Report of Workshop on Greenhouse Gas Removal from the Atmosphere: London, 28 April 2016

Workshop held at the Wesley Hotel and Conference Centre, London NW1 2EZ, jointly organised by the Natural Environment Research Council (NERC), Arts and Humanities Research Council (AHRC), Biotechnology and Biological Sciences Research Council (BBSRC), Engineering and Physical Sciences Research Council (EPSRC), Economic and Social Research Council (ESRC), Science and Technology Facilities Council (STFC), the Department of Energy and Climate Change (DECC) and the Met Office.

1. Background

An integrated research programme on the removal of greenhouse gases from the atmosphere is being planned by NERC and other funders. The Workshop was held to assist in scoping that programme, by exploring the scientific issues relating to the feasibility of greenhouse gas removal (GGR) from a technical, economic, societal and environmental perspective. Discussions focussed on the new knowledge needed to assess whether GGR might be deployed in addition to, not as a replacement for, conventional mitigation – thereby helping to avoid dangerous climate change and meet the goals of the Paris Agreement.

The aims of the workshop were:

- To identify the key research questions in greenhouse gas removal from the atmosphere in the remits of the organising bodies.
- To define the scope of a potential joint research programme linking key research areas to deliver a truly integrated interdisciplinary approach.

The announcement of the Workshop was posted on organisers' websites in mid-March, inviting potential participants to express their interests. Over 80 individuals, mostly research scientists, responded with requests to attend. Because of limited facilities, and the importance of group-based discussions, ~60 individuals were invited from ~40 organisations: that selection was based on balance of disciplinary expertise and institutional representation (Annex 1). Whilst eligibility to receive Research Council funding was an important consideration, 10 private sector/non-academic representatives were also included as workshop participants, on the basis of their interests as stakeholders and potential partners.

2. Workshop structure and introductory presentations

The Workshop agenda is given in Annex 2. Most of the time was given to two break-out discussion sessions and their plenary reporting. In addition, introductory presentations provided the funding, policy and scientific contexts for the proposed GGR programme, identifying issues for further attention.

Ned Garnett (NERC) summarised the conceptual development of the GGR research programme, noting the Research Councils' previous joint support for related initiatives on climate change and at-source carbon capture and storage (CCS). All organising bodies have been involved in planning the current Workshop, as potential co-funders of the GGR programme. The scale and scope of the programme will be determined by the level of co-funders' support, based on relevance to their interests and evidence for productive community engagement. The issues to be addressed were not expected to be limited to the UK: GGR research would seem to offer important opportunities for collaborative work with developing countries. Components might therefore be aligned to, and receive further support from, the joint

Research Council Global Challenges Research Fund (GCRF), under Official Development Assistance (ODA) arrangements.

Cathy Johnson (DECC) noted that nearly all climate models that limit end-of-century global warming to $2^{o}C$ currently rely on 'negative emissions' (i.e. GGR), mostly by assuming the future, large-scale deployment of bioenergy with carbon capture and storage (BECCS). Furthermore, the Paris Agreement includes the need to "*achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century* [i.e. implicitly assuming GGR] *on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty*". However, many of the assumptions relating to negative emissions are untested, with risk of over-optimism regarding their deployment scale and effectiveness. From a policy perspective, it is therefore crucially important to not only improve assessments of feasibility of BECCS, but also to consider the viability of alternative techniques and their implications. Life Cycle Analyses are needed, alongside consideration of whether low carbon energy is best used for other geoengineering technologies or other purposes.

Similar issues were covered in a scientific overview by **Phil Williamson (NERC/UEA)**. There has been a fourfold increase in global CO_2 emissions since 1950: avoidance of dangerous climate change (limiting warming to 1.5-2.0°C) now requires reversal of that trend, with both a very rapid decrease in emissions and near-certain deployment of GGR. A wide range of biological, geochemical and chemical GGR techniques, almost all for CO_2 removal, have been proposed, involving a wide range of storage processes, from short-term to geologically-permanent. However, none of the proposed approaches are well-characterised, and the wider implications of their large-scale application are highly uncertain. Important knowledge gaps include those relating to environmental impacts, cost-effectiveness, governance, financing, and public acceptability. The Convention on Biological Diversity has recently expressed support for research on GGR, although there is still ambiguity at the UN level as to whether forestry-based techniques, enhancing soil carbon and direct air capture should be considered as mitigation or climate geoengineering.

Initial plenary discussion at the Workshop raised the questions of whether the issues were primarily social, political or financial rather than scientific; whether closer linkage would be desirable not only with CCS research but also carbon capture, utilisation and storage (CCUS, or CCU); and if there was a 'guide price' for the economic viability of GGR. With regard to costings, the figure of $200 per tonne of CO_2 was provisionally identified as a likely upper limit of financial feasibility for a removal technique; however, it was noted that costs of new technologies typically decrease as they are more widely adopted (as occurred for solar panels). Furthermore, all greenhouse gases were under consideration, not just CO_2.

3. First discussion session: Comparative merits of different GGR approaches

Discussion guidance: *Which technique(s) offer the most potential in terms of their scientific, economic, political and technological feasibility and expediency in achieving removal of greenhouse gases from the atmosphere at a climatically-significant scale in 30-50 years' time? What are the most important knowledge gaps (weakest links) relating to the technical effectiveness of the identified techniques?*

Workshop participants were randomly allocated to eight break-out groups, that all addressed the same questions (above). Edited rapporteurs' oral and written reports are given in Annex 3. Common issues and key arguments included the following:

- There was no consensus with regard to which GGR technique(s) offered most promise. Indeed, only one group offered a shortlist, whilst acknowledging that the two options it identified primarily reflected the group's expertise. Ocean fertilisation was, however, identified by two groups as an approach of low priority for further research effort.

- It was recognised across the groups that technical feasibility might not be the biggest issue, and knowledge gaps in political, economic, social and environmental perspectives are very important to understand
- Significant attention was given to identifying the wide range of factors (technical, environmental and socio-economic) that could be used for structured technique evaluation and inter-comparison.
- The importance of public/political acceptability and life cycle analysis in such comparisons was emphasised, the former covering 'legitimacy' in a broad sense (social licence to operate) and the latter not just on a 'cradle to grave' basis, but including all other indirect impacts and consequences. Impacts were considered potentially more serious when they were uncontained, i.e. with risk of adverse consequences that crossed national boundaries.
- Scalability issues were a common concern. Successful deployment at local level does not necessarily translate to climatic-scale feasibility. A well-planned transition from laboratory to field studies, to pilot-scale, and to trial implementation would be needed to demonstrate overall viability, with close monitoring of effectiveness and impacts, and linkage to soundly-based modelling.

The policy horizon in the discussion guidance was identified as deployment at "a climatically-significant scale in 30-50 years' time". Such a timescale for potential implementation may need re-visiting; there are both longer-term and shorter term issues to consider, relating to energy policy, infrastructure, permanence of sequestration, climate system behaviour and the timescale for establishing a benchmark by which a 'worthwhile' contribution can be established for any particular GGR technique.

On the basis of the above, it might seem preferable that the planned GGR research programme should be unconstrained with regard to specific techniques, without any direction in that regard until research on as many options as possible has been completed – thereby allowing for comprehensive inter-comparison and evaluation. Such an approach extols the primacy of the scientific method and the accretion of knowledge, on the basis that the more we know the more robust will be the eventual policy choices. It also assumes relatively unconstrained resources.

An alternative approach for GGR programme-structuring is to either encourage, or prescriptively focus, research effort on a limited sub-set of options that are widely considered to be front-runners in terms of both climatic effectiveness and political viability, accepting that some other, relatively undeveloped ideas might thereby be excluded. To explore such issues, and elicit more specific research questions, the second Workshop discussion session was deliberately more technique-based, whilst also introducing geo-political considerations (in terms of developing country/developed country perspectives). Nevertheless, the four topic areas used for the afternoon discussions were still relatively broad, without prejudice to the programme funders' decision on what might or might not be favoured in any call for proposals.

4. Second discussion session: Technique-specific feasibility, cross-cutting issues, and relevance to developing countries

Discussion guidance for technique-based groups: *What are the wider feasibility issues (environmental and socio-economic) of the techniques under consideration? Do these differ between 'developing' and 'developed' countries? How can the knowledge gaps identified in the morning session and here best be addressed by targeted research?*

Discussion guidance for cross-cutting groups: *What criteria are most appropriate to assess comparability of different techniques? Do different considerations apply for 'developing' and 'developed countries? What are the key cross-cutting issues that can best be addressed by targeted research?*

Workshop participants divided into six break-out groups, four of which were technique-focussed (soil carbon, forestry and land management; BECCS; enhanced weathering; and direct air capture) and two of which were cross-cutting. Edited rapporteurs' oral and written reports are given in Annex 4. Main issues and key arguments included the following:

- Each of the technique-focussed groups included sufficient expertise to develop relatively detailed research agendas, all covering a range of technical, environmental and socio-economic considerations. Whilst the participation of different individuals might have highlighted different aspects, the research communities seemed relatively mature and inherently open to collaborative work based on interdisciplinary/transdisciplinary approaches.
- For the topic grouping of **soil carbon, forestry and land management**, the basic research question is how best to enhance 'natural' carbon storage at sufficient scale and durability, in agricultural systems and through forestry-based GGR approaches. A focus on tropical afforestation/reforestation would provide opportunity for developing country engagement. Integrated Assessment Models need further development to adequately represent land use change and carbon dynamics, and hence GGR effectiveness.
- Although the bioenergy part of **bioenergy, carbon capture and storage (BECCS)** might seem relatively well-researched, there are still many important knowledge gaps in a GGR context, relating to biomass and crop science, land use change and environmental impacts, process engineering and chemical engineering, and social and political considerations. BECCS necessarily involves developing countries, since global-scale application is necessary for climatic effectiveness.
- An overall need for R&D on **enhanced weathering and ocean alkalinity enhancement** is to increase reaction rates, testing the effectiveness of such manipulations under field conditions (pilot studies) and demonstrating technological feasibility and social acceptability at increasing scale. The socio-political implications of the transboundary impacts of these techniques also require consideration. The scope for using mining waste would seem to warrant research attention, with associated developing country opportunities.
- Cost reductions, socio-legal considerations, quantified energy requirements and engineering developments are crucial for **direct air capture (DAC)** that could be effective in removing greenhouse gases (and not just CO_2). The relative availability of solar energy in tropical regions favours such localities for DAC deployment, provided that suitable sites for carbon storage are also available
- The two **cross-cutting discussion groups** gave further attention to evaluation criteria for technique comparisons; to the development pathways by which GGR might achieve large-scale implementation, including consideration of policy development and governance; and to the importance of co-benefits. Market forces alone are unlikely to be sufficient to stimulate the necessary investment: thus state intervention (at national and/or international level) and more realistic carbon pricing are considered necessary.

5. Concluding comments and summary of outcomes

David Addison (Virgin Earth Challenge) described his company's £20m competition to help develop scalable and sustainable ways of removing greenhouse gases from the atmosphere. He emphasised that science is an extremely powerful tool, yet it requires critical thinking – and has limitations. Linking real world data to models, working collaboratively, and full engagement with social scientists are all crucially important for GGR development and successful climate change mitigation.

The overall outcomes of the Workshop can be summarised as follows:

- The event demonstrated strong community interest in GGR research, by both academics and stakeholders, covering the interests of NERC, AHRC, BBSRC, EPSRC, ESRC, STFC, DECC and the Met Office
- The proposed GGR programme would have high policy impact, at national and international levels
- A range of criteria for comparative evaluation of different GGR techniques were identified
- Specific research questions for four broad groupings of biological, geochemical and engineering GGR approaches were identified (soil carbon, forestry and land management; BECCS; enhanced weathering; and direct air capture), each covering technological, environmental and socio-economic aspects
- GGR research is highly relevant to developing countries, and a range of specific opportunities for productive research collaboration were identified.

Annex 1. Workshop participants

Organisers' names in italics

Name		Affiliation
David	Addison	Virgin Group
Hyungwoong	Ahn	Univ of Edinburgh
Myles	Allen	Univ of Oxford
Sarah	Batterman	Univ of Leeds
Michael	*Booth*	*BBSRC*
Isabela	Butnar	UCL
Robert	Chris	The Open University
Joanna	Clark	Univ of Reading
Natalie	*Clark*	*NERC*
Gareth	Clay	Univ of Manchester
Maggie	Cusack	Univ of Glasgow
Richard	Darton	Univ of Oxford
Leon	Di Marco	FSK, London
Baran	Doda	LSE
Iain	Donnison	Aberystwyth Univ
Sebastien	Facq	Univ of Cambridge
Maria-Chiara	Ferrari	Univ of Edinburgh
Piers	Forster	Univ of Leeds
Ned	*Garnett*	*NERC*
John	Gibbins	UK CCS
Pietro	Goglio	Cranfield Univ
Z. Xiao	Guo	UCL
Anna	Harper	Univ of Exeter
David	*Holtum*	*EPSRC*
James	Hourston	Royal Holloway Univ
Jo	House	GO-Science/Bristol
Cathy	*Johnson*	*DECC*
Martin	Jones	STFC
Joerg	Kaduk	Univ of Leicester
Tim	Kruger	Univ of Oxford
Tim	Lenton	Univ of Exeter
Nicola	*Lewis*	*NERC*
Simon	Lewis	UCL/Univ of Leeds
Jason	*Lowe*	*Met Office*
Sophie	*Martin*	*ESRC*
Salman	Masoudi-Soltani	Imperial College

Name		Affiliation
Dominic	Moran	SRUC
Oliver	Morton	The Economist
Euan	Nisbet	Royal Holloway
Steve	Pearson	Centre for Process Innov.
Roz	Pidcock	Carbon Brief
Nick	Pidgeon	Cardiff Univ
Steve	Rayner	Univ of Oxford
Phil	Renforth	Cardiff University
Paul	Rouse	Univ of Southampton
Richard	Sanders	NOC Southampton
Giulio	Santori	Univ of Edinburgh
Janine	Sargoni	Univ of Bristol
Beatrix	Schlarb-Ridley	British Antarctic Survey
Vivian	Scott	Univ of Edinburgh
David	Sevier	Carbon Cycle limited
Andrea	Sharpe	NERC
Lidija	Siller	Newcastle Univ
Kevin	*Smith*	*STFC*
Steve	Smith	Cttee on Climate Change
Colin	Snape	Univ of Nottingham
Saran	Sohi	Univ of Edinburgh
Clare	*Spooner*	*ESRC*
Dave	Stanley	Pasture Fed Livestock Ass.
Ailsa	*Stroud*	*DECC*
Peter	Styring	Univ of Sheffield
Brian	Sweeney	Calix Limited
Damon	Teagle	University of Southampton
Chris	Vivian	Cefas
Meihong	Wang	Univ of Hull
Mathew	Williams	Univ of Edinburgh
Adrian	Williams	Cranfield University
Phil	*Williamson*	*NERC/UEA*
Andrew	Wilson	AKW Technologies Ltd
Aidong	Yang	Univ of Oxford
Nicola	Yates	Rothamsted Research

Annex 2. Workshop agenda

From 09.30	Registration
10.00	Welcome. Introduction to proposed programme. *Ned Garnett, NERC*
10.10	DECC perspective. *Cathy Johnson & Ailsa Stroud, DECC*
10.20	Overview of research issues relating to greenhouse gas removal. *Phil Williamson, NERC/UEA*
10.30	***Tea/coffee***
11.00	*Breakout session #1* i) Table introductions ii) Discussion to develop group consensus on the following topics: • Which technique(s) offer the most potential in terms of their scientific, economic, political and technological feasibility and expediency in achieving removal of greenhouse gases from the atmosphere at a climatically-significant scale in 30-50 years' time? • What are the most important knowledge gaps (weakest links) relating to the technical effectiveness of the identified techniques?
12.15	Group reports from session #1
12.45	***Lunch*** Participants signup for afternoon break-out groups
13.45	*Breakout session #2* i) Table introductions ii) Discussion to develop group consensus on the following topics: • For technique-based groups: o What are the wider feasibility issues (environmental and socio-economic) of the techniques under consideration? o Do these differ between 'developing' and ''developed' countries? o How can the knowledge gaps identified in the morning session and here best be addressed by targeted research? • For cross-cutting groups: o What criteria are most appropriate to assess comparability of different techniques? o Do different considerations apply for 'developing' and 'developed countries? o What are the key cross-cutting issues that can best be addressed by targeted research?
14.45	***Tea/coffee***
15.15	Group reports from session #2
15.45	Concluding remarks. David Addison, *Virgin Challenge*
16.00	Close of meeting

Annex 3. Summaries of break-out discussions, session 1 (morning): Comparative merits of different GGR approaches

All groups considered the same issues and workshop participants were randomly allocated between groups. The sequence below follows the order of group-reporting on the day, rather than table-numbering; discussion guidance given in main text and Annex 1.

Group 1 *Rapporteur: Myles Allen (Oxford University)*

No shortlist of favoured techniques was identified. Consideration was given to the minimum deployment scale for a GGR technique to be considered climatically significant. This was estimated to be around 1 billion tonnes of CO_2 by 2100, reducing warming by at least 0.1°C. Other key scaling criteria for assessment of feasibility were considered to be food security, land use and biodiversity.

Knowledge gaps regarding effectiveness did not necessarily relate to 'technical' issues. More important factors related to political feasibility and acceptability ('legitimacy'), at both national and international levels. The current assumption in most climate models is that negative emissions will be possible: in effect that defers the risk to future generations, raising major ethical issues.

The group was unable to agree on a shortlist of preferred techniques, wishing to avoid winners/losers at this relatively early stage. However, categorisation and evaluation could usefully be based on the different steps involved. The term stabilization was preferred to removal/disposal, since the important issue was the separation from climatic processes. Under future conditions of (greatly) decreasing CO_2 emissions, other greenhouse gases would become relatively more important. In particular, the agricultural production of nitrous oxide (N_2O), related to fertilizer use.

Group 2 *Rapporteur: Robert Chris (Open University); additional notes by Damon Teagle (University of Southampton)*

No shortlist of favoured techniques was identified. The group noted that important greenhouse gases, in addition to CO_2, include methane, nitrous oxide and black carbon[1]. A range of removal technologies is likely to be needed, and much basic research has yet to be done. Thus it was not yet considered possible to pick winning GGR techniques; nevertheless, it might be possible to eliminate obvious losers. Scalability issues are crucial, requiring small-scale experiments and pilot studies; also the need to address full life cycle analyses, with comprehensive accounting, monitoring and verification approaches.

Issues for evaluation include: costs, energy requirements, water and land-use, fertilizer, pollution/waste, co-benefits and by-products, impacts on biodiversity and ecosystem services, and impacts on public health and well-being. Each criterion should initially be applied independently; subsequently multi-dimensional benchmarking would provide inter-comparisons.

There was an overall preference for techniques that are local (yet scalable), controllable without trans-national impacts, and that can be easily terminated. Hence favouring terrestrial rather than oceanic approaches; nevertheless, some marine opportunities (e.g. based on cultured marine algae) may be worth considering further. Ethical implications also should be considered.

State intervention/involvement in GGR would seem essential, since markets are not going to make this happen without financial incentives, based on community-wide benefits. Relevant stakeholders (and

[1] Not a gas, but may contribute climatically-significant warming. Halocarbons could also be considered as greenhouse gases that might be removed, e.g. by photocatalysis.

potential co-funders of the GGR programme?) include Innovate UK, Energy Technology Institute, UK Energy Research Centre, and other parts of Government.

Group 3 *Rapporteur: Colin Snape (University of Nottingham)*

No shortlist of favoured techniques was identified. However, key features highlighted for successful GGR were sustainability, scalability, acceptability and verification, all based on a full life cycle analysis. For some techniques, the supply of materials could be an important constraint. New variants in technology, for example 'direct ocean capture' (with ocean storage), should be considered, to encourage novel breakthroughs. The GGR research programme should be a step in the process, not an end in itself; it was therefore important to have strong industrial engagement from the outset.

Group 4 *Rapporteur: Mathew Williams (University of Edinburgh)*

Afforestation/reforestation and soil improvement were considered to provide particularly strong GGR opportunities, based on a matrix, informal ranking, and the group's expertise. These techniques were thought to have scale-up potential, and to be scientifically well-supported. Issues for consideration in evaluating the relative merits of different biomass-based techniques included: occurrence of co-benefits, e.g. in relation to Sustainable Development Goals and/or flood prevention; optimising geographical location; permanence of carbon storage; and the species used to provide biomass (monoculture, or encourage biodiversity?).

Life cycle analysis was regarded as crucial. Additional considerations included the knock-on effects of nutrients, either on land or in the sea. For direct air capture, energy and cost issues were likely to be critical; for ocean fertilization, political, governance and policy issues seemed the weakest link; whilst for BECCS, land availability and impacts on food security were problematic.

Group 5 *Rapporteur: Ailsa Stroud (DECC)*

No shortlist of favoured techniques was identified. The group considered that a socio-technological systems approach would be required for GGR planning and implementation, based on what we might want the world to look like in 2100. Comparable, but different, case histories include the development of policies for nuclear energy (inherently top-down) and renewable energy (much more bottom-up); both those issues necessarily involve humanities and social science as well as economics and engineering. GGR could have co-benefits as well as negative impacts; for example, helping with energy supply to remote areas.

Governance issues mostly relate to scaling and whether the technique is contained or 'feral', the latter risking non-local, potentially trans-boundary impacts (e.g. as would occur through ocean fertilization). The social impact of GGR could be extremely important, yet also unpredictable.

Group 6 *Rapporteur: Vivian Scott (University of Edinburgh)*

No shortlist of favoured techniques was identified. Although many techniques were considered potentially viable on a small scale, constraints and uncertainties seemed likely on a climatically-relevant scale. Scalability limitations may arise due to: physical constraints (perhaps insurmountable); techno-economic constraints (could potentiality be addressed); and ecological-sociological constraints (with many uncertainties and unknowns).

The problems associated with ocean fertilisation, including serious concerns regarding effectiveness, governance and verification, seemed sufficiently serious for it to be rejected from further consideration. For other techniques, there is a need to show plausible promise for a scaling pathway (overcoming constraints) from laboratory, to pilot, to demonstration, to climatic-scale implementation. Life-cycle issues are clearly important – but conventional 'cradle to grave' framing is inadequate. Instead there is a need to consider *consequential* life cycle, including the displacement of resources from other (potentially more effective?) mitigation actions.

BECCS could usefully be separated into macro-biological (e.g. wood for power generation, with CCS) and micro-biological (e.g. algae to fuels). For the former, sustainability of feedstock would seem the primary limit and challenge; for the latter, process-constraints. For removal of greenhouse gases other than CO_2, their low concentrations would be challenging. However, there may be some potential via biotechnology or agricultural approaches (although overlap with conventional mitigation?).

Social and political practicability is likely to be very scale-dependent and uncertain, despite research advances in attitudes and behaviour. Overall framing depends on rate of emission reduction, and possible reliance on GGR to remedy an overshoot and achieve climatic stability.

Group 7 *Rapporteur: Gareth Clay (University of Manchester)*

No shortlist of favoured techniques was identified. Instead discussions were based on what the group wanted the future world to look like, how that future could be structured, and uncertainty issues. One consideration was whether new research should be directed at less well-explored GGR techniques, so that all options might be at the same level of maturity for valid comparisons. What may seem ready for deployment may not necessarily be the most appropriate technique, or the one most in need of research.

Timescales of research and potential deployment decisions may not be easy to match. For example, monitoring the impacts (positive and negative) of GGR techniques may require baselines to be established before substantive actions, such as pilot-scale studies, are taken. The permanency of sequestration is also important, that may be a function of future climate change (e.g. stability of soil organic matter in a warmer world). Life cycle assessments should take account of possible feedbacks with other Earth system components.

Risks were discussed in terms of where failure might happen (technological, natural or political), the need to minimise them, and the implications of GGR performance targets not being met. Issues of policy, governance and public acceptability need to be investigated well before trying out any technological solution, and could act as an overarching theme to connect different GGR approaches. As such, the inclusion of humanities and social scientists was seen as crucial.

Group 8 *Rapporteur: Jo House (University of Bristol/ Government Office of Science)*

Although no shortlist of favoured techniques was identified, a range of options (with different implementation scales, and with different site-specific co-benefits) was considered. The starting point was what might be doable now at relatively small-scale, e.g. greening of cities or ecosystem restoration, as well as giving attention to feasibility of larger-scale, globally-significant implementation, with associated technological, social and economic issues.

Key overarching points were: i) the desirability of keeping a wide range of options open (with early investment); ii) the need for techniques to be spatially and temporally appropriate (site-specificity depending on resources, socio-economic/political environment, and co-benefits; timing issues including what can happen now, what in 50 or 100 years, what is constrained, and what is infinite); and iii) the importance of socio-political and economic constraints and barriers, with the need to address how they might be overcome (e.g. via appropriate incentivisation).

The main research gaps were considered to be: i) a well-planned, systematic comparative analysis of options with respect to scale, feasibility, co-benefits and trade-offs, economics, environmental impacts etc.; ii) identification of co-benefits and trade-offs, to be included in life cycle analysis and in cost-benefit analysis (including impacts on ecosystem services, although non-market valuation may be needed); iii) implications for integrated land management and land processes, including permanence and feedbacks (e.g. climate impacts on areas of suitability, fire and disease); and iv) establishing baseline and on-going monitoring, reporting and verification (MRV) for sequestration effectiveness (permanence of removal).

Annex 4. Summaries of break-out discussions, session 2 (afternoon): Technique-specific feasibility, cross-cutting issues, and relevance to developing countries

Workshop participants decided which group they wished to contribute to. The sequence below is re-ordered into four technique-specific groups followed by two cross-cutting groups; discussion guidance given in main text and Annex 1.

Soil carbon, forestry and land management *Rapporteur: Dave Stanley (Pasture Fed Livestock Association); additional notes by Simon Lewis (UCL/University of Leeds)*

GGR could be achieved in a relatively direct, cost-effective and non-controversial way by enhancing the land-based carbon storage in soil and biomass, via forestry, arable agriculture (with potential for biochar additions), grassland and other managed and semi-natural ecosystems. For temperate afforestation/re-forestation, carbon uptake (and its changes over time) is relatively well-characterised; however, the potential to increase carbon in agricultural systems and elsewhere (e.g. peatlands; urban areas) is not well known and warrants further attention. Relevant research questions include: what interventions are most effective to increase net CO_2 uptake and carbon storage? What are the costs involved? What are the potential co-benefits, e.g. in terms of flood/drought mitigation, pollutant degradation? What innovations could be developed to support mainstream delivery of such approaches? What is the effect of agricultural practices (ploughing, herbicides etc) on soil carbon storage?

A focus on forestry-based GGR techniques (afforestation/forest restoration/tree-based crops) in the tropics would provide the opportunity for developing country engagement, with close linkage to any BECCS-based research component. An initial research task could be to synthesise existing literature on: i) carbon sequestration rates of differing species, differing management practices and in different places; ii) permanence of the carbon stocks above/below ground; and iii) implications for other greenhouse gas fluxes (particularly nitrous oxide emissions from fertilizer), all on a global basis.

This synthesis could then be used to quantitatively assess the potential for increased carbon storage on land given differing constraints relating to land availability, management practices, species use etc; also the likely implications of forestry-based GGR when scaled to climatically relevant areas within an Earth system modelling framework (i.e. impacts on rainfall, runoff, local/regional temperature and albedo).

A closely-related research initiative would be to develop new Integrated Assessment Models (IAMs) with improved representations of carbon budgets and land-use processes, particularly in the tropics. IAMs used in IPCC AR5 are considered unrealistic with regard to negative emissions/GGR and their linkage to land-use change. The new IAMs need to be applicable on a country-by-country basis, linking to planned national emission reductions as currently proposed via the UNFCCC process (Nationally Determined Contributions, NDCs) and to assist in their subsequent updating.

Bioenergy with carbon capture and storage: BECCS *Rapporteur: Iain Donnison (Aberystwyth University)*

The bioenergy part of BECCS is itself highly complex, presenting a challenge in terms of communication to policymakers, media and the public. Thus there are many options regarding *biomass type* (land-based crops, such as *Miscanthus*, willow or poplar; marine biomass, seaweeds and micro-algae; and waste materials, agricultural or urban/industrial); *conversion technology* (thermochemical, biochemical and biotechnological); and *energy vectors* (heat and power, transport fuels, fossil carbon replacements).

In a GGR context, research objectives could usefully include: i) knowledge of how to grow carbon (crops) with a lower carbon footprint and maximising carbon sequestration; ii) conservation of carbon during the conversion process, e.g. via fermentation-based conversion processes, or creation/use of biochar; iii) life cycle analysis to determine displacement of carbon in energy, fuels, chemicals or materials; and iv) capability to determine the final requirement for CCS in addition to carbon substitution and carbon sequestration.

Whilst there is ongoing research relevant to the above (funded by BBSRC, EPSRC, ETI and NERC), there are also important gaps. Topic areas and GGR-specific research questions (bulleted) include:

Biomass and crop science: Land availability and constraint management (maximise use of marginal lands and degraded soils to help build natural capital); carbon partitioning (above vs belowground); longevity and fate of different forms of biological carbon (leaf vs root vs exudate; and lignin vs cellulose etc).

- What are the biological drivers for biomass and carbon partitioning in biomass crops? i.e. what is the genotype-environment interaction that results in crops partitioning large amounts of carbon below ground (e.g. as roots, rhizome, rootstock) in some locations and not in others?
- What is the relationship, and how can it be optimised, between plant derived carbon (roots, exudates, leaf litter) and the residence time of that carbon in the soil? i.e. do different biological fractions stay sequestered for longer?

Land use change and environmental impacts: Implications for soil carbon, greenhouse gas emissions and nutrient flows; domestic vs imported biomass; densification of biomass and transport; competition and complementarity of different land uses; opportunities to use marginal land, contaminated land and degraded soils; biodiversity, landscape, and governance.

- What are the wider impacts of land use conversion (positive as well as negative) on carbon, other greenhouse gases, biodiversity and broader ecosystem services? Site-specific factors (soil, climate and land use) are highly important here.
- What are the impacts and implications of utilising marginal land and degraded soils?
- How can food and energy production be integrated, from farm scale to local and national, for UK and other countries?

Process engineering and chemical engineering: Feedstock matching; conversion step optimisation (conserve carbon); carbon capture step and integration with conversion step; where carbon might be stored; permanence of storage.

- How can carbon be conserved during energy conversion and carbon storage, through process optimisation and integration with CCS processes?
- What is the contribution of displacement of carbon in energy, fuels, chemicals or materials?

Social and political aspects: Food vs fuel debate, and ability to articulate the complexity; indirect land use changes (ILUC); bio-economy and use of waste resources (municipal) and waste (marginal/contaminated) land; competition and complementarity between biomass uses (energy, industrial biotechnology and synthetic biology)

- How do we communicate complexity?
- What price is society willing to pay for carbon storage via BECCS?
- Who decides on how land is used?

Engagement with developing countries was not given much discussion, due to time constraints. Nevertheless, many/most of the above issues are globally applicable, whilst also involving spatially-specific environmental and geo-political factors. If BECCS is to be deployed at large scale, as implied by IAM modelling assessed by IPCC, international collaboration on technical and socio-economic research would seem essential.

Enhanced weathering and ocean alkalinity enhancement. *Rapporteur: Tim Kruger (Oxford); additional notes by Damon Teagle (Southampton)*

The group identified knowledge gaps, issues relevant to developing countries, potential advantages, and provisional research priorities for removal of CO_2 from the atmosphere by enhanced weathering and ocean alkalinity enhancement, using silicates (such as olivine) and other minerals These processes were thermodynamically favourable, but inherently slow. An overall need was to increase reaction rates, testing the effectiveness of such manipulations under field conditions (pilot studies) and demonstrating technological feasibility and social acceptability at increasing scales.

Important knowledge gaps include:

- *Engineering issues*: how can the natural CO_2 uptake rates for candidate minerals be accelerated? (effects of temperature, pressure, comminution, bio-catalysts, pH etc). How much engineering resource (mining, processing, energy and water use) would be required for a given amount of CO_2 drawdown? What is the inventory (amount and location) of appropriate minerals? What potential is there to use materials from already-existing mine tailings and other industrial wastes?
- *Environmental impacts:* what trace elements are present in candidate minerals, and what biological impacts would they have? (may be considered positive, e.g. iron increasing oceanic productivity, or negative, e.g. nickel toxicity). What are the other ecological consequences of large-scale implementation? (e.g. changes to soil characteristics, freshwater quality and river inputs to ocean for land-based enhanced weathering)
- *Socio-economic considerations:* How much would such methods cost, and how could they be incentivised? What are the socio-political implications of transboundary impacts of these techniques? e.g. through changes in river water chemistry and potential ocean impacts. Which industrial sectors should be involved?

Issues relevant to developing countries include:

- Large amounts of mine tailings (already crushed) that could be used, e.g. in Africa.
- Impacts of land-based enhanced weathering on agricultural productivity and biodiversity (may be positive or negative; need for site-specific studies and national assessments)
- Cost-benefit analysis to assist decisions on where to locate such activities. Income in a developing country could be used to improve livelihoods, even if that has environmental impact. Cultural values (of landscapes) and ethical considerations also involved: if the UK and a developing country both have appropriate minerals, is it acceptable to use UK money to export the mining problem? Is this any different from any other mining project?

Potential advantages include:

- Climatic benefits (via CO_2 drawdown) should be relatively easy to verify, at least for land-based methods, with geological permanence
- Potential to increase crop yields on land, and counteract ocean acidification at sea
- Use of mine tailings and other waste materials (slag, concrete, fly ash and fines) for land restoration would put waste materials to good use
- Scalable, yet can be easily stopped (but not reversed).

Suggested research priorities:

- Public engagement, responsible innovation and anticipatory governance: determination if such techniques have a social licence to operate, and under what conditions (nationally and internationally)
- Need for experimental/pilot studies in the field to test safety and effectiveness prior to potential engineering scale-up
- Inventory assessment: what quantity of mineral resources is there and where are they located?
- Assessment of environmental impacts (positive and negative), including developmental impact of using mine waste treatment
- How can we improve the kinetics? (avoidance of crusting that slows weathering of mineral particles)
- Holistic assessment of the budget for the range of enhanced weathering and ocean alkalinity enhancement techniques – use of water, land, energy, minerals, human resource, etc. How sustainable are such approaches, based on life cycle analyses? How do economic costs and benefits compare?

Direct air capture *Rapporteur: Robert Chris (Open University)*

A range of processes have already been developed for direct air capture (DAC), with pilot-scale systems in the US and elsewhere capable of directly removing CO_2 from the atmosphere by chemical means. Some attention has also been given to other greenhouse gases. Storage/sequestration is then necessary, as for BECCS. Whilst the captured CO_2 might also be used for a wide range of industrial purposes, its use for biofuel or enhanced oil recovery would not be considered a valid GGR approach, since no net climatic benefit (nor contribution to net zero emissions) would be achieved. A major research issue relates to energy requirements, since that is a key factor determining the cost-effectiveness of DAC.

Approaches currently under consideration include zero-water air capture (using moisture-swing sorbents), also renewed interest in solar chimneys (solar updraft power plants). The latter would involve large heat collectors with a km-high chimney, situated in an area of high solar insolation. DAC for CO_2 would be facilitated by the high volume of air movement, with electrical energy obtained from turbines driven by the updraft; methane, nitrous oxide and halocarbons could, in theory, be removed by photocatalysis. A pilot-scale solar chimney for energy generation was operational in the 1980s; an industrial-scale version, that might include GGR for a range of greenhouse gases, has yet to be constructed. Research attention would need to be given to air-flow issues, and in ensuring that the location of such a plant would not have adverse environmental impacts (e.g. local weather perturbation).

Other DAC systems would also seem most feasible in tropical regions (within ~35^{o} N or S of Equator) where renewable (solar) energy is most available. They are therefore potentially suitable for developing countries, provided that carbon storage/sequestration considerations, as well as infrastructure, socio-legal and employment issues, can be addressed.

Cross-cutting #1 *Rapporteur: Tim Lenton (Exeter University)*

The group considered how the GGR research programme could best combine technological and socio-economic components to assist wider governance and policy development, using Earth system and socio-ecological system approaches in the context of the Global Challenge Research Fund (GCRF). Within such frameworks, three plausible narratives were identified for future, large-scale GGR deployment:

i) based on top-down, government funding, driven by national policy requirements (e.g. direct response to national carbon budget commitments/NDCs relating to Paris Agreement)

ii) based on bottom-up actions, whereby GGR was itself a co-benefit of other financially/societally-beneficial activities (e.g. reducing air pollution; re-forestation for biodiversity, culture or recreation); this approach would be more messy and fragmented, but potentially has more vitality

iii) government pump-priming would initially stimulate activities, but then industry would respond (based on adequate carbon pricing).

Provided that GGR techniques have high public acceptability (with that likelihood enhanced if they have local co-benefits), then there would seem considerable scope for their inclusion in overseas development assistance, with relevant research supported through the GCRF mechanism.

Cross-cutting #2 *Rapporteur: Jo House (University of Bristol/ Government Office of Science)*

The group considered framing issues (assumptions, context, goals, and objectives); criteria for technique evaluation and comparison; developing country issues; and other over-arching factors.

The following criteria were considered important (not exhaustive list, nor prioritised):

- *How much?* Quantity of feasible removal. Relevant issues include uncertainty; details of methods; full life cycle analysis, including indirect effects; how removal will be measured/monitored; and what changes to policy are necessary to include GGR in international reporting and accounting.
- *Direct costs*. Likely to depend on scaling and timing (development of capital infrastructure),
- *Co-benefits/trade-offs (impacts).* Need for consistent methods for mapping across range of GGR options, with defined boundaries/limits.
- *Sustainability, resilience and feedbacks* of different approaches in time. Linkage to permanence of sink, also feedbacks to other parts of system/sectors.
- *Time line*: what is achievable now, what might be achievable in the future? What might become constrained by available resources?

Issues relating to *different perspectives for developed/developing countries* include: differences in research and monitoring capacities; differences in ability to cope with costs (relevance of development aid, carbon trading etc.); and greater importance of co-benefits in developing countries, e.g. via UN REDD programme (Reducing Emissions from Deforestation and Forest Degradation) and access to energy. Note that GGR itself may be the co-benefit, although it is unlikely to be deployed on a climatically-significant scale on that basis.

Overarching issues included the need for:

- a basket of GGR options, applicable at different places and time-scales.
- actions to help change relevant investment policies/decisions, public perception and behaviour
- scalability from field studies to pilot projects and implementation trials, with careful monitoring at each stage to quantify removal rates, costs, co-benefits and trade-offs, within overall MRV (monitoring, reporting and verifying) framework
- assessment of resources and capabilities over full range of scales, from global to regional, national and local (e.g. city). A top-down approach will give global framing and main feedbacks, whilst a bottom-up approach will provide a reality check on constraints and how to overcome them; i.e. providing information directly relevant to scalable implementation.

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