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| **Institution:** University of Oxford | | |
| **Unit of Assessment:** 7 – Earth Systems and Environmental Sciences | | |
| **Title of case study:** Assessing Routes to Greenhouse Gas Removal: informing UK Government Net Zero Targets and Actions | | |
| **Period when the underpinning research was undertaken:** 2003 to 2020 inclusive | | |
| **Details of staff conducting the underpinning research from the submitting unit:** | | |
| **Name(s):** | **Role(s) (e.g. job title):** | **Period(s) employed by submitting HEI:** |
| Prof. Gideon Henderson | Professor of Earth Sciences | 2000-present |
| Dr. Philip Renforth | Post-doctoral researcher | 2011-2014 |
| **Period when the claimed impact occurred:** July 2018 to 31 December 2020 | | |
| **Is this case study continued from a case study submitted in 2014?** N | | |

## 1. Summary of the impact

From 2003 onwards, Prof. Gideon Henderson conducted research on approaches to greenhouse gas removal (GGR) from the atmosphere. This research included leading the writing of a Royal Society publication which analysed the potential and risks of a suite of GGR approaches and developed the first quantitative assessment of the GGR potential for the UK, demonstrating that there was potential to balance residual mid-century emissions and therefore for the UK to achieve net zero emissions of greenhouse gases. This research directly informed consideration of GGR and emission targets by the UK Committee on Climate Change during their writing of *Net Zero – The UKs contribution to stopping global warming* (May 2019). That report recommended a 2050 net zero target to the UK Government, a recommendation that was accepted and signed into law in June 2019. The research described here has also led to developing government work on GGR policy, to governmental funding of significant further GGR research to inform that policy, and to an increased public and international recognition of the necessity of GGR if we are to achieve net zero and avoid dangerous climate change.

## 2. Underpinning research

Prof. Henderson has well-established research expertise in assessing the geochemistry of the carbon cycle on land and in the ocean. In 2003, his research interests expanded from assessment of the natural carbon cycle, to consideration of potential routes to deliberate change to this cycle. By this date, there was growing recognition that emissions of greenhouse gases were not decreasing, and that it might become necessary to remove $CO_2$ deliberately from the atmosphere. The potential for Fe addition to the ocean to drive enhanced biological uptake of carbon was an early candidate for such carbon dioxide removal (CDR), but the very poor understanding of the ocean Fe cycle made it impossible to assess the potential or risks of such an approach. This ignorance was a primary motivation to initiate GEOTRACES, an international study of ocean trace element cycles. During 2004-2006 Henderson co-led, with Bob Anderson (Columbia University, USA), a planning group with representatives from nine countries to define the research agenda for this programme, and publish its Science Plan (**R1**). He subsequently co-chaired (with Anderson) the programme for its first 6 years (2007-2012), working with scientists from more than 30 countries, during which GEOTRACES research revolutionised understanding of the ocean Fe cycle, and helped demonstrate the risks and limitations of Fe fertilisation that have led most experts to reject it as a viable route to CDR.

In 2008, Henderson's research expanded to consider the possibility of manipulating the inorganic ocean carbon cycle by changing alkalinity. A consultancy report arising from this work provided an early quantitative assessment of the potential of ocean alkalinity for CDR (**R2**). By 2010, the assessment of CDR (at that time considered as part of the suite of approaches for 'geoengineering') had become a significant focus of his research. In that year, Henderson was on the steering group for the *NERC Public Dialogue on Geoengineering*, and raised funding for and initiated the *Oxford Geoengineering Programme*, to assess the natural-, engineering-, and social-science aspects of CDR. Dr. Renforth was appointed as a PDRA in that programme (2011-2014) to pursue work on two routes to CDR: ocean alkalinity addition, and enhanced weathering of silicates on land. This research led to assessment of the theoretical potential of enhanced weathering for CDR. This included the first published assessment (**R3**) of the CDR that could be achieved with enhanced silicate weathering in the UK, including the source of

silicates and estimates of costs (subsequently cited by the CCC Net Zero report). It also led to a direct assessment of the weathering rate and CDR potential of mineral addition to UK agricultural soil. (**R4**). Based on this period of co-working, Renforth and Henderson subsequently co-wrote a synthesis and global analysis paper (**R5**), a comprehensive review of the theory, practicality, and limitation of ocean alkalinity for CDR which has become the standard reference for ocean alkalinity routes to CDR.

In 2017, the Department for Business, Energy and Industrial Strategy (BEIS) approached the Royal Society and commissioned them to produce, with the Royal Academy of Engineering, a report on possible approaches to CDR; by that time generalised to Greenhouse Gas Removal (GGR). This commission reflected the incorporation of GGR approaches into the reports and models of the Intergovernmental Panel on Climate Change (IPCC), which underpinned the UN Framework Convention on Climate Change (UNFCCC) *Paris Agreement* in 2015. Based on his past research and recognised expertise in this subject (e.g. **S1**), Henderson was asked to lead the group to write this GGR report. Henderson identified and brought together the team of scientists, engineers, social scientists, and economists to assess GGR approaches. That group undertook extensive literature synthesis and meta-analysis, discussion with a wide range of stakeholders and experts, and quantitative development of realistic scenarios for application of a suite of GGR approaches in the UK and globally. Henderson shaped the structure of the report, directed the novel analysis it conducted, and led the scenario approach used to assess GGR options for the UK in 2050. The report (**R6**) was peer reviewed by seven leading scientists in the UK and USA and published in 2018.

This Royal Society publication details a cross-disciplinary assessment of the potential and risk of a diverse range of approaches to GGR. It made eight recommendations to government, including to incentivise GGR, and to support demonstrators and early stage deployment of GGR approaches to allow assessment of the GGR potential and wider social and environmental impacts of each method.

Research conducted for the report also assessed realistic GGR scenarios for the UK and globally. This scenario work provided the first quantitative consideration of the potential for a suite of GGR approaches in the UK; the first of its type in any country. The analysis demonstrated the possibility to remove as much as 130Mt$CO_2$/year, and therefore the possibility of removing $CO_2$ from the atmosphere by GGR at a sufficient rate to balance expected mid-century greenhouse gas emissions. This work indicated for the first time that it was possible for the UK to reach 'net zero' emissions by 2050.

## 3. References to the research


R1. GEOTRACES Science Plan (2006) (ISSN 1932-7951). A peer-reviewed report from the International Council of Science. A version of the plan is also available as a peer-reviewed journal article: **G M Henderson,** R F Anderson *and others* (SCOR Working Group). "GEOTRACES - An International Study of the Global Marine Biogeochemical Cycles of Trace Elements and Their Isotopes." *Chemie Der Erde-Geochemistry* 67, (2007): 85-131 doi:10.1016/j.chemer.2007.02.001

R2. "Decreasing atmosphere $CO_2$ by increasing ocean alkalinity. The ocean dimension: would the concept work and what would the environmental consequences be?" **G M Henderson,** Rickaby, R E M, Bouman, H (2008). Research report for external body. https://www.earth.ox.ac.uk/~gideonh/reports/Cquestrate_report.pdf

R3. **P Renforth.** "The Potential of Enhanced Weathering in the UK." *International Journal of Greenhouse Gas Control* 10 (2012): doi:10.1016/j.ijggc.2012.06.011. Journal article. http://www.sciencedirect.com/science/article/pii/S1750583612001466.

R4. **P Renforth**, P A E Pogge von Strandmann, and **G M Henderson**. "The Dissolution of Olivine Added to Soil: Implications for Enhanced Weathering." *Applied Geochemistry* 61 (2015): doi:10.1016/j.apgeochem.2015.05.016. Journal article.

R5. **P Renforth**, and **G M Henderson**. "Assessing Ocean Alkalinity for Carbon Sequestration." *Reviews of Geophysics* 55, no. 3 (2017): doi:10.1002/2016RG000533. Journal article.

R6. Greenhouse Gas Removal 2018 https://royalsociety.org/topics-policy/projects/greenhouse-gas-removal/. **Henderson** established and led the group that wrote this peer-reviewed report. Research report for external body. (ISBN: 978-1-78252-349-9) (**S2**)

## 4. Details of the impact

Impact from this research falls into three areas:

**1. Supporting development of the UK net zero legislation and subsequent UK planning for net zero by 2050**

The Royal Society GGR report that Henderson "*...envisaged and led is now a corner stone of the evidence base for the UK's commitment to net zero 2050*" (quote from Royal Society Head of Policy, Resilience and Emerging Technologies, **S2**). It is one of five pieces of external research highlighted by the Committee on Climate Change (CCC) as informing their assessment during the writing of *Net Zero – The UK's contribution to stopping global warming* (May 2019) (**S3**). Emphasising its reach, The Royal Society describe the report as "*one of the most downloaded of all Royal Society reports in recent years (4,000 downloads and 18,000 lifetime views)*" (**S2**). The Chief Executive of CCC writes to "*… emphasise the importance of the… report, Greenhouse Gas Removals, for recent work of the Committee on Climate Change.*" (**S4**). This CCC report recommended that the UK should seek to achieve net zero emissions of greenhouse gases by 2050. Use of GGR approaches to make net zero a plausible target for the UK was an important component of the CCC report, which cites **R3**, and makes extensive use of the analysis of the Royal Society report (**R6**) (**S4**). The CCC report led, in turn, to the UK Government signing a net zero commitment into UK law (June 2019). The Chief Executive of CCC confirms the link between the Royal Society report and that legal commitment, stating how "*it [the Royal Society GGR report] informed our advice on greenhouse gas removals in the 2019 publication, Net Zero – The UK's contribution to stopping global warming, which led Government to reset the UK's statutory goal for emissions to 'Net Zero' greenhouse gas emissions by 2050*" (**S4**). The UK was the first major economy in the world to make this important climate commitment, and was able to do so because of significant underpinning research and analysis, including that presented in the CCC and Royal Society (**R6**) reports.

The impact of research represented in this case study was realised through extensive engagement with government and other stakeholders during and after writing of the Royal Society publication:

- To ensure relevance of the Royal Society report, representatives of BEIS and Defra were consulted regularly during the research and writing process (though they were not members of the writing team, to ensure independence of the research).
- A day-long workshop was held (March 2018) as part of the research for the report, involving academics and members of important stakeholder groups: government departments; the National Farmers Union (NFU); The WWF; The CCC; and the Joint Nature Conservation Committee. This process, and extensive informal follow up with stakeholders, ensured that the analysis presented in the report was realistic, considered social and political realities, and has had impact in these communities (e.g. in shaping thinking in the NFU Report, *Achieving Net Zero*).
- Following completion, the final report was sent to the Minister of State for Climate Change (Claire Perry). The Minister acknowledged the importance of the report in informing UK government policy in a letter of appreciation for Henderson's help, stating, that the *"impartial and expert advice [from Gideon and colleagues] is invaluable in helping [Government] to develop our approach to removal technologies*" (**S5**). Henderson also discussed the report directly with Minister Perry at the European launch of IPCC Special Report, *Global Warming of 1.5°C*, in London (Oct 2018).
- Findings of the report were communicated to the media at a Science Media Centre launch event (Sept 2018), at which Henderson and two other authors spoke. The release was picked up in media pieces by the BBC, Times, Financial Times, Guardian, Independent, and multiple online outlets. This media attention provided additional impact by informing the wider public about the potential of GGR to help reach UK climate goals.
- Henderson summarised the findings of the report to a lunchtime gathering of 10 CSAs from various government departments at the Government Office for Science in October 2018.
- Henderson presented the report findings to two All Party Parliamentary Groups in November 2018 (APPGs in Carbon Capture, Use and Sequestration; and in Agroecology).

- Henderson was invited to give oral evidence on 23rd April 2019 to the House of Commons Select Committee inquiry into Clean Growth Emissions Reduction Targets. Henderson was thanked by the chair of this committee, who stated, "*The committee will take note of Gideon's contribution in informing the Committee's work on technologies for meeting clean growth emissions reduction targets*" (**S7**). Henderson is mentioned ten times by name in the full report from that inquiry.

The summary of this Select Committee inquiry makes explicit recommendations to government: "*To reach net-zero emissions by 2050, will probably require the active removal of at least 130 million tonnes of carbon dioxide from the atmosphere annually by 2050. This is significantly greater than the extent of greenhouse gas removal envisioned in any of the Government's previous 'illustrative pathways' to meeting its original 2050 target, and is also at the limit of what is expected to be reasonably deliverable. The step-change in greenhouse gas removal required will necessitate a significant increase in current support for greenhouse gas removal technologies. Some urgently require research and development, whereas others could be deployed at scale now with the correct support. The Government should be ready to increase funding for research, development and demonstration of greenhouse gas removal technologies.*" (**S8**). This language closely reflects the recommendations of the Royal Society GGR report, including the scale of possible GGR (130Mt$CO_2$/year) and the importance of development and demonstration of GGR approaches. These recommendations have subsequently been followed by government policies to increase support for GGR technologies (see below).

Specific impact on government policy arising from the research in this case study is also demonstrated by the following:

- The report was presented to the Chief Scientific Adviser of BEIS at two meetings in BEIS. The first (17 July 2018) enabled discussion of the results of the work prior to publication, and the second (28 Aug 2018) enabled presentation of a final pre-release copy, and assessment of next steps for the Government to take in development and policy. The report was "*widely consulted within BEIS policy teams as a key information resource guiding their work. It proved an important input to that work and has been influential in the identification of the role GGR could play within the UK*" (**S6**).
- By highlighting the importance of GGR for UK net zero, the research led BEIS to recognise the need for commercial incentivisation of GGR approaches (**S6**), and they commissioned an external consultancy project to assess incentivisation options and associated regulation. Their report was published in July 2019, cites R6 and identifies policy options (**S9**); the CSA writes that "*GGR is now the focus of a dedicated Government internal committee to oversee its further application*" (**S6**)
- The Royal Society report is also cited as a key piece of evidence informing the UK Government position on GGR in late 2019 (**S10**).
- The Royal Society report is cited by and used as a point of comparison in other CCC reports including those on UK land use change, and policies for land-use (**S11**). These reports make recommendations to government and are directly influencing government policy. The CCC CEO states that "*the report further helped to shape my Committee's 2020 advice on policies to support the transition to Net Zero in land use and agriculture*" (**S4**).

**2. Directing significant research and development to realise UK leadership in GGR**

The challenge with many methods of GGR is that, while the approach has been demonstrated theoretically and in the lab, it has not been tested at scale in a field setting. The Royal Society report listed the need for demonstrators of GGR technology as one of its eight recommendations. This point was reiterated when meeting the BEIS CSA (August 2018), and as a result of this discussion BEIS championed a successful bid to UKRI for a Strategic Priorities Fund programme on GGR Demonstrators (**S6**). This GBP31,000,000 programme has now selected five demonstrators which will commence work in 2021. The Royal Society Report is identified as the key source of information for applicants in documents from the two co-lead Research Councils, and therefore defines the scope of future UK research and GGR demonstration (**S12**).

The UK Government has subsequently announced they will spend up to GBP100,000,000 on direct air capture (DAC) to support industrial development of this and other GGR technologies (**S15**). This follows the recommendations of the select committee for increased support for GGR, based on **R6**. The potential for DAC is described by BEIS as being 7% of present UK emissions, a number based on the assessment of potential in **R6** (i.e. **R6** suggested GGR of 25Mt$CO_2$/year from DAC; which is 7% of 2019 $CO_2$ emissions of 351Mt$CO_2$/year)

This significant expenditure on GGR committed by the UK Government is already helping develop UK policy and industry activity to assess the optimal suite of approaches for GGR as the country reduces net emissions towards its legislated net zero goal.

**3. International recognition of the potential for GGR**

By contributing to the international discussion of approaches to net zero, the research described in Section 2 has helped generate international action. The science and potential of GGR were presented by Henderson at a side-event held at the UNFCCC COP24 meeting in Katowice in December 2018 (**S13**), and a summary of the Royal Society report was translated into Chinese (**S14**). This international communication has helped increase understanding of the need for GGR and the routes by which it can be achieved. Other nations have now followed the UK in making legal commitments to net zero, including France, New Zealand and, in September 2020, China.

**5. Sources to corroborate the impact**

S1 An Economist article on Net Zero and negative-emissions technologies (NETs) concepts, "Sucking up carbon" (18th November 2017) demonstrates Henderson's acknowledged expertise in GGR. https://www.economist.com/briefing/2017/11/16/greenhouse-gases-must-be-scrubbed-from-the-air

S2 Letter from Head of Policy, Resilience and Emerging Technologies, Royal Society, stating role of Henderson in shaping the scope and research of the Royal Society GGR report

S3 Launch page of CCC Net Zero report, containing link to Royal Society GGR report

S4 Letter from CEO, Committee on Climate Change, stating usefulness of Royal Society report in shaping CCC thinking for net zero report and other activity.

S5 Letter from Minister of State for Climate Change at BEIS (October 2018), corroborating Government use of advice to develop approach to removal technologies.

S6 Letter from BEIS CSA, corroborating influence of Oxford University research on Government work on potential application of GGR technology.

S7 Letter from Chair of Science and Technology Committee thanking Henderson for giving evidence at Committee session (April 2019).

S8 Report of Science and Technology Committee as cited in Section 4: https://publications.parliament.uk/pa/cm201719/cmselect/cmsctech/1454/145403.htm

S9 Vivid Economics report, citing R6 (p.55), and providing advice to government on approaches to incentivise GGR technologies (p.56). https://www.vivideconomics.com/wp-content/uploads/2019/09/Greenhouse_Report_Gas_Removal_policy_options.pdf

S10 Government position paper on GGR (2019) citing the Royal Society Report (**R6**) https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/883115/geoengineering-position-statement.pdf

S11 Two CCC reports on land-use and GGR, both citing R6 which is acknowledged as important in their writing (**S5**): https://www.theccc.org.uk/publication/land-use-reducing-emissions-and-preparing-for-climate-change/; https://www.theccc.org.uk/publication/land-use-policies-for-a-net-zero-uk/

S12 UKRI programme calls for GGR demonstrators, citing **R6**; https://bbsrc.ukri.org/documents/ukri-call-for-proposals-spf-ggr-demonstrators-2019-2020/; https://nerc.ukri.org/research/funded/programmes/ggrd/news/ao-ggrd-dhub/spf-ggrd-dh/

S13 Presentation of Royal Society Report (R6) through two panel discussions at COP 24 (2018); https://royalsociety.org/topics-policy/energy-environment-climate/cop24/

S14 Chinese translation of Royal Society Report (R6): https://royalsociety.org/-/media/about-us/international/reports-zh/Greenhouse-Gas-Removal-executive-summary-booklet_zh_CN.pdf?la=en-GB&hash=1F6C6FDD343AF4C28E85375516A521A2

S15 UK Government announcement of funding for direct air capture research and technologies