The UKRI Strategic Priorities Fund Greenhouse Gas Removal Demonstrators (GGR-D) Programme

An overview of key research insights and cross-cutting lessons

December 2025

GGR-D PROGRAMME | Greenhouse Gas Removal Demonstrators Programme

UK Research and Innovation

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FOREWORD

A decade ago, the landmark Paris Agreement was reached. It represented a radical break with previous international agreements on climate change. Many countries increased their level of ambition due to stronger evidence about the current and future impacts of climate change.

To meet the Paris Agreement's call to limit temperature increase to 'well below 2 degrees', it was clear that measures to take greenhouse gases out of the atmosphere would be required. Whilst such measures are not a substitute for emissions reductions, they are very likely to be needed to balance emissions that are hard to reduce to zero - from sectors such as agriculture and aviation.

Greenhouse gas removals (GGRs) have therefore become an essential part of global and national strategies to meet the Paris Agreement's goals. This includes the UK's strategy to meet medium-term carbon budgets and the net-zero target by 2050. There are a wide range of options to remove greenhouse gases from the atmosphere. Some are familiar, such as planting trees. Others are more novel, such as enhanced rock weathering. Many of them require further investigation to understand their potential for removing greenhouse gases at a meaningful scale.

This need for better evidence and understanding provided the rationale for UKRI to fund the Greenhouse Gas Removal Demonstrator (GGR-D) programme. By demonstrating a set of GGR options and supporting a new research hub, the programme has supported essential research capacity and led to significant advances in understanding. It is a classic illustration of the value of public research funding, particularly when new technologies are at an early stage of development.

Over the past four years or so, the programme has provided vital new evidence and analysis to inform decisions about GGR deployment in the UK and globally. Compared to where we were at the start of the programme, we now know much more about which GGR options have the greatest potential to be scaled up, where they could be deployed at what cost, and what the potential impacts could be. Decision-makers also have a better understanding of the policies and regulations that are required to drive adoption, and how deployment can be carried out in a way that fits with the values of local communities.

> "Research will have an essential role to play as the deployment of GGRs gathers pace – to provide independent evaluations of how well GGR options work in practice and their interactions in real-world locations, and to learn lessons for further improvement."

But the conclusion of this programme is not the end of the story, or of the need for publicly funded GGR research. The programme's results have already influenced recent policy developments – including the recommendations from Alan Whitehead's Independent Review of Greenhouse Gas Removals. Some of these recommendations highlight the need to act on the findings from the programme, and to address the significant evidence gaps that remain. Research will also have an essential role to play as the deployment of GGRs gathers pace – to provide independent evaluations of how well GGR options work in practice and their interactions with real-world locations, and to learn lessons for further improvement.

It has been a pleasure to be part of this programme's journey. I'd like to thank the other members of the steering committee for playing such an active role in scrutinising and supporting the programme, the UKRI teams who have been involved in commissioning and overseeing it, and the countless organisations that have worked with the research teams. Most of all, thanks to all the researchers and innovators involved in the programme's delivery – particularly those who gave up their time to discuss their plans and results with the steering committee.

Professor Jim Watson
Director, UCL Institute for Sustainable Resources
Chair, GGR-D Programme Steering Committee

EXECUTIVE SUMMARY

The GGR-D Demonstrator Programme

Researchers have been working on a major UKRI-funded programme to enhance the evidence base on greenhouse gas removal (GGR) in the UK since 2021. The GGR Demonstrator (GGR-D) programme has piloted several GGR methods and investigated sustainable routes for large-scale removal of greenhouse gases from the atmosphere. This knowledge will support the UK in its climate change ambitions and position the UK to benefit from the future global demand for greenhouse gas removal, which may grow to around £400 billion. This report summarises the findings of the research to date and signposts more in-depth sources.

The GGR-D programme comprises a Hub (CO_2RE) and demonstrator projects for five GGR methods: *The Biochar Demonstrator*, *The UK Enhanced Rock Weathering GGR Demonstrator*, *PBC4GGR* (perennial biomass crops for bioenergy with carbon capture and storage), *NetZeroPlus* (woodland creation and management) and *The GGR-Peat Demonstrator*. Representing a range of technology readiness levels (TRLs) and supply chains, these methods could play a significant role in helping the UK to achieve its climate goals as well as delivering broader economic, environmental and social outcomes.

The five demonstration projects carried out large-scale field trials across the UK, documenting performance across a range of metrics. Researchers from the CO_2RE Hub have assessed economic policies, business model support mechanisms, the regulatory landscape and monitoring, reporting & verification (MRV) schemes that together would help build public, investor and business confidence and incentivise deployment. In addition to these research activities, the GGR-D programme has played a fundamental role in bringing together people and communities across the GGR landscape in the UK and internationally.

Key findings from the research

The research has delivered important findings. Firstly, we have made a step change in our understanding of the potential of these technologies to deliver genuine greenhouse gas removals. Secondly, the teams have developed a suite of policy, legal and evaluation insights and methodologies that can help build up the UK's GGR ability to scale the most promising technologies responsibly. The researchers have highlighted options to create, or manage the lack of, sustained demand for removals needed to get the industry off the ground, and delivering reliably. Thirdly, the technical trials have revealed insights into entirely new approaches: preliminary investigations show promising results for some co-deployments of GGR in one place e.g. biochar and peat.

The recommended actions would help **scale up a portfolio of sustainable GGR options in the UK (Chapter 2)**, increasing the current modest levels of GGR deployment up to the levels suggested in national and global pathways. The actions are

Above: Perennial biomass crops plot scale trials - establishing Miscanthus plug plants. Credit: Chris Ashman

“The recommended actions would help scale up a portfolio of sustainable GGR options in the UK, increasing GGR deployment up to the levels suggested in national and global pathways.”

relevant to all GGR methods – not just the land-based methods explored within the GGR-D programme[i]. These actions may need to be taken by one actor - for example, government - or by a number of actors working together. At the heart of these actions lies the CO_2RE Hub’s evaluation framework that allows assessment of GGR methods holistically on a coherent and consistent basis and can be used by a range of actors to support decision-making on sustainable scale-up.

It is clear that methods at earlier stages of development could benefit from a broad suite of policy instruments until they become viable. Policy makers should opt for tested, reliable polices, tailored to suit the characteristics of individual GGRs and appropriately sequenced; for example, policies to support deployment and diffusion such as revenue support mechanisms and integration into Emissions Trading Schemes need to follow earlier-stage R&D support. Policy gaps exist, especially for enhanced rock weathering and biochar which are newly included in the CCC’s Seventh Carbon Budget pathway but are not yet reported in national greenhouse gas (GHG) inventories.

Above: Enhanced rock weathering field trials at Plynlimon, mid-Wales. Credit: Alan Radbourne

A scattered approach to developing these policies will not work. A clear regulatory framework, informed by emerging scientific evidence, needs to be in place for industry and farmers to start or continue operations, or attempt to scale. Farmers and other actors involved in supply chains require policy stability, clear information on how GGR methods work and where, how they will benefit and best practice, to be confident about changing the way they operate. Regulatory hurdles and a lack of standardised methodologies and protocols for MRV that include sustainability impacts are key barriers for all GGR methods.

In shaping the early market for GGR and to overcome the risk of investment at this early stage, private or public actors could create public-private ventures. These ventures could enable private investment at scale enhancing value creation opportunities as well as reducing risk. Across the GGR-D programme, findings from research on public perceptions and concerns about GGR have provided important new perspectives. The scalable potential of GGR methods depends on them being developed in a way that is responsible to society and the environment, and maintains public trust. Regional differences in public perceptions indicate the importance of matching physical requirements for siting GGR methods with appropriate social contexts. Going forward, field trial locations remain valuable sites for bringing people together, identifying emerging public concerns and studying changing perceptions.

Turning to the broader GGR-D programme, large-scale field trails and modelling assessments, lifecycle and techno-economic analysis, and community and farmer engagement conducted by researchers from the demonstrator projects strengthened the evidence base on **the efficacy of carbon removal, co-benefits and impacts for land-based GGR methods (Chapter 3)** and identified **opportunities and barriers for scaling up land-based GGR methods (Chapter 4)**. A novel aspect of this research programme is the focus on co-deployment or ‘stacking’ of different GGR methods on the same land, which could enhance efficacy of carbon removal and co-benefits and use land more efficiently.

i Methods include direct air carbon capture and storage (DACCS), bioenergy with carbon capture and storage (BECCS) and energy from waste, as well as land-based GGR methods.

Broader considerations for deploying GGR

GGR methods make use of limited resources and interact with other systems. For land-based GGRs, competition for land, biomass and low-carbon energy means that the potential scale of deployment depends on broader policy decisions such as what kind of land use or biomass use is prioritised by government, and the rate of decarbonisation of the energy supply. Competition for land could be avoided in certain situations, for example, by using different feedstocks for different GGRs, while some GGRs involve changes in land management rather than land use change. The opportunity exists to optimise deployment within constraints, including through co-deployment.

Timing matters. Some methods require a much longer lead time than others before they deliver significant removals; for example, planting perennial biomass crops for BECCS would result in more rapid carbon sequestration in the near term than planting trees, while the rock used in ERW sequesters carbon gradually over time. Deployment needs to be targeted to meet the UK's carbon budget requirements. This programme also revealed that geography is a critical factor: the efficacy, co-benefits and impacts of GGRs vary spatially and impacts could range between positive or negative depending on where and how GGR methods are deployed. Public and community engagement has further shown the importance of careful siting.

GGR scale-up need not be driven by a GGR-first approach. In fact, opportunities for GGR deployment could result from other drivers; for example, the introduction of perennial biomass crops into less productive land. GGR deployment could help build resilience to climate change: for example, introducing *Sphagnum* mosses into upland peat could reduce wildfire risk, while re-wetting peat and growing crops suitable for wetland conditions (paludiculture) could improve flood resilience.

Above: Forest canopy, Forest Research long-term carbon dioxide monitoring site. Credit: Leslie Galstaun

Climate policy around GGR needs to be integrated with land policy – specifically the Land-Use Framework for England – as well as other policy areas including energy, industrial policy, waste, nature restoration and transport. It also needs to be integrated with climate mitigation and adaptation policy. Spatially targeted policies that reflect the variation of GGR outcomes according to location, drawing on emerging evidence including from this programme, can ensure successful space-based deployment that maximises local co-benefits.

Below: Goodbye Greenhouse Gas! Public engagement event at The Old Fire Station, Oxford, June 2024. Credit: John Cairns

What is needed next?

Paradoxically, the programme findings point to the need for both top-down and bottom-up approaches. A strategic national framework, clear objectives, policy frameworks, and coordination with other priorities are key enablers. Global engagement can align strategic goals and opportunities both within the UK and beyond. However, it is also clear that ground-up, place-based projects that deliver with and for local communities are fundamental for success. Across the whole GGR portfolio, continued support for 'learning by doing', aided by transparent and timely data sharing, flexibility, and ongoing review and update, would improve efficiencies and costs, reduce risks and enhance co-benefits. It would enable pragmatic scaling of GGR and allow science, business, regulator and policy communities to advance hand-in-hand. 'Learning by doing' is a foundational measure for de-risking investment and optimising deployment.

While there are remaining uncertainties and knowledge gaps, this programme provides evidence which demonstrates that GGR deployment in the UK can successfully contribute to the UK's net zero goals, and what is needed to scale up sustainable removals moving forward.

> "A strategic national framework, clear objectives, policy frameworks and coordination are key enablers. But place-based projects that deliver with and for local communities are also fundamental for success."

Above: GGR-D programme members at the UK GGR Event at the Royal Institution, October 2025. Credit: Natasha Martirosian

CHAPTER 1.
INTRODUCTION

1.1 The GGR-D programme and the evolving landscape

Scaling up Greenhouse gas removals (GGR) is vital to ensure the UK meets its legislated climate and environment commitments while positioning the UK to benefit from the global market in GGR [1], which may grow to around £400 billion. With this strategic goal in mind, the UK government established the £31.5m UKRI Strategic Priorities Fund GGR-D Programme in 2021 to assess sustainable routes for large-scale GGR in the UK.

This document provides an overview of the emerging body of evidence and insights from the GGR-D programme. This information is relevant to the independent review of GGRs [2], and the government's work to address the Climate Change Committee's advice on the Seventh Carbon Budget [3] and to explore ways to optimise the use of land through a land-use framework [4]. Funders of R&D, startups, project developers, farmers, land managers, agronomists and land advisors, businesses, investors, regulators and environmental organisations may also be interested in these research insights.

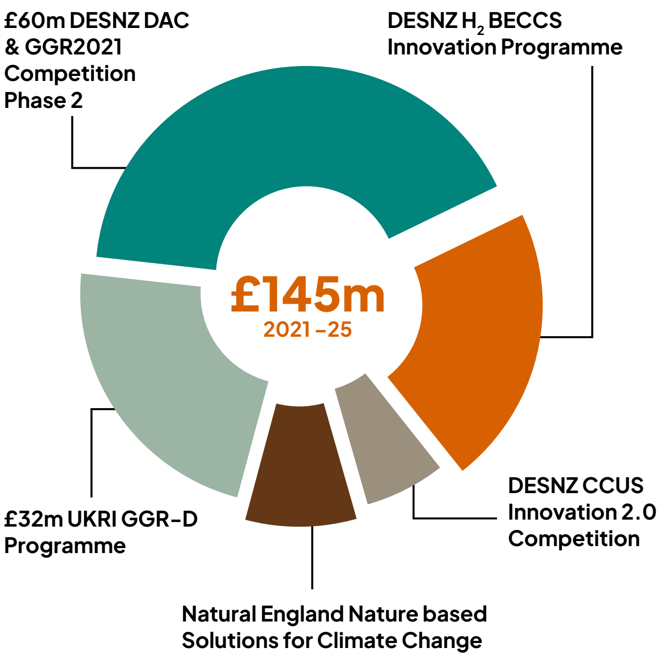


Figure 1 UK R&D funding for GGR 2021 to 2025

The GGR-D Programme comprises the CO_2RE Hub – the National Research Hub on Greenhouse Gas Removal – and demonstrator projects for five GGR methods which make use of the land: *The Biochar Demonstrator*, *The UK Enhanced Rock Weathering GGR Demonstrator*, *PBC4GGR* (perennial biomass crops for bioenergy with carbon capture and storage), *NetZeroPlus* (woodland creation and management) and *The GGR-Peat Demonstrator* (see Box 1). The programme has addressed key evidence needs [5] to ensure effective and responsible GGR deployment[ii]. It has nurtured early-stage research on other novel GGR methods through flexible funds, building the innovation pipeline and diversifying the UK's GGR portfolio, and supported GGR start-ups.

This programme has complemented other publicly funded initiatives such as the £60m government-funded Direct Air Capture and Greenhouse Gas Removal Innovation Programme, broadening the portfolio of GGR technologies receiving support to include direct air capture, bioenergy with carbon capture, biochar, methane capture and direct ocean capture [6,7], (see Figure 1). Meanwhile entrepreneurial and commercial activity outside these programmes has grown in recent years [8] and there has been a commensurate focus within government on developing policy for GGR [9].

The programme has helped to nurture this growing GGR 'ecosystem' not only through technical demonstration of some of the most promising methods, but also through engagement activities and capacity-building, including a CO_2RE Hub-funded 'Future Leaders Network' and numerous engagements by individual demonstrator projects. It has contributed to international collaboration: for example, by providing research knowledge and expertise to The Carbon Dioxide Removal Mission (part of Mission Innovation), and by convening international research communities [10,11].

ii At the time this report is published, evidence generation continues in some areas of the programme and academic publications and other outputs continue to emerge.

1.2 What is GGR?

GGR methods capture carbon dioxide (or other greenhouse gases) from the atmosphere and store it durably in a diversity of ways [12]. Figure 2 illustrates examples of key GGR approaches with respective capture processes – either biological or geological – and carbon storage pools. GGR methods also yield different environmental, social and economic co-benefits and trade-offs, or co-products. Some methods rely on carbon dioxide transport and storage infrastructure and/or on resources such as low-carbon energy, water and land and their scale-up will therefore impact broader systems. Section 2.1 describes the CO_2RE evaluation framework which incorporates these multiple dimensions.

As well as capture and storage, GGRs comprise additional supply chain activities such as transport or processing (Figure 3). These complex supply chains cross sectors and regulatory contexts, national infrastructures and private interests. Some GGR methods such as afforestation and peatland restoration are relatively well established and policymaking is mature, while others are 'novel' [14] such as bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), biochar and enhanced rock weathering, or may be co-deployed in novel ways, for example, enhanced peatland restoration. The potential to scale GGRs sustainably depends on environmental, geographical, supply chain and socioeconomic factors, in addition to technological and infrastructure considerations.

In order for them to scale sustainably, technologies need to fall in cost, business models and economic policies put in place, monitoring, reporting & verification standards developed, legal and regulatory frameworks implemented and public engagement carried out to ensure GGR methods are credible, sustainable and acceptable to the public and stakeholders. Institutional arrangements may also need to adjust accordingly [15]. In addressing sustainable scale-up, the full set of stages of a particular GGR method must be considered, including removal, storage and the supporting supply chains.

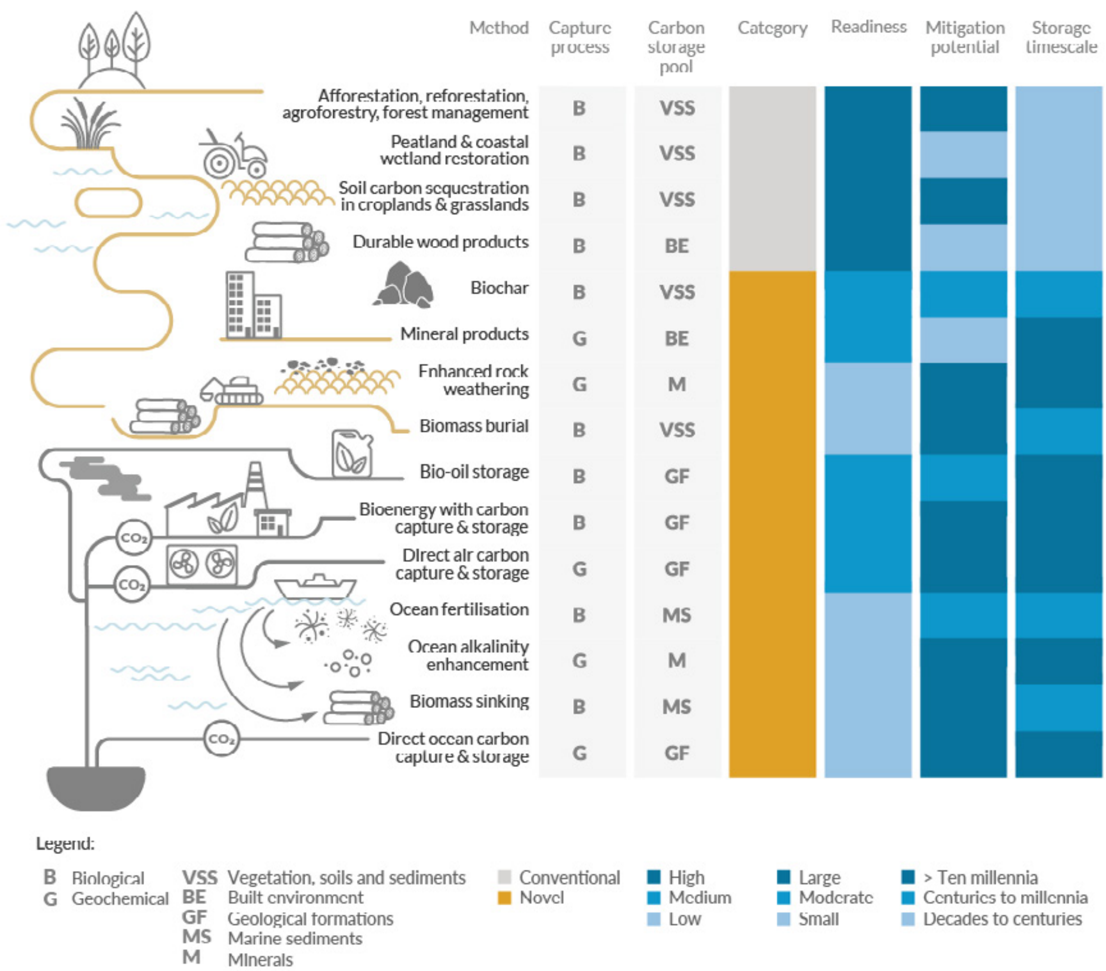


Figure 2 Diversity of GGR methods and key characteristics including capture processes, storage pools, relative technology readiness, relative mitigation potential and storage timescale. From *The State of CDR Report* [13].

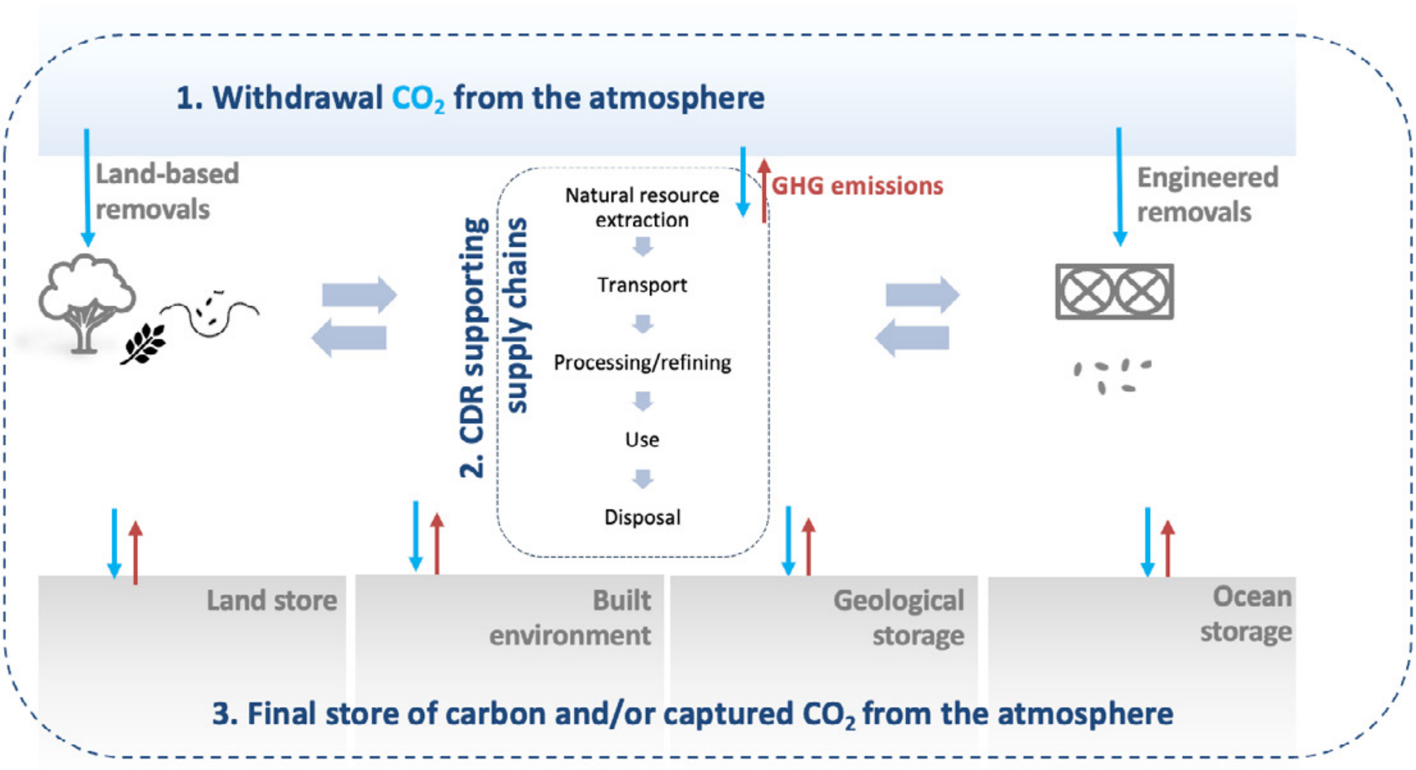


Figure 3 GGR methods comprise multiple stages including: 1. Withdrawal of CO2 from the atmosphere (capture), 2. Supporting supply chain activities and 3. Storage [16]

1.3 Land-based GGR methods

Land-based GGR methods play a significant role in the UK's carbon budget and help diversify the UK's GGR portfolio. UKRI's GGR-D programme comprises methods that have the potential to scale sustainably in order to help the UK meet statutory climate targets alongside delivering co-benefits such as energy security, food security and environmental goals. Together, the five methods are projected by the CCC to remove 63 $MtCO_2$ by 2050, representing 13% of the total abatement to net zero; this includes all forestry, BECCS, biochar, ERW and soil carbon from energy crops[iii]. Current deployment is around 18 $MtCO_2$ per year, essentially all from forestry [17]. Box 1 describes the various ways that the demonstrator projects are building the evidence base.

The five methods intersect with agricultural, forestry, energy, nature restoration and/or industrial sectors, with associated supply chains and regulatory contexts. They use land in various ways to remove carbon dioxide from the atmosphere and store it durably in geological or biological stores (see Chapter 3).

Above: Stakeholder site visit to ERW field trails at Rothamsted Research, North Wyke. Credit: Philippa Westbury

iii Note that these figures are approximations as only a fraction of the BECCS in the pathway is using perennial biomass crops; also, biomass crops are being used for other, non-GGR purposes in the pathway (e.g. liquid fuels, heat).

Box 1: Building the evidence base on land-based GGR for decision-making

Woodland creation and management is a well-established practice, and policymaking is relatively mature, although progress towards targets is slow. *NetZeroPlus* has filled in data gaps on carbon removal for different types of woodland including re-wilding, young stand growth and single rotation forestry, developed new monitoring, reporting & verification (MRV) methods, updated models to incorporate risks to storage permanence, improved understanding of all the consequences of land-use change, and provided decision-support tools for policymakers, businesses and individuals.

Peatland restoration is similarly well-established with relatively mature policies in place. GGR Peat focused on demonstrating **enhanced restoration** methods in uplands and on the application of agronomic and GGR-focused approaches to maximise CO_2 uptake and storage in lowland agricultural peatlands, some of which involve **co-deployment** of GGR methods. The project is quantifying direct and indirect benefits, and costs and risks including social and economic barriers.

Perennial biomass crops are established in the UK and grown to a limited extent for bioenergy. PBC4GGR investigated the potential to scale up their deployment for use as a feedstock specifically for BECCS. Research included best practices for establishment of crops such as Miscanthus and willow, factors affecting carbon sequestration, understanding farmers' motivations and constraints in growing these crops, modelling the spatial distributions of yields and implications for integrating land use and energy policy.

Biochar and **enhanced rock weathering** are 'novel' methods which have received less policy attention to date, although are now included in the CCC's Seventh Carbon Budget pathway. The two GGR demonstrator projects are the first large-scale field trials of these methods in the UK.

The Biochar Demonstrator has assessed biochar composition and stability, applied biochar to land in field trials to assess the response of soils and ecosystem services and identify co-benefits and trade-offs, conducted lifecycle assessment and techno-economic analysis to assess scalability and engaged with key stakeholders to understand their perceptions.

The UK Enhanced Rock Weathering GGR Demonstrator has measured weathering rates and carbon dioxide removal, and co-benefits and trade-offs, in field trials at arable, grassland and upland sites that are representative of large areas of UK agricultural land. It has carried out research on local community perceptions, developed models to forecast carbon removal in different future scenarios, and assessed supply chains and scalability.

A number of the demonstrator projects have worked together to investigate the **co-deployment** of different land-based GGR methods on the same land, potentially enhancing GGR performance and the efficiency of land use.

The CO_2RE Hub has coordinated across the GGR-D programme, co-creating harmonised methods and synthesising cross-cutting lessons on land-based GGR. It has carried out research on the development and alignment of MRV standards including socio-ecological indicators; policy, business and governance; and public perceptions, working across the Hub to produce an evaluation framework to underpin decision-making on GGR.

Across the programme, researchers have focussed both on GGR method-specific issues and on cross-cutting issues, working collaboratively to identify common themes and synthesise findings.

Above: Flux tower at the Knepp Estate field trials, NetZeroPlus

1.4 Scaling up GGR in the UK

Current GGR deployment in the UK remains modest, with the vast majority of removals delivered through forestry and grassland. Removals from novel methods are limited to demonstration projects such as those in the GGR-D programme, pilot projects and voluntary market activity. Figure 4 compares the current UK novel GGR pipeline and policy targets to CCC's 2050 Net Zero Pathway. Coordinated measures, including those set out in this report, will help ensure that the required level of GGRs are delivered when needed.

Scaling up of novel GGR methods in the short-term is vital if GGR deployment is to reach the levels suggested in national and global pathways. The optimal set of GGR methods is not yet known, and there remains scope to improve efficiencies and costs, reduce risks and enhance co-benefits. Support from policymakers for a portfolio of methods, while retaining a certain amount of technology neutrality, would enable a valuable phase of 'learning by doing'. In some cases, emerging GGR methods face regulatory gaps or barriers (see Section 2.4), even though evidence emerging from the GGR-D programme suggests they could be scaled sustainably and with co-benefits (such as ERW and biochar applied to land, and other methods involving waste feedstocks). In these cases, ways need to be found to continue trialling the GGR method, working rapidly and efficiently with regulators to ensure that regulations adapt while maintaining environmental and social safeguards.

Effective 'learning by doing' would require careful monitoring of public- and private-sector projects, and transparent data sharing between the stakeholders involved (see Section 2.7). This is a vital step in transitioning from the current modest levels of deployment [19] to future deployments at scale.

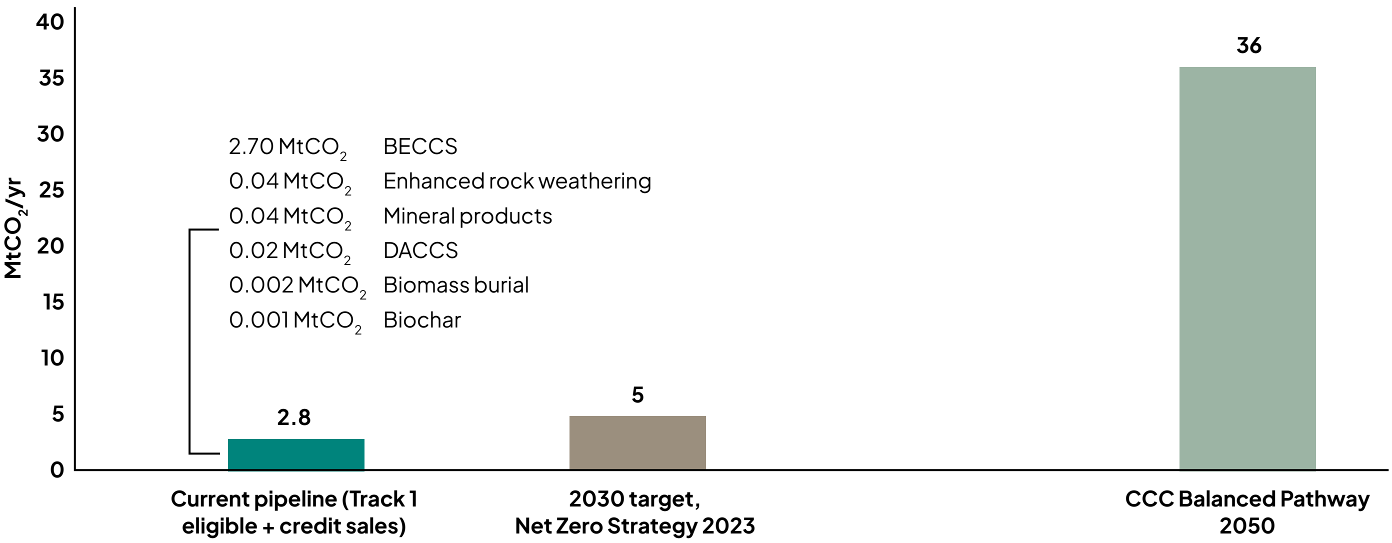


Figure 4 Comparison of current UK novel CDR pipeline and policy targets in Government's 2023 Net Zero Strategy to CCC's 2050 Net Zero Pathway [18]

GGR-D insights: Stakeholder perceptions

Understanding stakeholder perceptions has been central to the research across the GGR-D programme, helping to identify opportunities and barriers for scaling up. GGR methods can be viewed in different ways, with implications for how they are incentivised and promoted: for example, enhanced rock weathering and biochar applied to agricultural land could be viewed as GGR methods that are foremost for sequestering carbon, generating carbon market offsets for use by other sectors; alternatively they could be viewed as sustainable land management practices that deliver co-benefits to farmers and help the agricultural sector meet net zero goals. Currently farmers are more interested in biochar for its multiple farm benefits (improving soil health or contributing to on-farm biodiversity, for example) rather than for its role in carbon markets [20]. Similarly, in the absence of commercial-scale BECCS plants and geological storage, perennial biomass crops are typically regarded by agricultural stakeholders as an energy crop or a source of material for bio-based products, rather than a GGR technology.

CHAPTER 2.
WHAT IS NEEDED TO ACHIEVE SCALE-UP OF SUSTAINABLE GGR IN THE UK?

A number of enabling actions are required to help **scale up a portfolio of sustainable GGR options in the UK**. This portfolio should ideally comprise a diverse set of GGR methods that, when deployed in combination, would help the UK deliver climate goals and co-benefits within the constraints that exist, while mitigating any adverse impacts. The actions may need to be taken by one actor, for example government, or by a number of actors working together. This chapter sets out these actions, drawing primarily on research carried out by the CO_2RE Hub and with insights also drawn from the demonstrator projects.

CO_2RE Hub – key successes

Informed UK strategy on GGR through research shaped by stakeholder engagement	Supported the GGR community within the UK and internationally, including a Future Leaders' Network	Developed a framework to evaluate sustainable scalability of GGR methods on a consistent basis	Assessed policy options, business models, MRV protocols, regulations and public perceptions	Co-ordinated across the GGR-D programme on critical issues e.g. responsible innovation and LCA

2.1 Adopt holistic frameworks and tools to guide decision-making

Common frameworks for decision-making allow GGR methods to be assessed holistically and compared on a consistent and coherent basis as part of a portfolio of GGR options. The CO_2RE Hub has drawn on technical expertise from across the GGR-D programme and carried out extensive user engagement to develop the **CO_2RE Evaluation Framework** [21]. The framework comprises four sustainability and three governance dimensions, each with a set of indicators and underlying criteria; Box 2 provides a schematic representation of the framework showing the dimensions and indicators[iv].

This framework can help guide decisions by project developers and investors on deployment and investment, for example, or by policymakers and regulators on the interventions required to ensure responsible and effective scale-up. Three indicators are used to evaluate whether a GGR is genuine: net greenhouse gas emissions are negative over the GGR lifecycle, the removal is additional (greater than the counterfactual removal) and the greenhouse gas is durably stored [22]. Given the high reliance of GGRs on supporting supply chains, greater efficiency of removal and climatic impact will be achieved if these supply chains are rapidly decarbonised. Environmental, social and system considerations are embedded into the framework, each with their own set of indicators, along with key levers for credible scale-up: monitoring, reporting and verification, business models and legal regimes. In future, as GGRs are implemented

iv For the underlying criteria to assess and evaluate these indicators, please see the CO_2RE website: The GGR Evaluation Framework. https://co2re.org/ggr-evaluation/

and scaled up, the indicators and their underlying criteria should continue to be tested and updated with end users – including project developers, those involved in developing MRV methods, regulators and policymakers, investors, NGOs and the public.

CO_2RE researchers have assessed different GGR methods using the evaluation framework to determine their potential for sustainable scale-up, and to identify where evaluation data is robust and where it is lacking. Scorecards for individual GGR methods showing data availability and quality across the different stages of a GGR's lifecycle and across three dimensions of the evaluation framework (removal, environmental and systems) have been produced [23] (see also Section 2.7).

Box 2: CO_2RE Indicators for evaluating sustainable scale-up – a holistic approach to assessing the GGR portfolio

For a sustainable scale-up, any removal needs:

(1) To be genuine, i.e. deliver net removals from the atmosphere,

(2) To improve the natural environment in which it operates,

(3) To be supported by people, and

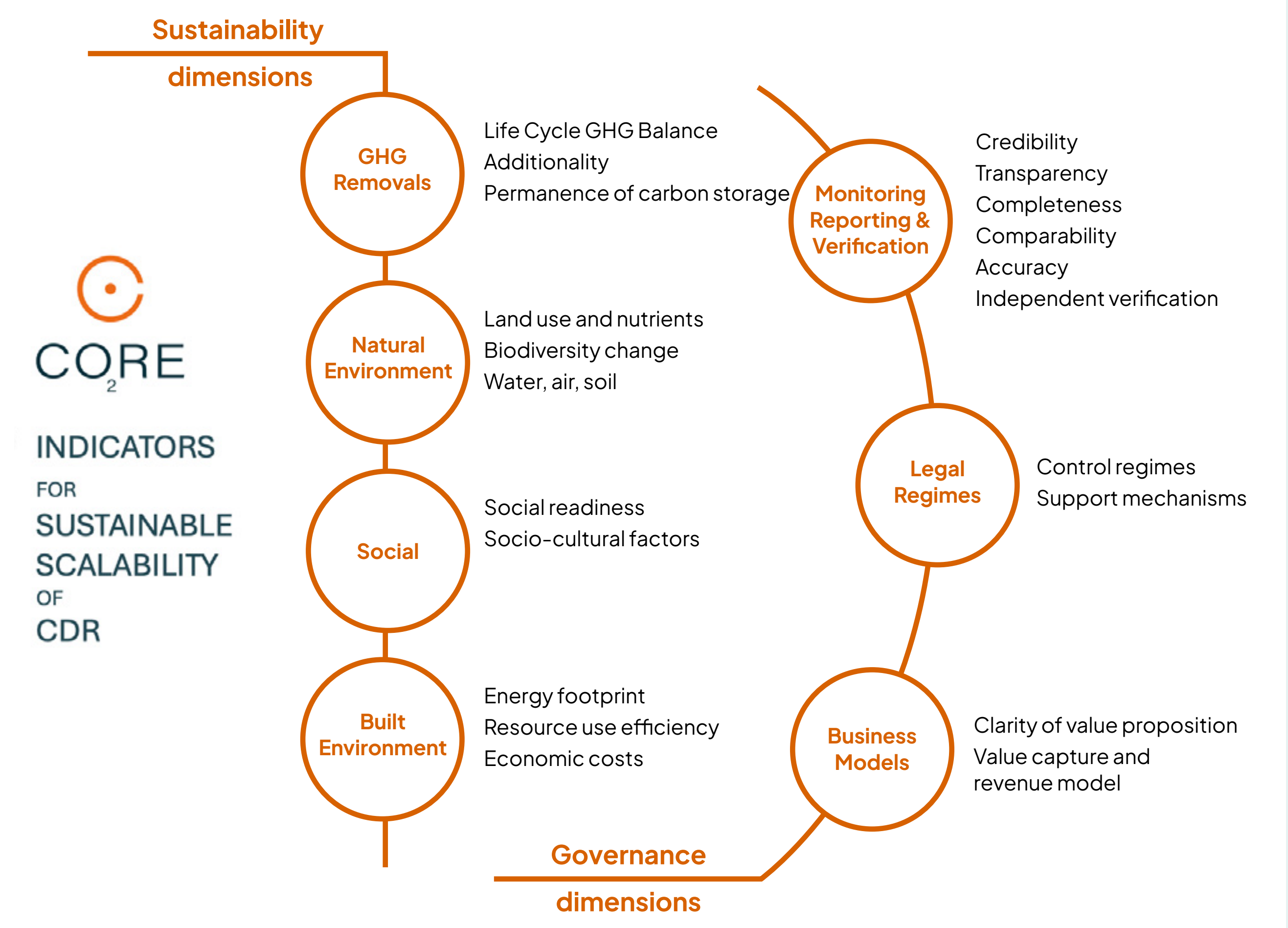
(4) To not exacerbate challenges in the man-made environment which supports it, e.g. through significant energy consumption.

To enable credible delivery of these sustainability dimensions, three cross-cutting levers need to be activated:

(1) Credible monitoring, reporting and verification across the four sustainability dimensions,

(2) Credible business models which consider the four dimensions, and

(3) Adequate legal regimes which ensure balance across the four sustainability dimensions as the GGR scales up.



2.2 Develop business models and liability regimes that create value and share risk

The role of business models in attracting private investment

Developing robust business models is essential to attract private investment and scale GGR technologies, particularly where innovation is required. Business models define how GGR companies create, deliver, and capture value, which is key to enabling sector growth. Unlike traditional clean tech sectors with tangible demand, established revenue models and existing ecosystem infrastructure, GGR firms must navigate emerging and uncertain markets for negative emissions offtake. Investors need to see how revenues will be generated whether through carbon markets, tax credits, or other instruments and what risks threaten those revenues. To date, most GGR start-ups and pilot projects have effectively been funded by high-risk capital from philanthropic funders, governments, or early corporate buyers. However, scaling beyond the demonstration stage will require more commercially viable and investable models by attracting risk-adjusted capital off balance sheet at acceptable costs of capital.

The current small scale of the global GGR market presents both a challenge and an opportunity for private investors. Understanding the perspectives – opportunities and risks – and providing clear direction and transparency to those commercial actors involved in GGR innovation and project development, including corporates and investors, is essential for investment to flow. Scenario-based tools, such as value pool modelling, can help test different business model options and assess where value might accrue over time and these insights can support the development of models that align incentives across developers, investors, and end buyers [24].

> "Understanding perspectives and providing clear direction and transparency to those commercial actors involved in GGR innovation and project development is essential for investment to flow."

GGR-D Insights: Delivering co-benefits alongside carbon removal through land-based GGR.

Given current uncertainties in costs and policies, many actors (companies as well as farmers and land-owners) are actively experimenting with strategies to enhance revenue generation [25,26]. Beyond traditional carbon credit mechanisms and voluntary carbon markets, there is a growing emphasis on co-benefits and co-products, i.e., additional marketable goods derived from GGR activities, which may also help deliver broader environmental, economic and social outcomes. For example, BECCS projects may produce electricity, hydrogen, bio-oil or biofuel alongside carbon sequestration. The biochar production process can yield biofuel and bio-oil as co-products. Biochar and enhanced rock weathering applied by farmers to agricultural soils can improve crop yield and reduce fertiliser use under certain conditions. Conventional methods, such as afforestation and peatland restoration, can offer biodiversity enhancements that could be subsidised or included in nature markets. This value needs to be defined, and may take the form of removal credits, physical products and monetizable or non-monetizable co-benefits.

Where GGR methods intersect with traditional agriculture, energy (biomass) or waste sectors, farmers and land-owners may take on various roles within the value chain; this value chain needs to be integrated forward or backwards to function successfully. All actors involved therefore need to be part of a participatory process for business model design. Farmers may be growing biomass or may adopt and operate products (biochar or rock dust, and machinery, for example), or may produce products themselves (for example, biochar).

By integrating co-benefits, companies and farmers or land-owners can diversify revenue streams. Companies may be developing their businesses primarily with removal credits in mind: a "carbon plus" business model can help mitigate uncertainties inherent in the evolving demand for carbon removal. In contrast, the business model for farmers might be "plus carbon": for example, perennial biomass crops deliver energy, while any carbon sequestration is seen as additional. Revenue stacking impacts the integrated value chain, backwards and forwards, with differential impacts according to the business model and the various roles of the value chain actors.

Taking into account investor perspectives
Despite growing interest, private investors remain cautious due to the substantive risks associated with GGR technologies' scale-up. The global GGR market is still small and fragmented, and many investors see the sector as a subset of high-risk deep tech. Uncertainties fall into four broad categories: capital, market, political/regulatory, and technological. Flexibility and adaptability in business models are highly valued by investors. Insights from interviews suggest that while investors are generally indifferent to the specific technological pathways or detailed revenue models of GGR firms, they strongly favour business models that demonstrate adaptability, ability to pivot, diversify revenue sources, and respond to changing market dynamics.

Government's role in shaping investment conditions
While the creation of carbon markets is a foundational step, governments must go further in the next five years by actively shaping investment conditions through clear, consistent policy frameworks and targeted risk-sharing mechanisms. A key unresolved barrier is the fundamental question of "who pays for GGR and how?" – a challenge that underpins many of the uncertainties facing the sector. Section 2.3 provides an overview of research to assess different economic policy options. Clarifying long-term use cases for GGR is essential not only for allowing capital to be better priced and unlocking broader pools of capital but also for establishing the institutional systems and processes that will be needed to support deployment.

Legal liability regimes
Legal liability is a cross-cutting risk that affects all parties along the entirety of the GGR value chain [27]. Varieties of liabilities include responsibility for storage reversals, routine environmental impacts (e.g. surface and groundwater pollution, noise and odour) and land-use planning considerations. Determining who is liable when a GGR project goes wrong and what are they liable for and to whom, requires a full understanding of the regulatory regime pertinent to a given GGR technology (see Section 2.4). These regimes are a mix of generic pre-existing regulation and new rules designed to address the particularities of GGRs. For example, in the case that geological storage fails in the DACCS or BECCS context, whether liability should sit with the project developer or offsetter is a key determinant of risk/reward allocation. Properly designed, liability rules enable the effective management of GGR risk and provide certainty for the GGR to be investable, and socially and environmentally robust.

2.3. Put in place policies and partnerships tailored to suit individual GGRs

Tailoring and sequencing policies to suit the technological characteristics of individual GGR methods
Novel GGR methods, including those that store carbon permanently at geological timescales, are still in pilot to very early commercial stages, thus necessitating policy support to bring down costs so they can become viable and reliable options. A broad suite of policy instruments is available that address the multiple barriers facing scale-up of geological carbon removal methods, each with distinct merits. These instruments have been evaluated by CO_2RE researchers both individually and in combination, taking into account government expenditure and administrative ease [28].

Policy instruments must be matched to a GGR's TRL and deployed in combination to address all externalities and technology-specific barriers, evolving as technologies mature (see Figure 5). While an Emissions Trading Scheme (ETS) and a revenue support mechanism – for example, 'Carbon Contracts for Difference' (CCfD) – can support relatively mature technologies such as BECCS, DACCS and Energy from Waste (EfW)[v], early-stage support through tax incentives or research grants, for example, is needed for lower TRLs to ensure that a diverse portfolio is maintained. This would allow technologies to cross the 'valley of death' and move towards a positive feedback cycle of growth and investment across the whole portfolio [29] (see also Section 2.8).

Designing an effective sequence of policies along the technology innovation and development process necessitates accounting for market conditions, firm dynamics, and learning effects. There is ongoing CO_2RE research to determine how policymakers can sequence GGR policies in order to reach net zero goals.

"Policy instruments must be matched to a GGR's Technology Readiness Level and deployed in combination to address all externalities and technology-specific barriers."

v Subject to the additional interventions outlined in the section above on business models.

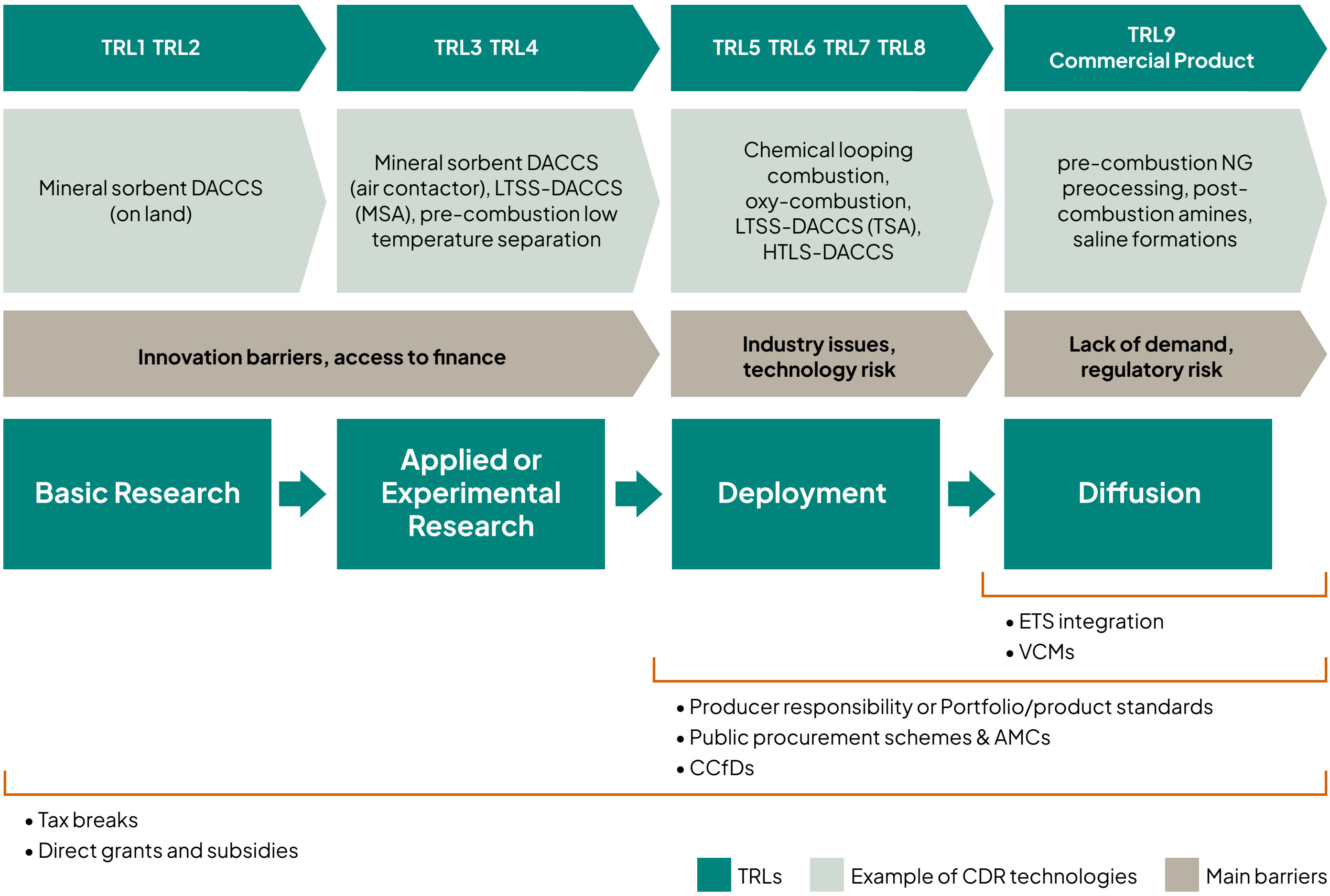


Figure 5: Technology innovation and development process diagram. The technology innovation and development process is structured into four key phases. Selected examples of GGR methods at various TRLs are depicted in grey while barriers to innovation are shown in green. The bullet points provide examples of policies that fit to the various TRL stages.

GGR-D insights: Policies for land-based GGR

While the policy framework developed here is broadly applicable to all GGRs, various factors affect the selection and design policies for GGRs that make use of the land [30]. These factors vary between individual land-based GGRs but could include: timing and durability of storage; MRV and carbon accounting issues; land-use and resource considerations; competition with more costly industrialised methods; balancing carbon outcomes with co-benefits; and farmer, land manager and public perceptions. In addition, land is a devolved area of policymaking. Therefore it is vital that GGRs are integrated into land-based policy – especially the Land-Use Framework for England – as well as other policy areas including energy, industrial policy, waste, nature restoration and transport.

Tailoring support according to market conditions and investor expectations

As well as tailoring government support structures to the unique characteristics of individual GGR technologies, these structures must also be carefully tailored to prevailing and future market conditions and investor expectations to attract private investment in the sector. A one-size-fits-all approach is likely to be inefficient and risk not achieving strategic effects.

One consideration is whether GGR technologies are dominated by capital or operating costs. For instance, support is essential for capital-intensive technologies like DACCS and BECCS. While CAPEX grants can reduce the need for revenue support mechanisms in capital-intensive technologies, they offer limited benefits for OPEX-dominated technologies such as biochar and ERW.

Public-private partnerships as enablers of investment

Although policy instruments such as integrating GGR credits into the UK ETS and revenue support mechanisms offer predictable revenue streams that potentially de-risk private capital, these instruments alone may be insufficient to attract private capital[vi]. Coordinated public-private joint ventures could be an enabler of private sector investment at scale. Public-private collaboration can reduce risk and enhance value creation opportunities. Strategic partnerships between government, industry, and investors can also improve access to affordable finance, encourage long-term policy certainty, and establish timely market rules.

In the case of public-private collaborations, Table 1 highlights the applicability of various types of public-private collaborations to greenhouse gas removal technologies and demonstrates the importance of designing technology-specific policies, particularly when new policy instruments are being introduced.

The following types of collaboration have been considered: **Joint venture:** a public entity and a private actor jointly develop, finance and operate a project; **build-operate-transfer**: a private-sector actor finances, constructs and operates a facility for a designated period, after which ownership is transferred to the public sector; **private finance initiative**: a private entity is responsible for financing, designing, building and operating a public asset, and the government repays the private partner over time based on the performance or availability of the service.

2.4. Address regulatory gaps and barriers to enable GGR to scale

A comprehensive regulatory review of GGRs in the UK and devolved nations has clarified how GGRs are currently regulated and where there are gaps and areas for improvement in the regulatory regimes [33]. The picture is extremely varied. In some UK jurisdictions, there is no existing legislation to regulate the GGR activity directly or comprehensively; for example, enhanced rock weathering activities. For other GGR methods, there are regulatory gaps or barriers in pre-existing legislation. Biochar and ERW are two examples where improvements to regulatory regimes across the UK would help to scale the activity and unlock investment (see GGR-D Insights box below on *Regulation of biochar and ERW*). In some cases, regulators are spotting gaps and working to fill them.

Although certain regulatory challenges are GGR method or jurisdiction-specific, there are cross-cutting observations which have become apparent through this review. One notable challenge is planning and permitting regulations throughout the UK, particularly for novel GGR methods in the industrial sector such as BECCS. The time taken for GGR project developers to receive the necessary permissions or permits, and the overall accessibility and understanding of planning law as relates to GGRs, are both noted as hindrances to most projects which participated in the review. Large projects may have the capacity to identify the appropriate

Policy	Joint venture	Build-operate-transfer	Private finance initiative
BECCS power		✓	✓
DACCS	✓	✓	
ERW	✓		
Biochar			✓

Table 1: Public-private collaboration applicability to greenhouse gas removal technologies [32].

vi To test how anticipated policy designs might influence investment viability, a vulnerability analysis of GGR technologies has been conducted using a financial model. For further information see reference [31].

support from the designated regulator, while start-ups can struggle to find the appropriate or efficient support or signposting. A fundamental issue which encompasses all GGR methods is a 'regulatory paradox': there is insufficient evidence (e.g. environmental impacts) from GGR activities to justify time-consuming regulatory updates while employing the requisite precautionary principle, but without a suitable and supportive regulatory framework, successful commercialisation is challenging.

> "A 'regulatory paradox' exists: there is insufficient evidence from GGR activities to justify regulatory updates, but without a suitable and supportive regulatory framework, successful commercialisation is challenging"

GGR-D Insights: Regulation of biochar and ERW

Biochar in the UK is regulated by waste law [34,35]. The waste regime imposes multiple and costly obligations on biochar operators, tying biochar to waste and hindering scaling without providing environmental safeguards. There is a clear risk that regulatory inadequacy damages the prospects of biochar as a GGR technology, dampening the interest of entrepreneurs and investors in biochar, without either implementing changes to legacy regulation or alternatively developing a new common framework for biochar across the UK. In the case of enhanced rock weathering, while each UK nation has slightly differing regulatory positions on ERW, there is currently no legislation in the UK that addresses ERW activity on agricultural land creating a lack of oversight [36]. Evidence gaps need to be unlocked for regulatory development; the lack of evidence fuels the 'regulatory paradox'. A clear regulatory framework needs to be in place for industry to continue operations or attempt to scale.

Above: The GGR Future Leaders Network site visit to the Suez energy-from-waste plant in Teesside, March 2025.
Credit: Teesside University

Above: Ince Bio Power Plant, Cheshire. Credit: Evero Energy

2.5. Embed sustainability into governance underpinned by pragmatic MRV standards

MRV for sustainable scale-up

The sustainability of GGR depends not only on what type of GGR method is being deployed, but how it is being deployed and where. GGR project-level assessments need practical but comprehensive monitoring, reporting & verification (MRV) schemes that incorporate multiple outcomes, and not just carbon removal (see Section 2.1 on the evaluation framework). The risk of offshoring environmental, social, energy and economic impacts can be avoided through establishing clear system boundaries and carrying out assessments of sustainability across the full supply chain, not just in domestic components, and over the full lifecycle of the project[vii].

There remains only limited information about the wider impacts (positive or negative) of GGR methods, especially when it comes to aspects that depend on the scale at which these technologies are deployed, and the way they are integrated within wider systems [37]. Robust MRV will help improve understanding of these wider factors, and guide GGR deployment so that co-benefits are maximised and negative trade-offs limited.

Rewarding multiple outcomes

MRV schemes can allow services such as biodiversity, food security, waste management, circular economy, reduced flood risk or enhanced water quality to be rewarded concurrently with carbon sequestration. Projects generating multiple outcomes can then be appropriately rewarded by 'stacking' or 'bundling' environmental goods (see also GGR-D Insights box on *Delivering co-benefits alongside carbon removal through land-based GGR*). Collaboration between DESNZ and DEFRA will limit the risk that one outcome is prioritised at the expense of another. For example, if carbon removal is prioritised over environmental benefits, inappropriate deployment of large-scale afforestation and biomass crops for BECCS could lead to ecologically damaging land-use changes. However, in some places, and under appropriate management, these activities could potentially provide ecological benefits – albeit at quite a limited scale [38].

vii CO_2RE researchers are currently exploring how and whether aligning MRV schemes with Sustainable Development Goals would help move global sustainability forward and maintain GGR integrity.

Above: Woodlands on Dartmoor, Devon. Credit: Mandy Schuster, NetZeroPlus

MRV standards for GGR governance

Voluntary carbon market (VCM) registries work independently, using private third-party verification that lacks transparency. Furthermore, current MRV protocols used by the voluntary carbon market focus exclusively on greenhouse gases, with sustainability being a "gateway" criterion at project initiation only. The same is true of rapidly developing international standards such as the UNFCCC Article 6.4 and the EU's Carbon Removals and Carbon Farming regulation [39]. Where socioeconomic and environmental co-benefits are advertised, there is little evidence that a well-established MRV approach is being employed [40].

Both business model support and regulatory approvals should ideally be underpinned by MRV standards. GGR methods such as BECCS and DACCS have been prioritised as the subject of standardisation by the UK government and BSI. They are considered relatively straightforward to standardise as they are engineered closed systems that provide "permanent' removals. In fact, the biomass supply side of BECCS is complex with uncertainties about scale-up. Other systems such as enhanced rock weathering and biochar are open natural systems, making standardisation more challenging and leading to higher MRV costs [41].

Schemes for key GGR methods need to be put in place to report GGR activity in IPCC (Intergovernmental Panel on Climate Change) national greenhouse gas inventories, including biochar, enhanced rock weathering and direct air carbon capture and storage, before they can be counted towards UK carbon budgets or international Paris Agreement pledges.

> "Schemes for key GGR methods need to be put in place to report GGR activity in IPCC national greenhouse gas inventories before they can be counted towards UK carbon budgets or international Paris Agreement pledges"

2.6. Scale responsibly by attending to societal concerns and preferences

The scalable potential of GGR methods depends on them being developed in a way that is responsible to society: the potential consequences must be anticipated, assumptions must be reflected upon, society must be engaged in decision-making, and lessons learnt must be acted upon to positively affect innovation trajectories. The responsible innovation and societal engagement work package in the CO_2RE Hub has collected a wide range of evidence through multi-criteria analyses, national surveys and experiments, deliberative workshops, ethnographies, critical reflections and analyses, and reviews and syntheses to support the responsible scaling of GGR in the UK [42].

Nationally representative multi-criteria appraisals of GGR show that the public supports the inclusion of GGR in UK climate policy. Regional differences in GGR appraisals show that certain UK regions could be more or less likely to support or oppose certain GGR deployments, making it important to match up any physical requirements for siting GGR methods with appropriate social contexts (Figure 6). In deliberative workshops, GGR was seen by the public as the responsibility of government and industry rather than of individuals. However, there is caution about whether biochar, perennial biomass crops, and peatland restoration would be "worth it", given concerns about efficacy, costs and trade-offs.

Going forward, field trials will have significant consequences for public engagement with carbon removal. Review and ethnographic research shows that while they are unlikely to settle controversy, field trials are important sites for taking into account emerging public concerns and understanding changing perceptions. Ethnographic research on protests sparked by Planetary Technology's trial of ocean alkalinity enhancement in St Ives, UK shows that the trial design did not account for place-specific impacts on everyday community life and the local environment, even though public consultation had been carried out. Public engagements must also explore disagreements about place-based impacts between those initiating the trials and local communities, and link trials with (existing) local climate action.

Synthesis and critical analysis of GGR research shows that GGR communication is susceptible to framing effects, requiring careful use of analogies, avoiding the 'nature-based' label, explaining that GGR can only help on the margins of substantial emissions reductions, and showing alternative implementation contexts. Specifically, framing GGR methods as 'nature-based' or 'engineered' is problematic because the line drawn between them is arbitrary, privileging certain methods for no substantive reason and diverting attention away from their actual qualities. Relatedly, the popularity of forestation when viewed ostensibly as a 'nature-based' approach is harming support for other GGR methods. We might therefore query the way in which tree planting is often conflated with climate action, and instead focus tree-planting policies on its other benefits, such as biodiversity support.

Survey experiments explored how public attitudes to two types of novel GGR – direct air carbon capture and storage and ocean alkalinity enhancement – varied in different implementation contexts [43]: different forms of governance (bottom-up versus top-down) and types of market (planned versus liberal economy) were considered[viii]. The surveys showed that for ocean alkalinity enhancement, GGR implementation in a bottom-up, planned economy scenario was preferred. For direct air carbon capture and storage, perceptions did not change across variety of alternative implementation contexts.

Above: Newly planted Miscanthus plugs under biodegradable mulch film - commercial scale trial at Bishop Burton College. Credit: Chris Ashman

viii Four scenarios were considered: 1. 'liberal market top-down' – neoliberal, market-led, UNFCCC-style governance; 2. 'planned economy top-down' – authoritarian sate rule, centralised large-scale CDR; 3. 'liberal market bottom' – free market, individualists and entrepreneurs, risk-driven, tech-centric; 4. 'planned economy bottom-up' – small-scale, grassroots community-led, decentralised / modular CDR.

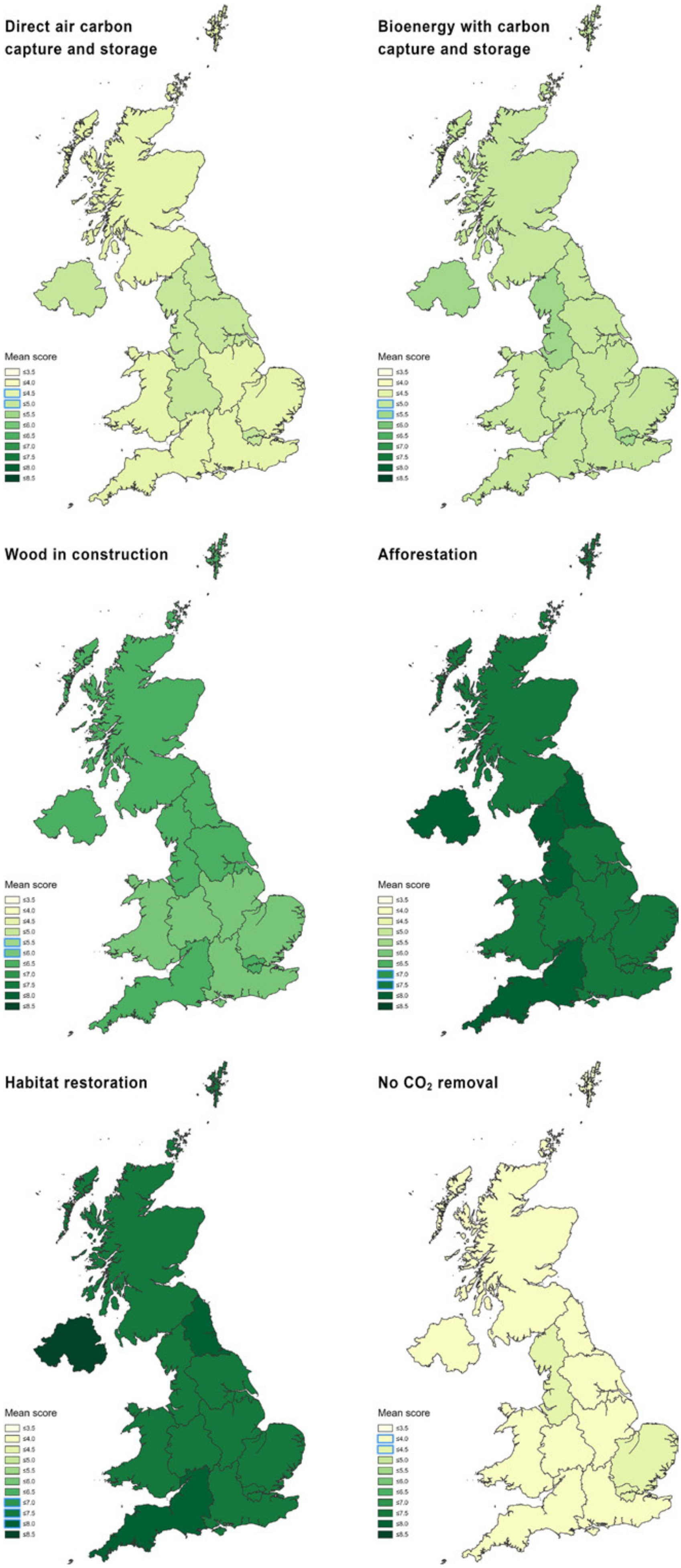


Figure 6: Public appraisal of GGR methods by UK geographical region [44]. Mean scores calculated from respondents' scoring of different GGR options against three chosen criteria [45].

2.7. Continue to collect data and share it to speed up rates of learning

Data emerging from the GGR-D demonstrators, alongside other publicly and privately-funded 'first-mover' projects in the UK, is a valuable resource for decision-makers. There are different kinds of data, from research data that informs scientific understanding of removals, co-benefits and trade-offs to commercial data that is useful to private sector actors. Data helps speed up learning curves, reducing costs and enabling the science, business, regulator and policy communities to advance hand-in-hand. It enables the shift from a situation where gaps in scientific knowledge prevent policies being put in place or investment decisions made, to one where scientific understanding allows any uncertainties and risks to be managed through policy; for example, through robust MRV protocols or buffer pools.

There is an opportunity to create value through sharing data effectively if the appropriate incentives[ix] and mechanisms are in place, benefitting all those involved in this nascent sector. However, much of the data is proprietary and commercially sensitive. An independent intermediary would be needed to facilitate data sharing underpinned by the appropriate frameworks and infrastructure. This data can feed into key tools used by the research community and government for assessing the scale-up of different GGR options such as lifecycle analysis, scenario modelling and value chain mapping, for example, or into decision-making tools for GGR project developers.

In turn, it will be vital to ensure the relevant data for decision-making continues to be collected through research trials and ongoing monitoring of projects on the ground, following well-established methodologies for sampling, testing and interpretation. For example, researchers from across the GGR-D programme have identified the value of 'consequential' lifecycle methods in assessing the evolution of GGR deployment over time alongside broader system impacts[x]. The researchers have adopted a data framework[xi] and mapped data availability, highlighting what data is useful and the need for continued data collection over the long-term as GGR methods scale up [47].

In addition, good visibility of what is happening 'on the ground' including the pipeline of projects being delivered by both public and private sector actors, is valuable for informing progress on scale-up. Data on novel GGR deployment in the UK and by UK companies operating abroad are currently limited and fragmented [48].

2.8. Maintain an innovation pipeline of GGR methods

Maintaining a diverse portfolio of GGR options increases the likelihood that the UK is able to meet climate commitments while ensuring that the UK does not rely on methods that later prove to be insufficient or are associated with negative impacts. An optimal combination of technologies can be sought with the flexibility to adjust as circumstances change (see also Section 4.3).

Key to this diversity is continued support for the GGR 'innovation pipeline', with review stages so that successful ideas can be nurtured and progress to commerciality, while other ideas can be filtered out at the appropriate stage. This support comprises three key stages:

1. Foster early-stage GGR innovations through **discovery science and proof-of-concept research**, to increase the pool of novel technology options. CO_2RE's Pathfinder programme and other flexible funds managed by GGR-D demonstrator projects highlight the number and diversity of promising ideas, if support is available.

2. Maintain support for **long-term field sites** which provide crucial data on real-world carbon storage, including durability, best practice in measurement, wider environmental effects, and deployment configurations. Trial sites should cover the breath of storage types which GGR must use: trees, soils (including peatlands), geological reservoirs, oceans (including coastal habitats), or products in the built environment (mineral and bio-based). The value of maintaining existing demonstrator field sites (which cover some – but not all – of these types) is further highlighted in Section 4.6.

3. Provide **pre-commercial innovation support** for higher-TRL technologies, to achieve commercial viability. The DESNZ Net Zero Innovation Portfolio supported some of these until 2025. In future, it will be important to maintain support for technologies, including those not yet integrated into the policy landscape. An assessment of policies applicable at different TRLs provides detailed information about suitable policies for pre-commercial support [49]. The importance of early-stage support as a

ix For example, buyers or funders of carbon removals can require data sharing, as is the case for Cascade Climate's ERW data quarry initiative

x This relies on time-dependent data on the full GGR life cycle and baseline, as well as background information; for example, the carbon intensity of the energy that has been used along the supply chain; see reference [46].

xi This framework is based on IPCC 'tiers' that identify the specificity of the data available to underpin lifecycle analysis: whether it is an international default, specific to a country or specific to location and point in time.

Above: 3rd International Conference on Negative CO_2 Emissions hosted by the CO_2RE Hub, June 2024, Oxford. Credit: Andrew Bailey

foundational measure for de-risking investment becomes evident when the GGR and offshore wind sectors are compared [50].

There will also be a role for continued support of GGR options, especially those involving land use, that may not offer the same magnitude of carbon removal but have valuable co-benefits such as delivering ecosystem services or benefits for agriculture.

2.9. Engage internationally to shape global decision-making and speed up deployment

As GGRs must be deployed more rapidly and in many more countries if the goals of the Paris Agreement are to be met, there is the opportunity for the UK to play a strategic role in enabling their effective scale-up internationally [51]. The UK will ultimately benefit from developments in other countries if they enable cost reductions through technological learning, and if the UK chooses to make use of international transfers under Article 6 of the Paris Agreement.

For example, the UK can support the development of credible climate finance flows to developing countries for funding GGR, as well as working in partnership with researchers from other countries to fill gaps in evidence and building on existing global collaborations such as the State of CDR initiative and Mission Innovation[xii]. It can also contribute to global governance[xiii], drawing on its extensive research base and expertise.

There is currently no institutional structure to foster the exchange of GGR data and capability building across countries. Mission Innovation provides some co-ordination – but it is limited in its duration, number of participating countries, and focus on technology innovation. A gap exists for an ongoing multilateral organisation to:

- monitor project developments, financing and deployments;
- build capacity across jurisdictions, especially in the Global South;
- share learning, support co-operation and build participation over time.

There are parallels between the current state of GGR and the state of renewables in the 1990s. At that time, wind and solar projects were a niche for committed environmentalists and engineers. Their path to success today (now providing essentially all new capacity additions for global power) stems in part from the creation of multilateral institutions such as IRENA[xiv] and REN21[xv] to enhance international data sharing and capacity building. The UK has an opportunity to do similar for GGR, building on its domestic capabilities and co-operation with Mission Innovation partners and others.

xii Mission Innovation: Carbon dioxide removal mission. https://mission-innovation.net/missions/carbon-dioxide-removal/

xiii For example, the upcoming IPCC methodology report on the inclusion of carbon removal in national inventories.

xiv International Renewable Energy Agency https://www.irena.org/

xv REN21: Renewables Now! https://www.ren21.net/

CHAPTER 3.

INDIVIDUAL TECHNOLOGIES FROM THE GGR-D PROGRAMME

3.1 Introduction

Table 2 sets out the key characteristics of the five land-based GGR methods from the GGR-D programme. The characteristics include the multiple steps in the full supply chain, and the associated routes by which GGR occurs through the carbon cycle. This highlights the range of steps that need to be considered when carrying out lifecycle analysis, identifying TRLs (which may vary for the different steps within each supply chain) and addressing policy design.

GGR type	Steps in a full supply chain required for removal accounting [52]	GGR route through the carbon cycle [53]
Woodland creation and management	Saplings cultivation in nurseries; seeding or sapling planting; young trees protection (e.g. fences); thinning and management; harvesting (if applicable); regeneration and replanting	(Biological capture via trees) -> (Storage in trees and soils)
Peatland restoration	Rewetting; revegetation by planting or seeding native species; hydrology management; soil amendment	(Biological capture via rewetting and revegetation) -> (Storage in soils)
Biochar	Biomass cultivation and harvest; biomass processing; biochar production; biochar application (to land or in construction materials or by burying)	(Biological capture via cropping and forestry residues, organic wastes, or purpose-grown crops) -> (Storage in biochar)
Enhanced rock weathering	Rock mining; rock crushing; rock transport; rock application to soil	Geochemical capture via spreading crushed silicate rocks on land or ocean) -> (Storage in the oceans or as bicarbonate or soil bicarbonates)
Perennial biomass crops for BECCS	Biomass sourcing (cultivation, harvesting, processing, transport); bioenergy production with CO_2 capture; CO_2 transport; CO_2 geological storage	(Biological capture via plant growth -> cropping and forestry residues, organic wastes, or purpose-grown crops) -> (Concentrated CO_2) -> (Storage in lithosphere)

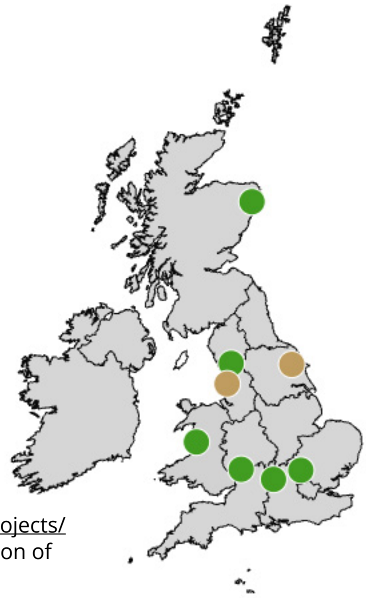
Table 2: Key characteristics of the five demonstrator methods including steps in a typical supply chain and GGR routes through the carbon cycle employed

The following sections provide an overview of the key research findings from each GGR method and the policy implications.

3.2 Perennial biomass crops for BECCS

The Perennial Biomass Crops for Greenhouse Gas Removal (PBC4GGR) demonstrator is led by Aberystwyth University, in collaboration with the UK Centre for Ecology and Hydrology, Rothamsted Research, University of Aberdeen, and the Communities and Countryside Research Institute. The project demonstrates establishment techniques that maximise yield while minimising greenhouse gas emissions, establishes the conditions required for farmer uptake and wider societal acceptance, and quantifies the scope for greenhouse gas removal [54].

Map of partner institutions and field sites



Visit https://co2re.org/ggr-projects/ to access an interactive version of this map

PBC4GGR – key successes

- Improved the evidence base on greenhouse gas impacts of transition of grassland to biomass crops
- Identified next steps to improve on best practice crop establishment agronomy
- Successfully established a commercial scale Miscanthus field from a novel seed-based variety that could overcome supply chain bottlenecks.
- Identified key barriers to farmers planting perennial biomass crops.
- Demonstrated the effectiveness of perennial biomass crops at delivering GGR when planted at different locations.

Demonstrator research and key findings

In the absence of commercial-scale BECCS facilities, perennial biomass crops are viewed by stakeholders as an energy crop as opposed to a GGR technology. However, since BECCS can provide GGR much faster than afforestation (because trees initially grow very slowly, whereas biomass crops grow rapidly), near-term GGR at scale has a very high reliance on perennial biomass crops BECCS, with the benefits of afforestation becoming significant after 2050. Biomass crops need to be planted at scale around 3 years before the hard infrastructure of CCS is commissioned in order to provide sufficient feedstock, and the location of biomass end users should play a large part in determining the areas for biomass planting in the early stages of industry growth [55].

Farmers have historically been reluctant to plant perennial biomass crops. There are many demands on 'marginal' land that is less suited to food production (e.g. to meet biodiversity goals and for afforestation) and it cannot be assumed to be available for biomass crops [56]. Farms that are already mixed enterprises are more open to perennial biomass crops, in part as they regularly consider the suitability of different areas of the farm for different purposes. However, biomass crops reduce flexibility because of the need for them to remain in the ground for more than 10 years, which is unappealing to some farmers, particularly given current policy and market uncertainties.

While the major GGR effect of perennial biomass crops is via end-use of the harvested above-ground material, the potential to breed varieties that increase sequestration below-ground is also of interest, and while we cannot yet breed specifically for this trait, we have observed differences between Miscanthus varieties in below-ground soil carbon accumulation [57].

The current best practice agronomies for establishing Miscanthus and willow have been proven to be the most effective, but active weed management is required, particularly in the first two years after establishment. Developments in technologies such as single-pass tillage/planting machines, and robotic weeders would decrease establishment costs and so would increase the attractiveness of the crops for farmers [58]. There is scope to decrease the greenhouse gas emissions of establishment with specific modifications, including via strip till[xvi] as opposed to inversion ploughing, and via addition of biochar. We have for the first time demonstrated at field scale a new high-yielding seed-propagated Miscanthus genotype which would allow planted areas to be scaled up much faster than with vegetative propagation. It also reaches commercial yields earlier than the most commonly planted variety, *Miscanthus giganteus*.

PBC4GGR has significantly improved the evidence base on the long-term carbon impacts of land-use transition to biomass crops, particularly in relation to the transition of grassland of different types and ages to biomass crops. It is now clear that rather than avoiding planting into grassland *per se*, we need to avoid planting into high-carbon soils as the carbon loss on transition will take many years to be reversed. This is important evidence to clarify the potential benefits of biomass crops when planted in different land types. We have also undertaken major revisions and updates to the models that underpin yield predictions for Miscanthus and willow, including incorporating data from previous studies and developing models for below-ground biomass and soil carbon change for both crops [59].

xvi Strip till is an approach to land cultivation where only the narrow strip that a row of crops is planted in is cultivated, as opposed to the whole field being ploughed. In the case of Miscanthus, this decreases soil disturbance by 50%.

Above: Miscanthus is a perennial that grows 2–3 metres each year. It sheds its leaves over winter, and the dry cane is harvested in the spring. Pictured here at full height (October) in the PBC4GGR demonstrator field at Bishop Burton College. Credit: Chris Ashman

Policy implications

Cohesive policymaking is vital to manage potential conflicts between alternative land uses [60]. For example, the funding for flower-rich grass margins, blocks or in-field strips within the Sustainable Farming Incentive (SFI) scheme in England resulted in a collapse in sales of Miscanthus and willow planting material.

Planted areas of perennial biomass crops in the UK have remained relatively static for around 15 years (approximately 10,000 hectares), with planting and removal rates of around 500 hectares per year. This compares to a 2050 target of 750,000 hectares. The key constraint for the first phase of industry expansion (from 10,000 hectares to 100,000 hectares) is a sufficiently high price for the crop to justify the upfront investment in planting material. A rapid evidence review on approaches to incentivising biomass crop planting and creating a market and value chain is required. Understanding the potential impacts of different policy levers is needed (e.g. if end-user industries were required to source a proportion of their biomass from the

Above: When grown as a perennial biomass crop, willow is harvested every 2–3 years in the winter. Pictured here in the PBC4GGR demonstrator field at Myerscough College. Credit: Will Macalpine

UK, or production of initial planting material was subsidised, or planting grants were provided to farmers). This could reasonably be followed by translating these findings into near-term policy. Opportunities for incentivising these crops by paying for the ecosystem services generated (carbon storage, flood mitigation) through new SFI actions, water companies and natural capital markets should also be examined. The industry is small – there are just two suppliers of Miscanthus – and it will require policy support to increase private sector investment in machinery and build up expertise amongst contractors to support expansion of planted areas. Evidence gaps and longer-term research needs (for example, relating to long-term impacts on soil carbon and biodiversity, risks relating to pests and diseases, breeding of higher yielding varieties, resilience to future climates [61,62]) will follow as the industry and planted areas expand.

Summary table

Is there sufficient land available?	✓
Are there sufficient varieties and agronomy for initial industry scale-up to 100,000 hectares?	✓
Is there a suitable policy and delivery framework in place?	✗
Is there a suitable farming advice service and contractor network?	✗

3.3 Biochar

The Biochar Demonstrator is led by the University of Nottingham with support from colleagues at Bangor University, the University of Leeds, Forest Research, UK Centre for Ecology and Hydrology and the Scottish Universities Environment Research Centre. The programme has addressed the interrelated topics of biochar production and stability, deployment, economics, stakeholder perspectives, and the implications for policy and regulation.

Map of partner institutions and field sites

Visit https://co2re.org/ggr-projects/ to access an interactive version of this map

Biochar Demonstrator – key successes

Classified low-cost feedstocks and identified optimum locations for biochar production	Developed a method for stability, accepted by the EBC	In field trials, demonstrated no detrimental effects of deployment at 10 T/ha	Identified co-benefits including moisture and nutrient retention, and improved crop quality in some cases	Identified a need for incentives and evidence on efficacy and co-benefits for farmers

Demonstrator research and key findings

Biochar production A range of agricultural residues and related feedstocks exist in a sufficient quantity to produce over 1Mt of biochar per annum, and hence enable economically efficient production. Optimal locations for biochar production can be identified by mapping the geographic distribution of these feedstocks; in particular, the geographic distributions of straw and anaerobic digestate (AD) have been mapped.

Broadening the available options for feedstocks, including unconventional but abundant feedstocks such as over-sized compost, food AD fibre and green waste, diversifies the pool of low-cost feedstocks and generates value for waste products, as long as the biochar produced meets relevant standards and regulation does not inhibit its use. Some of the feedstocks investigated as part of the demonstrator programme produce biochar that meets the European Biochar Certificate (EBC) agricultural grade while all the biochar produced meets the EBC requirements for aggregates used in construction.

Stability of biochar is a key determinant of its ability to store carbon durably. A method to test stability has been developed in collaboration with the EBC [xvii]. Radiocarbon measurements have indicated that minimal degradation of stable biochar occurs in mesocosm experiments. Adding basalt during biochar production could potentially enable its co-application with biochar, as long as stability is not affected.

Biochar deployment

Biochar was applied to one-hectare areas in eight arable fields at a rate of 10 tonnes per hectare. This was carried out across six farms located from north Nottinghamshire to Suffolk; soil textures range from sandy loam to heavy clay. Biochar was also applied at scale to three forestry sites and to a series of small-plot trials on two University farms. In total, over

xvii The EBC has been developed by the Ithaka Institute.

Above: Biochar being spread manually on a grassland farm at Henfaes Research Centre, Abergwyngregyn. Credit: Biochar Demonstrator

150 tonnes have been deployed. Biochar can be readily applied using a lime spreader or similar equipment, with no need to pre-charge with nutrients prior to application.

When applied to soils in different contexts, including arable and forestry sites, no detrimental crop or soil effects have been recorded to-date. A number of co-benefits have been identified in arable applications: for example, biochar has a liming effect on more acidic soils, thereby increasing some plant-available nutrients, while crop quality is generally greater in some wheat and barley crops. Other results indicate positive impacts on nutrient retention, and no significant long-term impact on biodiversity when biodiversity indicators such as microbial functional diversity, microbial respiration and earthworm biomass are used. In forestry, biochar enhanced survival and early growth of tree saplings subjected to drought. There is also potential to co-deploy biochar with other GGR methods in additional to forestry, including paludiculture for peat and the production of perennial biomass crops. In small plot trials, cumulative applications totalling 20 tonnes – representing a sequestration of 20–25 tonnes CO_2 equivalent per hectare –

Above: Biochar being applied with a tractor-mounted spreader during small-plot field trials conducted at Sutton Bonington, Nottingham. Credit: Biochar Demonstrator has been demonstrated, with considerably higher sequestration levels observed in grassland trials.

The above outcomes have been enhanced by the flexible fund where the two completed projects have demonstrated that (i) pyrolysis of biosolids (digested sewage sludge) to produce biochar is an effective means to remove environmental contaminants, while increasing nutrient retention in agricultural soils and (ii) biochar has the capacity to buffer fertiliser addition to soils, to deliver a more balanced release profile.

Policy implications

Overall, the findings indicate that the current deployment limit of one tonne per hectare in a single application set by the Environment Agency (LRWP 61) for arable land can be safely increased to 10 tonnes.

Current waste classification, which limits biochar amendment levels, and the lack of financial incentives have been identified as key barriers to the rapid scale-up of biochar deployment. For example, abundant feedstocks such as over-sized compost and food digestate currently carry waste codes.

Key factors for success include ensuring availability of low-cost feedstocks, operating at a large enough scale to minimise capital costs (approximately 10,000 tonnes of dry feedstock per annum), and identifying applications where biochar can attract value beyond sequestering carbon through co-benefits. The economics must be attractive for all supply chain stakeholders, including end-users such as farmers, if the potential of biochar is to be fully realised. The potential economic benefits and costs of biochar, including the economic value of soil improvements, require clarification.

In order to improve farmer confidence, there is a need to resolve questions around incentive mechanisms such as carbon trading and to provide evidence on the co-benefits of biochar to farmers. The public debate around biochar, as suggested by research on how biochar is represented in media, currently oversimplifies it as a climate and agricultural solution which limits debate about its benefits and risks.

Above: Preparation for biochar application during large-scale field trials at a Demonstrator Farm in Suffolk. Credit: Simon Watchorn

Below: Biochar in the field following application at Sutton Bonington, Nottingham. Credit: Biochar Demonstrator

3.4 Enhanced rock weathering with agriculture

The UK Enhanced Rock Weathering GGR demonstrator is led by the University of Sheffield, with co-Investigators at the Universities of Aberdeen, Leeds, Oxford, Heriot-Watt, Cardiff and Southampton, National Oceanography Centre, Rothamsted Research and UK Centre for Ecology and Hydrology. The project has established three major long-term ERW field trial studies to investigate the effectiveness of ERW on different types of agricultural lands typical of the UK, carried out lifecycle and scalability assessments, and modelling, and explored community perceptions.

Map of partner institutions and field sites

● Field sites
● Partner institutions

Visit https://co2re.org/ggr-projects/ to access an interactive version of this map

Enhanced rock weathering demonstrator – key successes

Demonstrated enhanced weathering delivers carbon removal in UK arable croplands and lowland and upland grasslands	Provided evidence on indications of improved soil health and no adverse effects from potentially toxic elements (PTEs) in soils or soil waters.	Produced a spatial inventory of UK silicate rock resources suitable as a feedstock	Showed that local communities are open to ERW but need evidence of efficacy and co-benefits	Assessed scalability of ERW in the UK and its possible role in UK GGR targets

Demonstrator research and key findings

Effectiveness of ERW, co-benefits and impacts

Rigorous quantification of carbon removal is essential for unlocking market-based financing and avoiding accusations of "green-washing". Rigorous methodologies for carbon removal quantification have been developed and applied in three contrasting enhanced rock weathering (ERW) field trials encompassing different soil types, crops and climate regimes across the UK.

Incorporating feedstocks into soil enables the highest rates of carbon removal, while carbon removal is also influenced by crop type and management strategy. New data and better understanding of carbon removal processes can inform commercial best practices, as well as improving models that can be used to predict carbon removal via ERW at any location, at any time point, and for any feedstock.

Potential co-benefits and dis-benefits of ERW include impacts on crop yields, soil properties (including any changes in soil organic carbon stocks) and water quality. Evidence on co-benefits indicates, on some soils increased soil pH, counteracting undesirable acidity in intensively farmed soils, lower levels of unwanted heavy metals in soil waters as they are taken up in secondary minerals that are environmentally stable, and indications of increased earthworm populations. However, these co-benefits appear to be variable across soil types; thus further investigation is required to robustly quantify such co-benefits. In terms of evidence regarding dis-benefits, no significant impacts on crop yield, or increases in metals of potential concern, nor impacts on downstream ecology have been observed to date in UK field trials.

Above: ERW field trials on lowland pastureland at Rothamsted Research, North Wyke

Lifecycle analysis and sustainability Lifecycle analysis suggests that there is a decrease in the impacts on ecosystems, human health, and resources by 2050, largely attributed to the anticipated decarbonisation of the energy used throughout the lifecycle. Additionally, a comparison of impacts with other GGR strategies indicates that ERW has relatively low impacts on environmental and human health indicators. The use of rock dust has been shown to increase plant biomass and yield in trials in the US. However, UK trials indicate that the degree of this impact varies based on several factors, including the local climate, soil conditions, the composition of the rock dust, and the quantity applied.

Scalability analysis A comprehensive spatial inventory of UK silicate rock resources suitable as feedstock for ERW has been produced, alongside a detailed upstream supply-chain assessment. Quarry-by-quarry data on current production and reserves of basic silicate rocks have been combined with UK cropland maps to simulate a range of up-scaling pathways for rock extraction and logistics to meet ERW demand in support of the UK's carbon dioxide removal targets. In every scenario, timing and location of quarry expansions and transport routes were optimised to maximise GGR under realistic supply chain constraints.

Public and stakeholder perceptions Research on public and local community perceptions builds knowledge on acceptability and on how local historical and cultural context affects people's understanding of benefits and risks. It also informs the debate on 'social licence to operate' and therefore potential deployment barriers and opportunities. Public acceptance is a critical issue for all emerging GGR approaches, but with very few exceptions very little is known about how place-based communities will view proposals for GGR deployment by local farms. And yet it is precisely these communities who will be asked to host ERW were it to be deployed in UK agriculture at scale. Deliberative community workshops held across England and Wales showed that concerns arose around the efficacy of the technique and local environmental impacts[63]. Critical differences across places were also found, not least the desire to think about innovative ways in which deployment at scale of ERW could support local agriculture and communities. New insights on socially optimal conditions for expanded quarrying and logistical activities have also been identified.

Above: ERW field trials on arable land at Rothamsted Research, Harpenden

Policy implications
The spectrum of scenarios, illustrating the inherent trade-offs between carbon removal potential, infrastructure demands and potential social and environmental impacts, provides a robust evidence base to support strategic planning and decision-making. This evidence can help policymakers to identify priority supply streams and where regulatory adjustments, accelerated permitting or targeted investments in transport and processing infrastructure will be needed to unlock scalable ERW.

ERW is debated through various frames: as a means of carbon removal, as a path to soil restoration for farmers, as a contribution to food security, or as financialisation through the system of carbon credits, with these different frames implying different solutions for policy.

Policies aimed at incentivising responsible deployment and gaining acceptability among directly impacted communities, such as agriculture, are essential to sustainable and long-term growth of ERW [64]. High initial prices, the lack of consistent methodology for issuing carbon credits and lifecycle carbon emissions associated with a deployment are the main challenges of scaling ERW through the voluntary carbon market. Future research needs to explore the co-deployment of ERW and other GGR technologies and utilise long-term (>10 years) instrumented ERW field trials to evaluate processes that regulate GGR efficiency and agronomic and economic co-benefits. In the UK, there is currently a significant regulatory gap: while each UK nation has slightly differing regulatory positions on ERW, there is currently no legislation in the UK that addresses ERW activity on agricultural land which creates a lack of oversight (see also Section 2.4). This presents a major barrier to scale-up of ERW.

Above: ERW field trials at Plynlimon, mid-Wales: upland, unimproved grassland. Credit: Jade Hatton

3.5 Woodland creation and management

NetZeroPlus (NZ+) is a UK Greenhouse Gas Removal (GGR) Demonstrator led by the Land Environment Economics and Policy Institute (LEEP) at the University of Exeter working alongside others at Exeter, the University of Aberdeen, Forest Research, the National Trust and UCL. The demonstrator examines all aspects of forestry, including forests, woodlands and hedgerows, soils and in timber products.

The demonstrator addresses not only the technical challenge of carbon sequestration but the broader systemic question: *How do we make better decisions about land use in a complex, interconnected environment?* GGR interventions like tree planting or peatland restoration bring significant carbon benefits – but also pose trade-offs, affecting food production, biodiversity, water quality, recreation, and rural economies. NZ+ provides a pioneering framework to help stakeholders navigate these trade-offs transparently and effectively[65].

Map of partner institutions and field sites

Visit https://co2re.org/ggr-projects/ to access an interactive version of this map

NetZeroPlus – key successes

- Filled key gaps in the evidence base on carbon removal by woodland creation
- Developed new MRV methods that provide real-time evidence and carbon accounting
- Modelled risks to storage permanence, including drought, fire, extreme weather, pests and disease
- Improved understanding of the full range of consequences of land-use change
- Provided open-access decision support tools for policymakers, businesses and individuals

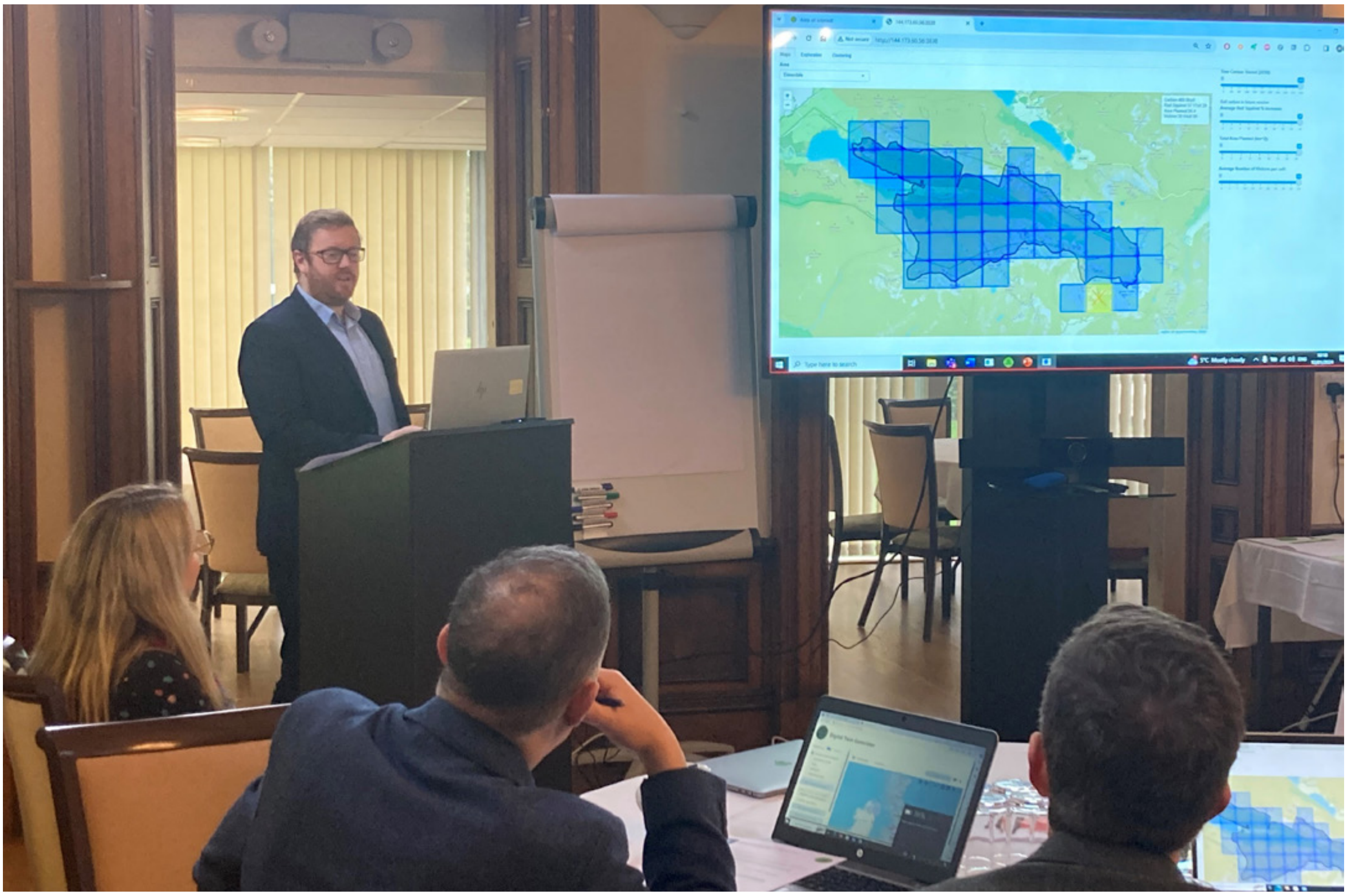
Demonstrator research and key findings

The project has created new evidence on carbon sequestration in different types of woodlands, including in natural colonisation or 'rewilding' and other types of woodland, through detailed measurements of the sequestration process. It has examined how climate change might affect different species of tree and hence decision-making on tree planting for climate change adaptation. It has also used novel remote sensing to estimate national woodland distribution.

Results show that the UK has very significant GGR potential via afforestation but stress that deployment must be guided by nuanced, whole-system analysis. Key findings include quantification of the impact of spatial targeting upon greenhouse gas storage. Planting in the right places can increase greenhouse gas removal by double, triple or even more. However, planting in the wrong locations can very significantly reduce storage or even lead to net emissions. The negative impacts of planting trees on peatlands (where they dry out the peat and emit greenhouse gases) are well known. However, the analysis of trade-offs delivered by NZ+ emphasised other potential pitfalls such as the impacts that planting on some types of agricultural land can generate; for example, by offshoring food production to higher-emission overseas farming systems. NZ+ research also highlighted the temporal dimension of afforestation for GGR. Trees store relatively trivial amounts of carbon in the early years after planting and only subsequently reach the rapid rates of growth which make afforestation such a cost-effective approach to GGR. Therefore tree planting to hit the 2050 net zero commitment needs to be front-loaded with a rapid deployment of planting to optimally contribute to the net zero commitment [66].

The researchers have co-developed decision-making tools in close collaboration with a range of key land and policy stakeholders to ensure real-world relevance and applicability. Partners include Forestry England, Defra, the Ministry of Defence, National Forest Company, National Trust, Woodland Trust, Network Rail and eftec. These organisations have helped shape the project's priorities, informed its scenarios, and tested its tools – ensuring the findings are aligned with real policy and land management needs[67].

Above: Carbon flux tower at Alice Holt Forest field site.
Credit: Kate Gannon



Above: Engaging with members of the User Advisory Group on a model underpinning real-time decision support for land-use change.
Credit: Kate Gannon

Policy implications
A systems-based land-use decision framework has been created using an integrated modelling approach linking both drivers (e.g. policy, subsidies, climate targets) and consequences (e.g. carbon storage, ecosystem health, food output) of land-use change. This marks a shift from siloed planning to holistic, systems-informed land management. It allows land-use change to be examined from the perspective of the landowner: what are the incentives and risks to the farmer or landowner if policy was changed? It also allows policymakers to identify policies that will achieve certain outcomes. In addition, the JULES app, developed as part of NZ+, allows users to assess carbon storage potential at any UK location – putting research tools directly into the hands of landowners, planners, and advisers.

While GGR is essential to net zero targets, **NZ+ demonstrates that land decisions must account for the full complexity of economic, environmental and social systems.** This project offers a replicable model for joined-up, informed, and strategic land-use planning that delivers long-term climate and environmental benefits.

NZ+ goes beyond the critical issue of GGR. It lays the groundwork for a new way of thinking about land, one that is systems-based, locally informed, and nationally relevant. This approach not only improves carbon outcomes but also ensures that economic, environmental and societal co-benefits, including food production, biodiversity, water quality and recreation, are all integrated into decision-making and policymaking on a fair footing.

Next steps for the programme include: scaling integrated models for national policy support; embedding trade-off analysis into subsidy and regulatory design, and supporting decision-makers with training, tools, and guidance.

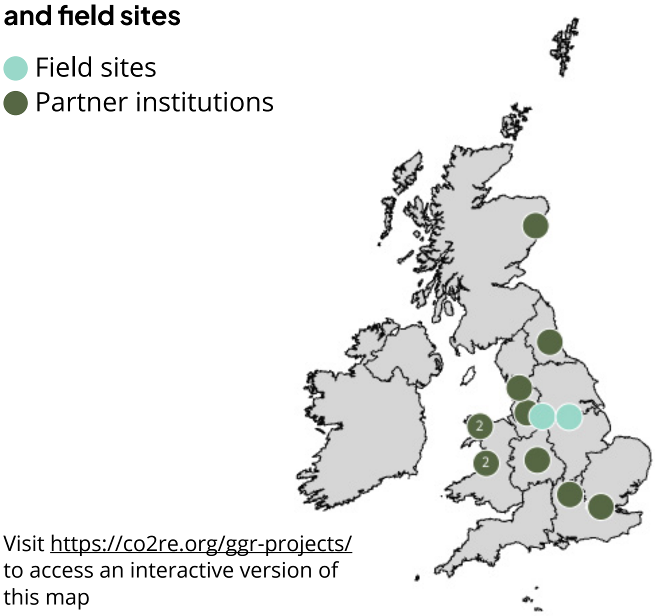
Above: Stakeholder visit to the Knepp Estate field site. Credit: James Morison, Forest Research

3.6 GGR Peat

The Greenhouse Gas Removals (GGR) Peat project (https://www.ggrpeat.org/) is led by the UK Centre for Ecology and Hydrology, with colleagues from the Universities of Aberystwyth, Aston, Bangor, Durham, East London and Manchester, and Scotland's Rural College (SRUC). The project seeks to leverage the UK's extensive areas of peatland – around 12% of the land area, and our largest terrestrial carbon store by far – to deliver large-scale land-based carbon storage and GGR.

Around 80% of the UK's peatlands have undergone some form of degradation, including large-scale drainage for intensive agriculture, extensive grazing and forestry. Whereas waterlogged peatlands can act as sustained CO_2 sinks and secure carbon stores over millennia, dry peatlands are vulnerable to rapid oxidation, releasing this stored carbon to the atmosphere. As a result, the UK's peatlands are currently estimated to be sources of around 4% of the UK's total reported emissions. Abatement of these emissions forms a core element of the UK government's Net Zero strategy through ambitious levels of restoration and re-wetting. This is supported by significant public investment in peat restoration across all four countries of the UK, and by growing private investment via the voluntary carbon market, based on established mechanisms such as the Peatland Code.

Map of partner institutions and field sites



Visit https://co2re.org/ggr-projects/ to access an interactive version of this map

At present, targets for peatland restoration focus solely on the abatement of emissions, with little or no incorporation of net CO_2 removal or GGR. This reflects the recognised challenges of restoring degraded peatlands to their natural CO_2 sequestration function, the relatively slow rate of this CO_2 sequestration under natural conditions, and the fact that – although peatlands exert a strong climate cooling impact in the long term – there is a risk that elevated methane (CH_4) emissions from re-wetted peatlands may cancel out this impact in the shorter term.

GGR Peat – key successes

Introduced the novel 'GGR peat' concept to augment the shift from land emissions to removals through peatland restoration	Showed that Miscanthus establishment and initial growth on rewetted lowland peat exceeds that on dry soils	Introduced novel upland peat restoration with *Sphagnum* mosses and biochar from mown heather	Demonstrated that methane emissions from re-wetted upland and lowland peat can be suppressed to maximise net GGR potential	Identified that farmers and land manager are open to new approaches if aligned with their values and financially viable

Above: GGR Peat high water level *Miscanthus* and biochar trial, Cambridgeshire. Part of the UKCEH Pymoor research platform, hosted by Oxwillow Ltd, with additional funding from NERC (AgZero+) and Defra (Lowland Peat 3). Credit: Cookie Cut Media

Demonstrator research and key findings
The GGR Peat project seeks to overcome the limitations of conventional peatland restoration through a combination of enhanced restoration methods in the uplands, and the application of agronomic and GGR-focused approaches to maximise CO_2 uptake and storage in lowland agricultural peatlands.

Specific interventions include the active management of existing biomass and planting of peat-forming *Sphagnum* mosses to speed up ecological recovery in the uplands, and the cultivation of biomass crops such as *Miscanthus* and willow on re-wetted former agricultural lowland peat. In each case, our aim is to accelerate rates of carbon input to the ecosystem, having first halted CO_2 losses resulting from drainage. In both settings, we are also trialling the production and application of biochar to enhance the rate of carbon capture and its persistence in the system, and testing the hypothesis that biochar produced at lower temperatures (and thus retaining more of the original feedstock carbon) will be stable under waterlogged conditions, which would not be the case following application to dry mineral soils. Finally, we are testing the effectiveness of a range of measures to reduce CH_4 emissions[xviii].

To date, our experiments have shown that the identified mechanisms are effective at achieving net peat GGR under controlled conditions, potentially at high rates if biochar can be produced and applied in sufficient quantities. Biomass crops can produce high yields on lowland peat, and active interventions can accelerate ecological recovery in the uplands[xix]. The project is developing a full set of lifecycle analyses for the four demonstration sites[xx], and integrated and economically viable farm-scale models that incorporate biomass and biochar production and peat GGR alongside continued food and renewable energy production, aiming to minimise economic trade-offs and impacts on food security. Biodiversity, water quantity, water quality and societal impacts, opportunities and trade-offs are also being considered.

xviii These include *Sphagnum* which can act as a natural CH_4 'biofilter', supporting microbes that remove CH_4 produced in the peat; biochar, which initial results suggest may suppress CH_4, nitrous oxide and peat CO_2 emissions; and gypsum, a readily available industrial byproduct which causes sulphate reducing microbes to outcompete those that produce CH_4 (a mechanism which stops brackish and saline coastal wetlands from producing CH_4).

xix Four large-scale demonstrators are now in operation, including established field-scale trials aimed at growing high-yielding *Miscanthus* and willow on re-wetted lowland peat.

xx This work is being carried out with the other demonstrators, as well as the DESNZ Reverse Coal GGR project and the UKRI AgZero+ project.

Above: Greenhouse gas flux measurement over biochar-amended plots on a lowland raised bog in Lancashire. Credit: Jenny Rhymes

Policy implications

Optimised management of the UK's peatlands ('peat GGR') would both enhance carbon storage and reduce methane emissions. The demonstrator is working with government and regulators to identify and address regulatory and economic barriers to the large-scale implementation of peat GGR. If these challenges can be overcome, and the effectiveness of the method can be demonstrated at scale, the UK GGR opportunities are large.

Unlike most mineral soils, carbon storage into waterlogged peat is effectively permanent if the peat remains wet. Because of the historic degradation of UK peatlands, large areas of lowland peat lie below current river and even sea-level, so can only be maintained in a dry condition via active drainage. The loss of several metres of peat from these areas also represents a vast unoccupied carbon store within the landscape – in the order of 2000 Mt CO_2. A modelling assessment shows how these GGR approaches could both increase net CO_2 uptake and and reduce emissions - the modelling assessment suggests a combined abatement plus GGR potential of 16 MtCO_2e per year[xxi] on areas targeted for re-wetting. It is indicative for now but provides an illustration of the scale of net climate change mitigation that could be delivered by optimised management of the UK's peatlands.

xxi A modelling assessment suggests that implementing the peat restoration targets in the 6th and 7th Carbon Budgets would lead to around 10 Mt CO_2e yr-^{1} of current emissions abatement, and 1 Mt CO_2e yr-^{1} of GGR by 2050. If the GGR approaches being trialled in the project were sufficient to double the rate of net CO_2 uptake and halve the rate of CH_4 emission, this would increase the amount of GGR for the same area to around 6 Mt CO_2e yr-^{1} by 2050. The combined abatement plus GGR potential of implementing peat GGR on areas already targeted for re-wetting would therefore be 16 Mt CO_2e yr-^{1}.

3.7 Selected science findings and gaps

Drawing on data mapping work carried out across the GGR-D programme, Table 4 sets out selected science findings and gaps to date [68].

GGR-D demonstrator	Selected science findings and gaps
Woodland creation and management	• Soil carbon balance is critical for the overall removal: if unsustainable maintenance and harvest, soil carbon loss far exceeds the removal by growth of trees even in long rotations, 70+ years • Robust data sets for mono-culture tree plantations, need longer term data/ trials for woodland regeneration • Long-term monitoring is critical as forest risks from pests, degradation, fires, wind are not static, but influenced by climate change: need a minimum of 30 years data for robust datasets
Peatland restoration	• Rewetting alone reduces peat GHG emissions, but is unlikely to deliver substantial net GGR • Biochar application supresses peat decomposition and methane emissions, and in combination with peat re-wetting has the potential to deliver substantial net GGR • Longer trials needed to evidence combined re-wetting, perennial crop and biochar contribution to CO_2 fixation and CH_4 and N_2O emission reduction • Continued engagement needed with government, regulators, land-managers and financial sector to develop viable business models to deliver peat GGR at scale.
Biochar	• No evidence of heavy metal accumulation in soil even for high biochar application rates of 10t/ha/yr • No human health risks detection if wet application and biochar incorporation in topsoil • Need longer term data to evidence improved soil water retention, increased yields, and CH_4 emission reduction if biochar applied to grasslands
Enhanced rock weathering	• No detection of heavy metals accumulation from basalt rock application at a rate of 40t/ha/yr • Need longer data logs (5–10 years) to evidence increased yields, plant resilience, terrestrial and aquatic biodiversity changes • Key losses in freshwater transport to the ocean – need to continue research investigating freshwater saturation with bicarbonates
Perennial biomass crops for BECCS	• Robust data on how to grow perennial crops in the UK, but socio-economic bottlenecks for scaling up production, e.g. rhizome nurseries, insufficient planting machinery, trained contractors. • Need to stimulate demand for perennial crops, e.g. use for biochar, CHP plants, besides various BECCS end uses. • Perennial crops are monocultures; to stimulate biodiversity, optimum size 2.5ha parcels, up to 10ha/farm • To reduce land-use change impacts, limit expansion of perennial crops to marginal lands

Table 4: Selected science findings and gaps for each of the five GGR-D demonstrators

CHAPTER 4.

LAND-BASED GGR: LESSONS FROM THE DEMONSTRATORS

The programme has yielded a number of cross-cutting lessons on what will be required for the successful development and deployment of land-based GGR methods, drawing on the experience of deploying these methods at demonstration scale[xxii]:

4.1 Build on UK advantages to realise the opportunities

Opportunities exist to develop and strengthen land-based GGR supply chains across many sectors, building on the UK's advantages and with associated economic and other benefits. The CCC's Seventh Carbon Budget pathway currently comprises greenhouse gas removals – including biomass supply for BECCS - delivered within UK territory. The UK has strong land-based expertise, research capabilities and sectors - agriculture, mining, forestry and nature restoration - and a climate that is good for growing things. In the case of enhanced rock weathering, the UK has its own supply of basalt and similar feedstocks [69,70]. Expertise in biomass plant breeding is yielding valuable innovations: for example, scientists from the University of Aberystwyth have bred the world's first Miscanthus biomass varieties to be registered with the EU's Community Plant Variety Office. Scaling up home-grown perennial biomass crops will enable the UK to oversee the sustainability of this feedstock for BECCS while enhancing energy security.

4.2 Geography matters – target policies spatially

The emerging evidence shows that the efficacy, co-benefits and impacts of GGRs vary spatially according to a range of factors including soil characteristics, local climate, type of farmland (arable, pastureland or upland) or type of peatland (lowland or upland agricultural), for example. Indeed, impacts could range between either positive or negative depending on where and how GGR methods are deployed. The relative location of different elements of the supply chain is a further consideration in deploying GGR; for example, proximity of quarries to agricultural land for enhanced rock weathering; or proximity of perennial biomass crop production to BECCS plants. The opportunities will therefore present themselves differently across the devolved administrations and local authorities according to varying local context, while land use and agriculture are both devolved policy areas. Figure 7 illustrates the spatial variability of 'effective GGR' according to location of Miscanthus planting, while Figure 8 shows the relative appropriateness of UK croplands for GGR through enhanced rock weathering.

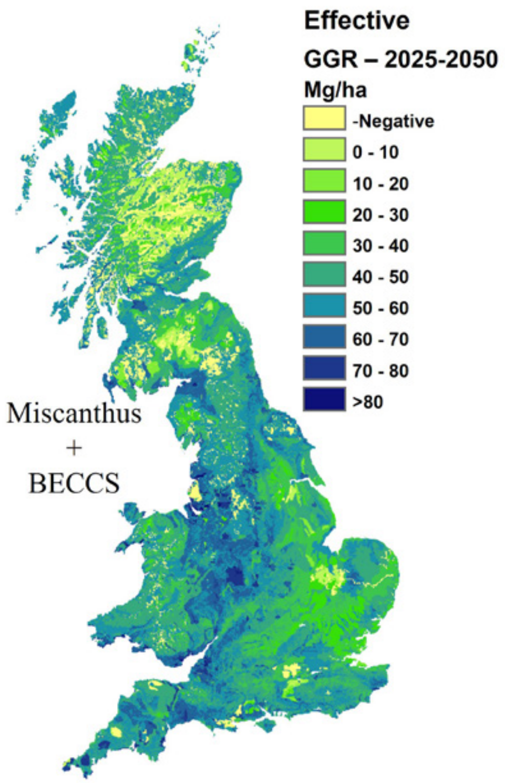


Figure 7 The map shows the modelled technical potential for GGR by 2050 if Miscanthus was planted in 2025. The model [71] incorporates factors such as biomass yields, soil carbon, BECCS efficiencies and future climate predictions. Planting into high carbon soils produces negative GGR (i.e. net emissions) and the effective GGR varies significantly by area.

xxii These cross-cutting lessons emerged from discussions at a GGR-D Programme workshop which was held in Birmingham in February 2025 and involved researchers from across the programme.

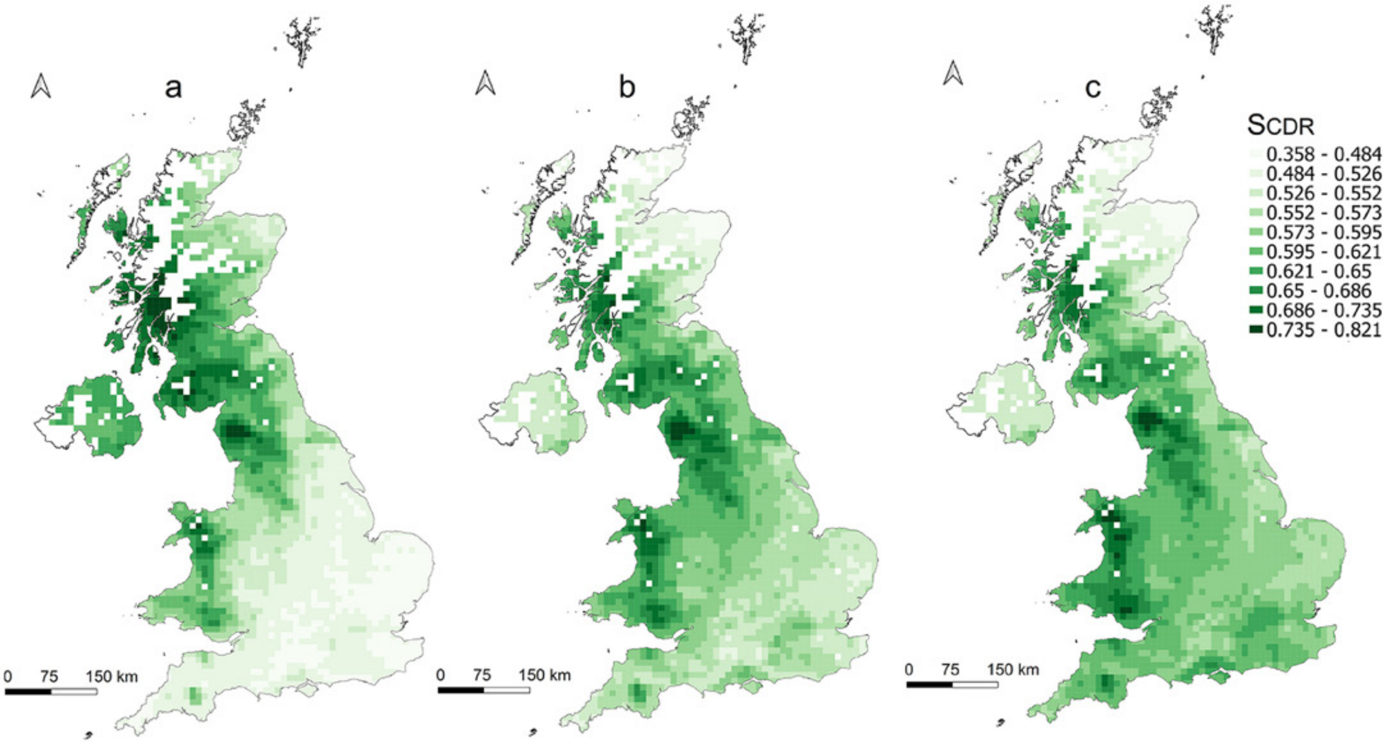


Figure 8 Relative appropriateness of the UK's croplands (10 × 10 km grids) for ERW via application of basic silicate rocks (a), legacy slags (b) and construction and demolition wastes (c) on croplands. Four factors that can control the net GGR potential in each cropland were considered: transport distance between resources and croplands, temperature, water availability and the soil pH [72].

Spatial prioritisation and targeting of policies to incentivise GGR in the right places underpinned by high quality data – including data on long-term co-benefits and potential negative side effects - would allow GGR deployment to play to the strengths of the land, a key principle of the government's proposed Land-use Framework for England. There are also opportunities to manage delivery according to the local social context, given regional differences in public appraisal of different GGR methods (Section 2.6) and information from local engagement (see Section 4.4 below).

4.3 Optimise deployment within constraints and identify opportunities to co-deploy

Integrating GGRs into overarching decisions about land-based policy is vital, making use of the latest information from the GGR-D demonstrators on optimal combinations of different GGR methods and locations for deployment. This should not be a stand-alone activity but rather should be integrated with policymaking that would otherwise be led entirely through other lenses. Competition for land, biomass and other resources such as low-carbon energy means that the potential scale of GGRs depends on broader policy decisions such as what kind of land-use or biomass use is prioritised by government, and the rate of decarbonisation of the energy supply – particularly where energy use is significant within a GGR's supply chain. Competition for resources also exists between GGRs. The 30×30 target (to protect 30% of land for nature by 2030), requirements on developers for Biodiversity Net Gain, and incentives within Sustainable Farming schemes all place further demands on land that need to be balanced with land requirements for GGR. As indicated by the Climate Change Committee, proposed shifts in the agri-food system (e.g. reductions in food waste, dietary shifts, increased productivity) will directly decrease greenhouse gas emissions with the added benefit of increasing land availability for biodiversity and GGR objectives.

Competition could be avoided in certain situations: for example, some GGRs can happen in combination with agriculture rather than requiring land-use change (e.g. ERW and biochar). Biochar could use different feedstocks such as waste-derived feedstocks rather than biomass and could be used in construction materials rather than applied to land.

Thorough testing and monitoring of policies will also be needed to minimise policy risks or conflicts that could limit the potential scale of deployment or

	Woodland creation and management	Peatland restoration	Biochar on soils	Enhanced rock weathering on soils	Perennial biomass crops	BECCS**
Woodland creation and management		O ↓ High	O ↑ Med	O ↑ Med	X ←→ High	X ↑ High
Peatland restoration			O ↑ Low	O ←→ High	O ↑ High*	X ←→ High
Biochar on soils				O ←→ Low	O ↑ Low	X ↓ High
Enhanced rock weathering on soils					O ↑ High	X ←→ High
Perennial biomass crops						X ↑ High

Table 3: Opportunities for co-deployment indicating land compatibility (does one method exclude another on the same land, or is there no competition), nature of interaction (enhancement or diminishment of GGR, inputs enable or outputs compete, or no connection) and certainty of interaction (high, medium or low). These are early indications which would benefit from further research.

* Potential positive interaction if grown without lowering the water table (paludiculture), though negative interaction if peat is drained.

** This column represents the combustion and capture process in a BECCS supply chain, downstream of soil / land capture and storage. Outputs from woodlands and perennial biomass crops both enable this part of the BECCS supply chain.

Legend:

Land compatibility
X One method excludes other on same land
O Deployable on same land

Certainty of interaction
High
Med
Low

Interaction
↑ Co-deployment enhances GGR, or outputs from one enable the other
←→ No connection
↓ Diminishment of GGR, or competition for inputs

cause other impacts, including the risk of displacing activities either within the UK or abroad. A holistic approach, avoiding single-objective policymaking, would help mitigate these risks, such as is embedded into NetZeroPlus's decision-support tools, for example.

There are opportunities to enhance GGR performance and the efficiency of land use through co-locating GGR methods (see Table 3); evidence on this is emerging from the GGR-D programme. For example, woodland creation & management and perennial biomass crops can be combined with biochar or enhanced rock weathering, while perennial biomass crops can be used alongside biochar in peatland restoration sites.

4.4 Continuously engage with local communities, land-owners and land managers

Changes to land management and land use necessary for delivering GGR will involve both transitional and transformational change, with implications for land-owners and managers, local communities and landscapes. For example, whereas applying biochar to soils is more of a transitional change for farmers, paludiculture requires investment in new machinery. Farmers are willing to try different practices but need the right information and incentives: many are open to opportunities that can diversify revenues and improve business resilience but are concerned about the legitimacy of claims about carbon reduction and about possible competition with food production [73,74]. Understanding current farming practices is also valuable; for example, farmers tend to plant perennial biomass crops in small-scale 'mosaics' rather than large-scale monocultures concentrated around power plants that would minimise transport requirements. Confidence in policy stability is vital here, especially where CAPEX is required so that farmers can be sure of a return in investment.

Both farmer and local community perceptions vary according to local contexts and a place-based approach to siting GGRs is needed which is sensitive to local concerns. For example, ERW requires significant volumes of basalt to be delivered to local farms and the local community has voiced concern about whether the local road network could cope. Community support for GGR deployment is also conditional: people want to see that GGR is being deployed with fair governance systems and that benefits accrue locally. For example, research with local communities has shown that people want transparent MRV to prove that the enhanced weathering works, as well as remediation for quarries, the provision of local jobs and financial sustainability for farms [75]. Perennial biomass crops have low labour input compared to cereal crops, which may be welcomed by some farmers and not by others.

There are uncertainties about how communities will respond in future to GGR as deployment scales, and a risk that social licence could be lost. Continuous engagement, upfront and throughout deployment, is needed to raise awareness and to educate, but more importantly for developers, regulators and scientists to understand fully and reflect upon both the place-based and the generic conditions that communities might wish to see met in order to grant a social license for responsible at-scale GGR deployment and governance [76]. Such engagement is vital for ensuring GGR is deployed with communities, farmers and other land managers in mind.

4.5 Create decision-making tools for land-owners and managers and share best practice

Decision-making tools that help farmers, other types of land manager and owner, agronomists and land advisors decide which GGR method or combination of methods is appropriate for a particular area of land, drawing on high-quality evidence, will help ensure effective deployment. Education and skills training with the help of high-quality teaching resources that address the practicalities of deployment, optimal siting and regulatory and permitting issues, for example, are valuable. There is potential to embed this into existing schemes that provide advice to farmers and land managers [77], and to extend established distance learning schemes to include GGRs[xxiii].

Given the urgency, there will be a need to reskill the existing workforce in addition to ensuring those entering the workforce have the right skills for future needs. However, careful messaging will be required in order to retain older workers (who make up the majority of the workforce in land-based sectors) and not exacerbate existing labour and skills shortages.

4.6 Maintain support for long-term field trials including co-deployment studies

There is the opportunity to maintain and build on valuable research resources and capacity that have been built by UKRI's investment in the GGR-D programme, maintaining the UK's leading position and capitalising on first-mover advantage. While the five land-based approaches are at different TRLs, all would benefit from continued support for long-term field trials which is vital for understanding long-term, cumulative impacts of land-based GGR methods and co-deployment opportunities. Positive or negative impacts may be scale-dependent and vary over time and according to when a given GGR technology is applied, and so extended pilot studies and modelling need to be supported over time to provide the necessary insights. While the demonstrator programme has begun to explore the various co-deployment opportunities, more research is needed to quantify the benefits and impacts.

In addition, communities have coalesced around the GGR-D programme through the various research and engagement activities, including from academia, industry, business, farming, NGOs, regulators, local, devolved and national government, and others. Continued support would enable ongoing knowledge-sharing and collaboration opportunities.

As GGR technologies are deployed in research programmes and by the private sector, data will emerge which is highly valuable in informing policy, business and investment decisions: putting in place mechanisms and incentives for ensuring data is accessible, useable and shareable, and that it can be employed in decision-making tools and frameworks, is vital for capitalising on early GGR development and deployment activities (see also Section 2.7).

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