of the range of materials possible.	Very interested but unsure about economics. Would need to conduct trials and consumer panel research before committing to investment. Specific questions: i) is biochar classed as a waste i.e. waste transfer licence required? ii) is dryness of feedstock an issue? iii) who supplies kilns?

ii) Biochar - physical

	Manipulation of water release within a loose fill peat replacement mix with high porosity – shelf life	Volume / fill issues	Physical characteristics of compressed blocks / Elleplugs / glue plugs	Use of large chunks of biochar to introduce body into peat media to improve product and open mix
1.	Interested in potential to manage the characteristic, but also felt that peat replacement products (PRP) was better than retailers believed.	Felt that PRP gave better fill. 90-95% of quoted volume for PRP vs. 80% PT	Saw potential as a constituent in plugs and preferred such solutions over modular loose fill due to labour savings that offset cost	N/A
2.	Saw it as a positive characteristic	N/A	N/A	N/A

	Manipulation of water release within a loose fill peat replacement mix with high porosity – shelf life	**Volume / fill issues**	**Physical characteristics of compressed blocks / Elleplugs / glue plugs**	**Use of large chunks of biochar to introduce body into peat media to improve product and open mix**
3.	Yes – quoted example of an organic herb grower retailing herbs who was adopting biochar on the basis of improved shelf life. Was concerned that over-watering can be an issue	N/A	N/A	N/A
4.	Yes but emphasised potential benefits of hydrophobic chars	N/A		Saw this as a possibly good application and highlighted the issue of difficulties in managing some peat. Thought hydrophobic chars may be particularly relevant.
5.	Valuable property, was actively looking for British sourced non-peat products to replace coir in wood based mixes	N/A	N/A	N/A
6.	Saw this as potentially interesting and also highlighted issues for particular plant types – mentioned herbs.	Yes – had opposite experience to informant 1. PRP had 20% lower fill.	Retain 20% compost used in media used for compressed blocks to improve wet ability and to reduce transplant shock – which is a major issue.	N/A
7.	Very interested in this aspect, seen as a major advantage for amateur gardeners particularly for grow bags, patio pots, baskets, etc.	N/A	N/A	Preferred the graded samples, worried about too many fines reducing AFP and dust issues

iii) Biochar – chemical

	Nutrient buffering	**Nutrient supply from nutrient rich wastes in a low odour and safe form**	**pH effect**
1.	Saw this as desirable	Highly desirable – only concern with sewage sludge was	No concerns raised

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	Nutrient buffering	Nutrient supply from nutrient rich wastes in a low odour and safe form	pH effect
		health and safety	
2.	Saw as desirable, greater emphasis on nutrient supply	Highly desirable – would have concerns regarding Gov't regulation	No concerns raised
3.	Seen as desirable	Highly desirable – Soil Association broadly supportive of recycling in this way.	May be of relevance in soil
4.	Seen as desirable	Highly desirable	No concerns raised
5.	Desirable, but requires evidence base.	Highly desirable – very keen to displace conventional fertilizer sources	No concerns raised
6.	Desirable but would requires good evidence and understanding of performance	Highly desirable – needs very specific information about nutrient forms and availabilities	No concerns raised
7.	Highly desirable where product is front loaded with nutrients e.g. growbags	Worried about excess salt levels	No concerns raised

iv) Biochar – response to samples

	Handled	Gloves	General comments and dominant observation
1.	Yes	No	Thought the product could be incorporated in a range of products. Dark colour was an advantage compared to some materials that are dyed to look soil like. Felt that differing size fractions would suit differing products intuitively felt that incorporating at 10-15% by volume would not affect overall characteristics of their mix and desirable characteristics were conveyed. Was particularly interested in nutrient rich biochar. Ultimately growing a "good plant" is the most important issue. Needs to be cost competitive – but savings in operations e.g. better fill, reduced nutrient costs, and operational improvements are all factored into this assessment.
2.	Yes	No	No concerns raised – based on a visual assessment the material seems acceptable. Fits well with commitment to the circular economy and up-cycling of by-products. Key factor: Quality – performance – price.
3.	Yes	No	Positive about the potential as a peat replacement in horticultural media, some reservations regarding use in soils. Conveyed concerns regarding potential risks of using biochar a soil amendment. Felt all materials could be used in some way in horticultural media.

	Handled	Gloves	General comments and dominant observation
			Were concerned about use of imported feedstock – Soil Association believes crop residues should be incorporated at site of production.
4.	Yes	No	Saw potential particularly as a diluent to improve peat based growing media. Research and communication needed.
5.	Yes	No	Felt materials were amenable to incorporation in wood based peat replacement products (which are the focus of this respondents business). Disappointed / envious of the attention and funding that biochar has received compared to wood based products. Would be concerned if materials led to nutrient tie up and was particularly interested in materials that either provided nutrient sources or allowed for replacement of coir. Needs to evidence and research based
6.	Yes	No	Materials appeared amenable to incorporation in loose fill products and potentially in compressed blocks. The potential to convert nutrient rich wastes into an odourless nutrient rich product was very interesting. Evidence of performance and data to support product claims are needed
7.	Yes	No	Liked the appearance of all, but concerned about dust/fines in some ungraded samples. Dust/Fines could lead to poor AFP, staining and polluting leachates. Low density of material an advantage for transport but would need covered storage to avoid loss/contamination by wind blow. Dark colour an advantage could improve appearance of co ingredients such as wood fibre which can be too pale. Bio solid derived appeared to be visually & odour acceptable but would depend on retailer reaction, would test in consumer panels. Worried about the aroma of 400 deg C cured product, volatiles might be phytotoxic to plants.

v) Opportunities

	General comments and dominant observation
1.	Business has moved strongly to incorporate best environmental practices. This is driven by the vision of the directors and the bottom line in terms of costs of operation. Environmental claims will not gain customers but may prevent loss of customers. Saw no benefit in Carbon offset claims
2.	Quality – performance – price
3.	Positive about the potential as a peat replacement in horticultural media, some reservations regarding use in soils. Conveyed concerns regarding potential risks of using biochar as a soil amendment. Felt all materials could be used in some way in horticultural media. Were concerned about use of imported feedstock – Soil Association believes crop residues should be incorporated at site of production.
4.	Saw potential particularly as a diluent to improve peat based growing media. Research and communication needed.
5.	Felt materials were amenable to incorporation in wood based peat replacement products (which are the focus of this respondents business). Disappointed / envious of the attention and funding that biochar has received compared to wood based products. Would be concerned if materials led to nutrient tie up and was particularly interested in materials that either provided nutrient sources or allowed for replacement of coir. Needs to evidence and research based

	General comments and dominant observation
6.	Materials appeared amenable to incorporation in loose fill products and potentially in compressed blocks. The potential to convert nutrient rich wastes into an odourless nutrient rich product was very interesting. Evidence of performance and data to support product claims are needed
7.	Saw potential to use in peat free product provided it provided an improved product and was comparable cost to other peat free ingredients. Consumer market will not pay a premium for peat free. Carbon sequestration benefit would be a difficult message to convey to consumers especially in a mixed ingredient product. Could see possible benefit in an integrated system as their wood fibre production facility is a heavy energy user. Company will continue move to peat free regardless of government policy (although it has its own peat bogs). Would need further feasibility and product research before committing investment. Alternative business models would be investment by existing waste producer, such as water company, biomass incinerator.

Table A4.1: Responses of Key Informants 1–7 interviewed in the project in the five areas of discussion

Appendix 5: Stakeholders interviewed in the project

ID	Category	Business	Location	Company / organisation
1.	Manufacturer	Peat-free compost in Derbyshire	Derbyshire	
2.	Grower	Herbs and tomatoes for retail market	West Sussex	VHB Herbs
3.	Environment NGO	Environmental campaigning (biofuels)	London	BiofuelWatch
4.	Manufacturer	Compost, including peat-free	Ireland	
5.	Manufacturer	Peat-free biochar-compost	Devon	Carbon Compost
6.	Advisor	Farmers/growers/suppliers (whole supply chain)	Hereford	
7.	Formulator and manufacturer	Biochar-compost for amateur market	Bristol	Carbon Gold
8.	Trade association	Representing producers and users of biochar internationally	International	
9.	Formulator	Growing media for retail and commercial markets	Lincoln	
10.	Technology company	Equipment for biochar production (continuous flow system)	Europe	Pyreg
11.	Grower	Salad crops for the retail industry	Cambridgeshire	
12.	Formulator	Peat-based growing media		
13.	Consultancy	Specialising in environment including agriculture	National	ADAS
14.	Trade association	For the waste industry / feedstock suppliers	National	WRAP
15.	Waste / recycling company	Advisors to Scottish Government on waste management	Scotland	
16.	Feedstock supplier	Wastewater treatment	West of England	
17.	Retailer	Compost and growing media to amateur market	Chester	
18.	Research	Independent centre for research and training in plant and microbial science, grant-aided BBSRC	Norwich	John Innes Centre
19.	Grower	Media-grown stock	West Sussex	Fleurie Nursery
20.	Trade association	Levy board of Agriculture and Horticulture Development (AHDB)	Warwickshire	
21.	Retailer	Operates 129 garden centres in England and Wales	National	
22.	Trade association	Represents 1600 businesses and 2700 outlets in all areas of the garden industry	Reading	The Horticultural Trade Association

ID	Category	Business	Location	Company / organisation
23.	Formulator and biochar manufacturer	Producing and marketing biochar to gardeners as a soil improver online and through garden centres	Oxford	
24.	Biochar and technology demonstrator	Project funded by Danish Ministry of Food, Agriculture and Fishing. Developed a pyrolysis unit / system and associated biochar product.	Denmark	Black Carbon

Table A5.1: Profile of Stakeholders telephone-interviewed within the project

Appendix 6: Stakeholder meeting reports

Prior awareness/knowledge – own and contacts in the industry / sector

ID	Prior	Own	In the industry
Media formulators and manufacturers			
1.	Yes	Became aware of biochar in 2010. Conducted trials in 2011 to address concerns raised by partners about its value. Product containing 10% biochar to be launched this year. Industry webinar in summer 2011.	Investigating the feasibility of an on-site pyrolysis CHP facility, using 4000 tonnes of green waste currently disposed of.
4.	Yes	Became aware of biochar about two years ago but, seeing it as a soil improver, did not consider it as a peat replacement for compost. Perceived water and nutrient retention characteristics lend biochar properties suitable in soil amendments – not the performance required by compost users.	Discussed biochar with the Sustainable Growing Media Taskforce but not the wider community / industry
5.	Yes	Founders heard about biochar three years ago through the internet and gardening press, directly leading to set up of the business.	Have not much discussed the benefits of biochar mixes with the wider growing media industry but have communicated them to their local area.
7.	Yes	First became aware of biochar as part of a project in India; previous company was involved in deploying biochar as a soil improver. Immediately excited by the potential of a biochar ingredient.	The growing media industry is looking at biochar as one of many options to replace peat. External pressure to replace peat is necessarily the main reason companies are investigating the merits of biochar.
9.	Yes	Have been aware of biochar as a soil enhancer for some years – but not its potential use in growing media. Biochar could be used as a bulk fibre to reduce odours.	They have not investigated further because of the costs quoted. £20–80/m^3 They have not had discussions about biochar within their industry.

ID	Prior	Own	In the industry
12.	Yes	First heard about biochar in 1990 – a senior company employee was Head of the World Forum for Growing Media and saw a paper on the virtues of biochar in growing media presented in Holland. Initial opinion was that expense would rule it a 'non starter'. Have not changed their initial opinion on its realistic potential.	Have been involved in many discussions about biochar as members of the Sustainable Growing Media Taskforce and have monitored its progress. Smaller niche companies may be looking at peat-free biochar blends – but the four top media formulators are not considering it at all.
23.	Yes	Established in 2010 specifically to fund further research into the benefits of biochar. Founder first learned about biochar in 2005 during PhD on carbon recycling in tropical forests – introduced by colleagues investigating *terra preta*. Co-founders helped create UK Biochar Research Centre and are involved with a number of biochar related projects such as the Big Biochar Experiment and present internationally on its benefits.	Setting up a new network to promote UK biochar studies, the UK Biochar Foundation
Professional users of growing media and their advisors			
2.	Yes	Became aware of biochar three years ago at an M&S Green Day event where it was presented as a carbon sequestration technique. Did not realise that biochar could be used as a soil enhancer/substrate. Compost supplier (in top five) was not aware of biochar in compost in the UK.	Have not heard biochar mentioned in the wider industry. Biochar fell off their radar (until this study).
6.	Yes	First heard about biochar at a 2009 conference in Peru. – it was presented as a barrier to a replant disease in asparagus production. Their opinion was that biochar needed a lot further development before it could be regarded as an alternative to peat. Concerned that the many different types of biochar that are being treated as one product	Have been focussing on waste products to create biochar in Europe, but producing poor results. Concerned about residues in biochar negatively interacting with compost ingredients. Aware of a proposal to HDC from elsewhere for the use of

ID	Prior	Own	In the industry
		when in fact, some biochar composts will be better than others depending on the source material. Have had success with biochar in US and Canada but using good quality wood as a feedstock.	biochar in growing media (not funded).
11.	Yes	First became aware of biochar two years ago at a conference. At the time they were unsure about the potential benefit to their business and were concerned about the availability of supply.	They have spoken to consultants to learn more about biochar and are currently running trials using Carbon Gold products.
13.	Yes	Knew about biochar for many years as a soil improver but not as a peat replacement for growing media. Their first knowledge of biochar in growing media was as a result of bidding for this project. Biochar was immediately interesting. There has been research on biochar as a soil improver with good results – so there was the potential for biochar in growing media.	Contact has not discussed biochar with people outside of the organisation but their expertise lies in environmental issues surrounding crop production – so own knowledge of biochar is limited.
19.	Yes	Part of the Sustainable Growing Media Taskforce, so heard about biochar 6-9 months ago. Did not learn about its use in growing media until the briefing document for this project. First opinion was that it could give growing media more structure, but that the cost was too great.	Not heard biochar discussed outside the Taskforce context.
Retailers to amateur market			
17.	Yes	First heard about biochar as a soil improver two years ago, meeting Carbon Gold at a trade show who told them about the benefits of biochar. Biochar was immediately interesting. Carbon Gold's original product was a soil improver – but the latest version is a better product and it is current for sale in their garden centre. They were interested in biochar before joining the Growing Media Initiative ((GMI), so the external pressure to reduce the use of peat didn't influence their decision however since.	They have not heard of any other biochar media producers or heard anyone else in the industry talk about it, their main growing media suppliers included.
21.	Yes	Became aware of biochar through publicity surrounding Carbon Cold biochar product 2–3 yrs ago. Currently supply organic New Horizon product from green waste instead of biochar, so no opinion on its benefits.	Have heard nothing about biochar from peers or suppliers in the industry.

ID	Prior	Own	In the industry
Waste and other feedstock interests			
14.	Yes	Heard about biochar through the Centre for Alternative Technologies in Wales three years ago. WRAP were interested but it was not part of their market development programme at the time. Have been involved in a steering capacity with an undergraduate project at the University of Reading looking at various amendments in growing media on the behaviour of herbicide residues; the treatments included an amended charcoal product	WRAP are contributing to the development of a 'Biochar risk assessment framework' (BRAF) with particular reference to aspects relating to the use of recycled waste materials in soils and growing media, and the impacts this might have on the food chain.
15.	Yes	First heard about biochar as a by-product or waste product of pyrolysis and gasification in 2009 – and from a carbon sequestration point of view. WRAP later organised for a biochar expert to present to them on properties potentially beneficial in growing media. They had not previously appreciated these additional functions. Interested to learn more about the recent developments in pyrolysis technology, economics and feedstock options relating to biochar.	Spoke to the UK Biochar Research Centre about biochar in 2010 but at the time there didn't seem to be a need to get involved.
16.	Yes	Learnt about biochar 4–5 years ago when looking at the possibility of gasifying sewage sludge to create biogas. As a by-product of this process they investigated how biochar could be used – but very little information available at that time.	They have not really discussed biochar within their industry. However, they did contact the University of Edinburgh through the ESKTN for more information on its potential benefits as a soil improver
Technology providers / demonstrators			
10.	Yes	First heard about biochar 4 years ago listening to a BBC programme on biochar production in Germany – visited the company in Germany to learn more and being so impressed by the technology I became and investor in the company and have agency for the UK and Ireland. Attended UK Biochar Research Centre conferences and presented at others.	Most of those dealt with have heard of biochar but not that well educated on its benefits in growing media. Interest from InCrops, not-for-profit organisation based in Norwich, working to develop the commercial potential of innovative crops / help regional companies adopt new technologies.

ID	Prior	Own	In the industry
24.	Yes	First aware of biochar in 2000 from Brazilian companies who were using biochar in growing media and as a soil improver. Interviewee was researching biochar at that time and considered it to have great potential.	Have discussed with European environmental ministers, a Danish growing media company and the Prince of Wales.
Trade associations			
8.	Yes	Founder became aware of biochar in 2005 when she was approached to research the merits of biochar as a soil improver. Initial impression was that it was too good to be true but upon further investigation it appeared that some claims could be substantiated.	Involved with many international conferences and policy workshops; due to release standards for biochar manufacture in the US.
20.		First became aware of biochar as a substrate at the conference of the International Society for Horticultural Science in Barcelona 2 yrs ago. Initial opinion was that an awful lot of work was needed to reach 'proof of concept' stage.	They have discussed biochar with the UK biochar research centre (PhD at University of Edinburgh).
22.		Aware of use of biochar in Orchid compost (in which it soaks up excess nutrients) for over 25 yrs. Investigated biochar ahead of the meeting and found much more information on biochar from companies in Australia, the International Biochar Initiative and Black Earth (a biochar product). It appears to have qualities useful in a growing medium such as water retention due to its structure. It appears to be a way of reducing the use of peat in growing media but it would never be a peat replacement. Doubtful about the many other claims being made, e.g. holding nutrients and slowly releasing them in a similar way to peat. Biochar is more likely to hold nutrients without re-release.	They do not believe many growers are aware of biochar and have not been involved in any discussions on its benefits.

ID	Prior	Own	In the industry
Environment and sustainability / other NGOs			
3.	Yes	First became aware of biochar in 2008 through in a bioenergy-related report and decided to investigate further. They produced their own report of the pros and cons of biochar. Are alarmed by the large amount of biomass that would be required to meet the demand from the growing media industry – estimate 100 m ha land. Concerned at lack of evidence to support claims that biochar is effective as a soil enhancer, or that it could store carbon in the soil for any length of time.	Asked by DEFRA for opinion of biochar. Also asked to be involved with a committee preparing standards for the biochar industry – but declined as the benefits of biochar have been adequately investigated. More peer-reviewed field trials are required to prove the potential benefits of biochar.
Research			
18	Yes	First heard about biochar in 2006, from a company looking to make a lignite cellulosic biofuel. It was a potentially interesting product, without an obvious market. First impression was that biochar could be interesting as a product but could not identify a suitable market.	Not heard biochar mentioned within their industry.

Possibilities and barriers to biochar use

ID	Activities and opportunities	Barriers and challenges
Media formulators and manufacturers		
1.	Last year investigated the potential of biochar as a growing media ingredient, using additional plant growth as a measure of its utility. Small scale trials revealed that 5% biochar content had little or no effect, 10% an improvement and 15% a negative effect. Properties of biochar such as holding nutrients and water were helpful in low fertility soils – but not applicable in the UK. Further investigation was needed on the blend of biochar and compost.	Interest in peat alternatives pre-dates prominent external pressure to reduce peat extraction. The decision to look into pyrolysis came as a direct response to a need to reduce costs. Investigating the feasibility of an on-site pyrolysis CHP facility using 4000 tonnes of green waste currently disposed of. The cost of biochar has been a barrier to its uptake on a commercial scale, however. For growing media companies who cannot install a pyrolysis facility

ID	Activities and opportunities	Barriers and challenges
		the cost will be a large deterrent. Government support would be needed to encourage a biochar industry to develop. The high cost of feedstock such as white wood is a barrier that cannot be absorbed by the industry alone: biochar is well over £20/m^3 whereas peat is £7/m^3. Biomass resources are a barrier, given the competition for land with other industries.
4.		Investment in a peat-free compost based on bark chips means they have little interest in biochar currently. They also believe that the cost of producing biochar will be too great to be relevant to their business. If the cost of biochar can be decreased to the same as alternatives and evidence is produced to prove the claims made about the potential of biochar they would reconsider – although a peat replacement would have to be a blend of several alternatives. Evidence that the biochar mix can meet the criteria of standard compost is required, i.e. availability, consistency, performance, weight reduction, reduced fertiliser use. The disposal cost associated with wastes from pyrolysis will need to be taken into account.
5.	Trials were conducted to establish viability of a biochar-containing product. Results from mixture of equine manure, biochar and a liquid component to activate biochar bacteria are outstanding and does not need further improvement. A successful business emerged. A patent is pending to ensure quality is maintained (not to prevent others adopting the mix). Biochar is excellent for displaying multiple positive properties relevant in growing media. The potential functions of biochar are numerous and include water retention, increased plant and fruit growth, improved root structure and the bacteria in biochar also helps to break up heavy clay soils. Positive anecdotal feedback of customers back up trial data.	Biochar was not adopted in response to external pressures to replace peat. Nevertheless the cost of biochar is likely to be the greatest challenge, but keeping the product simple (no fertilisers / overcomplicated components) enables competitive pricing (large bags comparable to traditional John Innes type ranges. Manufacturing requires some additional space – for the pyrolysis unit and for equipment used to break up (grade) the charcoal. Charcoal dust is an issue that needs to be considered if producing biochar on a large scale. The land required to grow the biomass needed to supply a large scale biochar industry could be a major issue - there could be a risk to supply.

ID	Activities and opportunities	Barriers and challenges
7.	Have conducted 15-20 trials with independent growers using biochar, confirming its water retention properties ($^1/_3$ less water than peat-based compost). Plants in the trials grew quicker, stronger and greener. Fruit trees matured/fruited 3 years sooner. Now conducting trials with 27 certified growers, testing performance and functionality for the amateur grower. A 90% biochar product is offered but it contains an additive to be mixed in. Biochar is better as blended compost rather than as 100% replacement for peat.	The additional equipment necessary to integrate biochar into operations was not too expensive and produced a good quality product. This equipment is available on the market so prices are competitive. The main challenge for biochar producers is handling a dirty and dusty ingredient. For the industry as a whole the main challenge is the lack of biochar producers to supply formulators. Interaction between biochar and other elements in the compost needs further investigation.
9.	Currently use composted bark and wood residues as an alternative to peat with their retail customers. They also use coir and green waste in some of their composts. Despite the cost of shipping the coir from overseas it is still a cheaper ingredient than biochar. However the cost of coir is rising so that may make biochar more attractive. They tend to use higher quality pine bark for their commercial customers as the level of contaminant in green compost is too high to meet their standards.	The cost is also a huge barrier. Peat is so cheap that it is difficult to build a business case for using alternatives. Their commercial growers may be aware of biochar but would not be willing to pay the high cost of products containing it. It is probably not well known amongst their retail customers (85% of their trade) and external pressure to eliminate the use of peat will not be enough to encourage their customers to choose biochar products over other peat-free. Biochar production will be competing with the biofuel industry for similar feedstock; shortage of feedstock supply is the main challenge. Government needs to either ban or heavily tax peat in compost for media formulators to invest in more expensive alternatives.
12.	There have been many claims made about the benefits of biochar such as nutrient retention. It should also be a sterile product.	There needs to be much more research into the chemical and physical characteristics of biochar. Until the claims are backed up by field trials and scientific evidence (rather than anecdotal claims), it is unlikely to be adopted by the growing media industry. If biochar is safe, it still remains expensive. With 4m m^3 of growing media used in the UK the practicalities do not stand up either: a lot would be required to replace peat and currently there is not the capacity to provide it. This has implications for the cost of biochar which would be greatest hurdle. If it became cost-competitive, biochar could have potential.

ID	Activities and opportunities	Barriers and challenges
23.	Have spoken to many garden centres and organic farmers about the benefits of biochar (increased productivity in plants, carbon sequestration and the potential for energy generation). Supply quite a few with their product. They have been approached by media formulators wanting to know more about biochar and provided samples for trials. Most companies would have space for biochar production. The equipment currently available is small-scale and could be accommodated.	Availability is one of the main challenges as there are few biochar manufacturers in the UK. One possibility is to ship biochar from China and Cambodia, where potential suppliers have made approaches – but this affects carbon footprint and raises the issue of where the feedstock has been taken from (their biochar is sustainably produced). Other key challenges are the scale of production (economies of scale), competition for feedstock with bioenergy companies, the need to increase customer awareness of sustainability of biochar. There is a need for trials to test the benefits of biochar on rich UK soils – most research has investigated the impact of biochar on soils of poor fertility.
Professional users of growing media and their advisors		
2.	Proactive on seeking peat replacements in their compost – did not require external pressure. Green waste and bark chips have been tried as soil improvers – so keen to investigate the benefits of biochar, seeing if it can improve the quality of their compost. They would need to test each herb separately – one compost is unlikely to suit them all; for some biochar may not be suitable or require different percentage content..	
6.	Interested to learn more about recent studies that confirm benefits from biochar and to investigate which types of biochar work best for different plants. Earlier studies oversimplified the parameters being tested – information currently available is not sufficient to judge claims being made. Biochar from waste / energy production is not worth investigating as poor quality feedstock will produce poor quality biochar.	Technology needs to be developed that decreases the cost of production. High energy costs and the high volume of biomass required mean that currently biochar cannot be a large-scale industry.
11.	Initial trials on glasshouse salad crops with biochar supplied by Carbon Gold were successful up to 20% biochar content. Higher content caused the blocks to crumble. Further trials are planned putting biochar in the field (a lot of the salad crops are grown outside). Also trialling biochar as a soil improver for their onion crop. The trials are assessing plant biomass and speed of growth. Together these trials will have covered the whole marketing operation from greenhouse	

ID	Activities and opportunities	Barriers and challenges
	to field. Not currently investigating the composition of the biochar mix itself They are also looking for adverse effects of using biochar, e.g. high levels of heavy metals, which depend on the feedstock.	
13.	ADAS has been interested in biochar as a soil enhancer but not as a component of growing media. There does seem to be technical potential. There needs to be evidence to prove that energy costs associated with pyrolysis are sustainable and that the carbon footprint is less than the product it is replacing, and other peat alternatives such as coir. The social impacts of biochar production should also be included, e.g.. health effects of dust, industrial accidents etc The fate of biochar needs to be mapped If biochar compost is used in a potted plant and once the plant is dead it is thrown in the rubbish and incinerated how much carbon is being lost into the atmosphere? The interaction of biochar with the environment needs to be better understood.	Cost and security of supply would be barriers to uptake. The main challenges are a supply of good quality, sustainable feedstock. In the worst case scenario, cheap imports taken from protected forests by unscrupulous companies could be used.
19.	Peat free alternatives have been investigated for some time. Not driven to reduce their use of peat by external pressures, rather their consciousness of their responsibility to the environment. Replacement products must give results as good as existing growing media. Training is provided to all staff on peat-free products, although at the moment these do not include biochar. Would be pleased to include biochar products in the future, following further investigation.	Confidence is required that biochar ingredients can live up to the claims of its properties. Also, why change to include biochar if it is only as good as the other peat free alternatives? Growers believe that a blend of peat free alternatives could be developed to give specific characteristics. Since media suppliers tend to be wedded to local supply, however, it is unlikely that a blend of ingredients will be practical. Blends containing biochar would need to be trialled by a reputable organisation, involving suppliers of growing media. Once the supplier is convinced, growers can be encouraged to try it. Building suppliers' confidence in any new product is a very slow process – best way is to directly involve them in trials. Best practice from Europe is not as good as UK evidence. The ability to define the particle size is of interest. This could be the advantage that biochar has over other peat free alternatives but it needs further investigation.

ID	Activities and opportunities	Barriers and challenges
		Availability of feedstock is an issue. Using wood pellets or miscanthus might be good options but biochar has to have a unique selling point to give them a reason to use it over other peat free ingredients.
Retailers to amateur market		
17.	Selling biochar containing growing media puts them in a good light, improving their figures with GMI. They have a display to raise awareness of the benefits of biochar in growing media to their customers. They are in the process of testing samples of the Carbon Gold product, growing plants. Biochar has the potential to be popular as it is light and compact and can be added to other products to improve structure, etc.	Currently they buy their biochar product from Carbon Gold but would prefer to buy it through their usual supplier. Their two main suppliers are reducing peat content but, to their knowledge, opted for green waste as a replacement. If the main growing media suppliers adopted biochar products, it would be much easier. The cost of biochar is an issue – customers tend to buy the cheapest growing media, so at the moment it is struggling to compete with peat products. Until the cost comes down customers will go for cheaper options. The cost of peat needs to go up – maybe by the addition of a tax
21.	Like to be at the forefront with new products and technologies and to help educate the public on peat-free products. Therefore, very interested in learning more about biochar and its benefits.	The main challenge for biochar is the lack of knowledge for customers. A government accredited brand would help that show that the biochar has been tested. Official testing carried out by a reputable institution such as the Royal Horticultural Society or Kew would be very helpful. If featured on a gardening programme or in a respected newspaper [clearly] showing why growers should opt for biochar its use would probably be helped. There is a need to see growing media composed of a blend of different types of peat free alternatives.
Waste and other feedstock interests		

ID	Activities and opportunities	Barriers and challenges
14.	Biochar has not been included in WRAP / Defra field studies to demonstrate the benefits of composts and AD digestates (the latter from anaerobic processes), and explore related GHG emissions. WRAP's market development activities continue to focus on products derived principally from food wastes and biochar remains out of scope. However, involvement in Biochar Risk Assessment Framework and other matters allows WRAP to keep a watching brief on this material, and it is possible that it could be included in WRAP's market development portfolio in the future. Too many uncertainties surrounding the product (different feedstocks and processes) for WRAP to comment on the market potential for biochar. Likewise, until the properties of biochar are fully investigated, it is impossible to accurately gauge its potential value. For example - if biochar is a good adsorbent for organic compound contaminants might it also adsorb pesticides deliberately applied to soils – reducing their efficacy?	There also needs to be much more evidence to prove the benefits of biochar (there is a tendency for biochar to be promoted as a cure-all for various soil related problems – which is unlikely to be the case, and could lead to a lack of confidence in the material). The benefits need to be communicated properly to the industry, e.g. why call it biochar rather than charcoal? A significant barrier to market uptake of biochar created from waste materials could be regulation (regulations for products derived from waste, regulations covering heavy metals in the food chain etc.) Biochar has been trialled as (and sold as) an ingredient in peat-reduced growing media. There is no consistent specification for these media or their ingredients (other than green compost) and this could present a barrier to further market penetration in this sector.
15.	Biochar is not a priority for the Scottish Government at the moment. The focus for growing media on AD digestate and green waste – there are also very few formulators of growing media based in Scotland.	Regulation is one of the main challenges - current regulations in Scotland would have to be changed to allow pyrolytic conversion of green waste into biochar to qualify for recycling credits. At the moment, credits for recycling green waste depend on producing compost. Another challenge is the supply of good quality feedstock. Using green waste would be in competition with AD and other green alternatives. Wood is at a premium in Scotland, especially with biomass plants now competing for feedstock.
16.	Have investigated the potential for biochar with a report finalised this month. Initially they were looking for other opportunities / uses for AD digestate currently converted to biosolids for agriculture. Incorporating the production of biochar into their current operations would require a multi-million pound investment. The facility needed to convert biosolids to biochar would need to be very sophisticated to produce the biochar quality needed for agriculture. Whilst the process would generate addition energy they would need to analyse the benefits of using the biosolids for biochar rather than selling them directly as fertiliser. Biochar gives structure to the soil and has water retention properties, but biosolids also have nutrients such as phosphate which may be more important to media formulators	The main challenge is that there is no large scale pyrolysis facility operating in the UK to provide industry with the confidence that biochar production offers a viable business proposition. Current waste regulations are also a major barrier to biochar being produced from food waste – especially if it is then being used to produce edible crops. The UK and EU rules defining biochar would need to be changed.

ID	Activities and opportunities	Barriers and challenges
	than carbon storage. This needs to be studied further to see where the market is.	
Technology providers / demonstrators		
10.	Has been investigating with InCrops the potential market and applications for biochar created by pyrolysis in an AD setting (i.e. using digestate from AD as feedstock). They have looked at issues relating to compost standards, i.e. will biochar created from digestate be of a standard high enough to be used in compost. See biochar production as a decentralised activity; a mobile system allows production to move to sources of feedstock such as farms. Biochar has huge potential, but the growing media industry must become confident in the product. It may be better suited as a niche product rather than as a large scale peat replacement – but they would both like to see biochar developing in the growing media market.	Challenges include the security of feedstock supply. Knowledge of chemical and physical properties of biochar is required. Applied field studies are required to prove claims. External pressure to replace peat in compost is not much encouraging the uptake of biochar –there is a lot of scope for educating the industry. Certification for feedstock, pyrolysis process and biochar product would provide customers assurance of quality. A PAS standard on biochar plus compost would help, maybe following on from a quality protocol. Development of biochar requires government support. Agrees that either a ban or tax needs to be applied to peat to encourage investment in peat alternatives. AD companies are concerned about the amount of energy required to process and dry digestate prior to pyrolysis.
24.	Companies that have been in contact have been very interested in the project and the benefits that biochar might bring to growing media. External pressure to reduce the peat content of growing media is not equal outside the UK. Biochar has been viewed as another product in the market with its own unique qualities such as the ability to suppress disease.	The main challenge in the use of biochar is its availability – there are very few manufacturers in the UK and Europe. The cost is also very high compared with peat, making it hard to compete in the market. The introduction of carbon credits to subsidise biochar manufacture is necessary. Peat is cheap. The quality of biochar is also a barrier to successful take up: not everything referred to as biochar is good enough to be used in growing media. There need to be standards for different types of biochar.
Trade associations		

ID	Activities and opportunities	Barriers and challenges
8.	Further investigation is required to understand the underlying mechanisms that are occurring i.e. link traits of biochar to specific results being seen in the growth of plants. Long term field trials are needed to study the stability of biochar in the soil, to understand how tightly it binds to potentially toxic components in the soil and to determine how long the benefits of biochar last in the soil. Biochar producers need to be able to link production parameters to certain biochar characteristics so it can be tailor for a specific need in horticulture – better evidence is needed for the benefits that are seen.	The biggest challenge is the lack of slow pyrolysis technology that works at large scale – very few projects go beyond demonstration scale (2 t/d biochar). Economies of scale do not work at these levels so tackling problems such as heat mass transfer, moisture content and particle size needs to be addressed before the market can expand. Market development is also a challenge – it is still early days and little has been done to promote biochar in different potential markets. Finally, the ability to supply the market is a challenge. In the US wood is the feedstock most commonly used, whereas Europe is oriented towards waste products (and not always green waste). Pure biochar can be used as a soil improver but a biochar compost blend has its place, depending on the market.
20.	Interested to learn more about biochar in growing media. There appears to have been much work on the use of biochar in arid soils – but the information available for growing media is quite weak. Growers have been looking for alternative growing media ingredients since the 1980s, independent of the current external pressure to reduce peat use.	Success for biochar will be market driven, i.e. based on price and availability. Competing uses for feedstock could be a serious barrier to biochar commercialisation. In addition to the cost and availability of biochar growing media, lack of evidence to support claims being made about its benefits is a key challenges to be overcome. Trials to show that biochar adds value to growing media required. Some growers have purchased biochar samples directly from manufacturers, but would prefer to buy their suppliers – if they stocked biochar.
22.	Prior to 2000 the Government invested £40m to support growers in adopting peat into growing media, but spending less than £500,000 per year to find a peat free alternative. Replacements will take time – it took 10 yrs before the growing industry adopted CRFs.	They are interested to know how many of the claims about biochar are true. They believe that biochar could be hype with no substance, or a Government-backed product without merit. Extensive evidence-based trials to back up claims being made are required. There needs to be a significant increase in funding to provide the confidence required by the industry. Many challenges still to be addressed, including how biochar interacts with heavy metals. Products can contain large quantities of heavy metals. Are biochar manufacturers confident that heavy metals will not leach and affect the crop?

ID	Activities and opportunities	Barriers and challenges
		Other questions yet to be answered are: does it perform as well in a mineral soil as it does in a non-mineral soil? If biochar stabilises heavy metals within its structure, will it do the same to herbicides? What is the cation exchange capacity of biochar compared with peat and other peat free alternatives? Do we know what level of radioactivity might be released from the feedstock? The HTA would welcome a PAS for biochar to help alleviate some of the concerns.
Environment and sustainability / other NGOs		
3.	Biochar contains a huge range of chemical compounds – a greater understanding of the different types of biochar and which ones might be beneficial is required. Further work needs to be done to prove the carbon sequestration potential of biochar in the field as well as laboratory / inferred from chemical structure (carbon sequestration requires carbon to remain in the ground for 100 years; studies seem to suggest that is not the case for biochar – the longest study was 4 years long and showed a reduction in the carbon content of the soil over time).	The generic statement that biochar made from all types of biomass is beneficial is a risk. There also needs to be a lot more study around the interaction of biochar with the soil and environment at large.
Research		
18.	Investigated the potential benefits of biochar in growing media and see opportunities. Need to look at European partners already using biochar successfully and learn from them, rather than reinvent the wheel. A biochar industry in the UK could develop around the best practice and scientific knowledge from Europe. Do not agree with the use of food waste or AD digestate as feedstock for biochar – pyrolysis will diminish the higher value of digestate in itself. The quality of the biochar created from waste could be questionable. Activated biochar in growing media could be of potential use in soil remediation.	The main challenge is the lack of available feedstock – strong competition for virgin wood. Last summer when wood supplies ran short pyrolysis companies sourced straw from wheat and rapeseed to fill the gap, pushing up costs for farmers seeking animal bedding. If perceived environmental and health risks associated with biosolids could be eliminated, it could have a value to agriculture – but the economics need to be right. Lower energy yield from slow pyrolysis (compared to fast pyrolysis) devalues biochar: the "carbon" value of biochar has to be recognised to allow it to compete with energy or other uses for feedstock. Government funding and a sliding FIT and ROC is needed to encourage a biochar industry.

ID	Activities and opportunities	Barriers and challenges
		Opportunities for the uptake of biochar (as well as products such as AD digestate and biosolids) for soil improvement can be destroyed by regulation though. Currently a product that meets PAS 100 / PAS110 would be subject to further regulations when it reaches the grower. Defra need to talk to their EU partners about updating EU rules.

Integration into the business / industry

ID	Activities and opportunities
Media formulators and manufacturers	
1.	Interested in the merits of energy generation as well as biochar production – currently preparing a cost analysis of installing a pyrolysis facility at their site.
4.	No knowledge of the capital and operating costs involved with setting up a pyrolysis unit, so unable to comment on whether they would consider creating energy as well as biochar to make the proposition cost effective.
5.	Pyrolysis unit on-site produces biochar but gas is currently combusted rather than used to export energy. Fortunate to gather willow feedstock as well as wood chip from local saw mills free of charge. Biochar works best with wood feedstock due to its structure.
7.	Pyrolysis unit is not currently used to generate energy – something to consider redressing in the future.
9.	Using relocation as an opportunity to look at green on-site energy options. Leaning towards AD with some wind energy – but open to other possibilities.
12.	The energy savings from producing biochar not adequate to make it cost effective. The investment needed to install the pyrolysis equipment is going to put others off too as the industry is not profitable.

ID	Activities and opportunities
23.	Companies will probably be interested in generating energy as well as biochar. Pyrolysis facilities are fairly small-scale (same size as charcoal kilns) so could be accommodated. However there is a need to increase the scale of current biochar production to make it viable.
Professional users of growing media and their advisors	
2.	Have gas fired CHP on site for energy and CO_2 enhancement in greenhouses. Not previously heard of pyrolysis but interested to learn more.
6.	Integration could be an option to make biochar cost effective – but only for the few who have biomass resources nearby. It might be useful to promote biochar to growers who already create their own energy from waste as a source of additional income.
11.	Too early to say whether they would ever generate their own biochar on site.
19	No – not of interest.
Retailers to amateur market	
17	Not something that they could do – they do not have space.
21	No – this is not something they would ever do.
Waste and other feedstock interests	

ID	Activities and opportunities
14.	Based on knowledge of decentralised energy supply from waste, they believe that the capital costs of setting up pyrolysis could discourage most media formulators from considering producing their own biochar. Not aware of any biochar pyrolysis facilities in the UK at commercial scale - companies would probably consider other options such as green composts before biochar.
15.	Renewable energy strongly supported by Scottish Government, so the ability to create energy as well as a growing media additive is interesting. However there are other renewable generation technologies higher up the list at the moment (AD). Pyrolysis energy generation might work for a small community if the feedstock was available and cost could be reduced – there is an opportunity in Scotland.
16.	Potential to incorporate gasification to generate additional energy from biosolids and biochar – currently assessing its value.
Technology providers / demonstrators	
10.	Their pyrolysis system creates biochar from AD digestate. Based in Germany, they are now moving into the UK market.
24.	Media formulators would be interested in generating their own electricity and heat as well as biochar. The current equipment is quite small so lacks economies of scale – but transportation costs are increasing making biochar production on site more attractive. Capital cost of such systems is the main reason for the limited production of biochar.
Trade associations	
8.	Operational projects yielding biochar in the US are linked to energy generation, with biochar the almost incidental by product of renewable energy generation rather than the primary goal.
20.	Growers are not producing their own biochar.

ID	Activities and opportunities
22.	The capital cost of installing a pyrolysis unit would be restrictive to most companies.
Environment and sustainability / other NGOs	
Research	
18.	The lack of stability in FITs and ROCS means that financing for renewable energy projects is difficult – opportunities for farmers to invest in pyrolysis are limited.

Marketing opportunities

ID	Activities and opportunities
Media formulators and manufacturers	
1.	Initial support for biochar will need to come from the Government to prove the benefit of biochar as a growing media and as a carbon reduction technology. The industry needs to improve the 'carbon story' when advertising the merits of biochar compost to the general public. Marketing needs an evidence base and UK-specific, Amazonian soils do not provide a suitable success story for biochar technology.
4.	Have focussed on making their operations as energy efficient as possible rather than looking for 'carbon abatement' technologies – though a wind farm and biomass provide energy for the site. The Government needs to de-regulate the rules on waste so it can be treated as a feedstock.

ID	Activities and opportunities
5.	Provides regular demonstrations on the merits of biochar and share the results of their trials with the local community – have become a successful biochar manufacturer using word of mouth. A biochar manufacturer's community could share knowledge and ideas. Trials results should be released to help educate the public and growers. The industry needs standardisation – a single brand that the public will recognise and trust. On the whole gardeners don't care about carbon sequestration but rather what helps their plants to grow. Product was originally promoted on carbon abatement – but now on performance.
7.	Opportunities for marketing biochar depend on evidence-based results produced by a neutral party such as RHS. It should demonstrate the performance and sustainability of the product as well as the cost and security of supply. Have five-year trials into the ability of biochar to sequester carbon in the soil – so they are keen to promote this quality.
9.	Calculated carbon footprint to help make carbon emission reductions. As well as being the largest user of green compost in the UK they are also involved in peat regeneration in the Pennines. The best way to market biochar will be to convince professional growers to change through provision of field trial evidence to back up claims – the retail market will follow. The cost of biochar will still need to be reduced significantly before it will be widely accepted by the consumer
12.	The carbon argument surrounding peat has been brought into question by the Sustainable Growing Media Taskforce; banning peat would not encourage growing media companies to invest in biochar. Biochar has not taken off extensively anywhere else in the world.
23.	Marketing should aim to explain the carbon gain resulting from use of biochar – there will be a good uptake of a biochar product once customers understand the concept. People will be willing to pay a little more if it is clearly explained. A certification scheme to show that the product is carbon negative would also help. This would prevent all biochar products being judged the same and avoid bad press. It will be important to mention the pitfalls of large scale deployment of biochar and the competition for feedstock.
Professional users of growing media and their advisors	
2.	Growers keen to adopt new products if evidence backs up claims. Would be willing to test improvement to plant quality using a supplier's sample. It might be better for HDC to test biochar independently and release the results to the wider industry – any test completed by companies would be subject to confidentiality. Test criteria should be performance, quality, sustainability and cost.

ID	Activities and opportunities
6.	Biochar would be best marketed as a soil conditioner for field crops. This would sequester far more carbon than in potted plants and improve organic matter, which is what farmers need. Biochar is not the silver bullet and needs considerably more research into its variability and also its interactions with the environment.
11.	Reserving judgement as they are still trialling biochar in their crops and would like first to see the results.
19	Amateur users will be interested in the carbon abatement aspect of biochar but purchasing decisions in the end come down to price. The carbon abatement of biochar also needs to be proved, still. Biochar should be tested against the Horticultural Trade Association/Growing Media Initiative Growing Media Performance standard once it's completed to provide confidence in the product for amateur growers. Commercial growers will not be interested in the carbon sequestration benefits of biochar – rather they want a growing media product that works. The best way to encourage the growers to adopt biochar will be to convince suppliers, who can then present it as a recommended product. The carbon story needs to be communicated in a much better way – there have been mixed messages from Defra and other environmental bodies on whether use of peat is harmful to the environment or not. Recent studies have shown that an unmanaged peat bog emits methane which is as bad as CO_2 emission resulting from its removal. The steer from government needs to be clear. From a performance perspective the benefits of biochar in growing media angle need to be confirmed. If advertised benefits of biochar fail to emerge, customers will not buy it in future. There need to be many immediate trials, to reassure nurseries that it is worth backing.
Retailers to amateur market	
17	A biochar brand similar to the 'red tractor' on food packaging – a universal symbol that customers would recognise – would help promote the use of biochar. The carbon abatement dimension is something promoted to customers. If carbon credits could be given to the biochar manufacturers for sequestering carbon – these cost savings were passed down the chain. Then, the cost of biochar growing media might be competitive. Biochar is an underutilised product with great potential. They are really pleased that the Sustainable Growing Media Taskforce is raising its profile through this project.
21	If the carbon dimension could be marketed well, giving a strong message about the lifetime benefit of biochar towards reducing climate change, customers might be willing to pay up to 15% more than for a peat-based compost.
Waste and other feedstock interests	

ID	Activities and opportunities
14.	Carbon sequestration is one way to market biochar. If a carbon tax is implemented then people might choose to buy biochar growing media and potentially be paid for sequestering carbon. Currently the public may not pay the extra cost for biochar just because it has a carbon abatement advantage – but if peat and biochar were a similar price and the benefits of biochar were publicised, it's possible that people would choose the latterproduct. Commercial growers are much more risk adverse and would need evidence of the potential from a growing media point of view in addition to the carbon abatement benefits. The biochar producers need to prove its safety and capability.
15.	Carbon sequestration benefits of biochar are under the radar at the moment. In order to market biochar in Scotland you would need to demonstrate its carbon reduction potential to see if there is the appetite for it. Demonstration needs to prove the benefits that biochar brings to growing media too – these advantages can be publicised.
16.	First step to define the market – farmers won't be bothered about the carbon reducing potential of biochar only what benefits it can bring to their crops. Field trials are needed to validate laboratory results. Feedstock and resulting biochar needs to be standardised so the trials are consistent and can be recreated, and growers have confidence in the product they are buying. There is a requirement for additional Government funding to move the industry forward. The cost of developing a pyrolysis or gasification plant is expensive. Collaborations between the private sector and research organisations are needed to build demonstration scale biochar facilities to validate small scale results.
Technology providers / demonstrators	
10.	Biochar should be marketed as a niche product, promoting the characteristics that peat-free alternatives do not, i.e. that biochar can be bespoke and created for a specific crop or function. The flexibility of the product is a unique selling point. Blending biochar with other compost materials will improve the quality of the compost. InCrops believe that the retail market will be willing to pay more for an environmentally friendly product if it is sold as a niche product, for a specific purpose. First company to develop pyrolysis equipment at the right scale for decentralised use. A third of the heat in the process can be converted to electricity (500-600°C) and the rest can be used to heat for e.g. greenhouses. This is in addition to the carbon sequestration advantages of using biochar. They see this as an important carbon abatement technology.
24.	The carbon abatement angle may appeal to a niche market accessed by Carbon Gold, but not be sufficient to see biochar replace peat – the costs will need to come down. Individuals would be willing to pay a little more to help the environment as long as the product was good. Branding would be a possibility but would add to the cost of the product.

ID	Activities and opportunities
Trade associations	
8.	There has been limited marketing to date and there is a great need to promote the technology to all the potential markets. Looking to potentially contract experts in marketing to help them tackle this in the US. It will need to be a regional programme, targeting each market in turn to have the greatest impact. Biochar is stable and will remain in the soil for over 100 yrs, else it cannot be classed as biochar. Studies have been conducted to prove the ability of amended soil to accumulate biochar.
20.	The carbon abatement dimension to biochar does not have value. Producing biochar is an energy intensive process, so carbon [emissions] would not be diminished. There are many competing uses for biomass. If the price for biofuel exceeds that for biochar, wood chips will be used for biofuel production. Horticulture cannot compete with large biomass power stations – horticulture would use a fraction of the wood needed for electricity generation.
22.	Biochar is currently a product looking for a home – a by-product that is being sold to growers with no evidence to back up claims for its benefits. As a cautious group, growers are wary. The carbon abatement aspect of biochar is not interesting to growers who simply want a product that will increase productivity. This will provide ammunition for environmentalist to use against growers, as another example of how growers have their heads stuck in the ground. Biochar needs to be marketed on proven growing benefits. Unless it can make a name for itself based on merit, it will not have much future in the growing media industry.
Environment and sustainability / other NGOs	
Research	
18.	Interested in the potential carbon abatement aspect of biochar – would like to know more about its extent and how to realise it. The market value of biochar as a growing media additive is not high – but there is an opportunity to add value from carbon credits. This needs to be further investigated.

Table A6.1: Responses of Stakeholders interviewed as part of the project in the five areas of discussion

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