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RECEIVED 02 July 2025

REVISED 31 October 2025

ACCEPTED 10 November 2025

PUBLISHED 10 December 2025

CITATION

Waller L, Cox E, Binner A, Garcia TC, Everett R, Henwood K, Ingram J, Morris C, O'Sullivan K, Pidgeon N, Price C, Reed M, Silvestri A and Bellamy R (2025) Responsible research and innovation of carbon removal: strategies for field trials. *Front. Clim.* 7:1658453. doi: 10.3389/fclim.2025.1658453

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Responsible research and innovation of carbon removal: strategies for field trials

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Demonstrating methods for removing carbon dioxide from the atmosphere is now a focus of research and development programmes designed to support decision making about future technology deployment. In this perspective piece, we outline some of the approaches to responsible research and innovation (RRI) being put to work in a United Kingdom-based programme organising field trials of various carbon removal methods. Unlike the disruptive technologies that predominate in RRI scholarship, many land-based methods for carbon removal have already been deployed, in some cases over many decades, with governance closely linked with longstanding fields of research and practice. We highlight why responsible innovation frameworks that developed in the context of geoengineering controversies may be only partially-suited to field trials of land-based carbon removal methods. We suggest that field trials of carbon removal methods are not simply evidentiary procedures but also strategic sites within an emerging innovation regime where RRI approaches can be both implemented and critically tested.

KEYWORDS

responsible research and innovation (RRI), carbon dioxide removal, greenhouse gas removal, field trials, demonstrators

Introduction

As governments, companies and other actors adopt “net zero” climate goals and seek ways to balance out hard to abate greenhouse gas emissions, methods for removing carbon dioxide from the atmosphere have become a fixture of official climate strategies.¹ Projects demonstrating carbon dioxide removal methods in field trials are now a focus of research and development programmes around the world which aim to support decision making and coordinate expectations about future technology deployment (Smith et al., 2024). In such programmes, field trials are evidentiary procedures for method-specific decisions but they are

1 The terms GGR (greenhouse gas removal), CDR (carbon dioxide removal) and ‘carbon removal’ are used interchangeably in this perspective. Though carbon removal is the focus of much policy discussion, research and demonstration programmes also focus on greenhouse gas removal methods such as methane destruction as well as interactions between carbon removal methods and fluxes of greenhouse gases like nitrous oxide.

also highly symbolic sites of demonstration within an emerging innovation regime. In this Perspective, the authors – all researchers involved in the United Kingdom’s greenhouse gas removal demonstrators programme (GGR-D) – outline some of the diverse, and potentially divergent, approaches to responsible research and innovation (RRI) being put to work around United Kingdom field trials of carbon removal methods.

In what follows, we assume (broadly speaking) that a central ambition of RRI is to bring together a normative deliberative approach to science and technology policy with social science methodologies for anticipating the consequences of research and development (Macnaghten, 2020). One expression of this, as we discuss below, is the (now widely cited) AREA framework (Owen et al., 2013; Stilgoe et al., 2013) which was adopted by the United Kingdom by the Engineering and Physical Science Research Council (Owen et al., 2021). The adoption of RRI as an official research policy in the United Kingdom, as well as the EU, has directed institutional support and resources to the pursuit of such ambitions. However, the official adoption of RRI also introduces tensions, and potential constraints, for both thinking politically about expert deliberation and for pursuing critical social research into the consequences of, and possible alternatives to, technological innovation. Putting RRI to work, as we discuss here, is therefore not simply a challenge of implementing established frameworks and methodologies but also of considering how deliberation and anticipation are being officially framed in emerging innovation regimes. As we discuss below, a critical sensitivity to such tensions can draw attention to the uneven governance landscape within which different land-based carbon removal methods are developing – e.g. how they are connected with (or disconnected from) established bodies of research and expertise – and therefore also to competing imaginaries of the emerging innovation regime.

The GGR-D programme discussed here centres around five demonstrator projects (the Demonstrators), each trialling a different land-based carbon removal method – together covering a variety of both “novel” and “conventional” methods (Smith et al., 2023), which include: biochar, peatland restoration, perennial biomass crops, enhanced weathering and tree planting.² Alongside the five demonstrators, a Directorate Hub (CO₂RE) combines interdisciplinary research, evaluation and programme administration; functions that are also present in the Demonstrators to varying extents. The GGR-D programme broadly takes the form of a “grand challenges”-style funding instrument which is closely linked with United Kingdom government policy priorities.³ RRI is a stated focus of some projects and not others,

but as we show here various analogous concepts, approaches and tools for anticipating issues and uncertainties of developing and deploying carbon removal methods are also being deployed throughout the programme. While the strategic significance of research and development programmes, like the GGR-D programme, has been widely constructed in relation to the official climate plans of governments (e.g., as evidentiary procedures), we propose that field trials can also be seen as strategic sites for testing RRI within an emerging innovation regime.

The perspective presented here emerged from a cross-programme working group, convened to address responsible innovation of carbon removal. In what follows, we highlight how prominent discussions about RRI and “geoengineering” may distract from specific issues and challenges posed by land-based carbon removal methods. We then elaborate the place of RRI within the United Kingdom’s GGR-D program and discuss how the normative-deliberative and anticipatory dimensions of RRI can both combine and conflict around research and development of carbon removal methods. In concluding, we elaborate the implications of approaching carbon removal field trials as sites where RRI can be critically tested.

Responsible research and innovation of carbon removal, beyond geoengineering

Discussions about RRI and carbon removal have often been subsumed within the topic of “geoengineering”: the deliberate large-scale intervention in the Earth’s climate system, in order to moderate global warming (Royal Society, 2009). The formulation of RRI that was developed from this encounter centred on the notion that for science to be responsive to society it must anticipate and “take care” of the futures brought about through research and development. In relation to geoengineering controversies in the mid-2010s, United Kingdom-based approaches to RRI were closely associated with the United Kingdom Research Councils – public funding bodies – which were seen to be strategic sites for decision-making (Stilgoe et al., 2013). The foregrounding of research funders reflected, in part, assumptions about the disruptive character of geoengineering techniques and the scale of deployment that would be required to have an impact on the global climate system; which, as some social analysts cautioned, could be incompatible with democratic governance (c.f. Horton et al., 2018; Szerszynski et al., 2013). In their widely cited framework, Stilgoe et al. describe a stage-gate procedure used in decision-making about a research project in stratospheric aerosol injection (SAI) (Macnaghten, 2020; see also discussions in Pidgeon et al., 2013; Stilgoe, 2015; Stilgoe et al., 2013). This process, they argued, performed as a forum in which complex issues relating to the governance of geoengineering could surface and be subject to deliberation (stage-gate procedures were also accorded an important role in the Oxford principles for geoengineering governance, see Rayner et al., 2013).

Unlike SAI – which provided the predominant focus for discussion about RRI and geoengineering – various carbon removal methods have already been deployed; in some cases over many

² That the GGR-D programme focuses on land-based methods may partly be an artefact of the way public funding for carbon removal has been apportioned through the United Kingdom Research Councils, with Demonstrator projects funding primarily distributed through the Biotechnology and Biological Sciences Research Council (Workman et al., 2022).

³ The GGR-D programme was initiated by United Kingdom research councils and funded through the United Kingdom Government’s strategic priorities fund, with the programme sponsored by the (now former) Department of Business, Energy and Industrial Strategy (BEIS). So-called “grand challenges” funding instruments typically position academic research in relation to a pressing social problem and are envisaged to stimulate technological

innovations that may not be prioritised (or seen as competitive) within private sector research and development (see discussion in Kaltenbrunner, 2020).

decades and often on the basis of well-established bodies of evidence from environmental research and management. Conflating carbon removal with geoengineering may obscure a “long history” of controversies over carbon sequestration via land-based sinks (Carton et al., 2020). This is particularly the case for the land-based approaches which make up the United Kingdom GGR Demonstrators (see Table 1), using understanding and techniques from long-standing fields of biological, environmental, ecosystem and agricultural research. Even those that are characterised as “novel” carbon removal methods (see discussion in Smith et al., 2023), such as enhanced rock weathering and biochar, can be (and in the case of biochar are currently are) commercially deployed for reasons other than removing carbon, such as soil management. It is also clear that generalisations about methodological novelty can erase existing knowledges and practices (in the case of biochar, see Morris et al., 2024). In some instances, carbon removal could be seen as simply the latest policy agenda towards which scientists justify long-standing research programmes (e.g. in ecological restoration or bioenergy research). Moreover, despite the proliferation of novel voluntary markets for removals, it is the integration of removals into existing carbon trading systems that currently provides the primary focus of official policy discussions (Smith et al., 2024). In short, where the scientific basis for trials of solar geoengineering was hotly contested (Stilgoe, 2015), in many cases trials of land-based carbon removal are designed around established research practices and bodies of expertise (including social science expertise, e.g., applied to soil carbon management practices, see Ingram et al., 2016). This does not mean that carbon removal trials are uncontroversial (c.f. Anderson et al., 2023) but rather that a much wider range of empirical objects, scientific fields, experts and policy actors may be implicated by research and development than was the case in the solar geoengineering controversies with which earlier work on RRI has focused.

Despite deliberate attempts to separate assessments of carbon removal methods from solar radiation modification (SRM) interventions (e.g., Cox et al., 2018)⁴, associations with geoengineering nonetheless endure. It is notable, for example, that a paper on responsible research and innovation of “climate engineering” follows the Royal Society’s (2009) formulation, addressing CDR and SRM together while noting their increasing disjunction (Low and Buck, 2020). Such associations can also be found in research on perceptions of carbon removal that often mix together CDR and SRM methods (Waller et al., 2024). Moreover, critical discussions about the potential for “moral hazard” (or “mitigation deterrence”) in discourse on CDR can be seen to be shaped by concepts developed in earlier debates about SRM (see discussion in Carton et al., 2023; e.g. McLaren, 2016). The stickiness of the concept of geoengineering can therefore be seen as bound-up with the hubristic, but popular, notion that science can “fix” the global climate crisis (Hulme, 2014); the predominance of the latter in climate policy making it challenging to “unframe” carbon removal methods from geoengineering discourses (Bellamy and Lezaun, 2017).

While debates about geoengineering are largely divorced from research and development of land-based carbon removal methods, it is nonetheless the case that the concept of geoengineering may be used by others actors to draw attention to uncertainties around the scale of interventions and to question motivations for field trials (Low et al., 2022). The latter draw attention to multiple ways that trials of carbon removal methods can be constructed as more-or-less symbolic sites for public contestation of research and development (c.f. Bonneuil et al., 2008). We do not therefore need to adopt planetary-scale framings of carbon removal to recognise how geoengineering labelling can (potentially at least) raise questions about the emerging innovation regime that may be otherwise unaddressed in much research and development.

RRI in the UK’s Greenhouse Gas Removal Demonstrators (GGR-D) programme

The account of RRI that developed around geoengineering focused on different roles that social sciences can play in the anticipating and responding to future uncertainties in research and technology development (Macnaghten, 2020; see discussions in Stilgoe and Guston, 2016). In the United Kingdom, such questions have been often refracted through the public understanding of science (PUS) movement and related attempts to institutionalise public engagement in a model of “two-way dialogue” and “upstream” consultation (see discussions in Rogers-Hayden and Pidgeon, 2007; Irwin and Michael, 2003; Pallett and Chilvers, 2022). Attempts to institutionalise public engagement have given rise to a variety of semi-standardised techniques for assembling lay groups and measuring their responses to science and technology, often repurposing methodological innovations developed in research on risk perceptions and deliberative studies on technological risk issues (Macnaghten and Chilvers, 2014; Pidgeon, 2021; Wynne, 2016). It is now well-established that such techniques not only produce representations of the public (e.g., as ‘scientific citizens’ see Bickerstaff et al., 2010) but also empower certain expertise to frame policy issues and define the scope of legitimate contestation (Lezaun and Soneryd, 2007; Marris, 2015; Pallett, 2015). While the legacy of PUS is often detectable in Anglophone accounts of RRI, discussions have also critically challenged instrumental positionings of social science in relation to decision-making and recast public engagement as a process of ongoing experimentation (Stilgoe and Guston, 2016).

In the architecture of the United Kingdom’s GGR-D programme, social science research is ambiguously positioned in relation to stakeholder and public engagement; being explicitly aligned in some projects and not others. Whilst RRI is not a focus of all the projects, it provided the organising concept around which the co-authors of this paper were convened by CO₂RE to discuss prospects for coordinating across the programme. The AREA framework developed in Owen et al. (2013) and Stilgoe et al. (2013) provided the primary entry point for discussions. While the framework’s organising concepts (anticipate, reflect, engage, act) appeared relevant to varying degrees for the Demonstrator projects, an attempt to co-design a stage-gate tool for land-based carbon removal techniques, centred around go/no-go decision points, proved unsuccessful. The challenge of neatly defining decision points drew attention not just to contrasts in the design of SRM and carbon removal trials (discussed above) but also to the normative deliberative focus of the framework, where the legitimacy of technology

⁴ For example, the concept of geoengineering has not featured in recent reports of the Intergovernmental Panel on Climate Change (IPCC) (see discussion in Beck and Mahony, 2018; see glossary in IPCC, 2018), which refers instead only to specific CDR and SRM techniques.

TABLE 1 Summary of RRI and social science engagement and practices in demonstrator projects in the United Kingdom’s GGR-D programme.

Demonstrator project	GGR method	Research practices involving publics, stakeholders, communities, and concerned groups	RRI-related concepts and/or tools
Biochar Demonstrator	Biochar application on arable, grassland, forested, and marginal land.	Biochar expert interviews; interviews with farmers (including trial farmers); Biochar expert knowledge exchange/deliberative workshops; Farmer knowledge exchange/deliberative workshops; Media framing analysis. Ongoing engagement with relevant policy teams in United Kingdom Government including negotiation with regulator over application rates on trial farms.	Szymanski et al. (2021) RRI and multispecies studies. Sovacool et al. (2019) critical energy justice framework. Tschakert et al. (2021) multispecies justice framework for climate-just futures with, for and beyond humans. McCauley and Heffron (2018) just transition framework. Hilgartner (2015) Capturing the imaginary: vanguards, visions and the synthetic biology revolution
United Kingdom Enhanced Rock Weathering (ERW) Demonstrator	ERW application on upland and lowland grassland, as well as arable land	Expert stakeholder interviews to position and contextualise ERW within evolving policy, regulatory, industry, research and environmental landscapes. This includes interviews with agricultural practitioners gaining insight into how ERW might be deployed within existing supply chains and drawing on existing land management knowledge, skills and practices; Public workshops with communities of place possibly implicated along ERW supply chain, including the three demonstrator field sites. Using creative engagement methods to gain insight into how participants perceive ERW might affect and interact with the locations, cultures and communities implicated in deployment including potential ethical concerns and social impediments.	Rogers-Hayden and Pidgeon (2007) Moving engagement “upstream”? Macnaghten (2020) The Making of Responsible Innovation. Pidgeon (2021) Engaging publics about environmental and technology risks. Rayner et al. (2013) The Oxford principles.
GGR-Peat	Peat restoration on lowland and upland	Semi-structured interviews, surveys, deliberative workshops with those directly linked to pilots Ongoing engagement with relevant policy teams in Defra and Scottish Govt.	3i analysis of relevant parties to ensure inclusive engagement tailored to each group’s needs (Reed et al., in prep.) and application of Life Framework to explore personal experience in landscapes (Kenter and O’Connor, 2022). Inclusive engagement goes beyond gender equality to consider intersectionality, following an ethics of impact (Reed and Rudman, 2023) that prioritises sensitivity to context, representation and legitimisation of diverse voices and the management of power dynamics.
PBC4GGR	Perennial biomass crops (miscanthus and willow)	Working with land managers, industry and decision makers in the land use sector and across the innovation system. Semi-structured interviews and participatory modelling workshops to assess (dis) benefits of PBC and deliberate future sustainable biomass cropping with respect to other land use options. Social acceptability using visualisation tools to prompt conversations and deliberations framed by Social License to Operate dimensions.	Anticipation (exercises to envisage future land use and impacts) and inclusion (multi stakeholder participation to co-design solutions) underpin this work (Stilgoe et al., 2013). Innovation Systems incorporating micro-scale experiences (Ingram et al., 2025a) Widening the concept of Social License to Operate (distributional, procedural, trust in governance) (Ingram et al., 2025b) to include multiple perspectives
NetZeroPlus	Woodland creation and management	Ongoing engagement with stakeholders including MoD, DEFRA, Forestry England, National Trust, National Forest, Network Rail (Through advisory group meetings, ongoing meetings). Participatory workshops focused on eliciting stakeholders needs, testing prototypes and gathering evaluative feedback. This includes Fuzzy Cognitive Mapping workshops across Forestry England to elicit factors that influence decision-making processes at various managerial and regional levels within the organization.	Spinuzzi (2005), Simonsen and Robertson (2013) participatory design.

(Continued)

TABLE 1 (Continued)

Demonstrator project	GGR method	Research practices involving publics, stakeholders, communities, and concerned groups	RRI-related concepts and/or tools
CO ₂ RE	GGR Directorate Hub looking across the five GR-D projects	Public perceptions using national survey, deliberative workshops. Ethnographic study of field trials. Ongoing engagement with relevant policy teams in United Kingdom and EU govts and devolved administrations.	Stilgoe et al. (2013) AREA framework and stage-gate procedure. Bellamy (2018) responsible incentivisation. Stirling (2008) social appraisal of technology.

This table was completed by the named authors of this perspective and is therefore not exhaustive. More detail on all the GGR-D projects can be found via the links at: <https://co2re.org/ggr-projects/>.

development and deployment is seen to rest on submitting competing expert claims to participatory discussion.

Such associations appeared less contentious for some “novel” land-based carbon removal methods where their deployment in global modelling scenarios provides the primary justification for field trials. However, for many other carbon removal methods mobilising longstanding fields of research and expertise, climate policy is far from the only or even primary justification for trials. With respect to more “conventional” methods of carbon removal (e.g., perennial biomass crops, peatland restoration and forestation) trials may be closely connected to established domains of environmental governance and forums for managing expert disputes. For many such methods, it is therefore the engagement of stakeholders with processes of policy design and evaluation – rather than constructing novel forums of public deliberation – that provides primary focus for legitimate development and deployment of carbon removal. Questions of RRI are far from irrelevant to the latter but take on a different emphasis, since expert controversies are less likely to expose a vacuum in existing governance arrangements. In our discussions, we therefore found the AREA framework to be generally more relevant to novel methods than to conventional carbon removal.

Alongside variegated challenges for RRI raised by different carbon removal methods, discussions also highlighted the double-edged sword of cross-programme coordination of RRI. In initial meetings, discussions about RRI and carbon removal were difficult to separate from questions about the internal governance architecture of the GGR-D programme, which approximates a “hub and spoke” model (i.e., CO₂RE and the Demonstrators), with functions of CO₂RE incorporating some programme administration and a focus on evaluation methodologies. Where attempts to coordinate RRI has afforded discussion and exchange on methodologies and cross-cutting concerns, our conversations about RRI have also expressed different positionings within the programme’s governance architecture. Some authors questioned whether coordination of RRI might, in effect, “responsibilize” social science for its implementation and addressing various risks, harms and overflows of carbon removal projects.

Table 1 presents an overview of some of the various research practices across the GGR-D programme with publics such as stakeholders, communities, citizens and other concerned groups. Corresponding to this, the final column of Table 1 presents some of the diverse concepts and tools put to work in these research practices. As Table 1 illustrates, deliberative research is a central component in the research of CO₂RE-affiliated authors which centre on perceptions of competing carbon removal policies among United Kingdom citizens and concerned groups. Questions about responsible innovation are also explicitly addressed by the Enhanced Rock Weathering Demonstrator, a novel carbon removal method, which also focuses on public engagement in tandem with stakeholder research. Deliberative methodologies feature across both

novel and conventional methods, including Biochar and Peatland Demonstrators; however, the emphasis here is more on experts, knowledge-holders and directly connected groups. In the case of Perennial Biomass Crops (PBC4GGR) and Tree Planting Demonstrators (Net Zero Plus), in so far as they are conventional carbon removal methods (i.e., not used for BECCS), research is much more closely linked with land managers, users and policy stakeholders affected by deployment proposals. In the case of the latter, research is less focused on deliberative appraisal and more on decision-making practices and interventions within longstanding domains of governance.

The AREA framework may well be, in theory, flexible enough to accommodate the variety of approaches outlined in Table 1, but in our experience it appeared, in practice, more relevant to researchers working on some trials and less to others. This cannot be simply explained away as a matter of the disciplinary orientation or methodological preferences of the particular social science teams because it also expresses, we have highlighted, divergences in the material aims and justifications for field trials and the uneven governance landscapes within which attempts to innovate carbon removal methods are developing.

Carbon removal field trials as a test for RRI?

Bringing RRI into research and development of carbon removal makes clear that what is on trial in programmes like the GGR-D programme are not only a particular suite of promising sequestration and storage methods but also techniques and arrangements for governing innovation and deployment. RRI frameworks, like the AREA framework, are powerful devices with which to approach field trials not simply as evidentiary procedures but as highly symbolic sites of demonstration within an emerging innovation regime. Nonetheless, as we found, the AREA framework applies neither neatly nor evenly to the demonstrator projects discussed above. In concluding, we briefly reflect on the wider implications of this insight for RRI and carbon removal.

As elaborated above, the United Kingdom is a distinctive setting for working with RRI frameworks because they have been adopted within official research policy. We’ve suggested that the official adoption of RRI frameworks potentially introduces tensions between their deliberative and anticipatory dimensions, exploring how these internal tensions have manifested within the United Kingdom’s GGR-D programme. Such tensions are, in large part, related to framings of carbon removal methods as more-or-less “novel.” As highlighted, the AREA framework emerged in proximity to debates about geoengineering and has informed various developments around carbon removal, including the design of components in this research programme. As discussed above, the framework’s normative deliberative dimension – which centres on agonistic discussion as a basis of legitimate technology development and

deployment – implies that the consequences of technology deployment will be socially disruptive and require novel governance arrangements. But, many land-based carbon removal methods being trialled in the United Kingdom's GGR-D programme can also be seen to be embedded within established fields of environmental research and bodies of expertise. Deliberation is unlikely to facilitate critical public engagement with carbon removal (of the kind normatively valued in the AREA framework) if established governance arrangements and forums are obscured by framings of methodological “novelty” and anticipatory methodologies that uncritically reinforce them. Examining how novel/convention distinctions between carbon removal methods are drawn (and contested) by actors in the field may therefore be critical to understanding how deliberation and anticipation are being officially framed – and how they could be framed otherwise – within the emerging innovation regime.

In this respect, we suggest that field trials of carbon removal methods are not simply sites for implementing established RRI frameworks and methodologies but also critically testing them. Programmes for research and demonstration of carbon removal are not unique to the United Kingdom and are now developing around the world (Minx et al., 2024). The United Kingdom's GGR-D programme has developed in close relation to United Kingdom government priorities but, as we have shown, field trials of carbon removal methods are far from straightforwardly national policy instruments. Critically testing RRI across diverse field trials, we suggest, may bring into view very different imaginaries of the regime governing the innovation of carbon removal. The situatedness of the emerging innovation regime is important to acknowledge because techniques for demonstrating the efficacy and acceptability of carbon removal methods developed in the United Kingdom may have quite different consequences in jurisdictions with different territorial potential for deploying land-based methods. As experiments that will shape how social responsibility for carbon removal is distributed and governed, we suggest that field trials can be approached as sites for testing not only promising technologies but also the deliberative and anticipatory promise of RRI.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

LW: Writing – original draft. EC: Writing – review & editing. AB: Writing – review & editing. TG: Writing – review & editing. RE: Writing – review & editing. KH: Writing – review & editing. JI: Writing – review &

editing. CM: Writing – review & editing. KO'S: Writing – review & editing. NP: Writing – review & editing. CP: Writing – review & editing. MR: Writing – review & editing. AS: Writing – review & editing. RB: Writing – review & editing.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. Authors associated with the CO2RE Hub are supported by the Natural Environment Research Council (grant ref. NE/V013106/1). Authors associated with the GGR-D Demonstrators are supported by the Biotechnology and Biological Sciences Research Council (BBSRC). Biochar Demonstrator (grant ref. BB/V011596/1), Enhanced Rock Weathering GGR Demonstrator (grant ref. BB/V011359/1), GGR Peat Demonstrator (grant ref. BB/V011561/1), NetZeroPlus Demonstrator (grant ref. BB/V011588/1), Perennial Biomass Crops for GGR Demonstrator (grant ref. BB/V011553/1).

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The author(s) declared that they were an editorial board member of *Frontiers*, at the time of submission. This had no impact on the peer review process and the final decision.

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