EXPERT PERCEPTIONS OF THE ROLE OF BIOCHAR AS A CARBON ABATEMENT OPTION WITH ANCILLARY AGRONOMIC AND SOIL-RELATED BENEFITS

Simon Shackley, Sarah Carter, Kirsten Sims and Saran Sohi
UK Biochar Research Centre (UKBCR), University of Edinburgh,
Crew Building, King's Buildings, West Mains Road, Edinburgh, EH9 3JN, UK

ABSTRACT
Biochar is the solid remains of organic material that has been heated to > 350°C in an oxygen-limited environment, frequently intended to be mixed with soils. Biochar frequently contains 80 - 90% stable aromatic carbon that is resistant to decomposition and mineralization (possibly for hundreds to thousands of years): it is, therefore, a potential way of removing carbon from the atmosphere for storage and has received considerable attention in the specialist media. Because the field is new there is no authoritative scientific assessment of the state-of-knowledge and its certainty. We therefore undertook an internet-based survey (n=145) to elicit expert opinion on the state-of-knowledge on biochar science and engineering. While expert opinion broadly supports the proposed benefits of biochar, the survey also identified a high degree of uncertainty attached to most of the knowledge-claims: more basic underpinning R&D will be necessary before policymakers will have confidence in implementing biochar projects.

1 INTRODUCTION

Biochar is produced from the thermo-chemical conversion (through pyrolysis) of biomass into a composite material containing high levels of stabilised carbon in aromatic ring structures, whilst releasing syngases and bio-oils. Pyrolysis is the chemical decomposition of organic matter that occurs spontaneously at high enough temperatures and differs from combustion in that it does not involve reaction with oxygen. Both the syngas and bio-oil by-products can potentially be utilised for energy production, though in reality their utilisation can be difficult and require additional processing steps. Charcoal is a form of biochar when it is applied to soils rather than burnt as a fuel, though many non-woody feedstocks produce a char that is quite distinct in appearance and properties from charcoal.

Biochar is a relatively new idea for combining carbon abatement from biomass with one or more of the following: sustainable energy production, sustainable waste management, enhanced agricultural productivity and sustainable soils [1, 2]. Contemporary biochar research and development originates from several different foundations: a) research on charcoal-rich *terra preta* soils from the Amazonia dating back to the middle part of the 20th Century and earlier (e.g. the pioneering work of Sombroek); b) research on the effects of charcoal on soils and plants, with initial contributions from the early- to mid-20th and more significant efforts in Japan in the 1980s; c) research on the properties and cycling of naturally-occurring black carbon and charcoal; and d) engineering RD&D on pyrolysis and gasification. Biochar has been described by many advocates and enthusiasts as a 'win-win-win' strategy, but like most new ideas that appear to be 'too good to be true', biochar has also invited its fair share of criticism and scepticism [3].

The idea of the long-term storage of carbon in a stabilised form as found in charcoal (benzene-ring type structures) was first proposed by Seifritz in 1993 [4], though his vision was storage in landscapes and as a constituent of forest plantation soils, rather than to enhance agricultural land. This proposal was somewhat ahead of its time, and it was not until the first half-decade of the 21st century that the growth of the climate change agenda provided a way of bringing the quite disparate areas of carbon abatement, soil science, agronomy, environmental science and engineering together under the banner of 'biochar'. Johannes Lehmann and Peter Read were important in making these conceptual linkages [5-10]

A series of meetings took place in the mid- to late- 2000s which began to define and consolidate the emergent biochar community of researchers, practitioners and entrepreneurs, including the first three meetings of the International Biochar Initiative (2007, Australia; 2008, UK; 2010, Brazil). In 2009, the first dedicated biochar book was published, edited by Lehmann and Joseph [1], while several comprehensive reviews of the biochar field were published in 2009 and 2010 [2, 11, 12]. A series of national and regional meetings were held in 2009-2011, including in the USA, UK, Australia and Malaysia. Dedicated biochar research centres have now been established in the USA, Germany, New Zealand and the UK, while existing departments, laboratories or field stations in the disciplines of soil science, pyroylsis engineering and agronomy are increasing turning their attention to biochar RD&D. Writing in 2010, biochar has now become a distinct cross-disciplinary field of enquiry, a remarkable achievement given that the word was not even in circulation in 2000.

One of the main problems in attempting to elucidate the advantages and disadvantages of biochar is the lack of empirical evidence and experience. For instance, it might be imagined that it would be reasonably straightforward to delineate and characterise the core technology behind biochar - slow pyrolysis - at the pilot or operational-scale with respect to its energy and carbon balance. This, however, has turned out to be difficult and fraught with large uncertainties at the current time because of the lack of operational experience with slow pyrolysis plants [13]. Hence, most analysts have relied upon data from just a few technologies, and this data is mostly not in the peer-reviewed literature. Reliable data is also lacking for most other components of pyrolysis-biochar systems (PBS), including feedstock suitability, defining what constitutes a 'good' biochar, understanding the impacts of biochar upon soils and agronomic productivity and evaluating the costs and benefits of biochar deployment. Research is now underway on all these aspects, but it will inevitably be several years before a substantive and authoritative body of knowledge is available.

We therefore decided to adopt a different approach to address the key questions by eliciting the international expert community's opinion. Expert elicitation is a well established technique in the social sciences and allows a snapshot to be taken of the views of the leading practitioners [14]. This method also permits a useful measure of uncertainty and ignorance by: a) producing a range of responses; b) inviting respondents to respond that they do not know the answer; and, c) also inviting respondents to indicate their level of knowledge of a particular topic. We used tried-and-tested questionnaire design approaches, building upon similar work that we [15] and others (e.g. [16]) have undertaken on expert and stakeholder perceptions of CO_2 capture and storage (CCS).

2 METHODOLOGY

An online survey, using a standard design (Bristol Online Survey Tool: www.survey.bris.ac.uk/) was distributed to individuals who are working on, or have a knowledge of, biochar and related issues. We also advertised the availability of the survey on our own website and to online networks interested in biochar, e.g. via the International Biochar Initiative's (IBI's) website. The survey was conducted during July and August 2009. The sample is not random since we deliberately approached individuals and organisations involved in biochar R&D and policy. In total 145 useable responses were received, of which 118 were complete. We asked for individual responses, whilst recognising that opinions will usually be shaped by the organisation in which that person works. Some organisations chose to submit a combined response on behalf of the organisation. The data was entered into the Statistical Programme for the Social Sciences (SPSS) and the results analysed using descriptive statistics. We first present the main results of the survey and then undertake an analysis of the findings and their implications for biochar deployment and RD&D needs. A copy of the survey and results is available upon request.

3 RESULTS

Time spend working on biochar

The respondents' self-declared job titles are summarised in Figure 1. Over a third of the sample are scientists and researchers, while the large majority of the rest of the sample is composed of business persons, project developers and managers, consultants and policy development officers. Only a very small number of farmers and representatives of environmental non-governmental organisations (ENGOs) completed the questionnaire. Participants were asked to indicate how much time they spent working directly or indirectly on biochar (Figure 2). It can be seen that most respondents (c. 60%) worked on biochar for less than a third of their time. Only 19% worked on biochar for more than 70% of their time. Many respondents had expertise in related issues, and 55% (n=145) spent >10% of their time working on either soils, bioenergy, agronomy or project development / carbon markets. Respondents were from a total of 21 different countries in Europe, Africa, Asia, Australasia and North America. The majority were from the UK, however (58%). Very few respondents considered that they had very high levels of expertise on biochar.

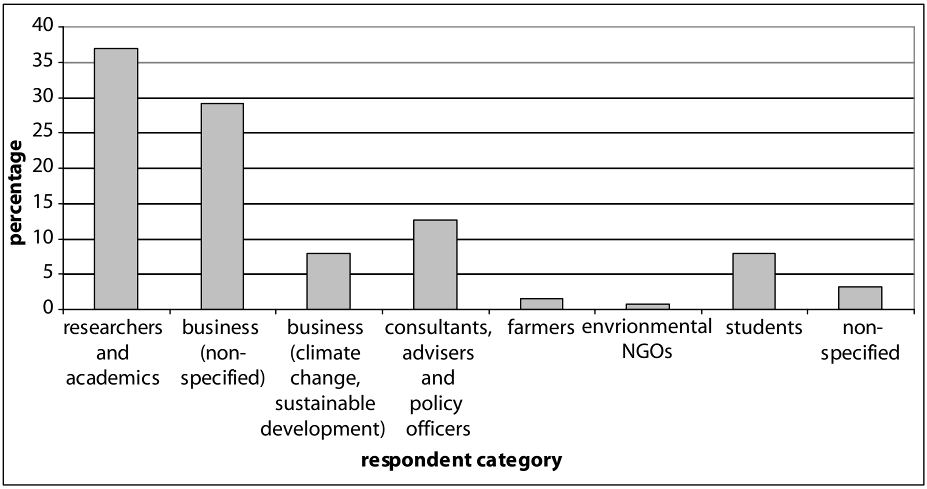

Figure 1: Categorisation of occupations of the respondents based upon self-declared job titles

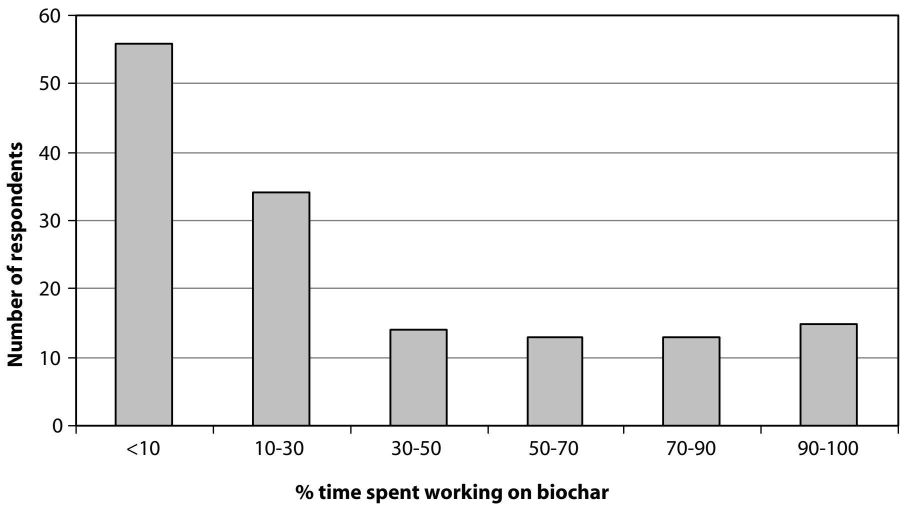

Figure 2: How much time is spent on average on issues directly or indirectly concerned with biochar?

Globally how much carbon abatement from use of biochar – in a sustainable way - is credible and by when?"

Respondents were asked to speculate about how much carbon abatement from the use of biochar – in a sustainable way – is credible by 2010, 2020 and 2030. As can be in seen in Figures 3 to 5, the general projected trend is for a growth of biochar use in the next 20–40 years. This would be slow initially (Figure 3): in 2010, 17% of the sample predicted that no carbon would be abated using biochar, whereas by 2020 no-one selected this option of zero abatement potential. By 2030, over 50% of respondents estimate that more than 500 million tonnes carbon (MtC) can be abated globally through biochar deployment. Perceptions of biochar carbon abatement by 2050 varied by several orders of magnitude: 8% of respondents thought that <100 MtC per year (yr^{-1}) could be abated, while 3% thought that >6000 MtC yr^{-1} was possible. There is considerable uncertainty in estimating the long-term prospects for biochar, just over a third of the sample responding 'don't know'. This uncertainty increased somewhat for the longer-term scenario.

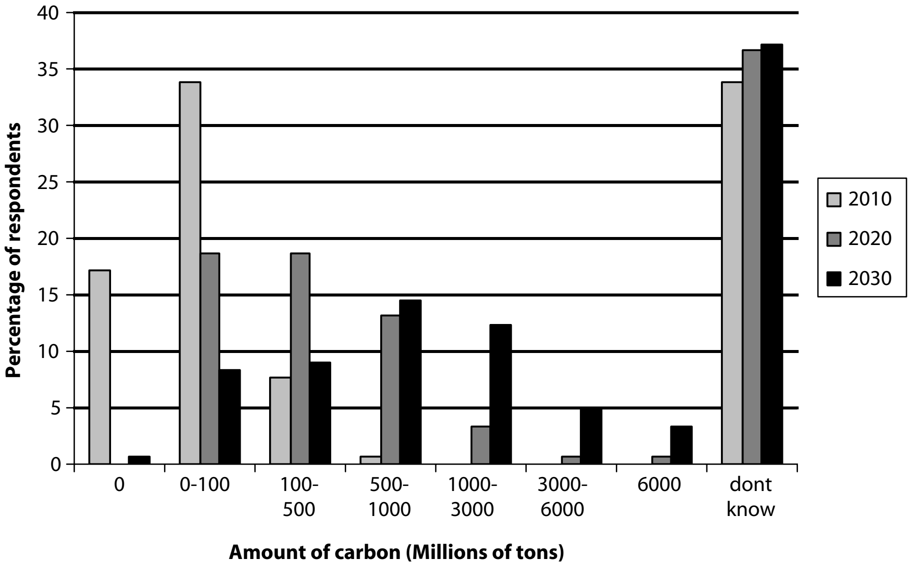

Figure 3: Globally, how much carbon abatement from use of biochar – in a sustainable way – do you think is credible by 2010, 2020 and 2030?

Data from UK respondents on whether they thought that the potential for biochar would be likely to be greatest in the developing or developed countries was analysed. Figure 4 illustrates that they expected that the most potential will be in developed countries in the next two decades, but that by 2050 the developing countries hold greater potential. There was, however, a large increase in uncertainty, from 17% 'don't knows' (N=84) for estimates over the next 10-20 years to 31% 'don't knows' for predictions in 40+ years (N=84).

Data was also analysed from the UK respondents about the potential in Europe in 2020 and 2050 (Figure 5). 63% (n=76) of respondents expected the potential for deployment to be 'very high', 'high' or 'moderate' by 2020, while 79% (n=75) of respondents chose these options by 2050.

What is the potential for carbon abatement from biochar in the UK?

Respondents were asked: "How important do you think biochar will be to deep carbon abatement in the UK by 2020 and 2050? (reductions relative to 1990 emissions of 212

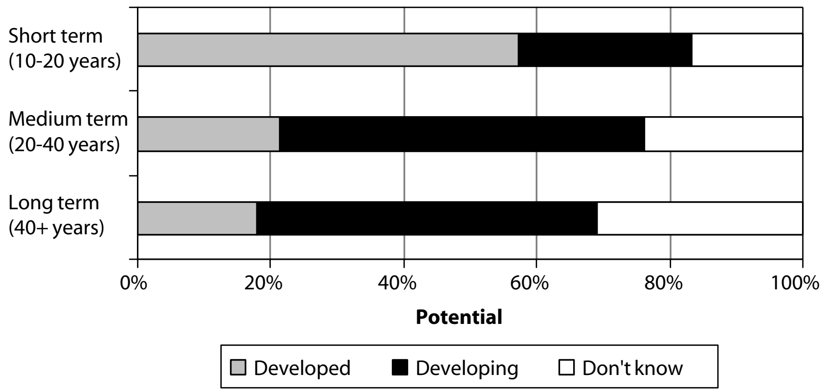

Figure 4: Overall, where do you feel there is most potential for biochar uptake (UK respondents only)?

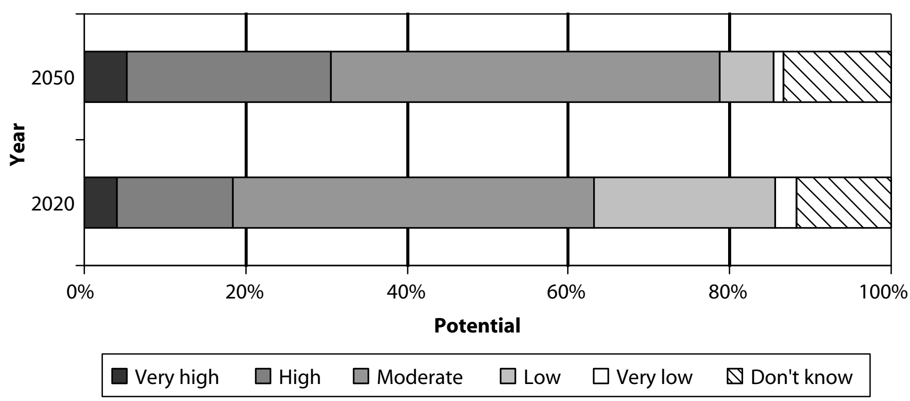

Figure 5: The potential for biochar deployment in Europe in 2020 and 2050

million tonnes of carbon equivalent). By 2020 - a reduction of 82 million tC is needed for a 40% reduction. By 2050 - reduction of 170 million tC is needed for a 80% reduction". We related tC abatement to % reductions so that the respondent could calibrate their response against national targets. The box plot shows the minimum value, the median (q2), the lower quartile (q1: 25% below the median), the upper quartile (q3: 25% above the median) and the maximum value. Any outliers are included, but extremes (outliers which are more than three times the Inter-Quartile Range or 3 box plot lengths from the mean) have been removed from this figure. Reductions are relative to 1990 emissions of 212 MtC eq. (equivalent). By 2020, a reduction of 82 million tC is needed for a 40% reduction. By 2050, a reduction of 170 MtC is needed for an 80% reduction. It can be seen that respondents expect larger reductions from biochar in 2050 than in 2020.

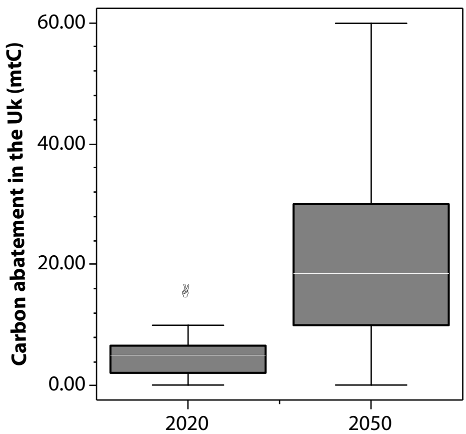

Figure 6: How important in terms of carbon reduction potential (in millions of tonnes per year) do you think biochar will be in achieving deep carbon abatement in the UK by 2020 and 2050?

Table 1: Millions of tonnes of carbon which can be abated per year through use of biochar deployment in the UK by 2020 and 2050

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

If the biochar carbon abatement expected by the mid 50% (or IQR) of the group was achieved this would constitute between 4 and 12% of the 40% reduction needed by 2020, and 6–17% of the 80% by 2050 reduction. The respondents' estimate for 2020 of between 4–12 MtC yr^{-1} abatement compares with results from Life Cycle Assessment (LCA) of net carbon abatement from biochar deployment for the UK that provide a figure of between 1–6 MtC yr^{-1} [2]. The range arises from three scenarios of biomass resources that may be available for biochar production (low, high and very high), utilising estimates of 'realistic available' total biomass resource as the upper limit. Another UK estimate is 4.3 MtC yr^{-1} CA from biochar by 2030 [17]. Respondents may, therefore, be somewhat over-optimistic on the availability of feedstock for biochar production in the UK: on the other hand, respondents were addressing this issue with respect to 2020 rather than today or the short-term (which is the focus of the LCA assessment). Furthermore, there are currently large uncertainties in exactly what organic feedstocks could be utilised for producing biochar. Even though the majority of the (small number of) responses (n=23) were quite compact, which suggests a consensus for the majority, there were still disparate views. Some respondents suggested that no abatement is possible, whilst others suggested that biochar alone could more than exceed the abatement target for 2020 and 2050.

UK feedstock potential

Potential biochar feedstocks for the UK were considered and the results presented in Figure 7 for UK respondents. Woodchip, municipal organic waste, paper sludge, arable crop residue and short rotation coppice (SRC) were considered to have the most potential. A range of scales was expected, with the biggest potential for small scale projects being for manure (46%, n=79) and arable crop residues (41%, n=81), and the biggest potential for large scale projects were from feedstocks that are already collected in large central

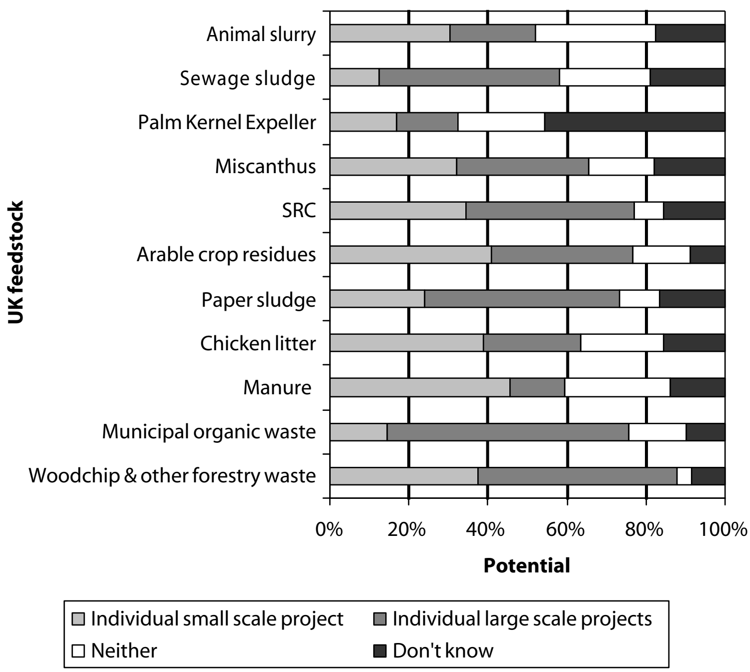

Figure 7: At present what feedstocks do you expect to have the most potential for biochar production in the UK? Small scale = individual projects involving <10t Biochar production / year, large scale = Individual projects involving >10t Biochar production / year). (SRC = short rotation coppice)

facilities (e.g. municipal organic wastes, forestry residues and sewage sludge).

Mean Residence Time

Respondents were asked to estimate the likely Mean Residence Time (MRT) of biochar (Table 2, Figure 8). The MRT is the inverse of the decay rate – that is, the average time for which carbon in new biochar remains present in a stabilised aromatic form. (The half-life, i.e. the time which elapses before half of the biochar decomposes,

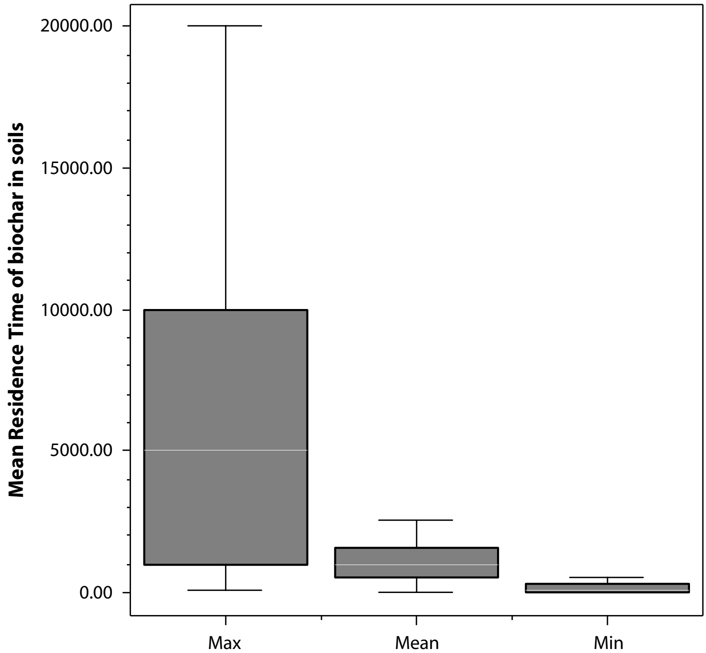

Figure 8: Estimates of the Mean Residence Time of biochar in soils (in years)

Table 2: Estimates of the Mean Residence Time of biochar in soils (in years)

	MRT-Max	MRT-Mean	MRT-Min
min	100	20	1
Q1	1900	500	43
Median	5000	1000	100
Q3	10000	1600	3901
max	1000000000	10000	7000

can be derived by multiplying the MRT by the natural logarithm of 2 [18]). We also asked for the respondents' assessment of the maximum and minimum residence times.

Nearly half of the sample (47%) (n=137, Table 3) state that there is insufficient evidence available at present to estimate the MRT of biochar; less than a fifth of the sample believe that there *is* sufficient information to address the question of the MRT. This level of uncertainty is very important given that the carbon equivalent abatement from biochar (and its cost and feasibility) is highly sensitive to the assumed MRT of biochar [19]. Furthermore, many of the respondents do not consider that they possess the specialist knowledge to answer the question concerning MRT: between 39 and 44% of respondents selected "don't know". Only 6% of the sample felt that they had sufficient knowledge to answer the question. And there were only five respondents

Table 3: The state of knowledge surrounding the estimation of the Mean Residence Time of biochar in soil

Respnose	cases	sample	%
In my opinion, there is not enough evidence available to answer this	64	137	46.4
In my opinion, there is sufficient evidence available to answer this	24	137	17.5
I feel I do not have enough knowledge of this subject to answer this question accurately	46	137	33.8
I feel I have sufficient knowledge of this subject to answer this question accurately	8	137	5.8
Other	42	137	30.7

from the whole sample who thought that there is enough evidence *and* that they personally had enough knowledge to estimate the MRT.

Data from those who responded "In my opinion, there is sufficient evidence available to answer this" (n=24) has been selected. The data shows a reasonable

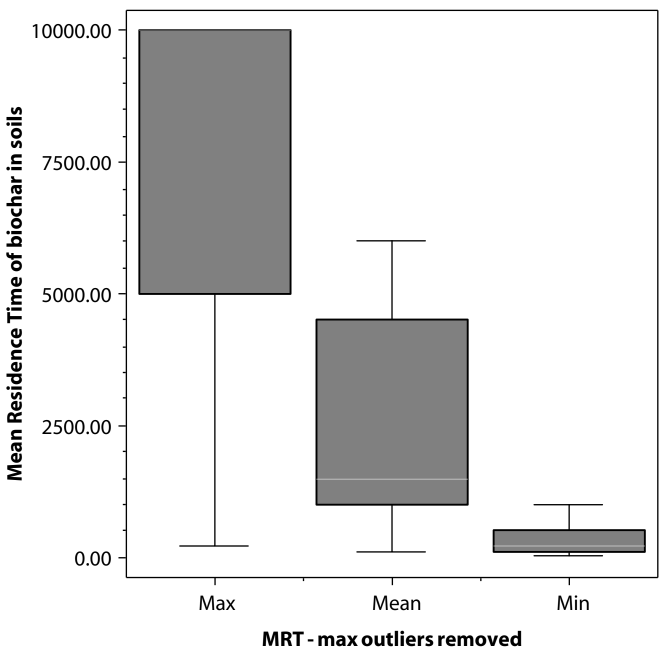

Figure 9: Estimates from those who feel that there is sufficient evidence to predict the Mean Residence Time of biochar in soil (in years)

Table 4: Estimates from those who feel there is sufficient evidence to predict the Mean Residence Time of biochar in soil

	MRT-Max	MRT-Mean	MRT-Min
min	200	100	20
Q1	500	1000	100
median	10000	1500	200
Q3	10000	4500	500
max	1000000000	10000	2000

consensus (Figure 9, Table 4). The values are also somewhat higher than for the estimates from the sample as a whole.

Public opinion

UK based respondents (n=71) were asked whether there may be any negative public opinion regarding biochar application. In the UK context, Figure 10 shows that concern over land use and associated impact on food prices is the largest expected

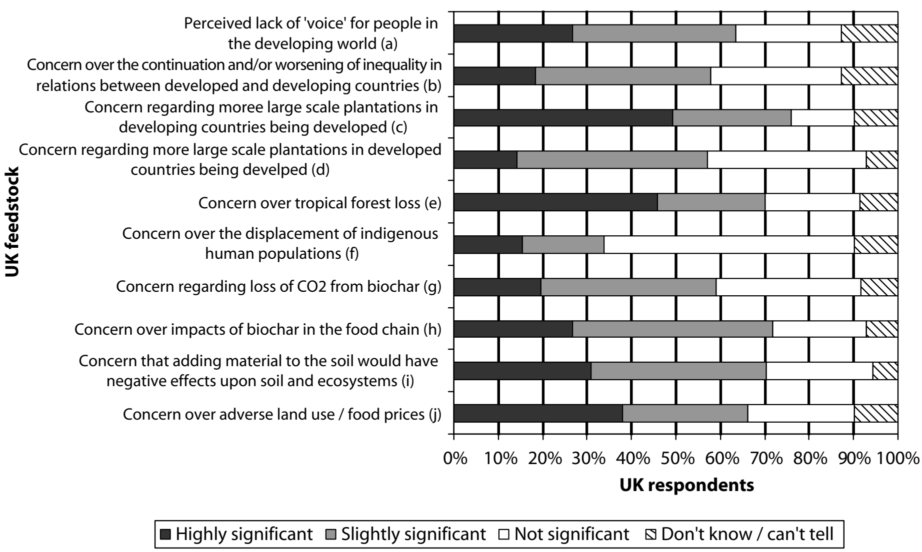

Figure 10: What do you think may cause a negative public opinion of biochar in the UK?

cause for concern from the public, with 66% of respondents suggesting a significant likely concern in the UK. Potential concerns at the global scale relate predominantly to land-use change, biodiversity loss and large-scale plantations.

Barriers

Figure 11 shows that UK respondents expected the major barriers to biochar

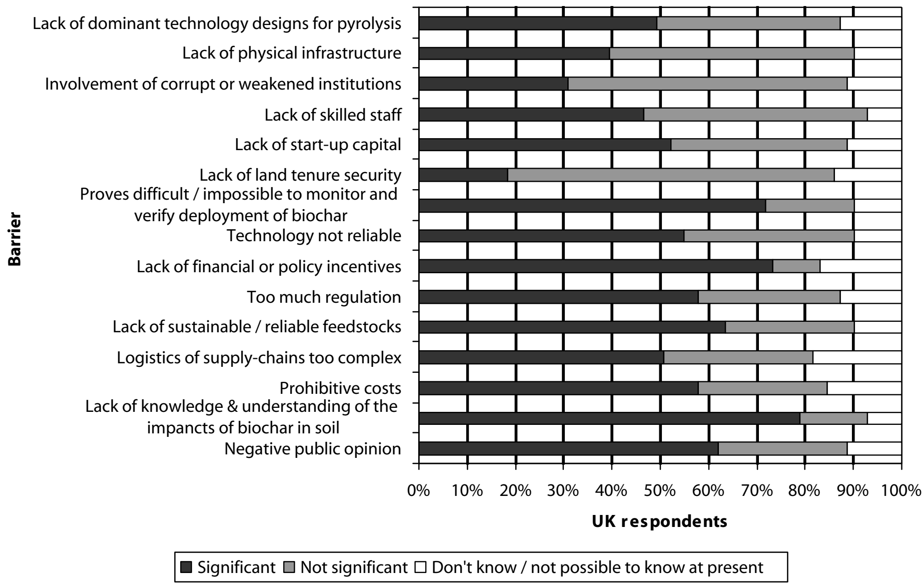

Figure 11: What barriers do you think are potentially going to reduce the uptake of biochar as a carbon storage tool in developing countries? (Significant = 'Highly significant' or 'Slightly significant', Not significant – 'Probably not significant' or 'Definitely not significant')

deployment in developing countries to be: 'Lack of knowledge and understanding of the impacts of biochar in soil (79%, n=71); 'Lack of financial or policy incentives' (73%, n=71), and 'Proves difficult / impossible to monitor and verify deployment of biochar' (73%, n=71).

Lack of financial / policy incentives was a particularly significant barrier, and this is reflected in the respondents views of the future carbon emission policy frameworks which are likely to emerge (i.e. >50% selected options a, b or c – relatively low targets), show in Figure 12. Note that the survey took place *prior* to the Conference of the Parties 15 to the UNFCCC in Copenhagen.

Figure 13 cross-correlates opinion on the extent to which a future global climate agreement is perceived as being tough (options d & e, n=38) or not (options a & b, n=31) with the perceived extent of carbon abatement from biochar by 2030. It can be seen that those who are more confident in achieving a tougher climate policy framework (options d & e) tend to regard the contribution of biochar to CA as being greater.

Potential impacts of biochar on crops and soil

Respondents were asked about two scenarios for adding biochar to a well-managed arable crop in typical UK conditions: i) a single application of 30 tonnes per ha; ii) a single application of 30 tonnes per ha followed-up by repeat applications at the rate of 1 t per ha per annum for the next 10 years. Respondents who rated their level of expertise in answering the questions in this section as 'very high', 'high' or 'medium'

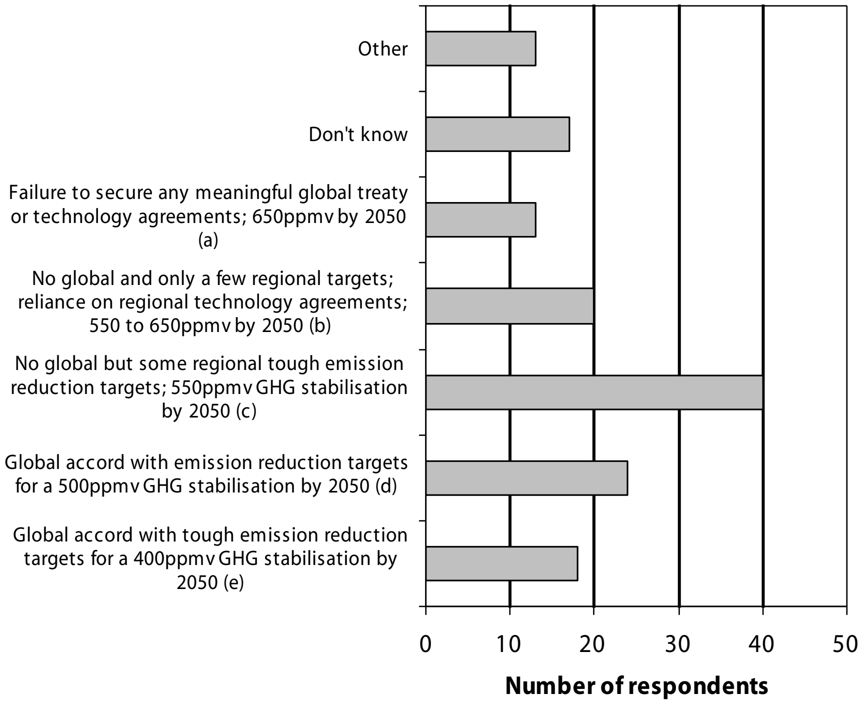

Figure 12: What climate policy framework do you think will emerge over the next few years? Note: ppm_v – parts per million by volume)

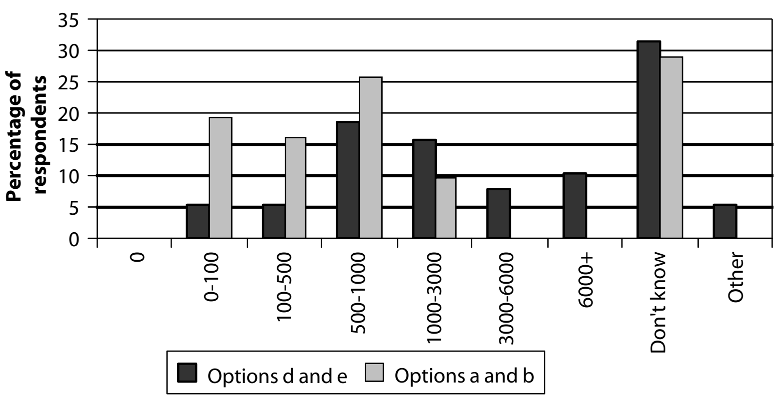

Figure 13: Cross-correlation of the perception of a future global climate agreement with perceived role of biochar in global carbon abatement (in millions of tonnes of carbon). (Option a: No global and only a few regional targets; reliance on regional technology agreements; 550 to 650ppmv by 2050. Option b: Failure to secure any meaningful global treaty or technology agreements; 650ppmv by 2050. Option d: Global accord with tough emission reduction targets for a 400ppmv GHG stabilisation by 2050. Option e: Global accord with emission reduction targets for a 500ppmv GHG stabilisation by 2050).

were included, while those who rated their expertise as 'low', 'very low' or 'no expertise' were not included.

The results in Figure 14 show that about half of the respondents thought that there would be an increase in crop yield in the year of an application. That percentage dropped to about 40% of respondents in the case of scenario (i) 5 years after a one-off application. Interestingly, 10% or so of respondents thought that crop yields might even decrease following the 30t application. There is a high level of uncertainty expressed;

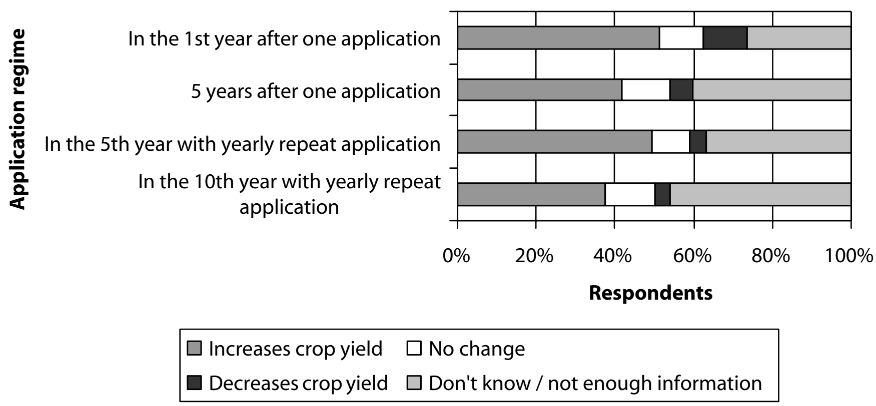

Figure 14: What are the impacts of biochar on crop yield?

this increased from about 25% of the sample selecting the 'don't know / not enough information' option for the one-off application, to nearly 50% selecting this option in the 10^{th} year with repeat applications. This, no doubt, reflects the lack of good experimental field data on the long-term impacts of biochar addition to soils [12].

Respondents were also reasonably confident that biochar improves the water retention of silty and sandy soils (60%), with virtually no one expressing the view that there would be a reduction in water retention from biochar addition to such soils. Opinion was much more split with respect to the impact of biochar on the water retention of clayey soils, some (20%) respondents believing that water retention would be increased, others (10%) that it would be decreased, in such soils.

Uncertainty dominates the response to many other questions on the indirect impacts of biochar, although positive effects to agricultural systems were more frequently expected than negative effects. The level of uncertainty also increased with the length of biochar addition. Regarding impacts of biochar on bio-availability of fertilisers 'don't know / not enough information' was the most common response (40–60%). There was a perception that bio-availability benefits would improve the longer the biochar remains in the soil; likewise for the impact of biochar on field operations. Nitrous oxide (N_2O) emissions from soils were expected to decrease from biochar addition to soils by just > 40% of the sample, with an equal percentage uncertain about this response, important because N_2O is 298 times more powerful as a greenhouse gas per molecule than CO_2.

Figure 15 suggests that 40% or so of respondents expected Soil Organic Matter (SOM) to increase with the addition of biochar, with less than 10% considering that

SOM levels would decrease. This is important because if biochar 'primes' the formation of SOC, there is a positive feedback loop which increases soil carbon sequestration yet further, while the inverse (i.e. biochar addition results in the loss of SOC) is also possible according to some authors [20]. In a scenario with a 75% removal of arable straw, which is then used in producing biochar and returned to the same land, more respondents perceived that there would still be an increase in SOC in year 1 (just under 30%) than a decrease (c. 15%), and the increase in SOC is perceived to increase over time, especially with repeat additions (Figure 16).

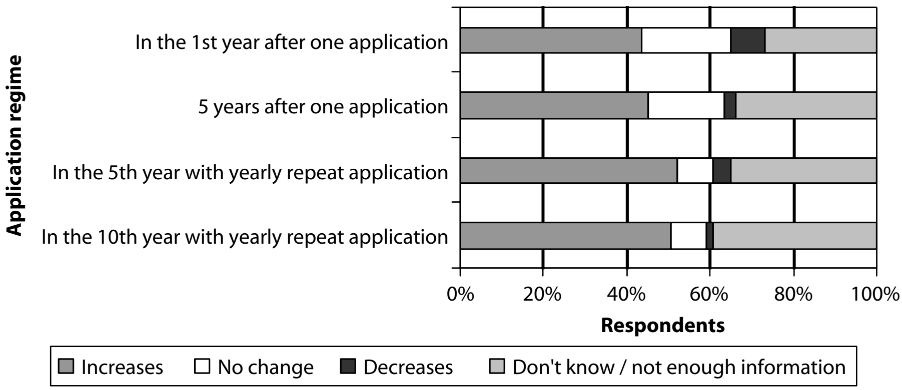

Figure 15: Assuming that Soil Organic Matter (SOM) is in equilibrium, what would be the impact of biochar on the existing SOM?

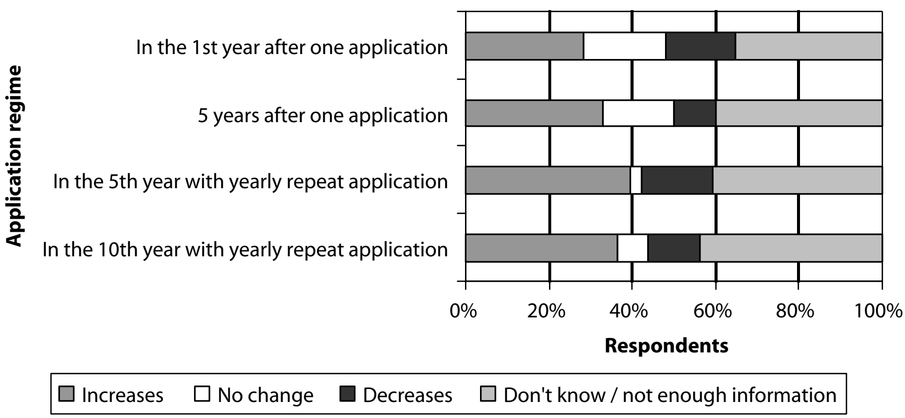

Figure 16: What are the impacts of biochar on SOM under the following scenarios on arable land in a closed system where 75% of residues are used to produce char for each application?

The risks of the loss of carbon from biochar

The main identified risk of biochar not being effective as a form of CA is the rapid loss of carbon in the highly labile biochar fraction, followed by the hypothesised 'priming' effect of biochar accelerating the loss of SOM (Figure 17). (Only respondents who rated their level of expertise in answering the questions in this section as 'very high',

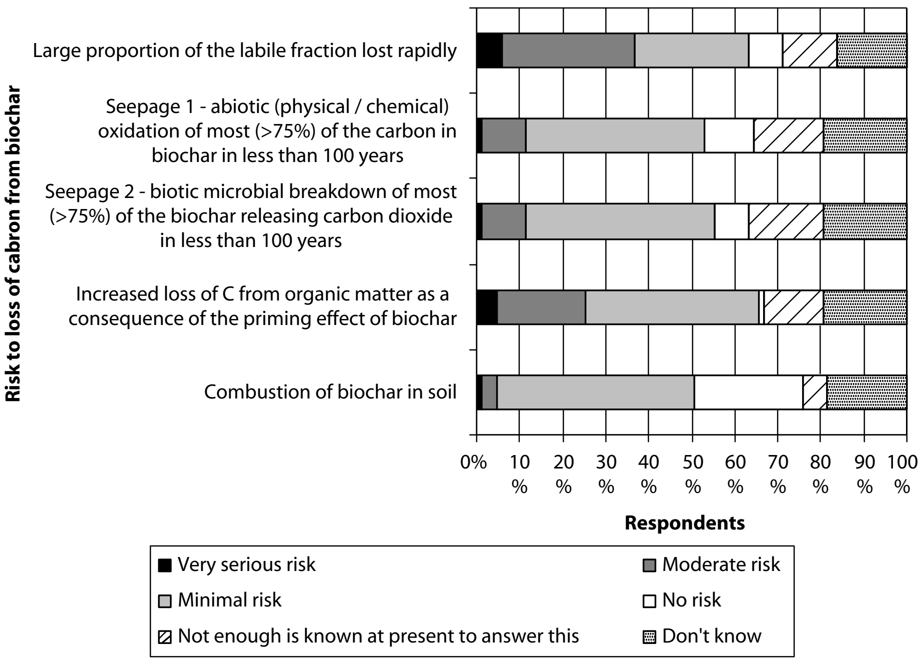

Figure 17: What are the potential risks of biochar not being effective in terms of the loss of carbon in the biochar?

'high' or 'medium' were included). The most common response was the 'minimal' category to the five risks included except for the labile carbon fraction. In comparison to some of the other questions, the respondents were relatively certain about these issues, with 17% of respondents suggesting that not enough was known about some of these issues (e.g. 'Seepage 2', n=87).

Biochar production factors

The production method can have an effect on the physical and chemical properties of biochar according to the respondents (n=47) who considered themselves to have expertise in this area. There appeared to be a reasonably high level of certainty and consensus on the importance of residence time, temperature, production method and feedstock. There was less consensus regarding the influence of pressure and particle size. Respondents also listed a number of other factors which would lead to a significant or slight variation in the properties of the resultant biochar, including: the status of the feedstock (moisture content, lignin content, granularity, age, residuals on the surface and micronutrient content); the environment within the pyrolysis unit (amount of steam, gas flow, oxygen content, catalysts used, etc.); technology required to meet emissions targets; the heating and cooling rates and the method for cooling the biochar.

Knowledge base

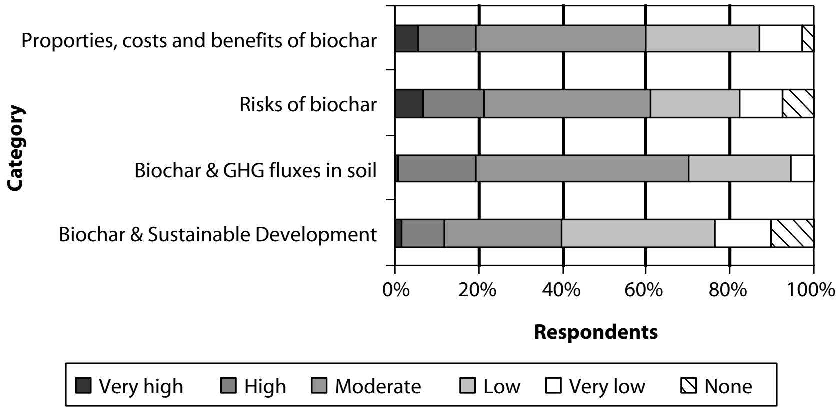

Figure 18: The level of expertise which the respondents felt they had after completing each section of the questionnaire

Respondents were asked to assess their expertise in each section of the survey (see Figure 18). Those with a self-professed 'very high', 'high' or 'moderate' level of expertise constituted between 39% (n=118) and 70% (n=124) of the sample. The most common response categories were 'moderate' followed by a 'low' level of expertise. The wider impacts of biochar, e.g. on sustainable development, is an area where the respondents had less expertise relative to the other categories.

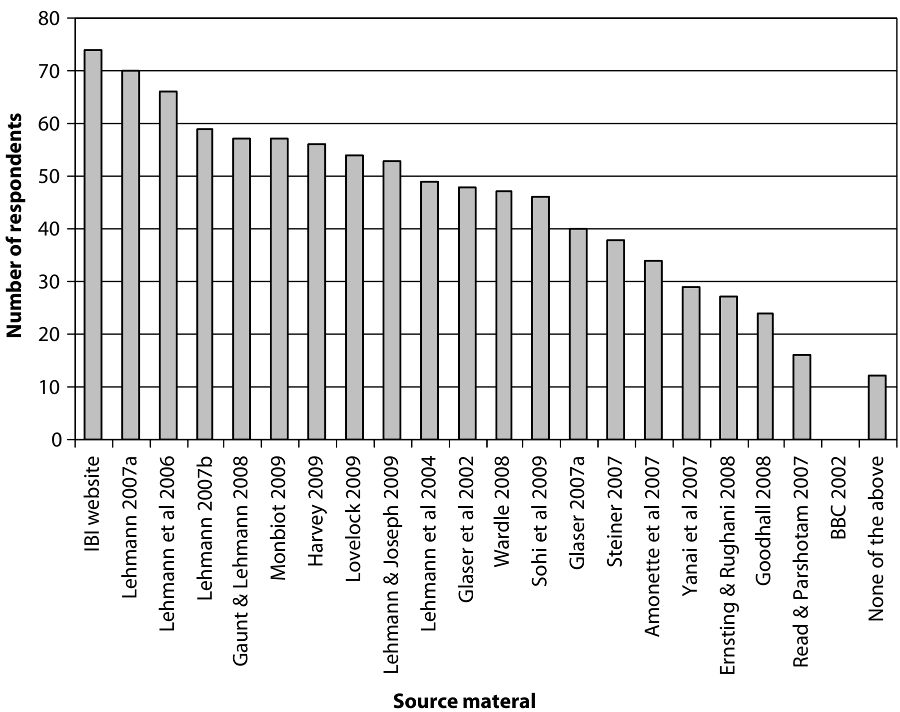

Figure 19: Which of the following have you read or watched?

We asked respondents about their sources of information on biochar (Figure 19). Peer-reviewed journals form the basis of many of the opinions in the survey; however other sources, including the International Biochar Initiative (IBI) website, are also used by respondents. In addition to acknowledged scientific experts, environmental campaigners such as George Monbiot and environmental scientist ‘celebrities’ such as James Lovelock have also been widely read on the topic of biochar.

4 DISCUSSION OF RESULTS AND IMPLICATIONS

The survey results have provided an insight into expert perceptions of biochar science and technology as of mid-2009. Clearly, the sample is non-representative in the sense that it is self-selecting and inevitably includes many biochar researchers who are more likely to be favourably, than non-favourably, disposed towards biochar. The strength of the sample, however, is that it is a well-informed one, hence there is value in asking the detailed and technical questions that were posed. The survey suggests that very few scientists consider themselves to have a very high degree of expertise with respect to biochar, however. Indeed, very few scientist are ‘dedicated’ biochar researchers. According to the respondents, there remain major uncertainties in the ‘biochar case’, as gleaned from survey, which we summarise below.

As a carbon abatement (CA) strategy, biochar must abate carbon on a sufficient scale and probably on at least a centurial time-scale. Otherwise, the carbon is mineralised and returned to atmosphere as CO_2 on too short a time-scale to make a long-term impact on limiting climate change. Large-scale leakage of carbon from biochar in a few decades time could be regarded as being counter-productive, though provided the relatively short term character of the carbon storage was recognised and properly accounted for, it could still ‘buy time’ while more recalcitrant biochar is developed. An analogy would be temporary or discounted carbon credits that are a proposed solution to the problem of impermanence in the storage of carbon in soils [21]. Some of the lower estimates of the MRT provided by our respondents would render the pyrolysis-biochar approach as a less effective carbon abatement strategy though it may still be desirable from the perspective of agronomy and sustainable soils. The mean response, however, was generally consistent with the desirable timescale of a century to a thousand years. The mean value also increased when the sample was restricted to those who felt that there is sufficient evidence to make a judgement regarding the MRT. Several respondents held a different perspective and commented that exact knowledge of the MRT is not necessary for biochar deployment. In their own words:

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

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

A remarkably small number of experts (five) considered that there is **both** enough knowledge to estimate the MRT and that they personally had enough knowledge to estimate the MRT given that the biochar concept rests upon the long-term recalcitrance of the biochar. This finding is broadly consistent with the notion of the ‘uncertainty trough’ of MacKenzie [22] which postulates that those closest to knowledge production are more aware of the uncertainties associated with that knowledge than the prospective 'users' (policy and decision-makers, developers and entrepreneurs, etc.). Hence, it is consistent with the uncertainty trough concept that those who are most knowledgeable about the science of biochar will also tend to be keenly aware of uncertainty.

The concerns that emerged about barriers and potential adverse public opinion largely reflect the contemporaneous debates regarding biofuels and bioenergy systems in the wake of indirect land-use change and food versus fuel issues [23, 24]. There has been much publicity of these issues and questioning of the sustainability of bioenergy and biofuels, in the popular, specialist and scientific media. The biochar community has itself been the target of such criticisms [3, 25] and this has led to heightened sensitivities within the biochar research and advocacy community. It is not surprising, therefore, that these concerns over land-use change, human rights, large plantations in the south, and so on, are identified as relevant by the respondents. The survey results on the agronomic and soil impacts of biochar are generally encouraging, though there is a wide range of opinion. The consensus viewpoint suggests that biochar will have one, and often more than one, benefit to soils and agronomic systems.

A final observation is the reliance upon a rather small number of publications in informing the respondents' viewpoints. A few key individuals, and a few key papers and reports, have been crucial in shaping opinion amongst the expert participants in this survey. One scientist in particular (Professor Johannes Lehmann of Cornell University in the USA) stands out as the primary opinion-former on biochar. It is perhaps typical of new research specialities that they are dominated by one or a few pioneer scientists. Biochar is not just like any other scientific speciality, though, in the sense that it is an proferred 'solution' to a set of perceived problems – primarily climate change, but also soil health, agricultural productivity and food security, waste management and renewable energy. The biochar research community organised early on as an advocacy organisation through the International Biochar Initiative, which was effective at capturing attention and interest from the media and certain policy communities.

Biochar therefore represents a fascinating example of interdisciplinary problem-based R&D that has mobilised and re-configured components of a range of scientific and technical disciplines. Yet, as this survey has illuminated, uncertainties in some of the key arguments for the concept are large. The research activity required to address these uncertainties satisfactorily will certainly take several years of effort given their novelty, complexity and sheer difficultly. Much therefore rests for the future of the biochar domain upon the judgements of the small coterie of scientists who creatively joined-up soil carbon science with climate change mitigation in the early years of the 21st century.

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