A common framework for comparing greenhouse gas removal options

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1. Why a common framework?

Achieving net-zero greenhouse gas emissions will require both rapid emissions reductions and greenhouse gas removal (GGR) to counterbalance residual emissions from hard-to-decarbonise sectors. Land-based GGR options, including woodland creation, peatland restoration, bioenergy with carbon capture and storage (BECCS), biochar and enhanced rock weathering (ERW), differ substantially in their costs, emissions, removal potential and compatibility with existing land uses. Their performance also varies across locations and over time, while competition with agriculture creates important opportunity costs. This study develops an integrated spatial and temporal framework to compare the net cost-effectiveness of individual GGR technologies and feasible combinations, accounting for implementation emissions, land suitability, agricultural opportunity costs, technology interactions and budget constraints.

Objective

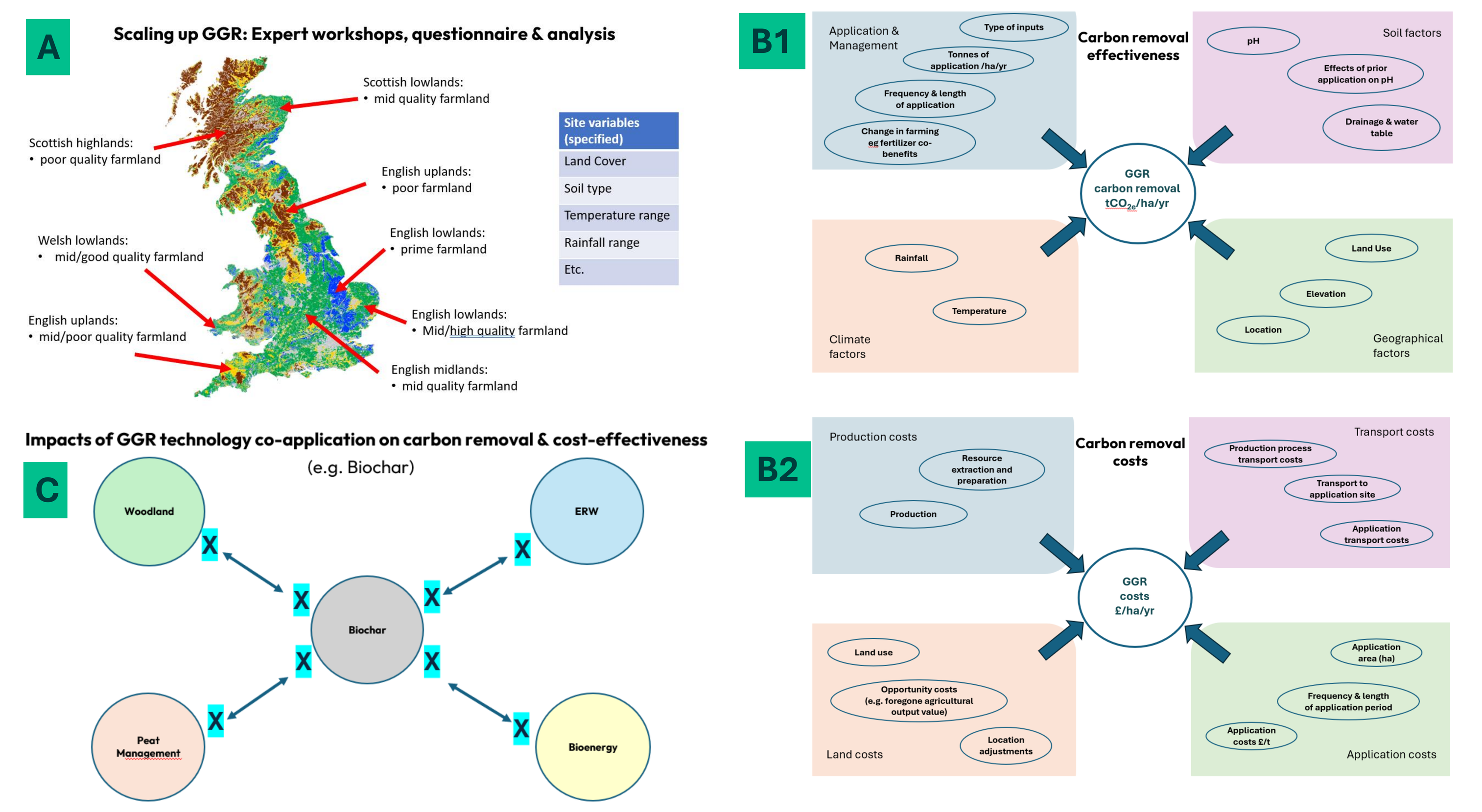
Can diverse GGR technologies be assessed fairly within conventional decision rules — including HM Treasury Green Book appraisal — and then optimised across place and time?

Research Questions

- What is the **effectiveness** (tCO_{2e}), **cost** (£) and **cost-effectiveness** (£/tCO_{2e}) of differing GGR technologies?
- How does cost-effectiveness change across **locations** and **time** and how can we use this information to optimise GGR strategies? (e.g. maximise removal for a given budget).
- How does cost-effectiveness change if we **combine** GGR technologies?

2. Methods and Theoretical Framework

- This study focuses on five land-based GGR technologies, each examined by a GGR-D programme research project: bioenergy with carbon capture and storage (BECCS), biochar, enhanced rock weathering (ERW), peatland restoration and woodland creation.
- Online workshops were conducted with the corresponding GGR-D project teams.



A. Using a case-study exercise, we explored the spatial factors affecting the deployment and performance of each technology. Participants considered its application across hypothetical locations in Great Britain that varied by elevation (upland or lowland), soil, temperature, geographical region (Scotland or England/Wales; west or east) and land use (lower- or higher-quality farmland, grassland or woodland).

B. Participants identified factors affecting (1) carbon removal (tCO_2 ha^{-1} yr^{-1}), grouped as application and management, soil, geography and climate; and (2) technology costs, grouped as production, transport, application and land costs.

C. Finally, participants reviewed available evidence and provided expert judgements on the co-application of multiple GGR technologies, including how combined deployment may alter carbon removal and the costs of each technology.

A spatial/temporal model of multiple GGR technology application for the UK

A spatially and temporally explicit framework was developed to evaluate cost-effectiveness across three components: carbon removal, carbon emissions and costs. Intensity parameters w_{kit} represent the deployment of each technology, while interaction parameters α_{kj} capture the effects of co-applying pairs of GGR technologies. The carbon-removal equations are shown below as an example.

Sum across all GGR technologies $k \in K$ (each of woodland, ERW, biochar, biomass, peat management)

CR = tCO_{2e} removal per ha at site i in year t

$$CR_{it} = \sum_k w_{kit} CR_{it}^k \qquad [1]$$

CR_{ti}^k = function allowing co-deployment of multiple GGR technologies k at site i in year t (see [2] below)

Site i = across all 1km grid squares across GB

Year t = all years to 2100 with target year T (e.g. 2050)

w = intensity level of GGR technology k at site i in year t; $w \in (0,1)$

CR_{it}^k = tCO_{2e} removal per ha by technology k at site i in year t

$$CR_{it}^k = \overline{CR}_{it}^k \Big(1 + \sum_{\substack{j \in K \\ j \neq k}} \alpha_{kj} w_{jit}\Big) \qquad [2]$$

$\sum_{\substack{j \in K \\ j \neq k}} \alpha_{kj} w_{jit}$ = change in tCO_{2e} removal by technology k when applied alongside technology j at site i in year t

$\overline{CR}_{it}^k$ = function relating tCO_{2e} removal by technology k to the environmental, climate, management and risk conditions at site i in year t (see [3] below)

ENV_{it} = variables describing the physical environment of site i in year t

$\overline{CR}_{it}^k$ = modelled tCO_{2e} removal per ha by technology k at site i in year t

$$\overline{CR}_{it}^k = f\big(ENV_{it}, CLIM_{it}, MGT_{it}^k, RISK_{it}^k\big) \qquad [3]$$

$RISK_{it}^k$ = tCO_{2e} removal risks of technology k at site i in year t

$CLIM_{it}$ = Climate variables for site i in year t

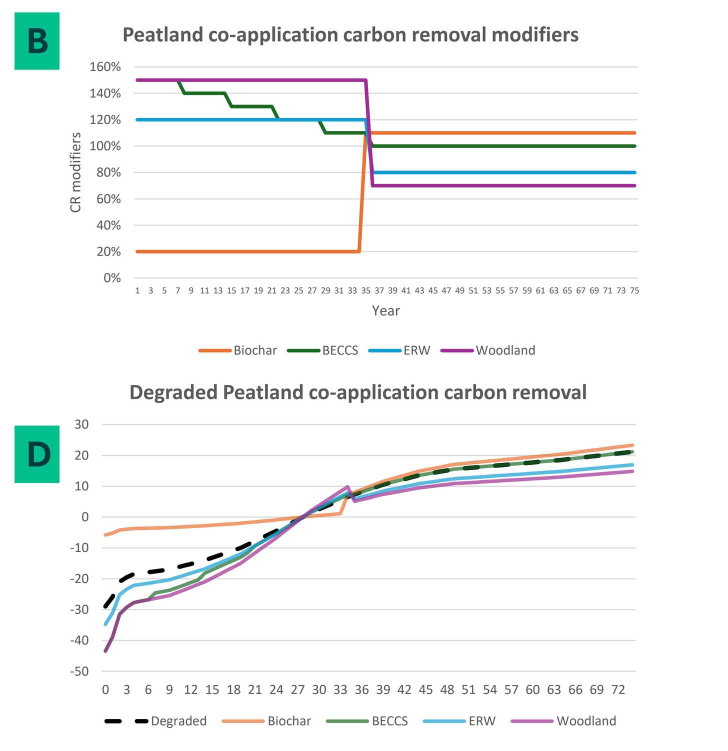
MGT_{it}^k = Management of technology k at site i in year t

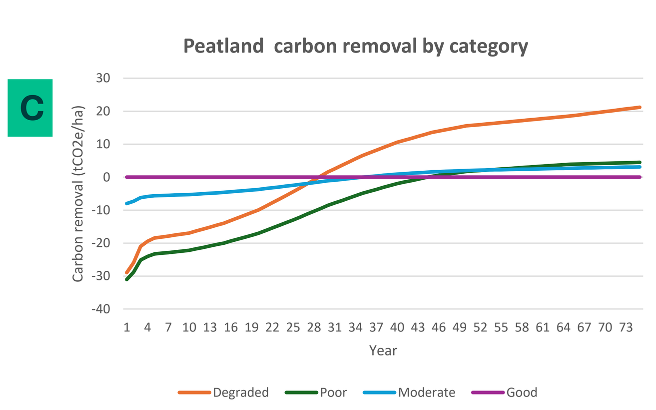
GGR Co-Application using cross-impact weight matrices (α_{kj})

Carbon-removal co-application weights vary by year to capture changes in impacts since co-application begins. (A) Weight matrix at Year 0. (B) Peatland co-application weights over time by partner technology. (C) Peatland carbon removal in isolation. (D) Degraded-peatland carbon removal under co-application.

A

YEAR_0	Biochar	BECCS	ERW	Peatland	Woodland
Biochar		1	1	1	1
BECCS	1.1		1.1	0.9	
ERW	1	1		1	1
Peatland	0.2	1.5	1.2		1.5
Woodland	1.1		1.1	0.7	





3. Preliminary Results

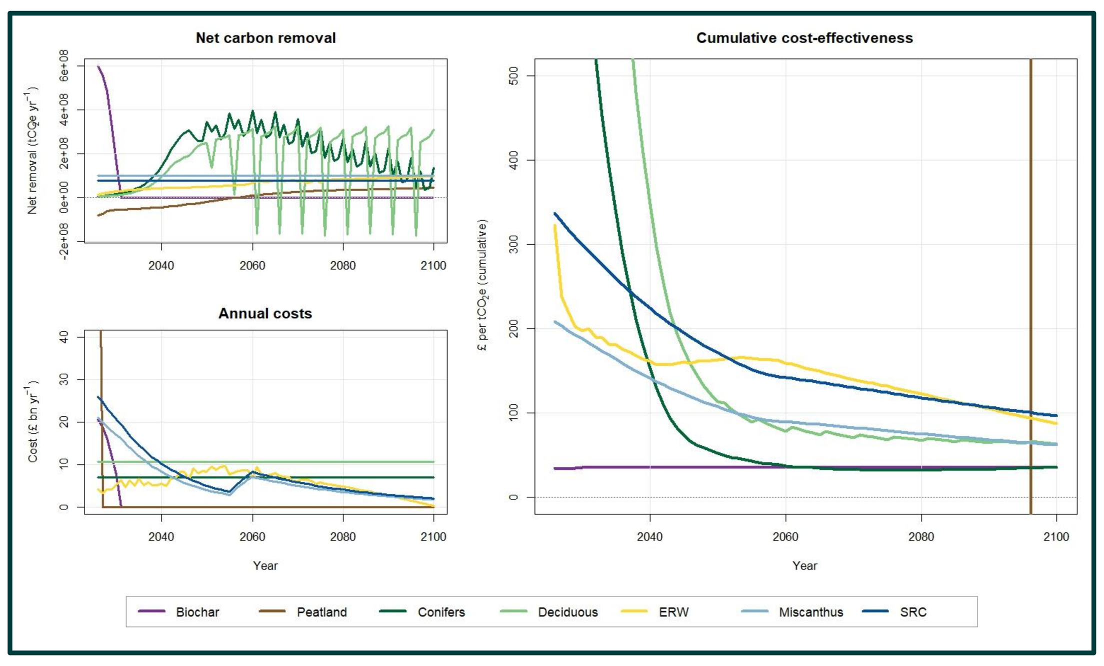


Figure 1. Yearly sum across Great Britain for each GGR technology. (a) Net carbon removal potential (tCO2e/ha/yr, difference between emissions and removals); (b) potential annual costs £ bn/yr); and, (c) overall potential cost-effectiveness of each in £/tCO2e.

Figure 1 presents the aggregate potential across Great Britain for each technology, assuming unconstrained deployment across all land considered available.

Technology performance varies substantially over time. **Biochar** can deliver carbon removal rapidly because removal occurs at the production stage. However, removals cease once the available land capacity for biochar is reached.

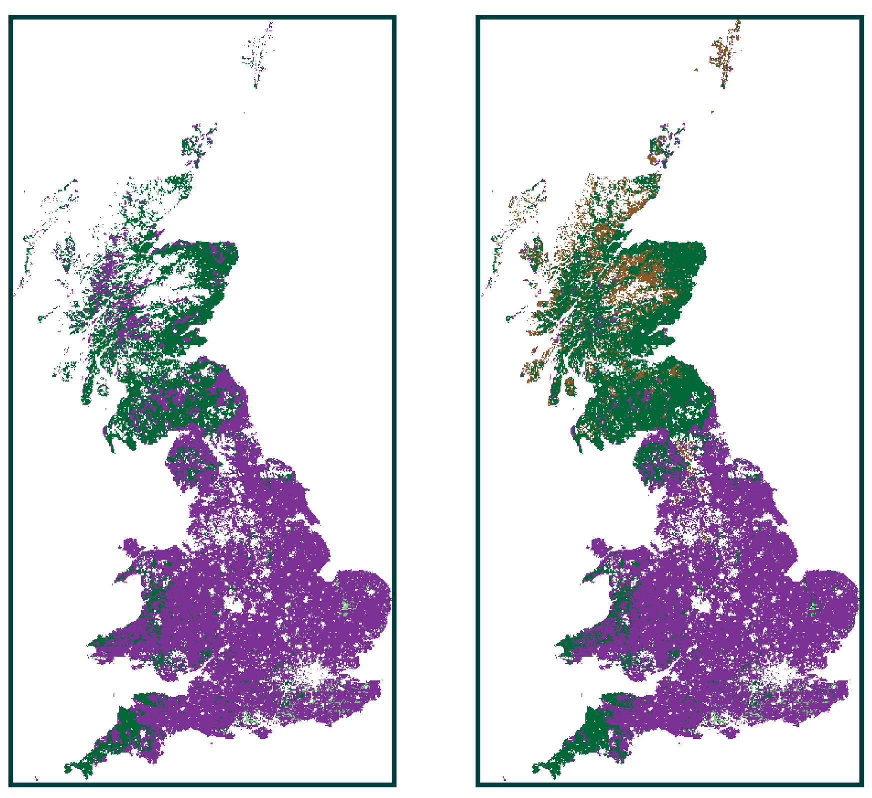
In contrast, technologies such as **woodland** creation and peatland restoration take longer to become cost-effective because removals increase over time. For **peatland**, initial restoration can produce a net increase in emissions, particularly methane. Several decades may therefore be required before recovery results in net-positive carbon removal and positive cost-effectiveness.

Technologies such as **ERW** and **BECCS** also exhibit declining costs per unit of removal over time, as annual costs fall while cumulative removals increase.

This has important policy implications: when governments set emissions-reduction targets for a specific year—for example, net zero by 2050—the optimal allocation of funding across technologies may vary with the selected target year.

The importance of timing is particularly evident from a spatial perspective. Figure 2 identifies the highest-performing technology, without budget or supply constraints, in each 1 km² grid cell across Great Britain for target years 2050 and 2100. Across most of England, biochar delivers the greatest potential, largely because it becomes cost-effective rapidly and can complement food production; this comparison therefore assumes no opportunity cost. However, biochar is strongly supply-constrained, limiting its deployment across multiple locations. Woodland creation is prominent across much of Scotland and in parts of Wales and Cornwall. With a 2100 target year, woodland creation becomes substantially more prevalent, alongside greater peatland-restoration activity, particularly in the Scottish Highlands.

These findings demonstrate the value of assessing GGR technologies within a common framework. Spatially and temporally explicit estimates of carbon removal, emissions and costs capture geographical variation in performance and help identify priority areas for intervention. The results also show that the choice of target year can materially influence which GGR strategies should be prioritised.



The model can compare how an optimal technology mix changes across geography and target year; the mapped allocation is provisional.

Peatland
Woodland (deciduous)
Woodland (conifers)
ERW
Biochar
BECCS (Miscanthus)
BECCS (SRC)

4. Moving forward

This framework establishes an initial basis for comparing GGR technologies in a spatially and temporally explicit manner while accounting for co-application effects. By representing differences across locations and over time, it provides a foundation for examining how technology performance and interactions may affect deployment choices. Three research priorities are required to develop this foundation into a robust, policy-ready decision-support framework:

- Develop **policy-ready spatial and temporal models** for individual GGR technologies using harmonised assumptions about future climate, energy supply, technological development and diffusion. A consistent modelling basis would enable like-for-like comparisons across technologies, locations and target years, while making the implications of alternative assumptions transparent to decision-makers.
- Strengthen the **evidence base for GGR co-application impacts**. Many potential cross-effects between technologies have not yet been assessed, and the available studies provide limited evidence on how their direction and magnitude vary across space and time. Further empirical and modelling work is therefore needed to characterise these interactions and represent their uncertainty within the framework.
- Broaden the framework beyond carbon-removal effectiveness to **include non-carbon effects of GGR technologies**, including consequences for food security, biodiversity and recreation. Linking the framework to a wider natural-environment modelling platform, such as NEV, could capture relevant trade-offs and co-benefits, extend cost-effectiveness analysis beyond carbon outcomes, and support the selection of GGR portfolios that maximise wider social value rather than carbon-removal efficiency alone.

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