Living With Environmental Change

LWEC Geoengineering Report

A forward look for UK research on climate impacts of geoengineering

Chris Jones[1], Phil Williamson[2], Jim Haywood[1,3], Jason Lowe[1], Andy Wiltshire[1], Tim Lenton[3], Andy Jones[1] & Dan Bernie[1]

[1] Met Office Hadley Centre
[2] University of East Anglia/Natural Environment Research Council
[3] University of Exeter

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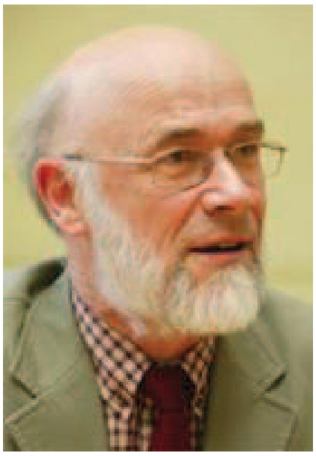
Foreword



More than 20 years ago, the first report of the Intergovernmental Panel on Climate Change (IPCC) concluded that global mean temperatures would likely rise by 3°C by 2100 if greenhouse gas emissions due to human actions were not curtailed. That report also noted that the temperature rise would not be steady because of the influence of other factors. The recently published 5th Assessment Review by IPCC's Working Group 1 reaches closely similar conclusions, now with much greater certainty. Despite these warnings of global temperature increases, with associated climatic disruption, the opportunity to reduce emissions at sufficient scale to avoid dangerous consequences may soon have passed, risking lives, livelihoods, economic development and irreversible environmental damage. Global emissions are still growing, and if this continues atmospheric concentrations will be more than double pre-industrial levels in just a few decades.

The UK government considers that large-scale and urgent emission reductions remain the most appropriate policy response to such threats, and the UK's own statutory targets are both exemplary and challenging. Yet might there also be a role for other interventions – climate geoengineering – to supplement mitigation efforts? A very wide spectrum of approaches has been suggested to counteract climate change, and it is now timely to assess (with due caution) which, if any, could play a significant role in that regard whilst meeting other crucial criteria for safety, cost-effectiveness and societal acceptability. Research into such techniques must not have any in-built implications for their eventual deployment, nor should such research diminish mitigation or adaptation effort. Indeed, additional knowledge of the risks and uncertainties, as well as potential benefits, of geoengineering may well show that the move away from fossil fuels has to be accelerated, rather than diminished, by demonstrating that there really is no feasible alternative.

This report began as a scoping study for the Natural Environment Research Council (NERC) identifying research gaps in climate remediation from an environmental perspective. Subsequently, it was expanded and updated by joint work with the Met Office Hadley Centre, to provide the Department of Energy and Climate Change (DECC) with a more comprehensive overview of climate-related geoengineering research activities and opportunities. The report is a forward look: it is not a strategy, nor a commitment, nor a formal funding proposal. Nevertheless, it raises key climate-related questions that warrant serious attention. And, as recognised in the report, such issues need to be considered in a wider multi-disciplinary context, encompassing technology, economics, ethics and law.

The above considerations make it essential to involve other funders, in addition to NERC and DECC, in the development of any new, integrated research initiatives in this area, as well as strengthening connections between ongoing, complementary work. The Living With Environmental Change (LWEC) partnership exists to foster such joined-up activities, and the topic of climate geoengineering is one where I am confident that LWEC can make a real difference, by encouraging careful and effective coordination, collaboration and co-funding.

Professor Andrew Watkinson

LWEC Director, 2008-2013

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Executive Summary

There is increasing scientific and political recognition of the need for careful, responsible and multi-disciplinary research on the potential risks and benefits of climate geoengineering. This report contributes impartial scientific analysis of key knowledge gaps to aid future planning of such research, thereby informing a rational debate on this issue. The scientific study of geoengineering does not imply any commitment for deployment: such research is therefore fully consistent with the UK government's stated view that a rapid global transition to a low-carbon economy is the best strategy to avoid dangerous climate change, and it is premature to consider geoengineering as a viable option for addressing climate change.

- Geoengineering can mean different things to different people. It is here used in a climatic context, to mean "the deliberate, large-scale manipulation of the planetary environment to counteract anthropogenic climate change". The 'counteract' part of that definition implies that geoengineering could potentially reverse, not just reduce, global warming during the 21st Century.
- There are a very wide range of geoengineering proposals; nevertheless most fall into two categories.
  - Solar radiation management or sunlight reduction methods (SRM) are intended to reduce incoming energy to the Earth system; they have high potential effectiveness, and, once deployed, could act rapidly if that were required. However, they also have high uncertainties and potentially large regional side-effects, which are unlikely to ever be fully resolved due to the complexity of climate behaviour. Many SRM techniques could be switched off quickly leading to potential rapid reversal of effects back to a non-geoengineered climate, which will depend on the greenhouse gases emissions that have occurred in the meantime.
  - Negative emission techniques (NET) (with almost all also being carbon dioxide removal, CDR) are intended to remove greenhouse gases from the atmosphere; they mostly have much lower potential effectiveness, and thus, to avert potentially dangerous climate change, they would need to be accompanied by either strong emission reductions or SRM approaches. NET mechanisms also have potential side effects but these are different from those of SRM.
- Fundamental, process-based research is required to better understand and quantify the detailed, regional impacts and implications of proposed geoengineering techniques and interactions between them. Existing research has shown potential large, regional climate changes could result from SRM, whilst NET, if carried out on a scale to affect climate, would constitute a major perturbation to the global carbon cycle and ecosystems and would require the use of large areas of land. Metrics such as regional scale food and water security to assess the impacts of individual techniques are required beyond existing simple measures of global scale efficiency.
- UK strengths in climate science, biogeochemistry and Earth system modelling make it well-placed to provide international leadership in geoengineering research. The fundamental process-based science required is essentially the same as that required for climate projections under various scenarios of greenhouse gas and aerosol emissions.
- Research to date on geoengineering has mainly focussed on individual techniques – and has shown that no single technique can be used as a "magic bullet" to address all of the issues of climate change. Nevertheless, if issues of acceptability, governance and cost-effectiveness were to be satisfactorily resolved, one or more specific geoengineering techniques might provide discrete elements (or "wedges") within a portfolio of response options to climate change. It remains an outstanding research question, and one beyond that of physical climate science considered here, to define what combination of responses might be considered as societally-optimal – taking account of potential interactions between geoengineering techniques, and with mitigation and adaptation measures, as well as socio-economic and geopolitical factors.
- This report is written from a climate-science perspective. We believe there is also a need to assess research gaps from the perspective of other disciplines, including engineering and social science. In

particular, ethical considerations, public acceptability and transparency are all crucial issues before any of the research gaps identified here (or others) might be taken forward to implementation. The interdisciplinary nature of this topic area makes it important that any initiative is developed in a wider national framework, as provided by the LWEC (Living With Environmental Change) partnership, thereby involving all Research Councils and government departments with interests and also facilitating dialogue with other key stakeholders.

- Ten specific research gaps are identified in this report. They can be grouped in three categories: those relating to quantifying potential effectiveness of geoengineering techniques; those relating to unintended side-effects; and those relating to interactions, synergies and monitoring. A more general research gap is also identified, relating to innovative (yet not unrealistic) ideas. A summary is provided below.

<table>
<tr><th></th><th>SRM</th><th>NET</th></tr>
<tr><td rowspan="2">Effectiveness (intended impacts)</td><td colspan="2">RG#1. Quantification of first order effectiveness. Continued effort in multi-technique comparisons, to quantify effectiveness and feasibility. Include aspects such as resilience of stores, life-cycle energy consumption and full greenhouse gas life-cycle analysis required, not just aerosol forcing and carbon removal.</td></tr>
<tr><td>RG#2. Regional and temporal implications. Improvements in assessing regional-scale and seasonal-scale forcing and effectiveness of atmospheric-based SRM, through model intercomparisons.

RG#3. Termination Effects. Additional model-based analysis of the impacts and implications of rapid cessation of SRM.</td><td>RG#4. Terrestrial carbon management. Improved quantitative understanding of NET techniques at UK and global scales.</td></tr>
<tr><td>Unintended impacts (side effects)</td><td>RG#5. Environmental effects of SRM. Improved knowledge of environmental effects of SRM, including impacts of changes in light quantity and quality on ecosystems.

RG#6. Surface albedo effects. Improved knowledge on scope for changing plant albedo, its scalability and implications. Including regional climate changes, seasonal/extreme changes and metrics such as precipitation, food and water.</td><td>RG#7. Land use implications of biomass-based NET. Better quantification of global land-use needs for terrestrially-based NET, and associated socio-economic implications. Need to consider reversibility under reducing CO_2 and the role of airborne fraction on effectiveness of negative emissions.</td></tr>
<tr><td>Synergies and Interactions</td><td colspan="2">RG#8. Interactions between geoengineering techniques. Quantitative assessment of additivity of, or interactions between, geoengineering techniques. For example, how SRM radiative forcings combine for multiple techniques, how NET applications compete for land or how SRM climate effects impact on NET through land carbon storage.

RG#9. Geoengineering techniques in the context of mitigation and adaptation policies. Assessment of interactions between geoengineering techniques and mitigation/adaptation strategies. How to define “optimal” pathways and combinations to achieve targets. Use of rapid, simple modelling tools traceable to complex models.</td></tr>
<tr><td>Governance / attribution</td><td colspan="2">RG#10. Detection and attribution. Development of methods to monitor possible effects of geoengineering (if it were to be deployed) to enable reliable attribution and decision making. How do we know when geoengineering is deployed if it has worked or if any subsequent events are caused by it?</td></tr>
<tr><td></td><td colspan="2">RG#11. Other innovative ideas. Opportunity to explore other innovative, yet not unrealistic, ideas.</td></tr>
</table>

1. Report scope

The purpose of this document is to identify important research gaps in the area of climate geoengineering, thereby assisting the focusing of national research effort. It does not claim to be comprehensive, recognising that there are undoubtedly many other issues that could be productively investigated (and references that might be cited). The report builds on an internal NERC scoping study, adding the perspective of the Met Office Hadley Centre.

Geoengineering covers a wide range of scientific, engineering and socio-economic disciplines. This report is a product of the climate science community, predominantly addressing issues that relate directly to climate physics and biogeochemistry. Ethics, economics, public acceptability, intergovernmental agreement and regulation are all recognised as being as crucial to the debate on geoengineering as climate science, engineering and environmental considerations.

This report provides the climate science community with a snapshot of the current state of the science, whilst also identifying research gaps that need to be addressed – within the context of a wider interdisciplinary dialogue on needs for geoengineering research.

Because of the multi-agency nature of funding for this type of research, we greatly welcome LWEC's role in bringing diverse communities together in this topic area.

GfK-National Opinion Polls (NOP) carried out the fieldwork and, on completion, provided the authors of this report with (i) the survey data in data tables and .sav files for use in the statistical software package SPSS and (ii) the transcripts of the focus groups. The authors were responsible for the design of the questionnaire and the discussion guide for the focus groups, as well as the analysis, interpretation and reporting of the results. The analysis presented here was partly informed by analysis undertaken by GfK-NOP and has taken into account previous work in this area.

2. Introduction

The very serious consequences of future human-driven climate change in the absence of adequate mitigation have stimulated interest in climate geoengineering – deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic global warming. Scientific attention to such approaches has greatly increased in recent years; nevertheless, the information and understanding required for a rational debate on geoengineering are still very limited.

The online "[UK] Government view on geo-engineering research"[1] (published September 2012) makes it clear that it is premature to consider geoengineering as a viable policy option for addressing climate change because there is insufficient understanding of its costs, feasibility, environmental and societal impacts. The UK Government also recognises that, "should the need ever arise to deploy geo-engineering techniques in the future, a thorough understanding of all the options available to counteract dangerous climate change and knowledge of their risks and benefits will be needed".

The primary question "could geoengineering work?" (in terms of delivering, in general terms, what its proponents claim) cannot yet be satisfactorily answered. Whilst we do know that the effectiveness and feasibility of different geoengineering proposals are highly technique-specific, the evidence needs are much broader than the physical effects on global radiation budgets[2]. Unintended impacts (particularly at the regional scale and considering quantities in addition to temperature) are crucially important, and the inherent uncertainty of the future behaviour of the Earth system, climatic and non-climatic, is fundamental to all discussion in this area.

Geoengineering proposals broadly fall into two categories. Those in the first category are intended to reduce incoming energy to the Earth system by *solar radiation management (SRM)*, sometimes referred to as sunlight reflection methods; such proposed techniques involve deliberate brightening of the Earth system to reflect more sunlight away from the atmosphere or surface, thereby inducing a cooling. Proposals in the second category, *negative emission techniques (NET)*, are intended to increase the energy leaving the planet, by deliberately removing greenhouse gases from the atmosphere, thereby reducing their associated heat-retention. Since carbon dioxide is the greenhouse gas of greatest concern, and its removal from the atmosphere is potentially the most tractable, NET research has focussed on carbon dioxide removal (CDR), and that acronym has been widely used to date.

This document is based on the premise that new fundamental and applied knowledge on geoengineering options are both urgently needed to inform future decision-making. That view is fully consistent with the UK government position that "the priority is, and must be, to tackle the root cause by reducing emissions… and adapting to those impacts that are unavoidable", re-iterating the Royal Society report (2009) "nothing now known about geoengineering options gives any reason to diminish these [emissions reductions] efforts."

The need for additional knowledge on geoengineering is challenged by some organisations and individuals who consider the basic concept to be fundamentally flawed. Whilst their main concerns (ETC group, 2012; ETC, 2013) relate to the riskiness and problematic governance of SRM, such criticisms are frequently extrapolated to all geoengineering approaches, citing the precautionary principle as justification for a moratorium on all geoengineering research. However, the precautionary principle does not provide clear guidance in this area: it exists in a plethora of different versions, many of which result in self-defeating scenarios (Elliott, 2010). The more scientific and balanced use of the precautionary principle in this context requires that the safety of geoengineering research, and (potentially) geoengineering itself, needs to be carefully assessed relative to the risks of inadequately mitigated climate change.

The situation is complicated by ambiguities and differences in the definition of geoengineering. For our purposes, it seems preferable to consider a wide field of potential approaches, with their commonality being large-scale interventions that might remedy future climate problems. The relatively broad, process-based definition given above is consistent with UK government (and Royal Society) usage. It includes BECCS (bio-energy with carbon capture and storage), also carbon sequestration based on land management (e.g. afforestation) if carried out for the purpose of climate remediation. Carbon capture and storage (CCS) at power stations that use conventional fossil fuels rather than biofuels is, however, excluded, on the basis that it is a preventative, not a remedial, measure, and is more commonly already counted as a mitigation measure.

Figure 1 (overleaf) provides a conceptual overview of geoengineering climatic effects and their environmental impacts, based on generic SRM and NET approaches. However, generalisations must be used with care, since – as already noted – many of the characteristics (and impacts) of geoengineering are highly technique-specific.

The Royal Society (2009) report provided an overview of geoengineering science and governance from an international perspective, and made seven recommendations for developing geoengineering research. Other major reviews of geoengineering and related research, that mostly reached similar conclusions to the Royal Society, include national reports by the US (Gordon, 2010: US Government Accountability Office, 2011) and Germany (Rickels et al. 2011; Ginzky et al. 2011); an IPCC Expert Meeting (Blackstock et al., 2012); an intergovernmental review of geoengineering impacts and governance (CBD, 2012a,c); and a DECC/AVOID study on Negative Emission Techniques (McGlashan et al, 2010). Since the Royal Society report, there has also been a NERC-led public dialogue (Ipsos MORI, 2010), and several hundred research publications. This document takes that material into account, but does not attempt a comprehensive assessment; instead it provides a focussed update of UK research priorities, building on the internal NERC scoping study and climate-related national research capabilities.

The framework used here considers the role of geoengineering as a potential additional option within a portfolio of future policy responses to climate change. It is not an alternative to the other two main approaches, mitigation and adaptation, since all three may become necessary to avoid dangerous climate change. Such a requirement is already implicit in scenarios for the 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) (Moss et al., 2010). For example the RCP2.6 scenario, whose aim is to avoid 'dangerous' climate change by limiting global average near surface temperature rise to below 2°C above pre-industrial levels, includes global negative emissions of CO_2 achieved through widespread use of BECCS.

The question is not "here are X approaches, choose one", but "here are X approaches, how should we choose a combination of them". In the same way that there is no objective definition of "dangerous climate change", there will not be an objective way to define the "best" - or least worst – way to combine geoengineering techniques with other policy options. Multi-disciplinary and integrated research is necessarily required to cover that range of physical, environmental and socio-economic issues, and

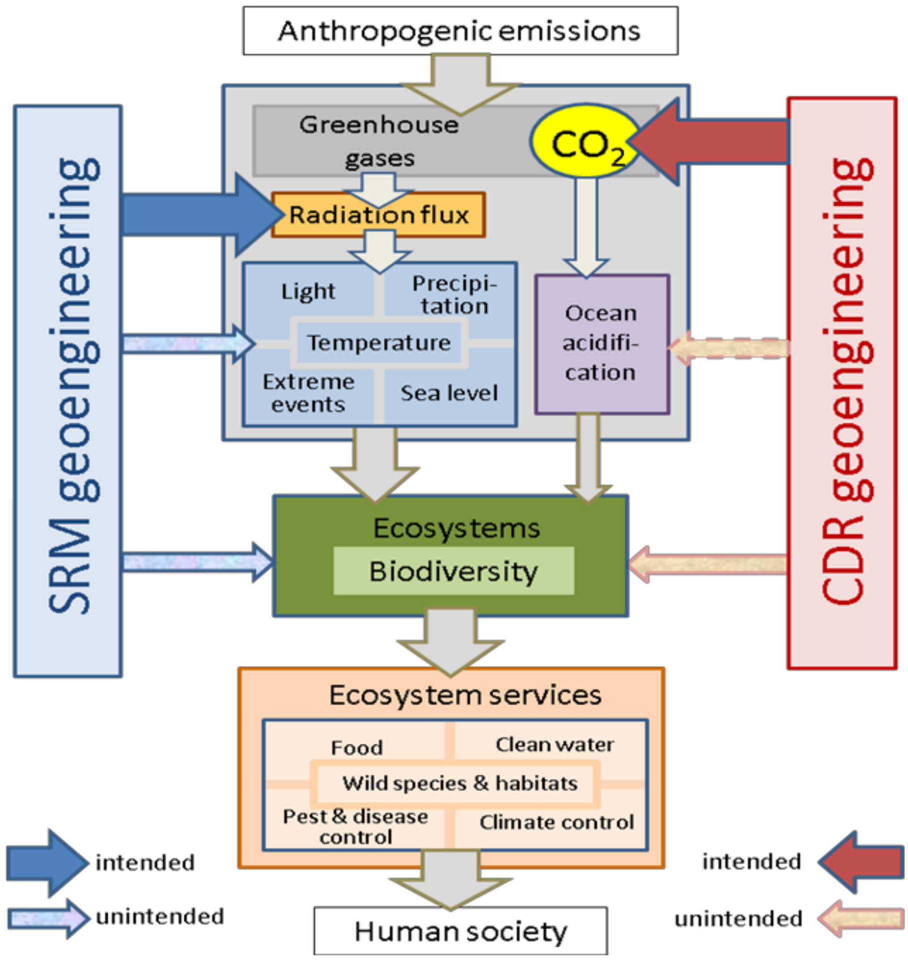

Figure 1. *Conceptual diagram showing main intended and unintended impacts for generic SRM and CDR techniques through their potential effects on the climate system, ecosystems and ecosystem services. Re-drawn from CBD (2012a).*

hence evaluate evolving combinations of responses over time taking into account issues such as cost effectiveness, robustness/flexibility against "surprises" or developing knowledge, and impacts on food, water and energy security, biodiversity and ecosystem services.

The research base therefore needs to move beyond assessment of single aspects in isolation towards an approach that incorporates synergies, interactions and competing effects between mitigation/adaptation responses and potential geoengineering options. Different combinations might interact spatially, e.g. in terms of land-use requirements (such as competing needs of biochar, BECCS and crop production) or in time (SRM may have very rapid effects whereas NET has longer, slower effects that accumulate). Process studies into individual measures need to be brought together into integrated studies of the interactions.

Figure 2 shows a compilation of estimated maximum radiative forcing from various geoengineering techniques. Such a summary has value as an initial comparison, to focus research effort on approaches that have climatically-significant potential, whilst excluding those that do not seem to meet that basic requirement. However, such a first-order analysis excludes other important aspects for the former, 'shortlisted' group, such as unintended impacts, regional differences in effectiveness, interactions between techniques, and public acceptability.

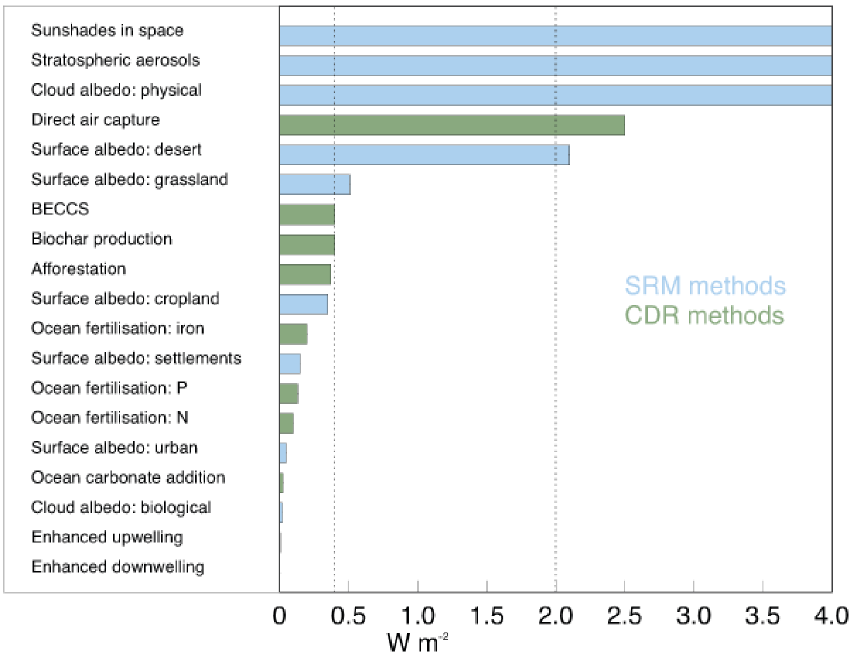

Figure 2. *Summary chart of estimated maximum effectiveness of a range of geoengineering techniques in terms of global radiative forcing, with NET estimates for 2100 relative to a strong mitigation scenario. This measure of effectiveness does not attempt to quantify regional climate effects nor any interactions between techniques which may not be additive. Data from Vaughan & Lenton (2011) and Lenton & Vaughan (2009). Vertical dashed lines indicate magnitude required to counteract 10% and 50% of a nominal mid-range radiative forcing of 4 Wm^{-2}.*

A recent bibliometric review of geoengineering research (Belter & Seidel, 2013) assessed how this rapidly growing body of research is evolving. They looked at 750 papers published since 1988 and found a high proportion (about 30%) were "non research" (i.e. reviews and editorials). The research papers themselves clustered into five distinct topics, but lacked linkages between groups or disciplines. The SRM group constituted 13% of the total literature, with four NET/CDR groups (ocean fertilisation, biochar, land-based sequestration, and direct air capture) constituting 68% of the literature. [Note: these authors did not include BECCS in their definition of geoengineering].

Interdisciplinary linkages are, however, now being developed in the UK, e.g. through the multi-institute Integrated Assessment of Geoengineering Proposals (IAGP) consortium project; the G360 network in Exeter[3]; the Oxford Geoengineering Programme[4]; and the GeoEngineering Assessment and Research (GEAR) initiative[5] at the University of East Anglia.

The impacts of different geoengineering techniques can be intended (positive climatic benefits, other expected co-benefits) or unintended (additional climatic, environmental and societal consequences). Simple offsetting of global mean radiative forcing does not mean satisfactory offsetting of the regional impacts of climate change. Similar levels of radiative forcing and hence global-mean temperature change can be achieved with very different combinations of CO_2, other greenhouse gases and aerosols. Since these have significantly different regional, local and seasonal climate responses, they will also have significantly different socio-economic and environmental implications; e.g. for freshwater availability, crop production, biodiversity and ecosystem services. A body of literature is emerging looking at regional changes under SRM measures that counteract global radiative forcing (e.g. Jones et al., 2011, Kravitz et al., 2011, Ricke et al., 2012; Haywood et al., 2013).

Metrics that assess the impact on local climate (including climate extremes); food, water, and energy security; and the natural environment are required (e.g. Ricke et al., 2010, MacMartin et al., 2013) in order to assess the "success" or otherwise of any potential application of geoengineering. As these metrics are harder to model, this inevitably introduces larger uncertainty into the consequences of geoengineering – hence uncertainty analyses and multi-model studies are also required to aid risk assessments of the range of potential geoengineering options.

An important issue for quantifying geoengineering impacts relates to the baseline conditions used for comparisons. In some ways it is logical for a non-geoengineered future world to provide the control for geoengineering interventions, rather than present-day conditions; however, the future control will be scenario-dependent, and subject to uncertainties. Even for a single emission pathway, the scale and relative importance of geoengineering impacts may be very different on decadal, century and multi-century timescales, and those temporal effects may be highly technique-specific.

As the complexity of options increases there is a growing requirement for relatively simple models to be able to include different possible scenarios of emissions and combinations of responses. DECC's 2050s Calculator[6] already includes options around CCS, bioenergy and geo-sequestration; such simple tools need to be refined to include more comprehensive understanding of the potential impacts and consequences of such choices. Vaughan & Lenton (2012) used a simple model to evaluate geoengineering implementation in the context of other mitigation policies, but their study did not incorporate all available knowledge from complex models, such as spatial patterns of forcing and response.

In this report we present gaps in geoengineering research grouped into intended impacts (i.e. effectiveness) (section 4), unintended effects (section 5), and interactions, where research is needed into combinations of approaches (section 6). Although the gaps themselves are intentionally broad, we use results from recent research to provide specific details or examples that fit under each gap or reinforce the need for the research. Only examples are given; many important publications are not cited here.

[3] *www.exeter.ac.uk/g360/geoengineering*
[4] *www,geoengineering.ox.ac.uk*
[5] *www.gear.uea.ac.uk*
[6] *www.decc.gov.uk/en/content/cms/tackling/2050/calculator_on/calculator_on.aspx*

3. United Kingdom research and summary of research landscape

The UK is estimated to have produced around 21% of the ~750 geoengineering research publications in the period 1988-2011, second only to the US (Belter & Seidel, 2013). Subsequent to the Royal Society's (2009) report, the main support has been via consortium-based projects, with funding led by EPSRC and ESRC (and including other Research Councils), also via UK participation in EU-funded projects. There have been relatively few research grants and studentships supported by UK Research Councils specifically directed at this topic.

As already noted, geoengineering has implications for natural science, social science and economics, whilst also including governance and ethical issues. However, a fully joined up approach from UK funders (Research Councils and government departments) spanning all research areas has not yet been achieved. Most funded research has been compartmentalised into research from, at most, two Research Councils.

There are currently five main geoengineering research projects with UK participants, as summarised below.

i) Geoengineering Model Intercomparison Project: GeoMIP

GeoMIP involves a large number of climate models (~18 coupled atmosphere-ocean models, of which 11 are involved in CMIP5 simulations) investigating climate response under nominally identical climate forcings. Four specific idealised simulations are performed, called G1, G2, G3 and G4.

- G1 balances the forcing from a 4 x CO_2 increase with a reduction in the solar constant.
- G2 balances the forcing from a 1% CO_2 increase per year with a time-varying reduction in the solar constant.
- G3 balances the forcing from a RCP 4.5 warming scenario with a time varying SO_2 injection into the stratosphere.
- G4 simply injects a constant rate of $5TgSyr^{-1}$ in the form of SO_2 into the stratosphere to offset a proportion of the forcing from a RCP 4.5 warming scenario.

UK participation is primarily through the Met Office Hadley Centre. For details see http://climate.envsci.rutgers.edu/GeoMIP and Kravitz et al., (2011).

ii) European Trans-disciplinary Assessment of Climate Engineering: EuTRACE

The EuTRACE FP7 Coordination and Support Activity is a large group of European research institutes providing an up-to-date assessment of geoengineering with the aim of providing a road-map for future funding for the EU. The groups involved include scientists, social scientists, social psychologists, and experts in responsible innovation and moral and ethical hazards. UK participation includes the Tyndall Centre/UEA, and the universities of Exeter, Bristol and Edinburgh (with links to other groups, including the Met Office Hadley Centre). Details at www.eutrace.org.

iii) Stratospheric Particle Injection for Climate Engineering: SPICE

SPICE is jointly funded by EPSRC and NERC and involves three work packages:

- WP1: investigating candidate particles for stratospheric geoengineering
- WP2: delivery systems including engineering a tethered balloon[7]
- WP3: evaluating climate and environmental impacts.

Participation includes the universities of Cambridge, Bristol and Reading, and the Met Office

Hadley Centre. Details at http://www2.eng.cam.ac.uk/~hemh/SPICE/SPICE.htm,

[7] *Work on this WP has ended, without field implementation*

iv) *Integrated Assessment of Geoengineering Proposals: IAGP*

IAGP is a multi-disciplinary assessment of geoengineering proposals, jointly funded by EPSRC and NERC. It includes a significant amount of public and stakeholder engagement. Focus is predominantly on SRM but NET proposals are also being considered. Participation includes the Tyndall Centre/UEA, the universities of Cardiff, Leeds, Oxford, Lancaster and Bristol, and the Met Office Hadley Centre. Details at www.iagp.ac.uk.

v) Climate Geoengineering Governance project

This project, jointly funded by ESRC & AHRC began in 2012 and will examine the governance and ethics of geoengineering. It is led by the University of Oxford in partnership with the University of Sussex and University College London. Details at http://www.geoengineering.ox.ac.uk/events/upcoming/?id=16

The Met Office Hadley Centre is involved in numerical modelling and assessment of geoengineering proposals, and provides independent advice to government. The Met Office is also involved via the G360 group of the University of Exeter in many aspects of the EuTRACE project.

Other research-relevant activities and reviews

In addition to the above, other recent major initiatives and developments (national and international) relevant to geoengineering/climate remediation have included:

- Royal Society meeting Geoengineering – taking control of our planet's climate? (London, November 2010); proceedings published in Phil Trans Roy Soc A; (Ridgwell et al., 2012).
- Issues relating to the governance of SRM research have been jointly reviewed by the Environmental Defence Fund (EDF), Royal Society and Third World Academy of Science (TWAS); report online at www.srmgi.org
- Current EU support for IMPLICC (Implications and risks of engineering solar radiation to limit climate change; http://implicc.zmaw.de); no formal UK involvement.
- San Diego workshop on geoengineering impacts held by the International Geosphere- Biosphere Programme with NSF/NERC co-support (January-February 2011; Russell et al., 2012).
- Policy-directed reviews of ocean fertilization published by the Convention on Biological Diversity (CBD, 2009), and jointly by the Surface Ocean-Lower Atmosphere Study (SOLAS) and Intergovernmental Oceanographic Commission (IOC) (Wallace et al., 2010), in context of developing regulation by the London Convention/London Protocol.
- CBD reviews on impacts of geoengineering on biodiversity, and on geoengineering governance (CBD 2012a, 2012c).
- IPCC Expert Meeting on geoengineering (Lima, June 2011; Blackstock et al., 2012); discussion of both SRM and NET expected to be included via WG1 in IPCC 5th Assessment Report, AR5.
- Two geoengineering sessions (on governance and engineering constraints, both UK-led) were included in the Planet under Pressure conference (London, March 2012).
- The potential impacts of geoengineering on biodiversity and ecosystems will be reviewed in 2013 by an expert consultation study by University of Cambridge, University of Oxford and Institute for Advanced Sustainability Studies (as part of EuTRACE).
- A Negative Emission Technologies initiative has recently been established by the Environmental Sustainability KTN; https://connect.innovateuk.org/web/negative-emission- technologies.

- The French RÉAGIR programme (Réflexion Prospective Géo-ingénierie de l'Environnement; www.arp-reagir.fr) is investigating the feasibility and implications of a wide range of human modifications of the global environment, not just limited to counteracting climate change.
- A workshop on Negative Emissions Technologies was organised by the Global Climate and Energy Project at Stanford University, USA (http://gcep.stanford.edu/events/workshops_negemissions2012.html), leading to a special issue of Climatic Change (http://rd.springer.com/article/10.1007/s10584-013-0757-9).
- A workshop titled, "Negative emissions and the carbon cycle" was organised by the Global Carbon Project (GCP) and the International Institute for Applied Systems Analysis (IIASA), in April 2013.

4. Research gaps relating to effectiveness

4.1 Upper limits of effectiveness at a global scale.

Quantified effectiveness is a crucial fit-for-purpose consideration, providing information on how well a proposed geoengineering option might be able to counteract global level climate change. An appropriate target would be for all techniques to be capable of fully balancing projected anthropogenic radiative forcing, estimated to be in the range 2-9 W m^{-2} over the 21st Century[8] as a result of increasing greenhouse gases from pre-industrial levels.

Effects on radiative forcing can be estimated for both SRM and NET techniques. However, the calculation for the latter is less straightforward, depending on emission pathways, the background level of CO_2 and climate feedbacks on the natural carbon cycle. Quantification of CDR effectiveness is therefore more commonly based on assessing the amount of CO_2 (or carbon) that might be removed annually from the atmosphere, for comparison with the amount added to the atmosphere by human activities (currently ~ 9 GtC yr^{-1}; projected to increase to 10-15 GtC yr^{-1}, and even as high as 25-30 GtC yr^{-1}, under different emission scenarios).

Figure 2 provides ranked assessments of proposed approaches in terms of the estimated upper limits of their effectiveness in terms of radiative forcing potential for both SRM and NET techniques. For the latter, forcing estimates relate to 2050, relative to a strong mitigation scenario (Lenton & Vaughan, 2009; Vaughan & Lenton, 2011).

McLaren (2011, 2012) has assessed the carbon removal potential of ~14 negative emission techniques, based on existing literature. Whilst McLaren obtained somewhat different rankings from those shown in Figure 2, the two analyses taken together indicate the following:

- Only atmospheric- or space-based SRM techniques (stratospheric aerosols, cloud brightening and sunshades in space) seem able to fully counteract the projected radiation change due to anthropogenic greenhouse gases, in terms of a single figure for the global heat balance. Since these techniques are also capable of relatively rapid deployment, they could contribute to an 'emergency use only' response to avoid a potential climatic tipping-point (Lenton et al., 2008). Whilst tipping point triggers are poorly known, they represent an important area of ongoing research.
- The amount of carbon removed by a specific technique will not exactly be reflected in the reduction in atmospheric CO_2. In the same way that fossil fuel emissions are partially removed from the atmosphere (the so-called "airborne fraction"), any CO_2 removal will lead to large scale adjustment of the Earth's

[8] *The IPCC AR5 Representative Concentration Pathways (RCP) scenarios result in forcings of 2.6 to 8.5 Wm^{-2} by 2100 and represent 10-90th percentile of published scenarios (van Vuuren et al., 2011; Moss et al., 2010). RCP 8.5 continues to increase after 2100 exceeding 12 Wm^{-2} by 2200*

major carbon reservoirs. The eventual reduction in CO_2 will be less than the amount removed, but the fraction of removal will depend critically on the rate of removal, the history of emissions up to that point, the degree of climate change and the climate-carbon cycle feedback.

- No single NET technique is currently estimated to be capable of counteracting more than around half of current greenhouse gas emissions on realistic timescales. The potentially most effective NET technique is direct air capture, for which the main concerns on operational scale relate to technological issues, economic viability and carbon storage capacity (Keith, 2009; House et al, 2011).

Recent literature on ocean fertilization has included a study showing that, under certain circumstances, long-term storage of carbon in the deep ocean can be achieved (Smetacek et al., 2012). However, the variability of that response, together with other factors, severely limit the usefulness of that approach as a viable geoengineering option (Williamson and Turley, 2012; Williamson et al, 2012).

A key consideration for terrestrial NET relates to land availability (Wise et al., 2009). In particular, Powell and Lenton (2012) found limited capacity for the expansion of biomass energy with carbon storage (BECCS) given land pressure for food production and changing dietary requirements. For large-scale BECCS development, significant changes to agricultural efficiency would be needed, and/or shifts to low meat diets. Similarly, multiple NET techniques which require significant areas of land cannot all operate together. Smith and Torn (2013) find that biological CDR may be constrained by ecological limits such as the available land, water and nitrogen required.

With regard to prioritisation for research attention, it would seem appropriate to focus on approaches that are able to counteract at least 10% of radiative forcing, based on Lenton & Vaughan (2009). Techniques lower down the ranking might nevertheless still be worth exploring further in the context of a 'multi-wedge' policy (Pacala & Socolow, 2004; Tavoni and Socolow, 2013), particularly if they might either be low-cost, deliver other benefits, or where further research could provide insights into natural climate dynamics and Earth system processes.

The following additional caveats and considerations apply to further comparative evaluations of maximum effectiveness:

- Differences between 'theoretical' and 'realistic' upper limits may be large, and strongly influenced by implementation-related governance and acceptability issues; for example, the number of decision-makers involved in approving a specific geoengineering technique before it can be deployed at sufficient scale to realise the intended climatic benefits.
- There may be bias (favouring optimism) in published estimates of the effectiveness of specific geoengineering options, since more are likely to be written by their proponents than by their critics, particularly initially. When techniques are subsequently subject to scrutiny, their estimated maximum effectiveness may dramatically decline (as occurred for iron fertilisation; Williamson et al., 2012). A full greenhouse gas budget is needed for both NET and SRM techniques. For example: i) whilst biochar has been suggested to reduce N_2O emissions, biofuel/BECCS N_2O emissions may outweigh the carbon saved (Crutzen et al, 2008); ii) no-till practices have implications for methane emissions; and iii) SRM might affect diffuse light and enhance carbon uptake as well as reducing incoming solar radiation. Permanence and resilience of stores are key issues for NET, with different timescales and different uncertainties for different techniques. For example: i) carbon stored in afforestation may be vulnerable to future climate change, disturbance events etc; ii) whilst biochar has a longer lifetime than much soil organic matter, some turnover will still occur (and may be affected by future conditions). Additional process-based research is needed to improve estimates of "realistic" and "realisable" effectiveness. For NET, climate-carbon feedbacks will affect the net removal from the atmosphere (in the same way as the airborne fraction for positive emissions), as discussed above. For SRM, tools such as large

eddy simulations can look at cloud microphysical processes that are beyond the scope of GCMs (e.g. Latham et al., 2012). For example will evaporative cooling of hydrated sea-salt particles lead to cold air sinking back to the ocean surface?

All the above factors mean that published estimates of maximum effectiveness should be interpreted with caution. Nevertheless, existing information provides a useful starting point for careful evaluation of which techniques might justify research attention, to reduce their associated uncertainties.

Research Gap #1. Quantification of first order effectiveness. *There remains a need for a comprehensive, quantitative and independent assessment of the overall effectiveness and feasibility of geoengineering techniques, to update Lenton & Vaughan (2009) and to include: i) a wider range of approaches and more recent literature, ii) assessments of the sensitivity of effectiveness estimates to greater process-level understanding of the underlying assumptions; and iii) life-cycle energy consumption as an important criteria for cost-effectiveness.*

4.2 Ability of SRM techniques to achieve desired climatic outcomes: non-uniform forcing and response

4.2.1 Uncertainties in regional climate projections

As noted above, several SRM techniques could, in theory, reflect sufficient incoming sunlight to counteract current and projected anthropogenic radiative forcing, causing annual-average global surface cooling of 1-2°C and potentially by more. However, such changes in the Earth's albedo (reflectivity), whether achieved in space, the atmosphere or at the surface, would not restore the planetary climate to what it would be without anthropogenic greenhouse gas emissions. Many modelling studies have shown this effect, with significant 'anomalies' in both polar and tropical regions (e.g. Caldeira & Wood, 2008; Jones et al 2010, 2011); hemi- spherically (Bala & Nag, 2011) and with regard to total and regional precipitation (Schmidt et al 2012).

Extensive use of the HadGEM2-ES Earth System Model, and other general circulation models (GCMs), has been instrumental in advancing our understanding of the climate system response to implementation and termination of various SRM techniques.

Both the implementation and effects of SRM may vary in time and space so more research is required into quantitative changes in regional climate metrics beyond global mean temperature, and differential responses to non-uniform forcing.

GeoMIP, the Geoengineering Model Intercomparison Project (Kravitz et al., 2011), is a sub- project of CMIP5 and uses a number of the basic simulations from the larger activity as controls for the GeoMIP experiments. There are four main GeoMIP experiments, designated G1 to G4. G1 and G2 both apply geoengineering by an unspecified or generic SRM method, realised in the models by a reduction of the solar constant, whilst G3 and G4 are more complex and use stratospheric SO_2 injection. G1 is based on the CMIP5 simulation known as "abrupt4xco2" and attempts to balance an instantaneous quadrupling of CO_2 from pre-industrial levels. G2 is based on CMIP5's "1pctco2" (1% CO_2 rise per annum from pre-industrial levels) and attempts to counterbalance the linearly increasing forcing from CO_2. G3 and G4 are both based on the CMIP5 "rcp45" simulation; G3 attempts to keep global temperature at the 2020 level by constantly varying the injection rate of stratospheric SO_2 to offset the time-varying changes in anthropogenic forcing. G4, on the other hand, uses a fixed injection rate of SO_2 from 2020. Figure 3 shows results of such geoengineering in HadGEM2-ES in terms of global-mean temperature and precipitation rate during the 50 years when geoengineering was applied.

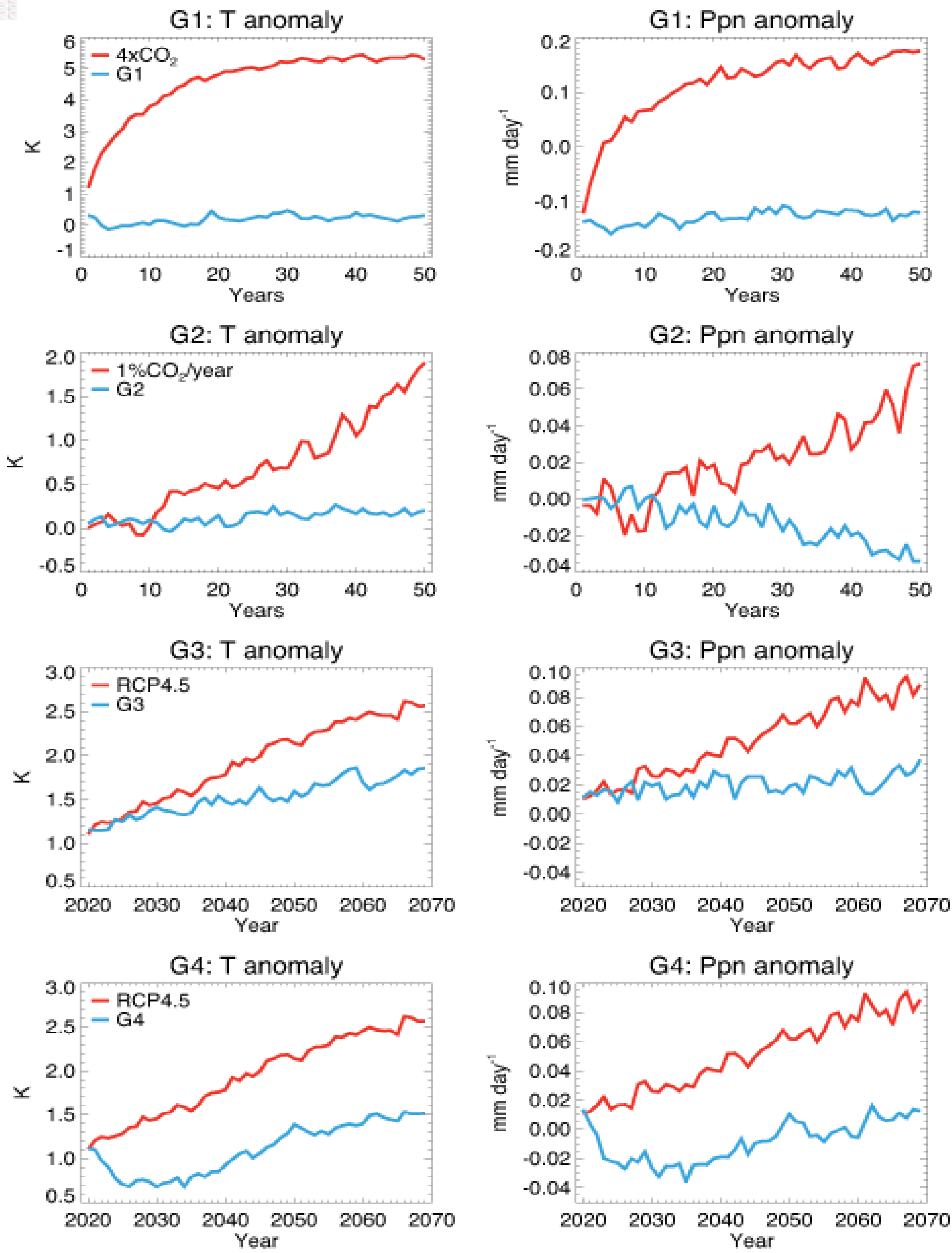

Figure 3. *GeoMIP results from HadGEM2-ES for simulations G1 to G4 (top to bottom) in terms of the annual anomalies with respect to the long-term mean of the pre-industrial control in global-mean temperature (left column) and precipitation rate (right column).*

There is a growing realisation that should a nation or continent embark on stratospheric geoengineering, that it is unlikely that stratospheric sulphate will be distributed evenly between the two hemispheres owing to the stratospheric Brewer Dobson circulation that tends to move aerosol from equator poleward. This uneven distribution is evident in the last four major volcanic eruptions that occurred in the period 1900-2000: Katmai (1912) preferentially loaded the northern hemisphere, Agung (1963) the southern hemisphere, El Chichon (1982) the northern hemisphere, and Pinatubo (1991) which loaded both hemispheres approximately equally. Haywood et al (2013) report on simulations where SO_2 is injected into either the northern hemisphere (G4NH) or the southern hemisphere (G4SH).

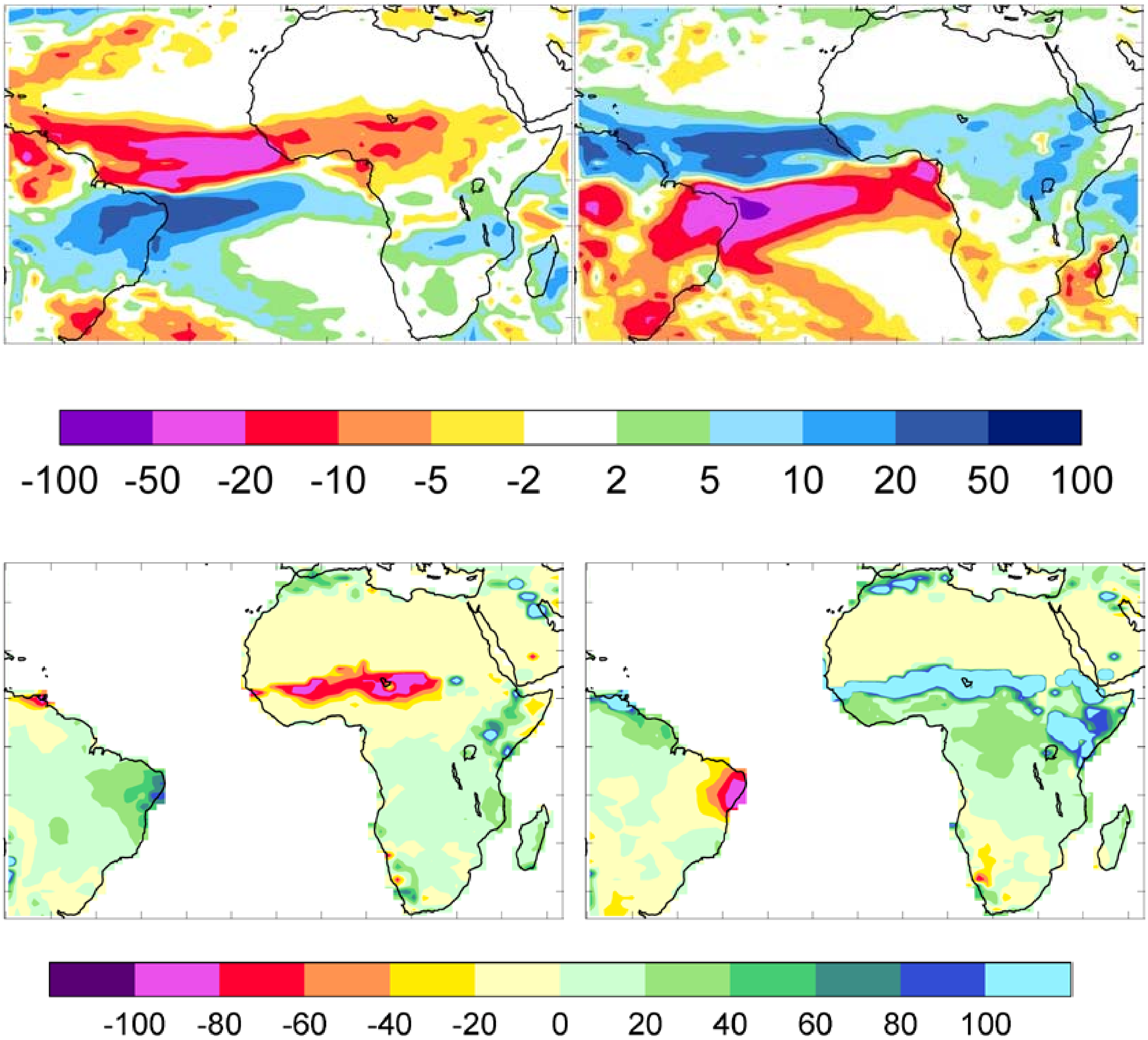

Figure 4. *The change in annual mean precipitation (mm month$_{-1}$) averaged over the period 2020-2070 for a) G4NH and b) G4SH. Also showing the percentage change in the Net Primary Productivity over the period 2020-2070 under c) G4NH, d) G4SH. Areas where the absolute NPP in the non-geoengineered simulation is negligible (less than 10$_{-3}$ kg[C]m$_{-2}$ yr$_{-1}$) are removed from the figure to aid clarity.*

Figure 4a and 4b show that aerosol injected into the northern/southern hemisphere causes the precipitation associated with the Inter-Tropical Convergence Zone to shift south/north which causes a dramatic decrease/increase in Sahelian precipitation. Haywood et al (2013) show a similar response of precipitation for both model and observed responses to hemispherically asymmetric volcanic eruptions. These results indicate that while SRM techniques can be used to reduce global mean temperatures, the latitude, altitude and phase of aerosols can give strongly differing side-effects on regional precipitation.

The consistent picture given by all of these studies is the vital importance of considering geographical variations in both the forcing and the response and considering the impacts beyond simply global temperature. Reliance solely on simple statistics of global radiative forcing (e.g. Figure 2) and global mean temperature change from different techniques is at best incomplete and at worst misleading.

Such effects, particularly at the regional level, have important implications for food production, freshwater availability, biodiversity and associated ecosystem services. They are also likely to be crucial for the political acceptability of SRM geoengineering, since they determine the distribution and scale of its benefits. The ethical dilemma is greatly increased if there is risk that SRM action might actually worsen climatic conditions (from a human perspective) for some regions, particularly if involving poorer nations with less adaptive capacity – and with less responsibility to date for greenhouse gas emissions.

High resolution, state-of-the-art climate models (including atmospheric chemistry and biogeochemical feedbacks) offer the best route to assess regional/global-scale risks. Nevertheless, projections of the future behaviour of the dynamic and complex climate system are necessarily probabilistic, and do not always translate into policy action even when high scientific confidence is achieved (e.g. the evidence may be rejected on ideological or cultural grounds).

It is clear therefore that quantification of effectiveness goes beyond global mean radiative forcing. Due to different feedback mechanisms, SRM and NET and even different SRM techniques may involve different climate sensitivities to a given radiative forcing and further investigation is needed. Simple conceptual figures such as global "Wm-2 per kg of SO_2" appear to be of little value as the effectiveness (and unintended effects) of different strategies depend strongly on details of their application such as latitude, altitude or season of emissions.

There remain significant and fundamental uncertainties in the response of the global climate system to projected increases in anthropogenic emissions of greenhouse gases and relevant aerosols. Model intercomparisons and multiple ensemble runs show that there is generally good agreement in the global average; however, regional expressions of climate projections forced by the same emission scenario can vary significantly according to model structure and tuning, particularly with regard to parameterisations of aerosol-cloud interactions (IPCC, 2007). Ongoing research is required directed at improving the global and regional skill of climate models, primarily through better understanding of relevant atmospheric, oceanographic, cryospheric and terrestrial processes, and their interactions at the decadal to century scale.

This directly leads to uncertainties in how specific SRM actions will affect the response of the climate system to projected increases in greenhouse gases and aerosols. The key processes involved in SRM manipulations – changes in radiation balance in the atmosphere due to aerosols and clouds, or variability in surface albedo – are, however, already included (to some degree) in most GCMs. Owing to stratospheric dynamics, injection height and latitude will profoundly influence the global and meridional distribution and lifetime of aerosols which in turn affect the regional climate response. More research is needed with models that adequately represent the stratospheric dynamics and composition response to these injection scenarios. Comparison of modelled and observed responses to volcanic eruptions shows there is still much to be understood, as models do not capture the right spatial patterns of response particularly the observed warmer wetter European winters that occurred after the eruptions of Mt Agung, El Chichon and

Pinatubo. All we can conclude with confidence is that non-uniform spatial patterns of change are of utmost importance to quantify.

Significant model development and inter-comparison work explicitly directed at regional responses is already underway, e.g. GeoMIP and IMPLICC (Kravitz et al, 2011; Schmidt et al 2012), with scope for enhanced UK involvement. The goal of such research would be to improve confidence in the regional magnitude of projected SRM climatic impacts (beneficial or otherwise) for specific techniques.

For SRM, research effort specifically directed at developing delivery hardware, or field-testing at the experimental scale, could be considered premature until regional effectiveness and associated safety issues have been satisfactorily investigated on a theoretical basis, together with further progress in resolving issues of governance and public acceptability.

Research Gap #2. Regional and temporal implications. *Most SRM modelling to date has been based on globally-uniform reductions in solar radiation, with relatively simple changes in greenhouse gas forcing. The GeoMIP experiments underway involve more realistic changes in CO_2 (RCP 4.5 forcing) and SRM based on stratospheric aerosol (SO_2) introduced either uniformly or at a point source at the Equator.*

Specific research required in this area is: i) wider range of UK modelling groups to participate in the GeoMIP exercise; ii) improve model parameterisations, based on process studies and analyses of natural events (e.g. volcanic eruptions); iii) extend the scope of the model-based experiments, including different RCP scenarios, different spatial and temporal patterns and implementation procedures for aerosol injection, and the use of other SRM techniques (e.g. marine cloud brightening, surface albedo changes).

4.2.2 Cessation of SRM deployments

An important advantage of space or atmospheric-based SRM techniques is that they could potentially be initiated relatively rapidly; an important disadvantage is that once that commitment is made, it is not easily reversed. Thus stopping may be technologically harder than starting (for space-based SRM), and/or the consequences of stopping may be climatically extremely severe. Thus, unless there is also strong mitigation (or NET geoengineering), atmospheric greenhouse gas concentrations will continue to increase – requiring future generations to continue SRM geoengineering on multi-decadal to century timescales, with ever-increasing intensity (Boucher et al., 2008). The alternative is to face termination effects that may be worse than the negative climate impacts previously avoided, since SRM cessation under conditions of unconstrained greenhouse gas forcing seems highly likely to cause very rapid warming (Matthews & Caldeira, 2007), with reduced opportunity for societal and ecosystem adaptation. If large-scale geoengineering is deployed to counteract increases in global temperature, then such efforts would need to be maintained for a very long time (Boucher et al., 2008). Even with carbon emissions reduced to zero the rate of reduction of atmospheric CO_2 by natural carbon sinks would be many times slower than its rate of increase has been (Lowe et al., 2009). Hence an investigation of the so-called "termination effect" is a research gap: what might be the climate impacts of a sudden termination of geoengineering after a number of years during which geoengineering was used as a counterbalance to greenhouse gas increases?

The termination effect has been examined in the context of one of the GeoMIP experiments, G2. This used the "1pctCO_2" CMIP5 simulation as a control and aims to maintain global- mean temperatures at pre-industrial levels for 50 years by gradual reduction of the solar constant. Geoengineering is discontinued after that time and the simulations extended for a further 20 years to simulate the effect of termination. It should be noted that both 1pctCO_2 and G2 are highly idealised simulations and not actual climate change projections. Nevertheless, they are a useful tool in examining the responses of a range of different climate models to geoengineering. Eleven different modelling groups have provided results for G2, summarised in figure 5 (Jones *et a*l., submitted).

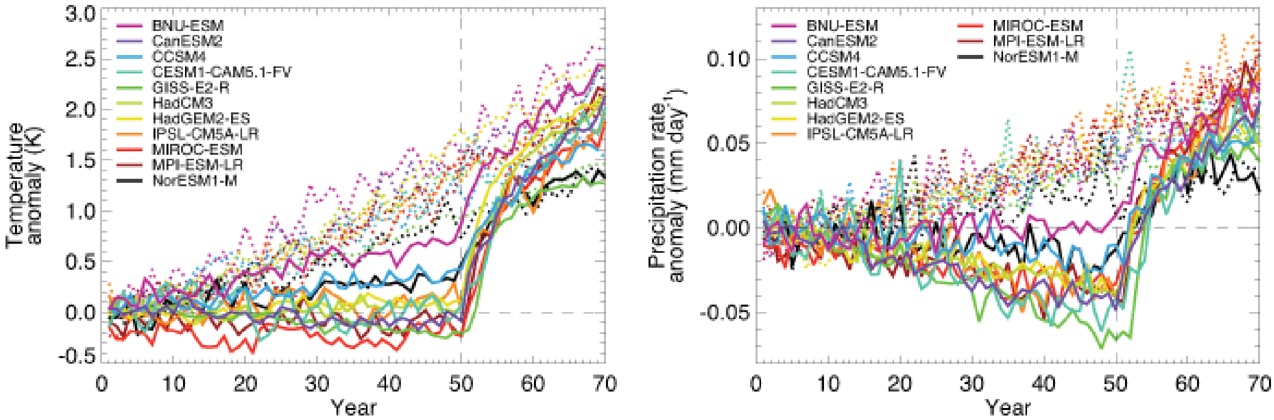

Figure 5. *Evolution of annual, global-mean near-surface air temperature anomaly (left) and precipitation rate (right) for the eleven models who provided results for the GeoMIP G2 experiment, with respect to each model's preindustrial long-term mean. Solid lines are from the G2 simulations (1%* CO_2 *increase per annum balanced by gradual reduction in solar constant), dashed lines are from the 1pct*CO_2 *simulations (1%* CO_2 *increase per annum only).*

The left panel of figure 5 shows the evolution of global-mean near-surface air temperature anomaly from the various G2 simulations (solid lines) and their corresponding 1pctCO_2 simulations (dashed lines). It is clear that while the goal of maintaining global-mean temperature near pre-industrial levels has been achieved with varying degrees of success by the different models, all models show a rapid return to their respective 1pctCO_2 temperatures when geoengineering is terminated. The right panel of figure 5 shows the evolution of global-mean precipitation rate. All models except one show varying degrees of reduction in precipitation rate during the geoengineering period, again followed by a rapid rise on termination.

Only a very limited number of variables has been examined (e.g. temperature and precipitation) and the response of ecosystems to such changes has not been investigated. Research is still lacking on different rates and magnitudes of termination or decrease of forcing. Use of high-resolution and/or near-term prediction techniques could be used to shed more light on the detailed responses to SRM termination.

Further modelling effort in this area would seem necessary to investigate optimal 'escape clauses', relating a wide range of deployment times (from 5 -100 years) to the time period over which SRM would need to be phased out to minimise adverse consequences, with and without other mitigation and remediation measures.

Note that a relatively short (5-10 yr) deployment of atmospheric SRM as an emergency response (in addition to other actions) is a scenario that might have greater chance of international political approval than a longer-term commitment. Even if longer SRM deployments were ever agreed, there would be high risk of early discontinuation, either due to changes in governments, other political instabilities, or the occurrence of regionally-severe extreme events, that may be perceived as due to the SRM action[9] (with consequences for public acceptability and international legal compensation) .

Research Gap #3. Termination Effects. *Atmospheric SRM deployments of 50 years are covered in GeoMIP experiments 3 and 4, with abrupt cessation at the end of that period. Model-based studies of the implications of both shorter and longer SRM interventions are needed, with both fast and slow phase-outs and in combination with other climate intervention scenarios. Such model runs would provide insights on how escape clauses might be developed for atmospheric SRM, to minimise adverse termination effects, and the potential deployment of such techniques for 'emergency use only'.*

[9] *Scientific attribution of a specific extreme event to the SRM action might be uncertain (in the same way that it is currently difficult to confidently attribute extreme events to global warming). However, since SRM is deliberate, the burden of proof would be reversed.*

4.3 Ability of NET techniques to achieve desired climatic outcomes

4.3.1 Efficiency and scalability of NET techniques

Currently climate mitigation research does not draw a strict distinction between geoengineering and emission abatement. For instance, in the IPCC fifth assessment the RCP2.6 scenario, which aims to stabilise climate at 2ºC above pre-industrial levels, requires globally net negative emissions before the end of the century and assumes around 100 GtC removal through BECCS by 2100. These negative emissions are associated with bio-fuel production and carbon storage. The inclusion of negative emissions in scenarios that are typically called "mitigation scenarios" has become common over recent years (for instance UNEP, 2010) because it enables a higher probability of limiting warming to 2°C without needing conventional mitigation measures to be outside a technically or economically feasible range. Therefore, it is important when considering scenarios of mitigation and NET together to first establish if a, so-called, mitigation scenario of interest already features some form of geoengineering. If it does, particular care must be taken to avoid any double counting when the effect of additional NET measures are quantified. Other limitations and interactions must also be considered. For instance, if a mitigation scenario uses the maximum capacity of CCS and applies it to fossil fuels before NET is considered, it may not be possible to achieve NET using a BECCS approach.

Since NET remediation/geoengineering directly tackles the main anthropogenic forcing of climate change, the uncertainty issues related to global climate modelling (Section 4.2.1) are generally less applicable. Whilst transient changes in climate and CO_2 levels will affect effectiveness of NET techniques (and rapid rampdown of CO_2, if achievable, could be climatically disruptive; Wu et al, 2010; Boucher et al., 2012), the main effectiveness constraints relate to uncertainties in efficiency and scalability, with associated carbon-accounting implications (verifying that the intended benefits have actually been achieved). In addition to the literature-based reviews of a range of NET techniques, to be covered by IAGP and RG#1, experimentally-based improvements in the estimates of the potential CO_2 uptake by a range of NET techniques would be highly desirable.

Forests are the largest terrestrial store of carbon, and large-scale management of them, through reforestation and afforestation potentially offers a way to reduce carbon emissions and ultimately remove CO_2 from the atmosphere. Use of forests for BECCS (bio-energy with carbon capture and storage) has been identified as potentially one of the most promising (and environmentally benign) forms of NET: it is prevalent in many emissions scenarios, such as RCP 2.6, where it is regarded primarily as a mitigation strategy rather than a geoengineering one. However, the demand for land for large scale BECCS is substantial and is likely to conflict with demand for food production (Wise et al., 2009; CBD, 2012a). Significantly, if competition for land enhances deforestation rates there will be direct emissions of carbon through deforestation as well as a loss of a potential future sink. Quantification of effectiveness and feasibility should focus on the potential for storage given projected future land requirements, also indirect climate impacts (e.g. effects on hydrological cycle and albedo; Arora & Montenegro, 2010) and the rate at which carbon can be sequestered. Furthermore, the indirect impacts of bio-crops driving deforestation and the associated emissions may significantly negate the benefits. An initial study by Hughes et al., (2010) of the capacity of the Miscanthus bio-crop to offset future fossil fuel emissions has been completed using a simple climate model (IMOGEN) (Huntingford et al., 2010; Huntingford and Cox, 2000). Under the SRES A2 (business as usual) scenario increased areas of suitability were found particularly in the high latitudes, which allowed bio-crop area to increase under climate change. However, the new regions displaced productive vegetation and were only marginally suitable for Miscanthus production. The pay-back time for bio-energy, defined as the time taken for the bio-energy CO_2 emission reductions to offset the indirect land-use change emissions, is less than 30 years in the tropics, but over 50 years in the high latitudes (Figure 6). But, the scenario used here does not factor in any carbon-capture and storage (BECCS) which may significantly increase the ability of bio-energy to reduce future emissions, nor the local biophysical effects of land-use change, which may alter the regional climate, and local ecosystem services.

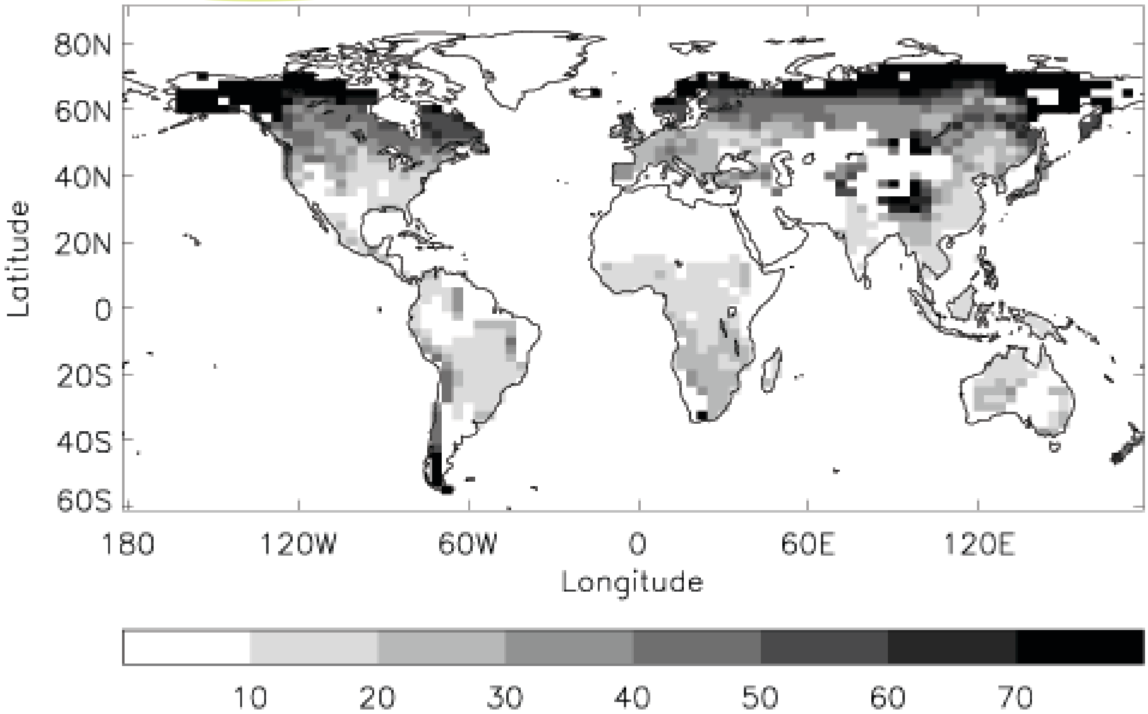

Figure 6. *Global distributions of pay-back times at 2050 (years). This is the number of years required of bio-cropping required to offset the loss of the natural carbon sink through extensive planting of Miscanthus.(Figure 3, Hughes et al., 2010).*

Other work on BECCS as part of the DECC/Defra AVOID program has assessed the potential upper bound of BECCS to mitigate climate change and the flexibility it may introduce to emission pathways that lead to various climate targets. The work used estimates of land area that could potentially be available for use with biofuels from the Committee on Climate Change's 2011 bio-energy review. The CCC's (Committee on Climate Change) review included an extreme bio-energy land use scenario, "Further Land Conversion" (FLC), which determined that there is up to 700mha of land potentially available for bio-energy globally, although this scenario would imply significant conversion of natural habitats and current agricultural land. Such a scenario would put a high degree of pressure on global food production and while considered as extremely unlikely by the CCC, it was as an upper bound on land potentially available for BECCS. Estimates of total biofuel production from the CCC were then combined with estimates of the effectiveness of CCS from DECC's 2050 analysis (2010) to produce a traceable estimate of the largest amount of NET that would be possible globally, about -3GtC yr^{-1}.

Aspects of three other NET approaches with high environmental relevance[10] are also briefly mentioned here: biochar (with linkage to bioenergy, soil improvement and waste management); ocean-based enhanced weathering; and wetland carbon storage (with linkage to emission mitigation and national carbon budgets, including both terrestrial and marine components). As follows:

Biochar merits additional study because of the high value claimed for potential carbon sequestration (globally up to 9.5 GtC yr^{-1} by 2100; Lehmann et al, 2006) and potential linkage to renewable energy generation, through BECCS (Lenton, 2010). There are also potential additional benefits, including improvements in soil quality and structure, and reduced N_2O emissions (Shackley & Sohi, 2011; Clough & Condron, 2010). However, there are important land-use issues and constraints (discussed under 4.3

[10] *The fundamental importance of technological and economic feasibility is fully recognised. Such issues are particularly crucial for direct air capture (and associated large-scale CCS) and there are many related research needs. However, such aspects are not considered in detail here, since this report is focussed on climatic and environmental research issues.*

below), and considerable variability in effectiveness of biochar has been reported (e.g. Major et al., 2010), that may be due to non- standard products, or different soil conditions and/or climatic regimes.

Ocean-based enhanced weathering involves adding alkaline minerals, such as calcium carbonate, calcium hydroxide or ground silicate rocks, to seawater in order to chemically promote ocean storage of CO_2 (Kheshgi, 1995; Harvey, 2008; Markels et al, 2011; Köhler et al, 2013). Although theoretically achievable, and with additional potential benefits in counter- acting ocean acidification, no small-scale field experiments have been carried out to demonstrate effectiveness; i.e. quantifying carbon drawdown from the atmosphere. There are currently major uncertainties regarding the timescale of this process (as also for land-based enhanced weathering techniques), and whether it might be accelerated (Schuiling & Boer, 2010, 2011). Although not explicitly covered by current London Convention/ London Protocol (LC/LP) arrangements, it is expected that LC/LP approval would be necessary for any experimental studies at non-trivial scale (even if carried out within UK waters), with appropriate prior impact assessments.

The potential for wetland management to increase carbon storage warrants further research attention (e.g. through peatland decomposition control; Freeman, 2012), and work in this area could link to other NERC/ Defra programmes. Globally, peatlands are responsible for storing around a third of total soil carbon (~450 GtC), although only covering 2-3% of the Earth's land surface. The role of salt marshes, mangroves and sediments in shallow coastal seas in carbon sequestration is significant but poorly quantified (Chmura et al., 2003; Nelleman et al., 2009), with scope for management interventions to promote net carbon uptake and enhance other ecosystem services (Laffoley & Grimsditch, 2009). CH_4 emissions from these ecosystems are high, making a full GHG balance essential for any assessment of proposed sequestration activity.

For all of these actions, account must be taken of the full greenhouse gas budget of each technique and a life-cycle analysis of energy requirements to deploy it.

Research Gap #4. Terrestrial carbon management. *Improved experimental quantification is needed of the CDR potential of forestry, biochar and other BECCS-linked terrestrial carbon management strategies at both the UK and global scales. Research should take account of the political likelihood of deployment, and any possible co-benefits (e.g. energy production, soil fertility, water retention and peat substitution) or limitations (such as competition for land). Such research would build on existing national expertise. For biochar, it could include: i) calibration of accelerated aging methods (to assess stability at decadal-to-century scales); and ii) field trials, with measurements of greenhouse gas fluxes (CO_2, CH_4 and N_2O), soil properties and crop productivity to quantify climatic benefits and assess which agricultural systems are best suited for sustainable biochar application.*

5. Research Gaps relating to unintended impacts

5.1 Potential for ecosystem impacts, including ocean acidification

The research gaps identified above primarily relate to the effectiveness (or otherwise) of intended impacts of geoengineering on the climate system, i.e. reduction in anthropogenic climate change via the 'intended impacts' arrows on Figure 1. There are, however, also likely to be unintended environmental impacts of geoengineering, with potentially significant consequences not only for the physical climate system but also operating directly on biodiversity and ecosystems, as shown generically by the 'unintended impact' arrows.

Both SRM and CDR[11] techniques have implications for ocean acidification, in different ways (Williamson & Turley, 2012). Under SRM geoengineering, ocean acidification would intensify in response to increasing

[11] *for ocean acidification we refer to removal specifically of CO_2 rather than other greenhouse gases, hence use of phrase CDR in this section*

atmospheric CO_2, although temperature-related changes in carbon sequestration by terrestrial biomass could decrease atmospheric CO_2 relative to the non-SRM control (by ~100 ppm in 2100 under IPCC A2 scenario; Matthews et al., 2009). Other second-order effects of SRM on ocean acidification, with uncertain overall consequences, include temperature-related changes in CO_2 and $CaCO_3$ solubility; effects of changes in light quality/quantity on marine photosynthesis (see below), and additional precipitation acidity, if SO_2 is used for stratospheric albedo enhancement.

Under CDR, the decrease in atmospheric CO_2 would reduce ocean acidification except in cases where the ocean is used directly for carbon sequestration. Related research issues are not discussed in detail here, since there is already a NERC-led research programme on ocean acidification, including global modelling studies – although without specific focus on geoengineering.

As well as ocean acidification, CO_2 has other direct effects on ecosystems adding further to the asymmetry of SRM and CDR techniques. The direct effect of CO_2 on vegetation growth may promote ecosystem resilience to environmental stresses and may increase crop yield. Higher atmospheric CO_2 through increasing plant water use efficiency and direct CO_2 fertilisation may enhance regional water resources (Betts et al. 2007; Wiltshire et al., 2013) , and crop productivity (Gornall, 2010). Reducing rates of increase of atmospheric CO_2 or reducing the total atmospheric burden may lead to the loss of some potential benefits.

5.2 Unintended impacts of SRM techniques

Excluding ocean acidification, for the reasons given above, there are three main groups of unintended impacts for SRM geoengineering, with varying degrees of technique specificity:

i) All atmospheric-based SRM techniques will increase the relative proportion of diffuse light, decrease the proportion of direct light, and reduce the total irradiance reaching both the land and ocean surface

ii) SRM techniques that involve increased sulphate aerosols in the stratosphere will enhance ozone depletion, particularly in polar regions (as occurred after the Mt Pinatubo eruption; Tilmes et al., 2008)

iii) Surface albedo changes at the scale necessary to have climatically significant effects will inevitably have implications for land or ocean ecosystems.

Issues (i) and (iii) are considered in greater detail below. Aspects of (ii) are already covered (to some degree) by other ongoing NERC-supported research on atmospheric chemistry, and parts of the Stratospheric Particle Injection for Climate Engineering (SPICE) project.

5.2.1 Effects of SRM on light quality and quantity

The net environmental effects of SRM-induced changes in both light quality (the ratio of diffuse/direct light) and quantity (particularly photosynthetically active radiation, PAR) are currently uncertain. For forest ecosystems, diffuse light is more effective at canopy penetration: atmospheric SRM could therefore be expected to result in a net increase in terrestrial primary production, despite the decrease in total irradiance (Mercado et al., 2009). Crop species may also benefit (Zheng et al, 2011) although inter-species differences are likely, as a function of canopy structure. There may also be latitudinal variation in vegetation response, and additional hydrological effects driven by the effects of the diffuse/direct ratio on evapotranspiration (Oliveira et al., 2011). Aerosol-induced 'global dimming' and enhanced cloudiness/cloud brightening may, however, differ in their effects on terrestrial carbon sequestration (Alton, 2008). Combinations of Earth System models such as HadGEM2-ES and impacts models have the ability to look at effects of radiation quality on ecosystems but little research has been carried out to date.

Marine cloud brightening can be expected to have negative impacts on ocean productivity. That is because diffuse light is less effective than direct light in penetrating seawater, thus raising the compensation depth (where phytoplankton photosynthesis and respiration balance). Thermal structure will also be affected, changing thermocline depth. Although the optical processes are relatively well-quantified (Morel, 1991), the implications of specific SRM geoengineering scenarios on photosynthesis, primary production, stratification and nutrient re-supply have yet to be quantitatively assessed.

Effects of changes in the diffuse/direct light ratio on the behaviour of terrestrial invertebrates and cold-blooded vertebrates could also be significant, but there is little data on this topic (CBD, 2012a).

Research Gap #5. Environmental effects of SRM. *The implications of SRM for light quality and quantity at the Earth's surface, and associated ecosystem effects, need to be much better understood, for both terrestrial and marine environments. Whilst relevant evidence for such effects does exist (e.g. from studies of volcanic eruptions, impacts of anthropogenic aerosols, and bio-optical crop modelling), further integration and synthesis is required, with a need for targeted experiments on potentially-sensitive aspects.*

5.2.2 Effects of large-scale land albedo changes

Increases in terrestrial surface albedo (desert, grassland or cropland) provide a second category of SRM techniques that could, in theory, make a globally-significant contribution to counteract global warming (Fig. 2), with the advantage of increased manageability and potential for seasonal and/or regional scale benefits (Ridgwell et al., 2009; Singarayer & Davies-Barnard, 2012). For centuries now human activity has perturbed the land surface and altered its albedo and other physical properties. GCM analysis of 20th century climate change due to land-use and land-cover change (de Noblet-Ducourde et al 2012) has shown the potential importance of anthropogenic surface albedo changes for local climate and surface energy balance. The impacts of surface changes manifest through other mechanisms than just albedo change. Changes in evapotranspiration and turbulent exchange represent climate forcings that are not captured when considering top-of-the-atmosphere radiation balance. Changes in the water cycle can have significant associated climate impacts on ecosystem services. Such studies also highlight that some regions and seasons may exhibit stronger sensitivity than others, highlighting again the need for finer space and timescales to be considered. In particular the impact on local extremes remains a research gap.

Whilst many aspects of the effectiveness and achievability of 'cooling with crops' (or grassland) can be investigated through either literature reviews, scenario development or climate modelling, i.e. under RG#1 and RG#2 above, there are also crucial scaling issues regarding potential physiological and environmental constraints – with associated unintended impacts – for vegetation-based changes in surface albedo.

Both laboratory and field-based experimental studies on these issues are needed, to reduce uncertainties in the technique's usefulness and potential impacts. Genetic Modification (GM) technologies could presumably accelerate the development of high-albedo strains; however, GM would introduce additional acceptability issues (particularly for food crops), and its use would not seem justified for initial studies. Nevertheless, GM might subsequently become necessary to achieve the climatic benefits at the scale required, and any wider assessment of deployment feasibility would need to take that into account.

The direct ecological impacts of large-scale albedo changes for deserts (Gaskill, 2004) and the ocean surface (Seitz, 2011) would undoubtedly be high, but are not considered further here since such manipulations are currently considered non-viable for other reasons. Ocean-based albedo change could, however, reduce the scale of inter-hemispheric climate effects likely to be caused by albedo changes at the land surface (Bala & Nag, 2011), due to the asymmetric inter-hemispheric distribution of land and ocean.

Research Gap #6. Surface albedo effects. *The effectiveness of vegetation-based SRM depends on the assumption that it is possible to increase canopy albedo by 10-20% for a range of plant species without: substantive loss of productivity; decrease in food quality (for humans, livestock or natural biodiversity); implications for the hydrological cycle; or impacts on other important ecosystem services. These issues warrant further quantitative investigation, based on i) reviews of existing information on the natural variability of plant albedo, its physiological significance, ecosystem implications, and the potential hydrological and economic effects of its large-scale manipulation; and ii) laboratory experiments and small-scale field trials to gain additional understanding, through quantification of key effects. In addition, numerical modelling is required on specific impacts of surface albedo changes beyond radiative forcing (such as surface roughness or evapotranspiration), with a focus on effects on climatic extremes*

5.3 Unintended impacts of NET techniques

As for SRM, many of the unintended impacts of NET approaches are technique-specific; whilst some of those impacts relate to associated resource use, others relate to processes involved in the capture or storage of carbon. However, not all such effects are negative – and not all are entirely unintended. Table 2 summarises available information.

Technique		Summary of side effects	Location of impacts		
			Resource use	Capture	Storage
Ocean fertilization	Direct addition of micro-nutrient (Fe)	Changes in marine primary production, biodiversity and foodwebs; increased ocean interior anoxia and acidification; also increased N_2O and CH_4 release?	–	Ocean	
	Direct addition of N or P		Land	Ocean	
	Up/downwelling modifications		–	Ocean	
Enhanced weathering and other mineralised storage	Enhanced ocean alkalinity (ocean liming) via ground carbonate or silicate rocks, or calcium hydroxide	Large-scale mining/processing on land with energy costs; local marine impacts of enhanced alkalinity and/or mineral particles; directly ameliorates ocean acidification	Land	Ocean	
	Enhanced soil alkalinity (e.g. via dispersed ground silicate rocks)	Large-scale mining/processing with energy costs; beneficial or uncertain effects on soil; beneficial re albedo; run-off to rivers and ocean	Land		Land (ocean eventually)
	Magnesium oxide cement	Alternative to lime-based cement; requires relatively rare mineral sources	Land		
Terrestrial ecosystem management	Afforestation	Land use/cover change; effects on albedo and hydrological cycle; may compete with food production	Land		
	Reforestation		Land		
	Enhanced carbon storage in agricultural soils (no-till or organic)	Mostly positive, but may lower yields.	Land		
	Enhanced wetland carbon storage	Positive conservation effects; uncertain implications for CH_4 and N_2O	Land and coastal		

<table>
<tr><th colspan="2" rowspan="2">Technique</th><th rowspan="2">Summary of side effects</th><th colspan="3">Location of impacts</th></tr>
<tr><th>Resource use</th><th>Capture</th><th>Storage</th></tr>
<tr><td rowspan="4">Terrestrial biomass</td><td>Bioenergy with carbon capture and storage (BECCS)</td><td>Land use/cover change; feedstock production may compromise food security; some risk of leak from storage</td><td colspan="2">Land</td><td>Sub-surface</td></tr>
<tr><td>Biochar</td><td>Land use/cover change; feedstock production may compromise food security; benefits for soil quality, structure and reduced N_2O release, but adverse albedo impact and potential health risks.</td><td colspan="3">Land</td></tr>
<tr><td>Ocean storage of crop waste</td><td>Decreases soil fertility (or requires extra fertilizer); damage to seafloor environments; eutrophication risk</td><td colspan="2">Land</td><td>Ocean</td></tr>
<tr><td>Storing (or burying) timber; linkage to afforestation/ reforestation</td><td>Land use/cover change</td><td colspan="3">Land</td></tr>
<tr><td rowspan="3">Direct air capture (DAC)</td><td>DAC for CO_2 with carbon storage in geological reservoirs (including deep injection in olivine/ basalt)</td><td>Water and energy use; local impact on vegetation of reduced CO_2; small risk of leakage</td><td colspan="2">Land</td><td>Sub-surface</td></tr>
<tr><td>DAC for CO_2 with carbon storage in deep ocean (mid- or deep-water injection as liquid CO_2)</td><td>Water and energy use; local impact on vegetation of reduced CO_2; damage to deep sea ecosystems; acidification of ocean interior</td><td colspan="2">Land</td><td>Ocean</td></tr>
<tr><td>DAC for methane using catalysts, enzymes or methanotrophs; combustion (or respiration) to CO_2</td><td>[Technology very speculative, but could have very low environmental impact]</td><td colspan="3">Land</td></tr>
</table>

Table 2. Summary of side effects (impacts other than atmospheric CO_2 reduction) for a range of NET and related techniques, based on CBD review (2012a), Royal Society (2009), Russell et al. (2012) and McLaren (2011, 2012).

As with deliberate surface albedo changes, land-use change through reforestation/afforestation, or deforestation for bio-crops is known to alter local climate through biophysical effects altering both local temperatures and the hydrological cycle. Research is required into the combined, net effect of the biophysical and carbon implications of any changes in land-use or management.

For techniques based on terrestrial ecosystem management or terrestrial biomass, a recurring issue is competing demand for land (Tilman et al., 2009). Nevertheless:

"Produced responsibly they [biofuels]are a sustainable energy source that need not divert any land from growing food nor damage the environment; they can also help solve the problems of the waste generated by western society; and they can create jobs for the poor where previously there were none. Produced irresponsibly, they at best offer no climate benefit and, at worst, have detrimental social and environmental consequences." (Oxburgh, 2007)

Very similar considerations apply to many terrestrially-based NET techniques. Thus the need is to develop (preferably jointly by NERC, the Biotechnology and Biological Sciences Research Council (BBSRC) and the Economic and Social Research Council (ESRC)) sophisticated models of the land-use dynamics, environmental economics and societal impacts involved in providing feedstocks for large-scale carbon sequestration, whether by biochar or more directly. Such work needs to explicitly be in the context of future population growth, food security issues (Godfray et al., 2010; Foley et al., 2011) and projected climate change; i.e. using IPCC RCP AR5 scenarios for changes to temperature and water availability in (say) 10-20 years time, on the basis that it is unlikely that large-scale and climatically effective NET (or SRM) remediation measures could be implemented before 2020.

At an extreme level, CDR could be employed not only to slow the rate of increase of atmospheric CO_2 but to reduce it. The thermal inertia of the climate system means that many aspects of the Earth system will continue to respond for decades after the implementation of NET. Modelling studies (Wu et al., 2010; Boucher et al., 2012) have also shown a temporary intensification of the hydrological system (i.e. a global increase in rainfall) in response to reduction in atmospheric CO_2. More research is required into the reversibility aspects of climate.

Research Gap #7. Land use implications of biomass-based NET. *For NET techniques, scaling issues apply as much, or more, to unintended impacts and side effects as to effectiveness in reducing atmospheric levels of greenhouse gases. Although first-order calculations have been made on the area required for land-based NET using biotic-capture and biomass or soil carbon sequestration, more detailed assessments and model simulations are needed of the environmental and socio-economic implications, at the national and global level, and in the context of the future development of biofuels and BECCS.*

6. Research Gaps relating to synergies, interactions and monitoring

As discussed in the introduction, model-based research is needed into interactions within and between multiple SRM, NET, mitigation and adaptation responses.

Many commentators have acknowledged that no single geoengineering technique could provide a "magic-bullet" solution to climate change (Ridgwell et al., 2012; Shepherd, 2012), and hence a "wedges" approach, combining multiple applications to reach a desired total would be required. But there has been very little quantitative research into the additivity of potential geoengineering techniques. For example if stratospheric aerosol injection and sea- salt injection into stratocumulus decks could both achieve -1Wm-2, would the combined effect of deploying both simply be -2 Wm-2? Similarly, by affecting surface climate and light levels would SRM techniques affect the potential effectiveness of NET options such as reafforestation?

Research Gap #8. Interactions between geoengineering techniques. *Additivity or competition between potential geoengineering techniques should be better understood. Quantitative research is required to address combined effectiveness of multiple SRM and NET techniques (e.g. do SRM radiative forcings combine for multiple applications?).*

Interactions with other climate response options should also be considered. NET techniques cannot rapidly reduce atmospheric CO_2 and are therefore inappropriate as an emergency measure. SRM however, can potentially work on shorter timescales. The two techniques may therefore be complementary and might be deployed within a portfolio of climate policies. Existing research does not allow us to answer questions such as: How could we achieve climate stabilisation below 2°C with optimal cost effectiveness, without compromising food and water security? Or how do delays in mitigation increase the need for short-term geoengineering application?

Continued policy emphasis on strong, urgent and global-scale emissions reductions is entirely appropriate. Nevertheless, there is a clear requirement to understand geoengineering in the context of other policy responses. Such questions need the development of simple model tools to quickly assess different scenarios of options. Nevertheless, simple models have their limitations: such tools should therefore be traceable to complex models which have been used to investigate the consequences of individual techniques. For example, Vaughan and Lenton (2012) use a simple model to compare NET, SRM and emissions reductions options, but assume that SRM effectively completely cancels out surface climate change, which is unlikely to be true (Ricke et al., 2010).

This approach could be extended to take into account local climate changes due to different SRM techniques found in complex models. Powell and Lenton (2012) assess the possible degree of negative emissions from BECCS in the presence of different assumptions around demand for land and food production. Important consideration needs to be given to the permanence of carbon storage. Permanent storage (centuries to millennia) would decrease atmospheric CO_2 on long time scales. However, non-permanent storage acts to delay emissions. Non-permanent storage may have benefits in combination with mitigation, as it may ‘buy time’ for mitigation policy and reduce the cumulative impacts of raised temperature (Dornburg & Marland, 2008; Stone et al., 2009).

Development and application of complex, process-based Earth system models is already a key UK strength and part of both Met Office and NERC strategies. This capability should be further utilised by the geoengineering research community. Both SRM and NET can be seen as new climate scenarios to investigate with such models, not only looking at impacts of geoengineering techniques, but also at interactions between them and with mitigation/adaptation strategies.

Research Gap #9. Geoengineering techniques in the context of mitigation and adaptation policies. *Quantitative assessment is required into the climate change and its impacts of different ‘storylines’ that achieve similar global mean temperature changes by different combinations of response options.*

A final requirement before deciding to proceed with any large scale deployment of geoengineering would be a well-defined ability to monitor and attribute its impacts (intended and unintended). How would we know if any weather event was caused by the geoengineering or might have happened anyway? Extreme climatic events such as the Pakistan floods or Amazonian drought in 2010 receive high levels of public attention. If such an event happened shortly after deployment of geoengineering it might be seen as the cause of the event. This is a methodology applied to extreme events already in the context of questions such as “did global warming cause the 2003 heatwave?” (Stott et al.,2004). It can never be said with confidence that global warming, or geoengineering, “caused” a specific event, but changes in the odds of an event happening under their influence can be calculated if the climate models available have demonstrable skill at representing the type of event in question (e.g. Peterson et al., 2012).

Research Gap #10. Detection and attribution. *If geoengineering were to be deployed, how would we know if it has worked as intended - or if it had caused subsequent extreme events? ‘Operational attribution techniques’ should be further developed in this context, in order to detect and attribute, with quantifiable confidence, the impacts of geoengineering.*

7. Other innovative ideas

The science of geoengineering/climate remediation is rapidly developing. For example, a large proportion of the references cited here were published in the period since 2009. It would therefore be presumptuous for a scoping document such as this not to include consideration of new and innovative ideas within a strategic framework of geoengineering and climate remediation.

Research Gap #11. Other innovative ideas. *Because of the wide range of possible techniques, mostly theoretical, some flexibility of support for a geoengineering programme is desirable. The main criterion for an ‘innovative idea’ award would be the quantifiable reduction of uncertainties for an approach that may be speculative, yet not beyond the realms of possibility. Thus evidence would need to be provided that at least preliminary consideration had already been given to such issues as capacity, scalability, limiting factors, side effects, estimated costs, verification/carbon accounting and public/political acceptability. The climatic or environmental aspects of one or more of those issues could, however, provide the main focus of a technique-specific research project, which might be based on ideas not mentioned in this scoping study.*

8. Concluding remarks

This report is based on a climatic and environmental perspective on geoengineering, identifying where additional research would seem desirable. The single biggest emerging issue is the need for research beyond global metrics, with growing need also to consider the interactions between geoengineering, mitigation and adaptation options.

Whilst usage of the term geoengineering in this document is considered to be clear and unambiguous, the term can be problematic, with semantic difficulties that have yet to be resolved at the international level (CBD, 2012b). Climate engineering, climate remediation or climate counteraction may therefore be preferred description for future research initiatives in this area.

Ethical considerations, public acceptability and transparency are all recognised as crucial issues for planning and implementing geoengineering research. Framing within a wider socio- economic and policy context, as provided by LWEC and additional stakeholder linkages, is therefore considered essential.

The Royal Society report (2009) recommended a 10 year, nationally-funded programme of UK research in geoengineering. This would need to cover a much broader scope than just the climatic and environmental focus of this report, but the research gaps identified here form initial priorities that should be included in any such programme. Support for a balanced portfolio within the subject area would seem desirable, not focussing exclusively on either SRM or NET, nor on effectiveness rather than unintended impacts. The table below shows the balance of research if all of the research gaps identified here were addressed:

	SRM	NET
Effectiveness (intended impacts)	**RG#1.** . Quantification of first order effectiveness. Continued effort in multi-technique comparisons, to quantify effectiveness and feasibility. Include aspects such as resilience of stores, life- cycle energy consumption and full greenhouse gas life-cycle analysis required, not just aerosol forcing and carbon removal.	
	RG#2. Regional and temporal implications. Improvements in assessing regional-scale and seasonal-scale forcing and effectiveness of atmospheric- based SRM, through model intercomparisons. **RG#3.** Termination Effects. Additional model-based analysis of the impacts and implications of rapid cessation of SRM.	**RG#4. Terrestrial carbon management.** Improved quantitative understanding of NET techniques at UK and global scales.
Unintended impacts (side effects)	**RG#5. Environmental effects of SRM.** Improved knowledge of environmental effects of SRM, including impacts of changes in light quantity and quality on ecosystems. **RG#6. Surface albedo effects.** Improved knowledge on scope for changing plant albedo, its scalability and implications. Including regional climate changes, seasonal/ extreme changes and metrics such as precipitation, food and water.	**RG#7. Land use implications of biomass-based NET.** Better quantification of global land-use needs for terrestrially-based NET, and associated socio-economic implications. Need to consider reversibility under reducing CO_2 and the role of airborne fraction on effectiveness of negative emissions.
Synergies and Interactions	**RG#8. Interactions between geoengineering techniques.** Quantitative assessment of additivity of, or interactions between, geoengineering techniques. For example, how SRM radiative forcings combine for multiple techniques, how NET applications compete for land or how SRM climate effects impact on NET through land carbon storage. **RG#9. Geoengineering techniques in the context of mitigation and adaptation policies.** Assessment of interactions between geoengineering techniques and mitigation/adaptation strategies. How to define "optimal" pathways and combinations to achieve targets. Use of rapid, simple modelling tools traceable to complex models.	
Governance / attribution	**RG#10. Detection and attribution.** Development of methods to monitor possible effects of geoengineering (if it were to be deployed) to enable reliable attribution and decision making. How do we know when geoengineering is deployed if it has worked or if any subsequent events are caused by it?	
	RG#11. Other innovative ideas. Opportunity to explore other innovative, yet not unrealistic, ideas.	

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