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# Strengthening MRV standards for greenhouse gas removals to improve climate change governance

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Policy report

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# Contents

# Summary


### Key messages

- A lack of transparent and robust monitoring, reporting and verification (MRV) is a barrier to scaling up the greenhouse gas removal (GGR) sector.
- Well-designed, flexible MRV regulations are a market enabler and will help drive growth, innovation and credibility in the sector.
- An inconsistent patchwork of MRV exists. This has created a complex system, making navigation and meaningful comparisons between different types of GGR challenging.
- Ocean-based GGR faces significantly more MRV scalability risks than other types of removals.
- MRV policy development for direct air capture with carbon storage (DACCS) needs to accelerate in order to certify and meet large future demand.
- Current complexity will only worsen with time as more companies develop new standards.

### High-level recommendations

1. Promising but under-researched GGR methods, such as ocean-based biological and geochemical methods, suffer from a lack of foundational science, which hampers MRV development. Governments should address this shortcoming through targeted funding for longitudinal experiments to explore the GGR potential of these methods, to create an empirical research base and dedicated community from which to build MRV frameworks.
2. R&D and demonstration support should be made available by governments to reduce costs for expensive MRV processes. Greater data-sharing between project developers, MRV providers and selling platforms should be incentivised so that market analyses are regularly published to increase transparency. This would also highlight market risks and identify where effort is needed to reduce MRV costs.
3. Regulators should seek to support the development of seller-liability for non-subsurface storage reservoirs for methods such as ocean fertilisation, afforestation and enhanced rock weathering. To ensure a fair allocation of risk between public and private entities, seller liability could be underpinned by government-backed carbon reinsurance schemes that sellers must procure.
4. Policymakers in jurisdictions developing GGR strategies such as the UK need to develop minimum standards for MRV to ensure interoperability across selling platforms. Minimum standards should be differentiated from preferred methodologies. This could begin with identifying where in the MRV ecosystem there is duplication, low credibility, and unnecessary complexity among voluntary and compliance MRV providers.
5. Policymakers should consider regulating minimum standards for MRV. Risks will persist for all GGR methods if the sector continues to develop under a light-touch regulatory regime. These risks justify stronger regulation. An MRV regulator with sufficient powers would provide confidence that all removals are high quality.
6. Policymakers should develop a wide portfolio of GGR methods to manage MRV risks. This needs to be part of a broader governance framework to manage the risks of moral hazard and poor environmental integrity.

## Why are greenhouse gas removals needed?

Most scenarios for meeting the Paris Agreement objective of limiting warming to well below 2°C and pursuing efforts to limit warming to 1.5°C include greenhouse gas removal (GGR). The role of GGR in the net zero policy suite has been strengthened by analysis from the Intergovernmental Panel on Climate Change (IPCC), which finds that reaching net zero emissions without GGR is unavoidable; the IPCC's modelling shows that 100–1,000 gigatonnes (Gt) of carbon dioxide removal over the century would compensate for 'residual emissions' (those unlikely to be mitigated) and limit global warming to 1.5°C with limited or no overshoot. However, the IPCC is also clear that removals are not a substitute for immediate and deep emissions reductions.

## Growing momentum for GGR

Attempts are being made to rapidly scale up the supply of GGR to deliver future removals through terrestrial and ocean-based biological, chemical and geochemical methods such as afforestation and reforestation, soil carbon sequestration, bioenergy with carbon capture and storage (BECCS), direct air carbon capture with carbon storage (DACCS), enhanced rock weathering (ERW) and ocean alkalinisation/fertilisation. Although there is considerable momentum behind GGR, this must not detract from the primary task of reducing gross emissions, nor blind policymakers to the risks inherent to different GGR techniques.

## Robust MRV for upscaling GGR

There is broad acceptance that in addition to policy incentives and commercialisation mechanisms, advances in techniques that monitor, report on and verify (MRV) greenhouse gas removals are critical and need to keep pace with GGR methodological development. MRV standards assess the veracity of an emissions removal claim, and provide assurance that removals are highly durable, additional and not harmful to local environments or communities. Without such assurance, trust in GGR as a mitigation option will be slow to develop and this may hamper the scale-up of GGR.

The importance of MRV has been recognised, but the risk of inaccurate or poorly designed MRV frameworks is undermining confidence in the market, halting capital flows, and stymying innovation and policy development, which will ultimately slow down global mitigation efforts. These problems stem from the complexity and rapidly evolving nature of MRV for GGR, which raises questions about oversight and quality, and creates a landscape that is challenging for regulators, policymakers and developers to navigate. It is in the interest of the whole GGR ecosystem (project developers, intermediaries, MRV providers, brokers and buyers) that claimed removals are indeed highly durable, and that MRV frameworks can reduce the risk of impermanence (i.e. high quality MRV can identify risks of leakage/sink instability through a combination of digitised, automated monitoring and reporting with high frequency third party audits) as much as is practicable over a climate-relevant period of 100–1,000-plus years.

For some GGR methods the foundational science underpinning the method of greenhouse gas removal is advanced, and MRV methodologies have been able to build on this knowledge base. This includes in the areas of industrial carbon capture, utilisation and storage (CCUS) in the case of BECCS and DACCS, petroleum geosciences for subsurface storage, and $CO_2$ mineralisation or forest science for afforestation/reforestation. MRV availability has been hampered, however, in the case of GGR methods that are difficult to measure in isolation from natural processes, such as open-loop ocean-based methods, and where there is still uncertainty over the rate of $CO_2$ accumulation, as with ERW and biochar.

MRV for open-loop systems (i.e. those where humans intervene in natural biogeochemical processes to stimulate $CO_2$ removal) is particularly important because these have big advantages in terms of thermodynamic efficiency (enhancing pre-existing natural GGR processes can be more efficient, cost-effective and scalable) over closed-loop GGR (i.e. where $CO_2$ is drawn down from ambient air through approaches which capture, contain and store $CO_2$ with a much higher degree of human intervention across all steps of the process GGR process). Ensuring that a diverse portfolio of open- and closed-loop GGR remain in policy pathways is therefore necessary, given the intrinsic advantages of open-loop GGR.

While MRV is of critical importance, it is not a panacea for all the market failures preventing GGR from being scaled up. It may never be possible to have certainty that a tonne of $CO_2$ sequestered by a land-based sink is equivalent to either a tonne of $CO_2$ captured by BECCS or DACCS, or an abated tonne of $CO_2$ (i.e. curtailing output from fossil fuelled energy production). Expectations for MRV may need to be dampened and policy frames adapted accordingly. Nevertheless, ensuring that GGR is accurately measured, reported to regulators and verified remains critical to the healthy functioning of the sector and wider societal acceptance of the need for GGR.

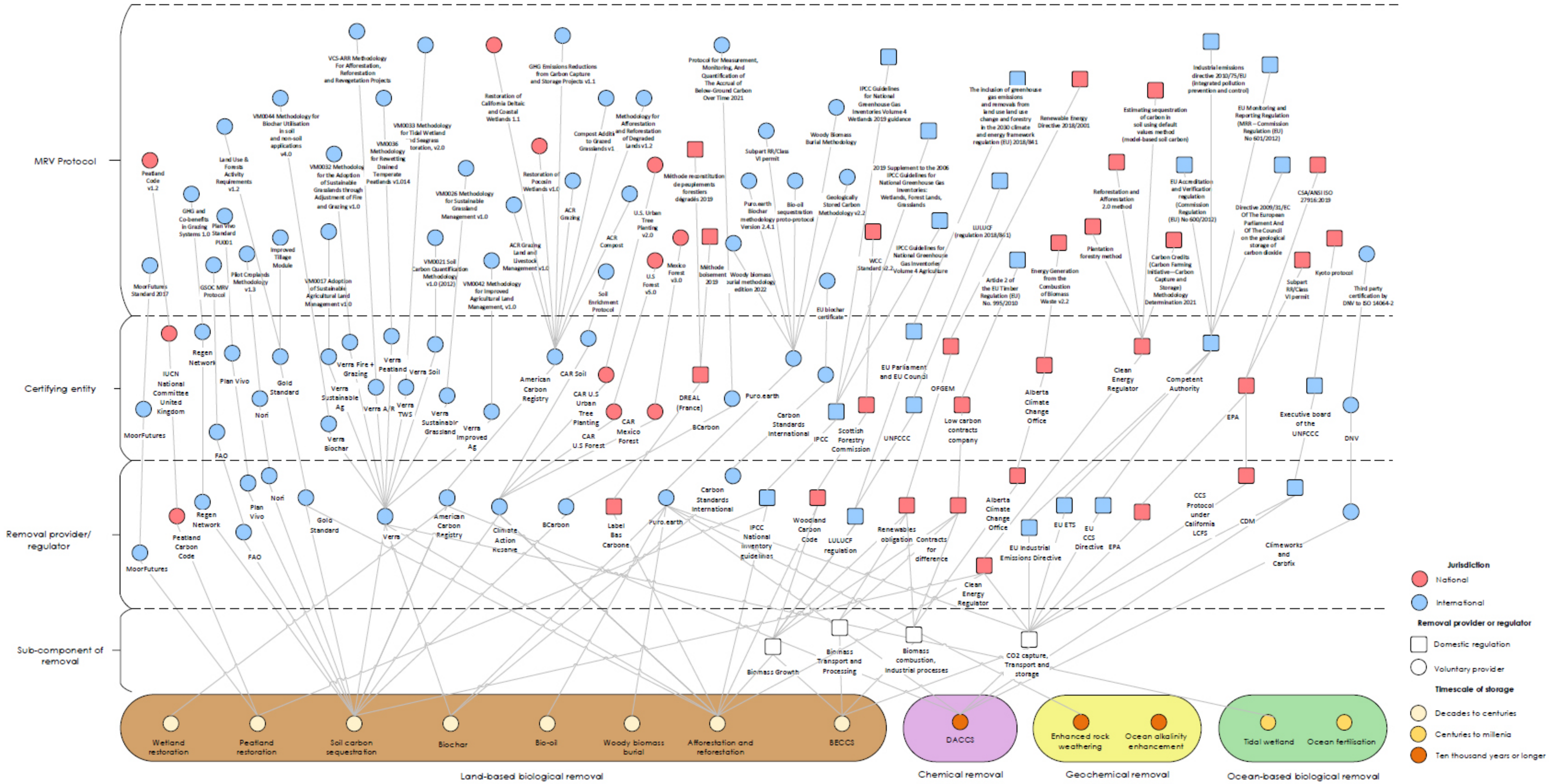
## Mapping current MRV to highlight features and gaps

The current MRV landscape is crowded, with numerous entities operating across the voluntary carbon market (VCM) and compliance mechanisms offering MRV standards for different GGR methods. A network mapping exercise has helped to identify interrelationships between regulations, certifying entities and MRV protocols (see Figure S1). Although this mapping aims to provide clarity, it should be viewed with the following caveats in mind: although every care was taken to be comprehensive, the mapping and database of MRV providers will likely have omissions, as the ecosystem is evolving rapidly; certain organisations do not make their standards publicly available; the diagram is biased towards removal providers who publish their MRV protocols in English. There will also undoubtedly be a bias towards high-income countries. The mapping should therefore be viewed as a non-exhaustive, flexible starting point.

### Key features

- Of the 69 protocols identified, 56 certify land-based biological GGR activities. There are 9 chemical protocols (all for DACCS), and one geochemical MRV protocol. There is currently one verified ocean-based biological MRV protocol for marine biological removal methods – tidal wetland and seagrass restoration.
- Most MRV development is for land-based biological methods, especially for soil carbon sequestration (16), and afforestation/reforestation (13).
- Of non-regulatory entities, Verra certifies the most removal activities, with 9 MRV protocols registered.
- Existing policies that could be latterly adapted for MRV pertain almost exclusively to BECCS and DACCS, given the CCS component. The EU's Competent Authority provides MRV certification for $CO_2$ capture, transport and storage relating to BECCS and DACCS under the EU ETS, EU CCS Directive and EU Industrial Emissions Directive.
- Puro.earth provides the widest range of MRV services (through registry hosting and connecting project developers with third party certifiers), for biochar, bio-oil, ERW, woody biomass burial, and geological injection that stores $CO_2$ from BECCS and DACCS.
- Other large certifying entities such as the Climate Action Reserve and Verra only provide MRV for land-based biological methods.
- There is stratification among MRV providers who appear to develop and approve GGR methods and facilitate or provide MRV for these in-house methods. Increased competition may be useful in driving down costs and spurring innovation, but disparate methods could also lead to siloing whereas the complexity of the challenge may require a greater degree of collaboration. One possible solution could be to allow MRV providers to license their products to others under a joint agreement. This could enhance collaboration while protecting intellectual property from being copied.

## Figure S1. Mapping of the landscape of MRV for greenhouse gas removals

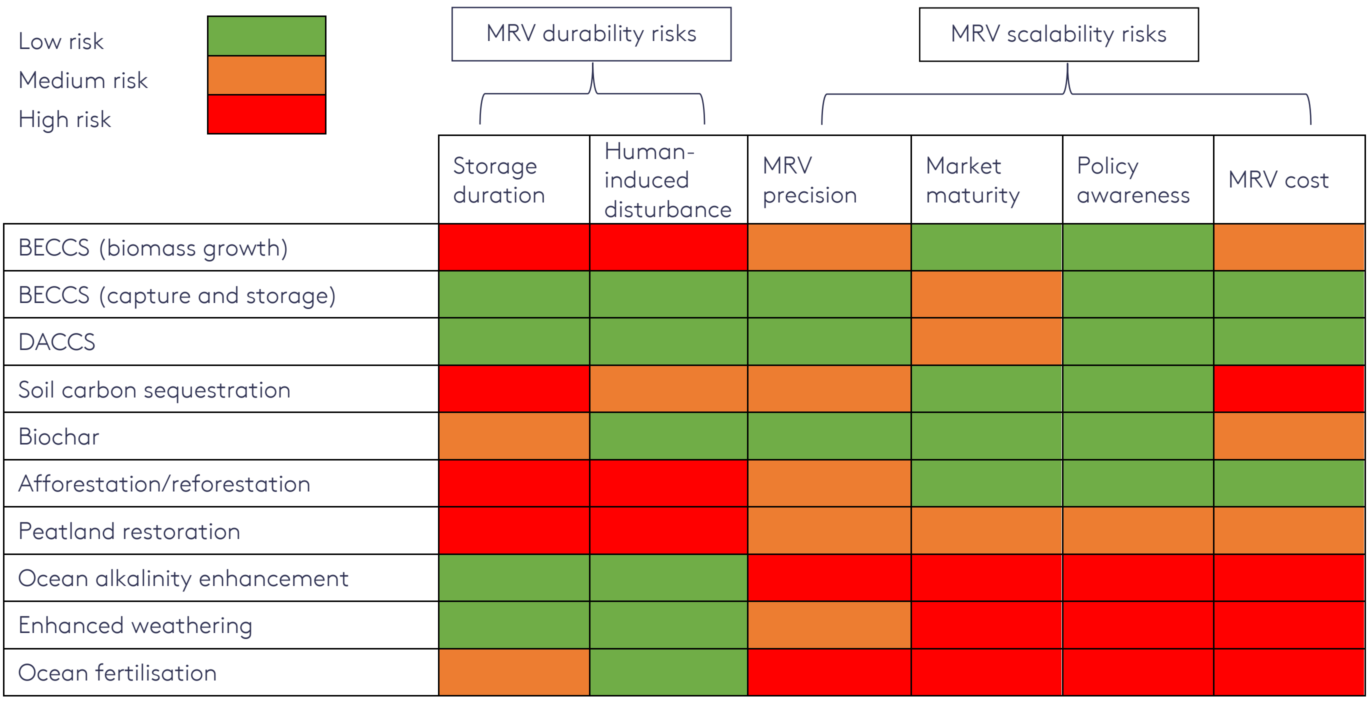



*Source: Authors based on primary and grey literature analysis and interviews. (NB. A separate PDF download of this mapping is available from the **report landing page** along with the underlying data).*

- The majority of MRV is being developed for land-based biological removals from public and private certifying entities. Aggregated data from cdr.fyi, an open-source data repository that tracks GGR purchases, indicates that advanced market commitments (i.e. the ex-ante purchasing of GGR carbon credits) favour chemical processes such as DACCS. Given that full chain MRV certification for this method is in the main provided through regulation and IPCC guidance, regulators will need to ensure that MRV coverage percolates beyond regulatory instruments, including by supporting MRV protocol development so that project developers can reliably meet demand.

Figure S2 presents an MRV risk matrix. The matrix builds on earlier work by Chay et al. (2022) and assesses risks to the adequate development of MRV across six dimensions: two relate to durability (denoting durability ranges in low levels) and four to scalability. The colours (green, amber, red) reflect the risks relative to each other and should not be misconstrued as meaning significant absolute risks. The GGR methods that scored the highest across these criteria include BECCS, DACCS and biochar. GGR methods that scored poorly were generally open-loop systems such as ocean alkalinity enhancement and ocean fertilisation (which are both nascent methods without a strong foundational science base). Risk will change over time as research and innovation take place. Investing in MRV processes with a large number of risks (i.e. those highlighted in red below) to reduce uncertainties will help enable the development of a broad portfolio of GGR techniques with high potential.

Figure S2. Relative risk matrix for MRV for greenhouse gas removal




*Source: Authors. (Please see Appendix 1 for an accessible version in greyscale.)*

## Priority areas and recommendations to advance MRV for GGR

We have identified six priority areas and corresponding recommendations for policymakers related to the development of information architecture, market design settings and minimum standards relevant to different GGR stakeholders.

**1. Foundational science.** The state of science underpinning categories of removals reflects MRV development. There are clear MRV gaps for ocean-based biological and geochemical methods when compared with land-based biological approaches. Although the foundational science is sound, better incentives for research and innovation in ocean-based GGR (alongside environmental impact assessments) are needed to aid development. For GGR such as DACCS, where MRV is mainly provided through regulatory instruments, private MRV providers should be incentivised to develop MRV to ensure advanced market commitments can be met and upscaling continues.

> **Recommendation 1.** **Government should address the fact that promising but under-researched GGR methods, such as ocean-based biological and geochemical methods, suffer from a lack of foundational science (hampering MRV development): through targeted funding for longitudinal experiments to explore the GGR potential of these methods, to create an empirical research base from which to build MRV frameworks.**

**2. Cost of MRV.** While there are estimates available of the anticipated total cost of different GGR methods, the cost of MRV pertaining to specific GGR methods is not available. MRV work being done is often in-house and not visible externally, with its costs bundled within overall cost estimates. This makes it challenging to highlight where there are uncertainty or risks over various GGR approaches. Moving forward, a price is needed for different MRV processes in order to put monetary value on risk. This will be useful for those actors considering capital investments in GGR and for policymakers who will need to outline funding strategies for research into, legitimation of and market demand for GGR technologies. Publishing costs could also enable the development of a cost curve that could come down over time – although publishing costs does not automatically achieve this. Better transparency would also need to be supported by policies that in the near to medium term see targeted R&D, demonstration support and demand-pull for GGR, within an innovation system that connects national and subnational agencies with GGR developers and financiers. Moves to standardise and structure buyer claims through changing norms and proposed regulation could bolster transparency and naturally lead to open-source, digitalised and transparent MRV providers being favoured. Highlighting costs may also lead to a more honest conversation about GGR, especially when comparing open- and closed-loop systems, where removing fungibility might be useful.

> **Recommendation 2.** **R&D and demonstration support should be made available by government to reduce costs for expensive MRV processes. Greater data sharing between project developers, MRV providers and selling platforms should be incentivised so that market analyses are regularly published to increase transparency. This would also highlight market risks and identify where effort is needed to reduce MRV costs.**

**3. Liability for GGR credits.** There is a fundamental need to decide where responsibility for MRV sits within the value chain. The GGR value chain is complex with many different actors, therefore it is important to have reliable monitoring and reporting that can be verified by a third party. Legal provisions need to be developed to manage asymmetric risk allocations between buyers and sellers should the results of MRV suggest carbon leakage or impermanence of removal. Historical discussions on carbon capture and storage policy frameworks and forestry under the REDD framework, Kyoto Protocol and Clean Development Mechanism (CDM) provide useful context. Experience has shown that buyer liability may soften credit demand, whereas seller liability has clear contracting benefits. In the absence of legal precedent and policy frameworks to manage legal liability for MRV across nascent GGR methods (such as enhanced rock weathering), negotiation between buyers and sellers allocates risk.

Today, sellers are not countries but a combination of private companies supplying directly to buyers via bilateral contracts, or large platforms that aggregate and retail a number of GGR credits from smaller developers. Extending the previous jurisdictional concept of seller liability (under the CDM) would imply that liability management sits with the platforms selling GGR. It will be necessary to refine this concept to take account of the Paris Agreement where countries with nationally determined contributions (NDCs) face *de facto* liability for carbon reversals from storage sites that they host, alongside the greater role of non-jurisdictional actors (such as credit registries) who develop projects, retail credits and provide MRV services. A solution could be to make use of insurance schemes whereby selling platforms have initial liability, but this is underpinned by government-backed carbon insurance schemes that must be procured.

> **Recommendation 3. Regulators should seek to support the development of seller-liability for non-subsurface storage reservoirs for methods such as ocean fertilisation, afforestation and enhanced rock weathering. To ensure a fair allocation of risk between public and private entities, seller liability could be underpinned by government-backed carbon reinsurance schemes that sellers must procure.**

**4. MRV efforts undermined by disparate actors and protocols.** This makes comparing different methods of removal extremely difficult. The plethora of different MRV standards could prove counterproductive. Variability in MRV is preventing developers and regulators from accurately understanding risks specific to each GGR method, hindering progress in scaling up removals. Private entities purchasing removals typically bundle purchases from different suppliers, each of which may have its own MRV protocol. In many ways this is a result of the patchwork jurisdictional approach to incentivising and regulating GGR, e.g. the EU has an economy-wide emission trading system and is developing a framework for certifying GGR under the Carbon Removal Certification Framework, a process happening in advance of developments in the UK and USA – so differences may emerge in how MRV frameworks develop at a jurisdictional level. Discrepancies between certifying entities can undermine the credibility of MRV and removals more generally – but also, they hinder those purchasing removals from assessing their own purchases within and between supply chains. This challenge will only get worse as new market actors emerge.

> **Recommendation 4. Policymakers in the UK and other jurisdictions developing GGR strategies need to develop minimum standards for MRV to ensure interoperability across selling platforms. Minimum standards should be differentiated from preferred methodologies. This could begin with identifying where in the MRV ecosystem there is duplication, low credibility and unnecessary complexity among voluntary and compliance MRV providers.**

**5. An MRV regulator.** There is no apex body to provide oversight and compliance functions for the MRV methods used to certify GGR, nor a mechanism to ensure that removals align with policy direction and contribute to carbon budgets and NDCs. A laissez-faire approach enables industry to develop GGR methods with freedom – however, there may be wasted effort if certain techniques do not remove $CO_2$ with the requisite permanence or within adequate safety guidelines. An MRV regulator should sit between project developers and national governments with a remit to co-develop MRV and minimum standards for GGR. Another function would be to promote transparency alongside development and enforcement of minimum standards to make certain features readily available for scrutiny, such as removal providers, the purchaser, date of retirement and other pertinent project details including the level of permanence.

> **Recommendation 5. Policymakers should consider regulating minimum standards for MRV. Risks will persist for all GGR methods if the sector continues to develop under a light-touch regulatory regime. These risks justify stronger regulation. An MRV regulator with sufficient powers would provide confidence that all removals are high quality.**

**6. Managing MRV risk.** Stronger MRV is just one tool available to policymakers to manage durability and scalability risks related to carbon removal. MRV should be seen as part of a multi-faceted and intertemporal policy and governance framework for GGR. This includes considering separate accounting targets for GGR and conventional emissions abatement, removing perfect fungibility between GGR permits and carbon market permits, and promoting a wide range of innovation and technology-specific mechanisms to drive currently expensive, yet highly scalable MRV processes down the cost curve.

> Recommendation 6. **Policymakers should develop a wide portfolio of GGR methods to manage MRV risks. This needs to be part of a broader governance framework to manage the risks of moral hazard and poor environmental integrity.**

## Conclusions

There are clear gaps in MRV readiness (based on author assessment) across the range of terrestrial and ocean GGR methods. There is significant MRV stratification, with many protocol developments occurring in voluntary carbon markets. MRV risks lie mainly with GGR methods that do not have an advanced base of science to build upon. Challenges exist for public and private bodies supporting MRV development and will need to be addressed through greater provision of finance and incentives to develop nascent methods, alongside a carefully designed regulatory environment that stimulates GGR innovation with high integrity and durability. Without these measures to support MRV readiness, scaling up GGR to deliver the quantity of removals called for by the IPCC will continue to be impeded.

# 1. Introduction

This report seeks to identify the factors underpinning the monitoring, reporting and verification (MRV) of greenhouse gas removal (GGR) across the spectrum of biological, chemical and geochemical techniques, and the risks associated with GGR-specific MRV. It provides recommendations for policymakers to reduce the complexity and ensure the industry continues to innovate with high levels of integrity.

## Why are greenhouse gas removals needed?

Greenhouse gas removal (GGR) techniques are becoming increasingly important as nations and corporations seek to achieve net zero or net-negative emission targets. The role of GGR in the net zero policy suite has been strengthened by analysis from the Intergovernmental Panel on Climate Change (IPCC, 2022), which finds it will not be possible to reach net zero emissions without GGR; 100–1,000 gigatonnes (Gt) of $CO_2$-equivalent will need to be removed over the course of this century to compensate for 'residual emissions' (those unlikely to be mitigated; see box) and to limit global warming to 1.5°C with limited or no overshoot (IPCC, 2018). However, the IPCC is also clear that removals are not a substitute for deep emission reductions. Ho (2023) powerfully concludes that we must stop talking about deploying GGR as a solution today when emissions remain high as if it could replace radical, immediate emission cuts.

A growing number of national pledges to reach net zero emissions between 2040 and 2070 have been made in recent years. The UK, China and India are targeting net zero by 2050, 2060 and 2070, respectively. Net zero commitments are now cascading from nations to corporations. Around a quarter of the biggest 2,000 global firms have committed to net zero targets on similar timeframes (Mac Dowell et al., 2022). In total, almost two-thirds of global emissions and a slightly higher share of global GDP are now covered by net zero targets (Fankhauser et al., 2022). Within the Organisation for Economic Co-operation and Development (OECD), there is an implicit reliance on GGR in national net zero targets given that these countries' long-term decarbonisation strategies suggest that on average 18% of current emissions will remain post-2050 (Buck et al., 2023).

### Terminology

The IPCC defines '**carbon dioxide removals'** (CDR) as nature-based or technological activities that remove $CO_2$ from the atmosphere and durably store it in geological, terrestrial or ocean reservoirs. The term '**greenhouse gas removals**' (GGR) is the convention used by the UK government and equates to the same concept. This convention is followed herein. In the international literature, **'carbon dioxide removal'** (CDR) and '**negative emissions technologies**' (NETs) are terms used as well as GGR. We also use these terms where appropriate.

**Residual emissions** are typically related to aviation, long-distance transportation, structural materials, heavy industry, and baseload electricity. The level of unabated emissions that are considered 'acceptable' and thus 'residual' is not agreed and is contingent on values, norms and interests (Lund et al., 2023). 'Residual emissions' is therefore a dynamic social and economic construct that depends on the policies and actions of government, business and other stakeholders.

Developments in this nascent sector have global relevance. As an example of one of the many countries giving attention to this issue, the UK in its recent Net Zero Strategy (BEIS, 2021) set a target of at least 5Mt$CO_2$/year of GGR by 2030. Institutional guidance on reaching net zero in the UK is provided by the Climate Change Committee, which contends that a net zero strategy must involve reducing emissions in line with relevant sectoral pathways as much as possible, with the residual amount (estimated at 15% of 2019 levels) offset by GGR (CCC, 2022). This equates to approximately 57 Mt$CO_2$/year in 2050 (CCC, 2020). With such a large delta between near- and long-term targets, GGR requires significant upscaling if this is to be achieved in the UK.

## Growing momentum for GGR

GGR businesses are currently growing rapidly to give effect to the emission cuts called for by the IPCC and mandated by domestic laws. Methods include afforestation and reforestation, land restoration and soil carbon sequestration, bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), and enhanced weathering and ocean alkalinisation (Allan et al., 2021; Bey et al., 2021b; Fuss et al., 2018; Minx et al., 2018) – descriptions are provided in Section 4.

While the quantity of removals necessary to limit temperature rise to 1.5°C is considerably beyond the capacity of present-day GGR methods, this could change as investment is flowing towards approaches such as BECCS and DACCS, which are beneficiaries of considerable government support[1] and private equity investment. Smith et al. (2023) estimate publicly funded capital flows of US$4 billion for research, development and demonstration (RD&D) for GGR and a US$200 million investment flow between 2020 and 2022 for nascent removal methods. The EU has proposed a regulation to certify GGR and is presently consulting on how this could develop. But such political and financial support must not detract from the primary task of reducing emissions, nor blind policymakers to the risks inherent to different GGR techniques.

## Why monitoring, reporting and verification (MRV) is key to building trust in GGR

GGR is not without controversy. Historically it has been driven by expanding terrestrial carbon sinks through providing credits for emission avoidance and/or removal. Avoided emissions should not be conflated with GGR. For example, GGR techniques such as BECCS have industrial carbon-capture, utilisation and storage (CCUS) applications in bioethanol plants. While the methodologies and processes to capture $CO_2$ emitted at source are identical for bioenergy power plants and ethanol plants, CCUS is not considered to be a form of GGR as it *reduces* emissions from existing industrial processes rather than creating an additional and permanent $CO_2$ *removal,* as BECCS power does.

The GGR industry may be compared unfairly with earlier iterations of the voluntary carbon market (VCM) or the Kyoto Protocol's Clean Development Mechanism (CDM). Commentators have often referred to the VCM as the 'wild west' (Valiergue and Ehrenstein, 2022), given the reliance on vulnerable terrestrial biological sinks that have significant reversal risks, the proliferation of dubious project developers, and challenges associated with market and project leakage, and verifying additionality and monitoring permanence (Kollmuss et al., 2015; West et al., 2020).

Experience has shown that poor MRV can also result in the certification of non-additional, high-leakage credits. For example, recent reporting by *The Guardian*, *Die Zeit* and *SourceMaterial* has indicated that MRV processes for projects aiming to reduce deforestation have substantive flaws, which has resulted in systematic over-crediting of rainforest conservation projects (Greenfield, 2023). Similarly, under the Kyoto Protocol's Joint Implementation Initiative, there are estimates that up to three-quarters of 'verified offsets' did not represent additional emission reductions (Kollmuss et al., 2015). In addition to the significant structural challenge of deploying GGR at the requisite scale to reach the 1.5°C target, segments of the population are ambivalent about the technology and grapple with the role technological GGR should play in a decarbonisation strategy (Cox et al., 2020). Popular critiques include reliance on GGR detracting from the larger goal of reducing gross emissions and the perception that GGR is as an attempt to greenwash, allowing business-as-usual emissions to continue (Mac Dowell et al., 2022). Concern also relates to the reliance on speculative technological GGR techniques, which may result in not meeting net zero targets if claimed reductions cannot be achieved or may delay immediate mitigation. This phenomenon has been described as "moral hazard par excellence" (Anderson and Peters, 2016), owing to the risk of being locked into a high-temperature pathway if we rely on GGR which is not deployed or does not remove emissions at the necessary scale.

### Objectives of MRV

What gives confidence to claimed removals is the MRV frameworks that assess the veracity of a removal claim and provide assurance that removals are permanent, additional and not harmful to local environments or communities. MRV uses a multi-step process to measure the amount of greenhouse gas emissions reduced by a specific GGR activity over time and reports these findings

[1] The 2022 US Inflation Reduction Act offers a **tax credit** for carbon capture and storage of US$85/tonne, up from $50.

to an accredited third party. This third party then verifies the activity has followed the applicable GGR standard and certifies the resulting credits.

MRV mechanisms have two main objectives: firstly, to ensure that carbon credits (whether representing emissions removals or avoidance) are real, measurable, additional, do not result in leakage, are not double-counted, and are permanent; and secondly, to facilitate wide uptake and implementation of GGR, maximising the potential positive impact on the climate (Mitchell-Larson et al., 2022). In this context, MRV can be seen as a vital enabler for upscaling GGR by giving confidence that GGR is delivering what is expected (Harvey et al., 2022).

Although the importance of MRV has been recognised (BEIS, 2021), the ecosystem is crowded, complex and evolving rapidly. This not only raises questions about oversight and quality (Arcusa and Sprenkle-Hyppolite, 2022), but also makes it hard to navigate for regulators, sellers and buyers – stymying investment and undermining market confidence.

### Steps in an MRV process for greenhouse gas removals

The World Bank provides an outline of an idealised MRV process. In summary:

An emissions baseline must first be generated, against which progress can be measured. This could be annual net $CO_2$ emissions from a gas-fired energy plant or net emissions over a longer period for a terrestrial GGR project such as peatland or woodland restoration. This baseline is generated in accordance with the relevant MRV standard.

Once a project is underway, data is collected (in line with the relevant MRV standard) to determine the quantum of removals and compare it against the pre-GGR project baseline. Emissions can be measured through direct emissions monitoring (such as with a Continuous Emissions Monitoring system) or be derived obliquely from emission factors. As with the above examples, data collection might involve quantifying total $CO_2$ captured from flues at a BECCS power plant and injected into geological reservoirs, or the net change in removals in a forest after a management intervention.

The results are then collated into a report for review by a third-party auditor, who assesses whether the project has complied with the relevant MRV protocol. Once the claimed removals have been verified, the standard-setter certifies them (as per the third-party review) and issues credits on the relevant carbon registry.

*Source: World Bank,* ***Climate Explainer: MRV:***
https://www.worldbank.org/en/news/feature/2022/07/27/what-you-need-to-know-about-the-measurement-reporting-and-verification-mrv-of-carbon-credits.

### Structure of the report

- Section 2 outlines why MRV frameworks are needed in the field of greenhouse gas removals.
- Section 3 describes the state of the market for carbon removals and the rate of innovation in MRV for GGR.

- Section 4 evaluates the state of science and policy for existing and nascent removal methods.
- Section 5 develops a network mapping that links the predominant removal methods with project developers, registries/polices and the relevant MRV protocol.
- Section 6 identifies where in the MRV landscape there can be confidence in claimed removals and where policymakers and civil society need to pay close attention to claims being made, including through development of a risk matrix that identifies key risk factors for predominant GGR techniques.
- Section 7 provides actionable policy recommendations to support the development of robust minimum MRV standards for GGR.
- Section 8 concludes.

# 2. Why are MRV frameworks needed?

The credibility of emission reduction claims is integral to the functioning of the GGR sector and has implications for wider societal trust in the need to utilise GGR techniques to reduce the concentration of $CO_2$ in the atmosphere. There are few open-source and freely available MRV frameworks or registries that provide certainty about the quantity, credibility or permanence of removals. The increased use of principles (such as the Integrity Council for the Voluntary Carbon Market's core carbon principles) and better information architecture – such as credit ratings and better integration of data and disclosures pertaining to issuance, credit price, vintage and retirement date – have the potential to bolster trust in GGR project developers and certain classes of GGR (Smith et al., 2023). However, in the absence of robust MRV, assessing the quality of GGR projects will continue to be difficult.[2]

### A GGR market with integrity by design

MRV is an important component of the information architecture for GGR. The well documented credibility challenges associated with certain classes of carbon credits such as 'avoided deforestation' illustrate the necessity of avoiding credibility issues, which can be achieved through careful design of the GGR market. Determining the additionality and durability of removals has improved since the inception of the voluntary carbon market (VCM) and the over-reliance on terrestrial sinks (Ruseva et al., 2020). However, novel technologies still present myriad challenges associated with quantifying permanence and durability. As such, a growing number of commentators are calling for more robust MRV to reassure market participants (e.g. Kreibich and Hermwille, 2021).

Scale is one part of the GGR challenge (Khan and Minor, 2022). Of equal importance – and a mutually reinforcing condition of scalability – is trust in the various GGR approaches, particularly those nascent technological solutions. Khan and Minor argue that without trust, two types of constituents critical to the success of the industry will be lost (ibid.). The first constituents are those individuals and communities who will live near or host GGR solutions. The second constituents are the taxpayers whose support is needed to generate the political will to effectively support and incentivise GGR to reach the scale needed. A third constituent, not mentioned by Khan and Minor, is private capital and philanthropic funds and the extent to which a lack of trust poses a barrier to effectively leveraging this capital to invest in a broad portfolio of promising and highly scalable GGR techniques.

### A variety of monitoring challenges

Even at this embryonic stage in the development of GGR, there are barriers to equality of opportunity between different types of removals (Ellis, 2023). This is partly a function of the fact that monitoring is more challenging for some removals than for others. This is the case, for example, in 'open-loop'[3] removals, such as ocean alkalinisation enhancement, which manipulate natural carbon fluxes (in this example by enhancing the ability of the ocean to draw down $CO_2$ by adding alkaline materials to the ocean). Monitoring and isolating the effect of this intervention from the pre-existing natural carbon flux is fraught with challenges given the current state of knowledge and techniques to monitor these complex processes. This creates additional quantification uncertainty, requiring a higher burden of proof embedded within MRV systems.

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[2] Notwithstanding the financialisaton of the sector – i.e. greater provision of ratings and analytics to lower risk.

[3] Open-loop systems entail human intervention in open and natural biogeochemical processes to stimulate $CO_2$ removal and involve a high proportion of GGR steps outside of human control. Closed-loop GGR refers to pathways (such as DAC and mineralisation) that involve a high degree of human control and engineering to durably remove $CO_2$ from the atmosphere and store it in sub-surface reservoirs or other materials.

Resolving areas of technical and scientific uncertainty is more complex and may deter political or financial support, but it is essential to advance MRV so that open-loop systems can fulfil their potential. These systems have mitigation potential that is an order of magnitude higher than other GGR (Smith et al., 2023) and big advantages in terms of thermodynamic efficiency and long-run scalability. Developing MRV would also ensure that a diverse portfolio of open- and closed-loop GGR remains in policy pathways. A more detailed discussion on the need for a portfolio approach is provided in Section 7.

### Recognising the limitations of MRV

As policymakers in the EU and UK seek to utilise carbon markets as a policy lever to upscale GGR, the question of whether GGR carbon stocks can ever reach a level of acceptability and parity with the way carbon emissions are measured becomes more pertinent. At the heart of this is whether the codification of $CO_2$, or other greenhouse gases, as a tangible commodity should provide GGR with absolute fungibility with established emission reduction measures. Implicit in the assumption of fungibility is that a tonne of $CO_2$ sequestered by a natural sink is equivalent to either a tonne of $CO_2$ captured by an engineered solution such as BECCS or DACCS, or a tonne of $CO_2$ not emitted in the first place (abated). Fungibility exists between GGR (through afforestation) and emission reductions in certain compliance schemes, such as the New Zealand and California emission trading systems (ETSs). Notwithstanding the difficulties and uncertainties associated with assessing fungibility between removals from afforestation and emission reduction, it remains to be seen whether and under what conditions policymakers would treat chemical and geochemical GGR as fungible with other carbon credits.

The assumption of fungibility must recognise the distinct contexts in which these very different solutions operate and the risks embedded within them, especially as it can be difficult to scientifically define the equivalence between one unit of negative emissions generated through a given GGR technique and one (positive) unit of emissions abated. If these two units are to be considered entirely fungible, long-term durability and overall net additionality of emission reductions need to be ensured in both the capture and storage of greenhouse gases, to be confident of there being genuine and permanent emission reduction. Inclusion of GGR in carbon markets therefore raises important considerations for regulation and temporal governance in relation to MRV. Robust MRV is a necessary precondition for upscaling a future market that is liquid and allows trading of GGR credits (Burke and Gambhir, 2022).

Even if the expectations for monitoring accuracy need to be dampened, and the policy frames adapted accordingly (such as not allowing the integration of GGR into conventional carbon markets or having separate targets for GGR and mitigation), ensuring that emissions are accurately measured, reported to regulators, and verified will remain critical to the healthy functioning of the sector and wider societal acceptance of the need for GGR. It is in the interest of the whole GGR industry that claims of permanent removal are true, and that MRV frameworks can provide assurance of permanence over a climate-relevant period of 100–1,000-plus years (Mac Dowell et al., 2022). The risk of MRV frameworks being inaccurate or poorly designed undermines confidence in the market, halts capital flows, and stymies innovation and policy development, which ultimately will slow down global removal efforts.

## 3. Market demand for carbon removals and the pace of MRV innovation

### Delivered and committed market demand for carbon removals

Figure 3.1 shows the quantity (in tonnes) of carbon removals purchased between 2019 and 2023. Figure 3.1a shows removals that have been delivered; 3.1b shows removals that have been delivered (as per the first chart), plus removals where a commitment is made to purchase a quantity of removals at a later date.

Figure 3.1a shows that biochar accounts for 86.6% (64,159 tonnes) of carbon removals already delivered, bio-oil for 9.6% (7,149 tonnes), and enhanced rock weathering for 3.7% (2,776 tonnes).

Figure 3.1a. Delivered carbon removals in tonnes, 2019–2023

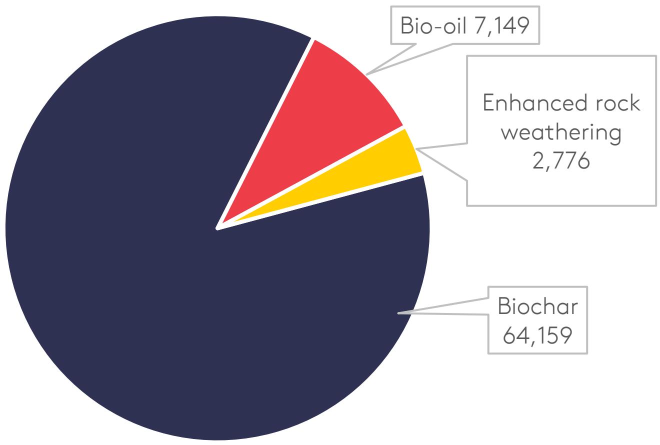
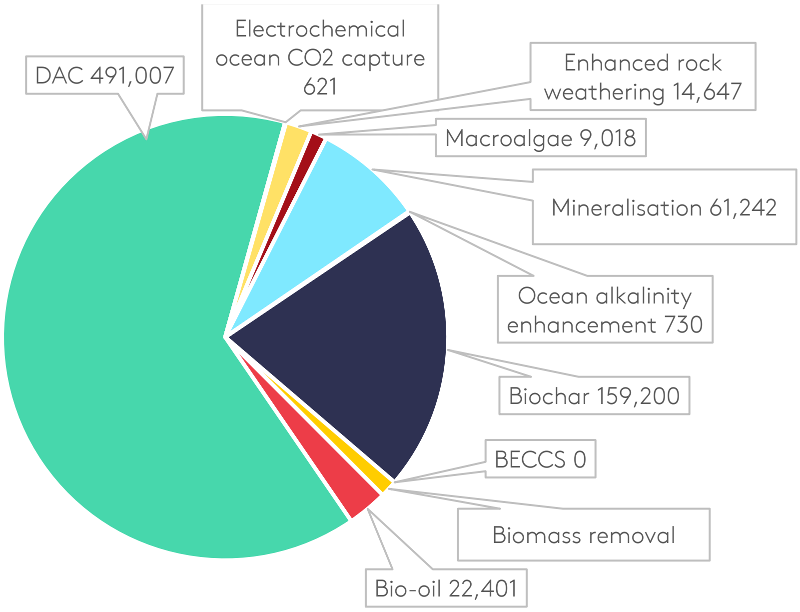



Figure 3.1b shows a stark difference with the above when removals that have been purchased but not yet delivered are included.

Figure 3.1b. Delivered removals plus advanced market commitments in tonnes, 2019–2023




*Source: cdr.fyi, accessed 20.2.2023. See Section 4 for descriptions of different GGR methods.*

Figure 3.1b shows there has been significant forward purchasing of Direct Air Carbon Capture (DACC). The Frontier advance market commitment[4] and an agreement by Airbus to purchase 400,000t $CO_2$ from DAC provider Carbon Engineering underpin this dynamic. With undelivered

[4] The Frontier advance market commitment (of US$925 million) aims to accelerate the development of carbon removal technologies by guaranteeing future demand for technological GGR that is high quality and has the greatest long-term potential. The founders of Frontier are Stripe, Alphabet, Shopify, Meta and McKinsey Sustainability. See **https://frontierclimate.com/**

removals included, biochar now represents 20.7% (159,200 tonnes) of removals (despite demand growing by 2.5 times), much less than DACC, which accounts for 63.9% (491,007 tonnes). This demonstrates just how large expectations are for the potential of DACC. Mineralisation (which is likely to derive from DACC projects – see Section 4) is the only other removal technique that makes a material contribution (7.9%).

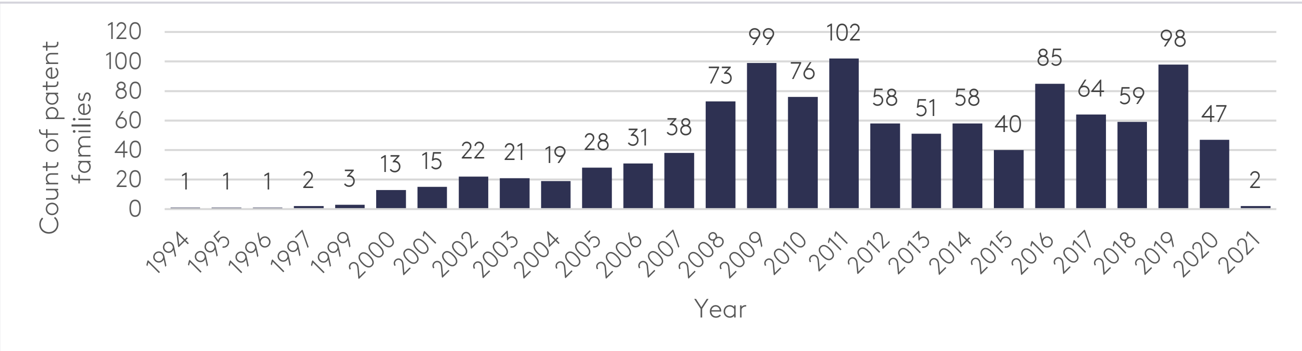
These charts also indicate that future market demand does not align with the dominant source of GGR available today – i.e. biochar – and that the market instead expects removals to come from DACC. This evolution in market demand has implications for MRV policy today and in the future. For example, is the current MRV framework for biochar robust and commensurate with the scale of current demand? Equally, is the current MRV framework for DACC able to deal with large increases in future demand?

### Innovation in MRV

In Figure 3.2 below we analyse patent class 'Y02P90/845', which is 'inventory and reporting systems for greenhouse gases'. This can serve as a proxy to measure innovation in MRV for GGR as patenting activity can indicate the pace of invention and where (within a given technological field) innovation is occurring.

While our examination of MRV patenting activity at the global level suggests an overall increase over the last 20 years, since 2017 MRV innovation has not kept up with the scale of increase in demand for GGR (e.g. from the Frontier advance market commitment). There are two reasons why the data suggest the pace of innovation/invention is not keeping up with increasing market demand. Firstly, the data for years 2021 and 2022 are incomplete, and secondly, there is often a lag between current market fundamentals and the time taken to feed through into inventive activity. While not in scope for this project, future research could examine MRV innovations by GGR method to show which removal technologies have the most MRV innovation.

Figure 3.2. Annual number of MRV patents, 1994–2021




*Source: Authors' analysis of PATSTAT. Data for 2020 and 2021 are incomplete.*

Overall, the United States has been the most innovating country, with the largest number of filed patents, at 198 between 1994 and 2019. South Korea has the second highest number (156), followed by Japan (58), Taiwan (18) and the UK (16). Combined, these countries account for 88% of all patenting activity in MRV for GGR.

# 4. What does the current science look like for different types of GGR?

The focus of this section is mainly on the monitoring component of MRV, as this is where the biggest scientific and technological barriers occur. Without reconciling this first empirical question, the reporting and verification that follows will have shaky foundations. Hence, we discuss the topic of permanence of carbon removals here, rather than methodological considerations, because permanence can be separated out and is the more challenging area of the technology. The science underpinning monitoring for each GGR is discussed in turn, with an assessment made of the current shortcomings that may prevent GGR from being upscaled.

### Overview

Across the GGR techniques described below, there are methods where MRV coverage is robust. In these cases, the foundational science underpinning the method of greenhouse gas removal is mature, and MRV methodologies have been developed based on these advances, whether for industrial CCUS in the case of BECCS and DACCS, petroleum geosciences for subsurface storage or forest science for afforestation/reforestation. Where a GGR method is difficult to measure in isolation from natural processes, such as in the case of ocean-based methods, or the rate of $CO_2$ accumulation still has unknown variables, as in enhanced rock weathering or biochar, MRV development has been limited.

### Direct air carbon capture and storage (DACCS)

Direct air carbon capture and storage is a class of GGR that comprises several distinct technologies to remove dilute $CO_2$ from the atmosphere through chemical trapping, desorption into a high purity stream and injection into deep saline aquifers or depleted oil and gas fields (Bey et al., 2021b). There are two dominant DACCS methods:

1) **Liquid systems** ('L-DAC'), where air is passed through a chemical solution, mainly consisting of hydroxide sorbents such as calcium hydroxide, which binds $CO_2$.
2) **Solid systems** ('S-DAC'), where air is passed through solid sorbent 'filters', which chemically bind with $CO_2$. (Fuss et al., 2018)

There are currently 18 operational direct air capture (DAC) plants around the world, which are estimated to collectively remove 0.01 $MtCO_2$/year (Budinis, 2022). Given that $CO_2$ in ambient air is considerably more dilute (0.04%) than at the flue of a power plant, DAC facilities require three times more energy than conventional carbon capture, usage and storage (CCUS) facilities, and thus have considerably higher capital costs (Budinis, 2022). Absorption and adsorption of $CO_2$ is energy-intensive, with L-DAC requiring process heat at 900°C and S-DAC heat at around 80–120°C. DAC technology is still nascent (the first commercial plant became operational in 2013).

Most of the surface system inputs used in DAC are easily measurable, and monitoring subsurface injection or mineralisation draws from technology used in the oil and gas industry. Nonetheless, privately developed MRV for $CO_2$ capture and storage lags behind certification provided through regulatory instruments.

The foundational science and advances in industrial/energy CCUS bolster the MRV for S-DAC and L-DAC (IEA, 2021). Similarly, there is robust MRV for the transportation and subsurface storage of $CO_2$ (expanded on below). These factors mean that policymakers can have a high degree of confidence in the processes underpinning S-DAC and L-DAC. However, there is a need for pilot projects to commercialise, scale up and assess plant performance in different geographical regions and climates, given the colossal expansion of DACCS that will be needed to meet IPCC removal targets. An estimated 1,250 DAC plants, each removing 1 $MtCO_2$/year, are required to remove 30 $GtCO_2$/year by 2030 (Ozkan et al., 2022). The paucity of large-scale DACCS plants in operation means there are significant uncertainties relating to the capabilities of these plants, such as their removal potential (which is contingent on proximate subsurface storage capacity and availability of low-carbon energy), maintenance needs, capital/operational costs and social license (Element Energy, 2021; Fuss et al., 2018; Royal Society, 2018).

For many of the newly established DAC companies, $CO_2$ capture methods and MRV is proprietary information and not available for public scrutiny. This is a natural commercial development – however, transparency across the technological process is desirable to give confidence and support upscaling.

For more experimental approaches, such as electrochemical DAC,[5] there is much less confidence in the technological process. This obviously has implications for both the state or existence of MRV, and confidence in MRV for electrochemical DAC. There is a need for larger-scale demonstrations that trial liquid/solid systems and nascent electrochemical approaches to provide more data on the cost and capture efficiency of DACCS.[6] This in turn will spur on MRV developments (and understanding of the cost, and gaps in coverage), which have until recently been limited to in-situ experiments and small-scale field trials.

## Bioenergy with carbon capture and storage (BECCS)

BECCS can permanently remove $CO_2$ from the atmosphere if the carbon sequestered in biomass, which is then combusted, is captured in its entirety (or at levels above a specific baseline) and is durably stored in subsurface reservoirs (Fajardy et al., 2019). BECCS is a GGR which also has industrial CCUS applications through its growth of plants for bioethanol. While the methodologies and processes are identical in many areas, it is once more important to note that CCUS is not considered to be a GGR as it *reduces* emissions from existing industrial processes (i.e. fossil power plants and heavy industry) before they reach the atmosphere, rather than removing $CO_2$ directly from the atmosphere and permanently storing it after post-combustion $CO_2$ as BECCS does. To highlight this distinction, globally there are an estimated 17 bioenergy CCUS plants in operation, which cumulatively remove 31.5 $MtCO_2$/annum, but only a fraction of this, 3.7 $MtCO_2$, is permanently sequestered.[7]

For the purposes of this section, the MRV requirements of BECCS as used in electricity production are expanded upon. BECCS has four broad processes (which overlap with the MRV requirements of other GGR types discussed below) that need tailored MRV to give assurance over reported removals. These are: biomass growth, biomass processing and transport, interaction with the carbon cycle, and $CO_2$ capture, transport and storage. We discuss some of these aspects below.

### Biomass growth, processing, transport and capture

BECCS needs combusted biomass to be provided with low or zero embedded carbon emissions (Honegger et al., 2022). This assumption is subject to biomass carbon stocks being maintained post-harvest, and any production of biomass not causing land use changes that result in an increase in $CO_2$ emissions, e.g. conversion from forested land to ruminant agriculture would produce an increase in emissions (Zakkour et al., 2014). Biomass sources can include dedicated bioenergy crops, forestry/crop residues and municipal waste (tested by relevant agencies to ensure bacteria and toxins are not present) (Bey et al., 2021b). When biomass is combusted to generate energy, the embodied carbon is re-emitted to the atmosphere. When BECCS is deployed, these emissions can be captured[8] at source (such as in the flue of an energy plant) and injected into underground reservoirs. Provided that emissions drawn from the supply of biomass and capture of $CO_2$ do not exceed the amount removed by photosynthesis, BECCS can support a net transfer of carbon from the atmosphere into long-term storage (Fajardy et al., 2019).

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5 Verdox is testing a methodology that traps $CO_2$ molecules passed through a stack of charged electrochemical plates. The technology operates like a battery and absorbs $CO_2$ during charging and releases the captured $CO_2$ during discharging.

6 For example, Skytree has patented a small modular DAC system for applications in indoor farming, and commercial building air filtration. Heirloom has developed the USA's first L-DAC facility using limestone to absorb $CO_2$ and has partnered with Vulcan Materials to mineralise captured $CO_2$ in concrete. However, neither company appears to provide MRV documentation on its website.

7 CCS facilities database, 2018, Global CCS Institute: https://www.globalccsinstitute.com/projects/large-scale-ccsprojects

8 Post-combustion capture (PCC) refers to the separation of $CO_2$ from flue gas derived from combustion. As an example, coal combustion results in a flue gas mixture consisting of $N_2$, $CO_2$, $H_2O$, $O_2$ and other compounds such as $SO_x$, $NO_x$ and heavy metals. Some of these are removed using existing technologies such as selective catalytic reduction (SCR), electrostatic precipitation (ESP), and flue-gas desulphurisation (FGD). A PCC process then selectively separates $CO_2$ from the remaining gas mixture using solvents involving either ammonia or proprietary amines (Global CCS Institute, 2012). As with DACCS, after chemical adsorption, these solvents undergo desorption using waste heat to release captured $CO_2$, before being pressurised and injected into subsurface reservoirs.

The process underpinning BECCS is complex and involves many different actors contributing to the supply chain[9] (Broad et al., 2021). Thus, the key question for Life Cycle Analyses (LCA) and MRV of BECCS projects is whether the bioenergy feedstock (which could be drawn from oil, sugar or starch crops, or lignocellulosic biomass such as forestry or crop residues) incurs a carbon debt (from land use change) in excess of forecast removals from operating the bioenergy plant itself (Mac Dowell et al., 2022). Assumptions about the embodied carbon within a given unit of biomass over its lifecycle influences whether there is net $CO_2$ removal from the atmosphere after post-combustion capture (or pyrolysis) and subsurface injection.

The MRV process for captured $CO_2$ for both BECCS and DACCS is broadly similar, and benefits from industrial CCUS advances. However, at present, and perhaps as a result of the aforementioned considerations, there exists no independently certified full chain MRV process that can verify removal claims by BECCS facilities. MRV coverage is currently patchy (as outlined in Figure 5.1 – the landscape mapping), with voluntary standards, national regulations and international guidelines variously providing assurance for different elements of the BECCS chain (Arcusa and Sprenkle-Hyppolite, 2022).

The IPCC has developed Land Use, Land-use Change and Forestry (LULUCF) guidelines, which provide a basis for countries to track and compile emission inventories. The LULUCF chapter of an inventory is based on the estimated carbon stock change in land use categories such as forests, grasslands, peatlands or land under agricultural management. LULUCF guidelines should provide a strong framework under which to assess biomass. However, there is significant variability in the quality of these compilations and countries consequently significantly underreport net LULUCF emissions.[10] If the LULUCF inventory compilation is poor quality, then the assumptions underpinning the carbon stock within a unit of biomass could be incorrect and the net greenhouse gas removal assumption underpinning BECCS could be flawed (Zakkour et al., 2014).

Monitoring post-combustion capture of emissions operates under existing regulations such as the EU Industrial Emissions Directive or the CCS Protocol under the California Low Carbon Fuel Standard (LCFS). These regulatory instruments are mature and well-functioning – giving few causes for concern. However, where facilities operate outside national regulation or international guidance when procuring biomass feedstock and capturing $CO_2$, close attention should be paid to removal claims.

### Subsurface $CO_2$ storage[11]

The critical challenge for the MRV of $CO_2$ injection is the need to accurately quantify the $CO_2$ stored in a reservoir and the stability of the $CO_2$ plume over time. In direct $CO_2$ sequestration, $CO_2$ is less dense than water, and as a result it rises to the top of its deep underground injection layer and spreads out across the underside of the impermeable cap layer that contains the $CO_2$ (Kivi et al., 2022). When carrying out MRV of this process, a firm must be able to measure the total mass of $CO_2$ injected, plus the rate of injection and of leakage over time. Recent research indicates that a $CO_2$ gas plume injected at 1,500m into suitable rock formations will only rise 200–300m over one million years (ibid.). There is a high degree of confidence in these assessments, borne out of knowledge of $CO_2$ subsurface plume behaviour from the petroleum geosciences (IEA, 2022; Kivi et al., 2022; Royal Society, 2018).

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[9] In the UK, for example, this is typified by the Drax BECCS trial plant on the Humber. According to Drax, the pellet feedstock is generated in Canada and created from harvest (20%) or sawmill (80%) residue. These pellets are then transported to the Drax power station and used as a fuel feedstock. The Drax trial plant is estimated to remove 4.6 $MtCO_2$/year with an extra 3 Mt removal targeted by 2030 (IEA, 2023).

[10] A *Washington Post* investigative analysis ahead of COP26 found that the 196 parties to the UNFCCC had underreported their emissions by 8.5–13.3 billion tonnes.

[11] The relevant ISO standard is 27914:2017: Carbon dioxide capture, transportation, and geological storage.

MRV frameworks for long-term storage of $CO_2$ in geological reservoirs need to monitor the potential for leakage at both the injection site and in the reservoir itself. This requires the use of geophysical and geochemical monitoring techniques, and tracers to track the movement of $CO_2$ within the reservoir. Additionally, monitoring must be able to detect changes in the pressure, temperature and composition of the reservoir over time, as these can affect the rate of leakage. The experience of the Sleipner oil field in Norway has provided a robust evidence base to show that injected $CO_2$ is stable when injected into a sandstone formation and its state can be effectively monitored using seismic time-lapse techniques (Royal Society, 2022). Advances in the understanding of subsurface $CO_2$ plume behaviour has occurred through observation of naturally occurring $CO_2$ stores which globally are estimated to contain at least 310 $GtCO_2$ (ibid.).

Geological 'carbon mineralisation' describes a reaction between $CO_2$-bearing fluids and calcium- or magnesium-rich rocks to form a solid carbonate (Royal Society, 2022). This process has been commercialised by CarbFix, which mineralises liquid $CO_2$ (captured by Climework's direct air capture facilities in Iceland) using a novel 'solution trapping' method (Sigfusson et al., 2015), where $CO_2$ co-injected with water into basaltic terranes at a depth of 330–360m dissolves at high pressure and undergoes mineralisation (Snæbjörnsdóttir et al., 2018). The key MRV challenge for mineralisation lies in detecting the quantity of $CO_2$ lost during the injection process and monitored at a downstream observation well. In-situ carbon mineralisation needs further study at much larger scales than that piloted by CarbFix. The process has been described as an "understudied, high-risk, high-reward opportunity solution" (National Academy of Sciences, Engineering, and Medicine, 2019).

### Subsurface $CO_2$ storage

Active or passive seismic monitoring are commonly used techniques to monitor and verify the state of a $CO_2$ plume in a saline aquifer or depleted oil and gas reservoir. The principles of active seismic monitoring involve interpreting the composition and change in speed of a seismic wave as it refracts on different strata (Royal Society, 2022). This process is the predominant technique used to locate oil and gas deposits but it also allows movement of a $CO_2$ plume to be tracked and leakage assessed through monitoring changes in fluid density.

Limitations of active methods derive from the high cost of this approach and technical considerations such as seismic waves usually being larger than 10m which may not measure, at the necessary resolution, smaller horizontal $CO_2$ plumes. Other general challenges include estimating the mass and ratio of mobile $CO_2$ to structurally trapped $CO_2$, due to reflection distortions (Royal Society, 2022). In marine environments, it is challenging to differentiate natural, baseline $CO_2$ leakage from anthropogenic leakage and complex natural processes. Further, correctly attributing leakage to the correct reservoir is poorly understood (Bey et al., 2021a).

Passive seismic monitoring uses receivers on the ocean floor/land surface or a borehole to record micro seismicity data to monitor a plume. These are the same principles as in active seismic monitoring but with lower operational costs, which enables monitoring over a timescale of decades. Passive methods are particularly useful for mapping development of fracture networks, which can lead to fault reactivation and the release of $CO_2$ (Royal Society, 2022). Gravity and geoelectrical monitoring, and controlled source electromagnetic monitoring, measure small changes in the Earth's gravitational or surface conductivity to deduce the state and change in composition of subsurface $CO_2$ plumes.

Storing $CO_2$ in geological formations is more durable (e.g. resilient to policy change and natural disturbance) and permanent, relative to other methods, e.g. storing within biomass. The IPCC (2022) assumes in its models that injection and mineralisation permanently trap $CO_2$ for 1,000 years or more. However, there are still risks that $CO_2$ will escape. The International Energy Agency finds that a risk-based, site-specific approach to MRV that is contingent on and responsive to baseline data measurements during site characterisation can mitigate these risks (IEA, 2022). In practice, a combination of active and passive monitoring techniques can provide data on the stability of a reservoir and the risk of a leak. Subsurface $CO_2$ storage is guided by the IPCC[12] and regulated under existing instruments such as the EU CCS Directive[13] (2009) and the US Environmental Protection Agency's Class VI permits.[14]

Some of the literature contends that storing $CO_2$ in geological formations does not present major MRV challenges (EU Commission, 2022). However, the Royal Society (2022) has highlighted further technical MRV challenges that will need to be overcome to provide market assurance if $CO_2$ storage is to scale up to 7–8 $GtCO_2$/yr globally (Bouckaert et al., 2021):

- Improving detailed predictions of plume migration and storage capacity of specific fields, which requires a combination of geological, geophysical and geochemical data collection and flow modelling to test and calibrate the models, coupled with quantification of the considerable uncertainties about subsurface formations.
- Assessing storage safety and the critical pressures for failure of the seal rocks, potential ensuing leakage pathways, and developing assurance of the long-term safety of the system.
- Testing and combining monitoring strategies for subsurface $CO_2$ detection, including the use of seismic surveys, tracer tests and potentially other geophysical techniques.
- Developing approaches to enhance the storage capacity of a given system, using novel additives or modifications to well-arrays and injection strategies.

## Afforestation and reforestation

Afforestation refers to planting trees on land that has not been forested in recent history (a reference value of at least 50 years is commonly used) (Fuss et al. 2018); reforestation refers to the replanting of trees on more recently deforested land (IPCC, 2000). Trees absorb $CO_2$ from the atmosphere during photosynthesis in above- and below-ground biomass (in trunks, roots and soil), and the resulting $CO_2$ is incorporated into the tree's biomass as it grows.

Afforestation/reforestation is already part of many existing voluntary and compliance certification mechanisms (with voluntary examples including the Verified Carbon Standard and the Woodland Carbon Code,[15] and a compliance example being the New Zealand emissions trading scheme[16]). There are well established methods to quantify the carbon sequestered in above-ground biomass in forests and this can be monitored and verified using a combination of remote sensing and fieldwork. Assessments of carbon stocks in forested areas are based on manual measurements of the basal volume of a sample of trees, or, in many instances, emission factors are applied that take into account sequestration per hectare based on species, number of stems per hectare and climate/soil characteristics.

The slow growth rate of trees presents challenges for MRV. Without accurate remote sensing and/or data on the growth rates of different species (by region and climate), project developers/regulators are obliged to revisit locations to quantify gains in above-ground biomass.

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[12] 2006 IPCC Guidelines, Vol 2, Chapter 5.

[13] The EU CCS Directive (2009) is a legal framework for the environmentally safe geological storage of $CO_2$ to contribute to the fight against climate change. It covers all $CO_2$ storage in geological formations in the EU and the entire lifetime of storage sites. It also contains provisions on the capture and transport components of CCS.

[14] Class VI wells are wells used for injection of $CO_2$ into subsurface rock formations for long-term storage, or geological sequestration. Class VI wells are regulated by the US EPA unless a state applies for primacy enforcement authority. Currently only North Dakota and Wyoming have this authority.

[15] The Woodland Carbon Code (WCC) is the apex MRV framework for voluntary woodland creation projects in the UK. Woodland Carbon Units are assigned to registered landowners for projects that establish additional woodland through planting and natural regeneration.

[16] The New Zealand ETS requires eligible landowners to manually measure and report the carbon stock change of their forest if it is larger than 100ha. If the forest is smaller than 100ha, 'look-up tables' which present regional emission factors by forest species can be used. In the NZ ETS, remote sensing has been successfully employed to monitor forests, and audits (circa 1-3%) of five-yearly mandatory emission returns are used to ensure compliance.

Multi-resolution optical, synthetic aperture radar (SAR) or light detection and ranging (LiDAR) are the predominant remote sensing technologies employed to monitor forests. These technologies are not infallible and are still limited by the current generation of sensors. However, remote sensing allows project developers to discriminate by forest-age and growth-stage using data-fusion methods and LiDAR height metrics (Mitchell et al., 2017).

MRV for afforestation/reforestation must strike a balance between expensive and time-consuming field surveys and the ease of remote sensing and forest growth models that draw on empirical data. Labour and time pressures constrain field-based MRV and result in reductions in sampling intensity (ibid.). Some lower- and middle-income countries do not have the required data for certain tropical tree species to generate the allometric equations needed to calculate above-ground biomass (FAO, 2011).

As the climate changes, wildfire risk and pestilence pose huge threats to standing forests. Strategies to mitigate these risks by bundling forestry parcels across age, geographical region and species are beginning to be factored into investment decisions (e.g. Biffis et al., 2023). However, afforestation/reforestation MRV needs to be reactive to the risks inherent to the type of removal and to utilise buffer pools and other insurance mechanisms to ensure reversals (e.g. sequestered carbon emitted through forest fire) are accounted for.

Internationally, there are a plethora of standards that measure GGR from afforestation. Compliance schemes such as the New Zealand ETS and the California ETS account for removals and have developed stringent MRV protocols to ensure the integrity of national carbon accounting systems. Other state-backed voluntary schemes also exist, such as Label Bas Carbone (France) and the Australian Emissions Reduction Fund. IPCC guidelines[17] and the EU LULUCF Regulation[18] provide further MRV guidance. Other afforestation projects have been created under the Kyoto Protocol's Clean Development Mechanism (CDM) and there exist MRV frameworks for afforestation/reforestation in the VCM internationally, as seen in Figure 5.1 (next section).

MRV for afforestation/reforestation is underpinned by many decades of empirical data in the forest sciences, giving confidence to these projects, and is supported by remote sensing approaches, as described above. The techniques that measure above-ground biomass are advanced and reliable, but those for other carbon pools such as below-ground biomass and dissolved organic matter still suffer from uncertainty. Further, strong property rights and contracts are needed to ensure permanence of carbon removals, given the high reversibility risks inherent to this form of GGR.

## Peatland and wetland restoration

Peatland and wetland restoration seeks to slow and eventually reverse the degradation of organic soils. When drained, peatlands and wetlands release stored carbon, methane and nitrous oxide (Bey et al., 2021a). Rewetting or restoring drained peatlands and wetlands predominantly involves blocking drainage channels to raise the water table. This process slows the release of carbon and allows the peatland to increase its carbon stock through plant growth and deposition (Olesen and Andersen, 2021).

The carbon cycle for upland peatlands is considered to be better understood than for lowland peatlands (Environment Agency, 2021).[19] There are knowledge gaps relating to the impacts of agricultural fen restoration on carbon cycling and the negative emissions potential of peatland under agricultural production versus peatland that has not been in production; nor are

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17 Chapter 4 on Forest Land in 2006 *IPCC Guidelines for National Greenhouse Gas Inventories*.

18 Regulation (EU) 2018/841 of the European Parliament and of the Council.

19 Lowland peatlands comprise fens and raised bogs and constitute waterlogged peat soils under 200m altitude. Fens are extensive areas of low-lying wetland comprising peat soils which receive water from groundwater and surface run-off. Upland peatlands generally consist of blanket bog and are defined as semi-natural habitats where water accumulates from rainfall, mist and snow, which develops a raised water table on upland plateaux (Environment Agency, 2021).

factors affecting emissions beyond changes in the water table level fully understood (Peacock et al., 2019).

The carbon benefits of peatland and wetland restoration can be calculated using the indicator of carbon dioxide-equivalent (which considers $CO_2$ and $CH_4$ [methane]) to estimate avoided emissions, based on land use, water table depth, vegetation cover, and climatic/ phytogeographical region. Expert judgement, project, regional, or national-level reference data are used to derive emission factors for different land types (and water table depths and vegetation cover), which are categorised and multiplied against an emissions factor (Bey et al., 2021a).

MRV coverage for peatland and wetland restoration is currently limited. There are IPCC guidelines[20] that provide guidance for agencies registering changes in carbon stock in national emission inventories for restoring drained organic soils and inland/coastal wetlands. Voluntary standards exist, but the quantity of verified removals is small relative to the wider GGR market at 643,113 $tCO_2e$.

Where there are no protocols for peatland/wetland restoration, the development of projects relies on expert judgement to develop unique emission factors for local contexts, using field tests and remote sensing to classify land categories. For example, MoorFutures, a German peatland removals developer, calculates baselines based on historical data, expert opinion and local economic and social conditions (Joosten et al., 2016). Such an approach has evident limitations to scaling up, and is risky due to the lack of standardisation (Bey et al., 2021a). While there is a strong science underpinning peatland/wetland restoration and understanding of its requirements, the market for these removals and the related MRV ecosystem remains small. The MoorFutures example shows that projects are attuned to local conditions, but MRV will need to standardise and upscale to provide more confidence.

### Biochar

Biochar is produced by heating biomass to approximately 300–800°C in low-oxygen conditions, a process known as pyrolysis[21] (Element Energy, 2021). Biochar production and deposition into soil disrupts the natural carbon cycling or decay of biomatter, where carbon stored through photosynthesis during growth is released. Pyrolysis fixes this carbon into a stable form that is resistant to degradation, and under the right conditions provides a long-term carbon sink (Fawzy et al., 2021). When added to soils, biochar can increase soil carbon stocks and also improve soil fertility and other ecosystem properties such as water retention (Fuss et al. 2018).

A meta-analysis of 24 studies by Wang et al. (2016) identified that biochar's mean residence time in soil is strongly determined by feedstock type, pyrolysis conditions, the soil's clay content and the length of experiment. The results across the study indicate that for 97% of interned biochar, the mean residence time in the stable carbon pool is 556 years (ibid.). Among the empirical challenges that need to be overcome to aid the development of robust MRV are improving understanding of the long-term decomposition of biochar in soils, including the influence of different biomass feedstocks and pyrolysis techniques (Element Energy, 2021; Fuss et al., 2018). Moreover, measuring changes in soil carbon stocks has proven difficult to isolate from background levels (Royal Society, 2018).

Other uncertainties relate to the durability of biochar under different soil types and land management regimes; there are indications that acidic soils, and higher temperatures in tropical and sub-tropical regions, reduce the stability of biochar (Fuss et al., 2018). More longitudinal in-

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20 Chapter 7 in *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*.

21 Pyrolysis also produces bio-oil as another by-product, which can also be injected into sub-surface reservoirs and is considered a durable long-term carbon sink. US-based Charm Industrial has claimed to have removed 5,541 $tCO_2$ and has developed a registry, methodology and MRV proto-protocol to account for removals from this nascent process.

field analyses, foundational science and meta-analyses need to be funded to develop databases which host information relating to the rate of decay by soil type, pyrolysis technique and feedstock. This will help to deepen understanding of these dynamics and the impact on durable GGR. The current lack of these analyses means the feasibility, long-term mitigation potential, side-effects and trade-offs from using biochar remain largely unknown (ibid.).

In spite of these challenges, the carbon removal marketplace Puro.earth has developed MRV standards for biochar. The company allows biochar offsets to be sold on the marketplace if the project developer has been certified by either the European biochar certificate or the USA-based International Biochar Initiative (Wang et al., 2016). Puro.earth also requires a production facility audit by an independent auditor. If these certifications are not forthcoming, it stipulates a lifecycle analysis from a certified actor.

## Soil carbon sequestration (SCS)

Soil carbon sequestration in mineral soils occurs when land management change increases the soil organic carbon (SOC) content, resulting in a net removal of $CO_2$ from the atmosphere. SOC is lost during land-use change and subsequent agricultural or horticultural production, where crop rotations are simplified, soil is exposed for periods alongside crop stubble removal, and where arable and livestock farming operations are not integrated, and also through soil erosion (Bey et al., 2021a). The level of carbon in the soil is a balance of carbon inputs (e.g. from leaf litter, crop residues, roots or manure) and carbon losses (through respiration and soil disturbance) (Fuss et al. 2018).

Measuring and crediting SCS is a complex science. The efficacy of soil carbon interventions is dependent on local climatic conditions, land management history and soil characteristics (Zelikova et al., 2021). Monitoring SOC stocks can be done via modelling or field measurements (or a combination of both) (Bey et al., 2021a). Empirical models have become ascendant as they are less costly than field measurements; however, uncertainties accumulate if information is not obtained on-site. These uncertainties might relate to factors that influence SOC quantity and stability such as the time between taking samples and their depth, assumptions and input data in modelling of SOC stock changes, and a lack of data on current existing levels of SOC (ibid.).

Zelikova et al. (2021) conducted a meta-analysis of MRV standards for a variety of existing and incoming SCS protocols.[22] Their findings indicate that across 17 standards (applying to a wide range of geographical regions, land uses and agricultural practices) there were a number of challenges relating to sampling methodology, additionality tests and durability. Only three protocols required direct soil sampling, while the remainder relied on models that generally assume SOC to accrue linearly and to exist thereafter in a state of equilibrium – an assumption that is increasingly called into question (Sanderman and Baldock, 2010). Moreover, protocols did not require rigorous stratification, sampling randomisation or >30cm sampling depths (Zelikova et al., 2021). Only one protocol required a permanence period of 100 years, with the rest defining permanence periods of between eight and 40 years; nor were buffer pools commensurate with permanence horizons.

SCS project developers[23] have proliferated globally – offering certification, intermediary services and retailing to emitters directly or through brokers. These project developers and offset providers

[22] The protocols under analysis were: Gold Standard, Nori, Plan Vivo, Regen Network, ACR Grazing, ACR Compost, CAR Soil, Verra Fire + Grazing, Verra Sustainable Ag, Verra Improved Ag, Verra Soil, Verra Sustainable Grassland, BCarbon, FAO, Australia Measurement, Australia Estimation and Alberta Cropping.

[23] Haystack claim development of "...a scalable, high-accuracy soil organic carbon (SOC) measurement system that employs elements of spectroscopy, dry combustion, remote sensing, and automation". However, beyond these claims little technical

use proprietary technology to help landowners assess soil carbon baselines and accumulation and package and sell these removal credits accordingly. However, there is no reference to the relevant ISO standard[24] these methodologies work to, nor detailed documentation of the MRV processes these firms employ to provide certainty that offsets are additional, credible and permanent (perhaps as a result of the use of proprietary technology). The degree of opacity and questioning of assumptions underpinning models (e.g. see Sanderman and Baldock, 2010) in the SCS market should give pause for thought when purchasing this kind of credit.

## Enhanced rock weathering (ERW)

Weathering is the natural decomposition of silicate rock via chemical and physical processes. It is controlled by temperature, reactive surface area, interactions with biota and water solution composition (Fuss et al., 2018). A chemical reaction removes $CO_2$ from the atmosphere through mineral carbonation. The use of *enhanced* rock weathering (ERW) as a form of GGR accelerates this natural process from geological to humanly-relevant timescales by favouring chemical reactions that have the potential to sequester relevant amounts of atmospheric $CO_2$ (Royal Society, 2018). It aims to artificially stimulate this process by grinding or milling silicate rocks such as basalt, or silicate waste from mining, cement or ash, to increase their surface area, thus increasing mineral dissolution. The ground material is applied to land – especially agricultural land – where plant roots and microbes accelerate the chemical reaction (Environment Agency, 2021).

The first ERW protocol has been developed and released by Puro.earth. The standard was developed by a "...working group of carbon market experts, project developers and scientific researchers, and was approved by Puro.earth's Advisory Board after a period of public consultation."[25] Ex-post issuances are disbursed to project developers after field-data measurements and simulations have been achieved. This MRV model is more robust than one that disburses issuances based on modelled results. Other companies[26] are developing ERW offerings, but the market is currently limited.

Feasibility of ERW is limited by the ability to source rock with sufficiently high silicate content and by the high energy requirements for crushing silicate rocks to the small particle size associated with higher mineral dissolution (Royal Society, 2018). The high energy inputs required to do this will impact GGR effectiveness (Höglund, 2020). Berg et al. (2017) find that improved efficiency of the rock grinding process results in a 40% energy-saving, thus improving GGR potential. Other research highlighted in Bey et al. (2021a) shows that the lifecycle efficacy of ERW improves if material is procured as a by-product of industrial processes.

Current ERW monitoring[27] occurs via: manual static flux chambers measurements (weekly or bi-weekly); automated chambers that facilitate hourly data collection; and eddy covariance[28] monitoring methods. We are unaware of any remote-sensing MRV applications, which means

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information or evidence of third-party accreditation/verification is provided to give certainty to the claimed approach. With similarly little back-up information, Yardstick claims a three step process to assist landowners to measure their SOC with a web-based planning dashboard to develop a sampling plan; a "...cloud-enabled handheld device instantly which [sic] collects SOC and bulk density measurements to a 45cm depth; and in-house data management and analytical tools ...to rapidly understand project progress, quantify stocks and changes, and share this information with a variety of key stakeholders, including participating growers, third party verifiers, and offset end customers". Agricarbon provides a more comprehensive breakdown of its SOC sampling process, which relies on 1m field samples which are analysed using proprietary Automated Soil Carbon Analysis and Dumas dry combustion to assess SOC percentage, bulk density and soil carbon stock.

24 i.e. ISO 23400:2021.

25 See https://puro.earth/articles/enhanced-rock-weathering-in-soil-methodology-public-consulta-788.

26 Dutch company GreenSands sells $CO_2$ 'clean-up certificates', which certify ERW through dispersing ground-up olivine. The company claims to have spread 53,572t and 'cleaned up' 3.836 $tCO_2$. No MRV guidance could be found on its website. A British company, Sequestr8, is developing an ERW process using mine tailings, but its website and documents indicate this is not close to commercialisation.

27 The Working Lands Innovation Center at UC Davis has trialled all three of these methods in its rangeland trials but peer-reviewed results are not available.

28 Eddy covariance is a micro-meterological measurement method that can directly observe gas exchange between an ecosystem and the atmosphere.

monitoring must occur through field sampling, which is expensive and time-consuming. The dearth of other protocols may be a result of the mainly theoretical or model-based research into ERW to date (Fuss et al., 2018). Although empirical understanding of ERW dynamics is adequate, the lack of any clear MRV guidance in the primary and grey literature is illustrative of the immaturity of the approach, and further research, development and demonstration are needed, including more longitudinal field trials to test a variety of different variables, e.g. particulate size, aggregate material, climate, region and soil pH, to build the evidence base and MRV methods (Bey et al., 2021a; Royal Society, 2018).

### Ocean alkalinity enhancement (OAE)

The oceans are by far the largest active carbon reservoir on the planet, storing around 38,000 $GtCO_2$ (Tanhua et al., 2013) (for contrast, the atmosphere is estimated to hold 750 $GtCO_2$ [Green and Byrne, 2004]). Artificially increasing the alkalinity of seawater to increase the rate at which $CO_2$ is dissolved into carbonate and bicarbonate ions is a promising GGR technique.

The oceans are complex, open-loop systems, have not historically been anthropogenically modified to emit or remove $CO_2$, and mostly fall outside national boundaries (thus it is not currently possible to confidently attribute a single intervention to a particular jurisdiction). As a result, there are no IPCC guidelines regarding OAE and substantial MRV gaps.

The complexity of ocean geochemistry has created difficulties in isolating the effects of OAE from natural processes during large field experiments in a specific area. Empirical models can estimate GGR through OAE, but not with the precision necessary to develop monitoring and verification standards that would enable the sale of GGR credits (NOAA, 2022).

Planetary Technologies has recently developed the first OAE MRV protocol to guide field trials. The company is planning a second open ocean field trial in St Ives Bay, Cornwall (UK) in Spring 2023, where 200–300 tonnes of magnesium hydroxide will be deposited and monitored.[29] This protocol is unverified but takes into account the current maturity of the field by applying a discount factor to provide a confidence buffer of removals that can be issued retroactively as confidence in the application increases. Other companies exploring OAE include Vesta, which has conducted field research into coastal enhanced weathering by depositing rock containing ground olivine onto coastlines where it can dissolve in seawater, thereby increasing the rate of $CO_2$ absorption by the ocean.[30] Vesta does not have any imminent plans to commercialise this process and does not mention any MRV protocol in its reference documents.

### Ocean fertilisation

Ocean fertilisation enhances the ocean carbon sink by increasing the transfer of $CO_2$ from the atmosphere to the ocean via biological and physical carbon pumps (NOAA, 2022). Micro- (iron) or macro-nutrients (nitrogen or phosphorus) are introduced to increase phytoplankton growth, which improves the efficiency of $CO_2$ fixation and ocean carbon export via the biological pump.[31] As iron is often the limiting nutrient in the ocean, deliberate iron fertilisation stimulates algal blooms and is theorised to fix carbon for long timescales in sediments and shorter timescales in the water column (Fuss et al., 2018).

Similarly to OAE, there are significant knowledge gaps relating to the sequestration potential of ocean fertilisation, the relationship between the addition of macro- or micro-nutrients and $CO_2$ uptake, and how to isolate any sequestration taking place through background processes (NOAA, 2022). A 2012 ocean fertilisation test near the Canadian Haida Gwaii archipelago (to boost

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[29] See https://www.planetarytech.com/projects/cornwall/.

[30] See https://www.vesta.earth/science#Introduction.

[31] For an explanation of the biological pump see www.lse.ac.uk/granthaminstitute/explainers/what-role-do-the-oceans-play-in-regulating-the-climate-and-supporting-life-on-earth/.

salmon stocks) illustrates how controversial some GGR methods can be (Omand, 2016), and the need for governments and companies to gain local consent and educate communities in the process and desired outcomes of a GGR to ensure social licence is retained (Cox et al., 2020).

Notwithstanding the significant technical and scientific challenges behind ocean fertilisation, several companies are attempting to commercialise the process. Running Tide is developing an approach to ocean fertilisation through sinking algae; the method is still undergoing R&D, and it has not published MRV documentation. Brilliant Planet is now scaling up production of its ocean fertilisation (algal bloom) methodology after a period of R&D and field trials in South Africa and Morocco. Once more, this approach has not been commercialised and no MRV protocol is forthcoming.[32]

[32] See www.runningtide.com/carbonremoval and www.brilliantplanet.com/.

# 5. A snapshot of the MRV landscape for GGR

The current landscape of MRV for GGR is crowded, with numerous entities operating across the voluntary carbon market and compliance mechanisms offering MRV standards for different GGR methods. For nascent removal techniques, MRV developments are often made to create proprietary information and do not filter through into the public domain.

There is a need to contextualise the MRV landscape and identify where coverage is either adequate or patchy for existing and emergent GGR methods, and where current and future market demand might be (see Figure 3.1 above). This is intended to be a complement to, rather than a comparison with, the analysis of the science underpinning monitoring outlined in the previous section. By examining both, the aim is to provide a more complete picture of the constituents of MRV.

In this section we map the landscape and identify where key risks are. Inspiration has been taken from Arcusa and Sprenkle-Hyppolite (2022), who have provided a snapshot of the Carbon Dioxide Removal certification and standards ecosystem, which serves as a helpful starting point for the removal ecosystem in its entirety (rather than focusing on MRV). In contrast, we look specifically at the different actors and protocols in the MRV value chain, focussing on one granular aspect of the whole market. Further, Arcusa and Sprenkle-Hyppolite focus on emissions removal *and* avoidance, whereas we focus solely on removal.

**Distinctions need to be made between different components of an MRV system. Accordingly, the mapping figure below is conceptualised with five levels:**

- The first level is organised according to four carbon removal categories – land-based biological, chemical, geochemical and ocean-based biological. These are drawn from IPCC (2022). Within each category are corresponding carbon removal techniques, colour-coded based on the expected duration of storage, based on IPCC (2022).
- Second is the carbon removal subcomponent, which applies to removal technologies with multiple inputs: for example, BECCS, which accounts for growth, combustion and storage of biomass emissions. Because BECCS is categorised as a biological removal approach by the IPCC, all subcomponents are here.
- Third is the removal provider and/or regulator. Alongside the private entity providing GGR, this includes private organisations providing MRV and public policy that is not bespoke to carbon removals but could be analogously expanded or developed for MRV purposes as it already includes some form of minimum standards for emission accounting and reporting.
- The fourth level is the entity that provides the removal standard for a given form of GGR (this is conceptualised as a high-level set of prescriptions to which MRV providers or project developers must adhere).
- The fifth level details the MRV protocol, which is the specific technical methodology that is worked through to ensure the removal meets the MRV standard.

### Caveats

Although the mapping aims to provide clarity, it should still be viewed with the following caveats in mind. First, although every care was taken to be comprehensive, the mapping and author-composed database will likely have omissions, as the landscape is evolving rapidly. Second, certain organisations do not make their standards publicly available. Third, the mapping is biased towards removal providers that publish their MRV protocols in English. There will also undoubtedly be a bias to high-income countries. The mapping should therefore be viewed as a non-exhaustive but flexible starting point. MRV protocols that were active in late 2022 and early 2023 have been included.

## Key observations

Table 5.1 provides some descriptive statistics from the mapping. In total, there are 69 MRV protocols across 15 removal methods highlighted. Of these, 57 of the protocols certify land-based biological GGR activities. There are 9 chemical protocols (all for DACCS), and one geochemical MRV protocol. There is currently one ocean-based biological MRV protocol. Overall, there are far more international actors (44) than national (36).

Of non-regulatory entities, Verra certifies the most removal activities, with 9 MRV protocols registered. Puro.earth, the American Carbon Registry, provides MRV for 6 removal methods and the Climate Action Reserve provides MRV protocols for 5 removal methods. The EU's Competent Authority provides MRV certification for subcomponents of $CO_2$ capture, transport and storage relating to BECCS and DACCS under the EU ETS, the EU CCS Directive and the EU Industrial Emissions Directive. The US Environmental Protection Agency provides MRV for 4 subcomponents of BECCS and DACCS.

Table 5.1. Descriptive statistics of MRV landscape mapping

| Category | Method | No. MRV protocols |
|---|---|---|
| Land-based biological | Soil carbon sequestration | 16 |
| | Afforestation/reforestation | 13 |
| | Wetland restoration | 2 |
| | Peatland restoration | 5 |
| | Woody biomass burial | 1 |
| | Biochar | 3 |
| | Bio-oil | 1 |
| | Bioenergy with carbon capture and storage (BECCS) biomass growth | 4 |
| | BECCS biomass transport and processing | 2 |
| | BECCS biomass combustion; industrial processes | 2 |
| | BECCS $CO_2$ capture, transport and storage | 9 |
| Ocean-based biological | Ocean fertilisation | 0 |
| | Tidal wetland | 1 |
| Chemical | Direct air capture with carbon storage (DACCS) | 9 |
| Geochemical | Enhanced rock weathering (ERW) | 1 |
| | Ocean alkalinity enhancement (OAE) | 0 |
| **Total number of MRV protocols** | | **69** |

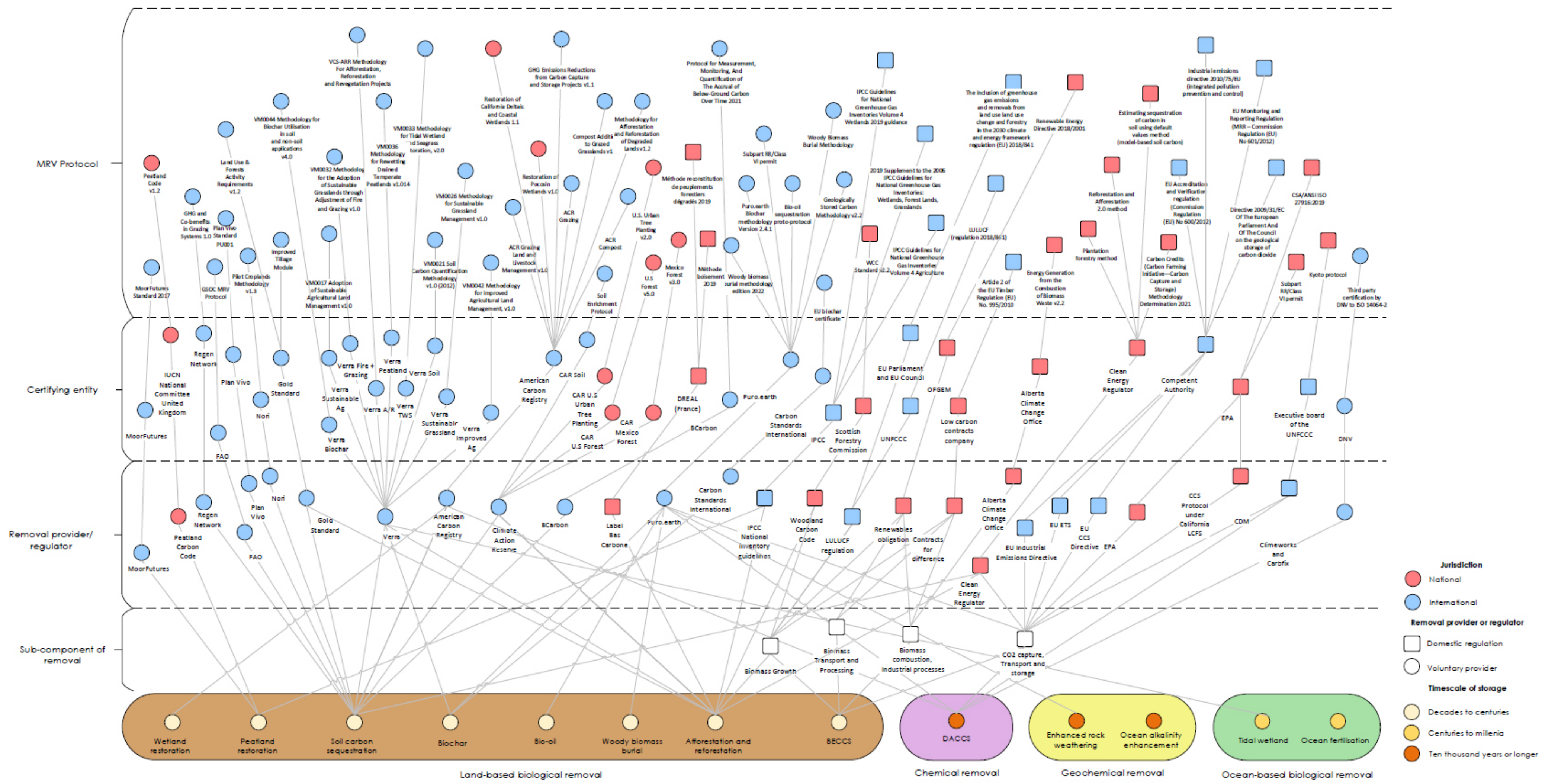
Some certifying entities cover a range of removal categories. Puro.earth, for example, provides the widest range of MRV services, across biological, chemical and geochemical methods, for biochar, bio-oil, ERW, woody biomass burial, BECCS and DACCS. Other large certifying entities such as the Climate Action Reserve and Verra only provide MRV for land-based biological methods. The American Carbon Registry is the only other larger certifying entity that provides MRV for land-based biological methods *and* one protocol for a chemical method, DACCS.

Entities certifying MRV on behalf of a state, or because they regulate certain activities, such as the UK's Low Carbon Contracts Company or the EU's Competent Authority (which references the specific EU member state agency with regulatory responsibility), could provide MRV for chemical and geochemical removal, namely BECCS and DACCS. Exceptions to this exist for the Alberta State Government and the Australian Emissions Reduction Fund, which certify land-based biological removal.

The mapping clearly illustrates the following:

1. There is competition between actors, with different companies producing their own bespoke MRV methods. Increased competition may be useful in driving down costs and spurring innovation, but disparate methods could also lead to siloing whereas the complexity of the challenge may require a greater degree of collaboration.
2. The majority of MRV development is occurring with land-based biological removals from government and private certifying entities. The mapping also highlights activities that currently have no or few actors or MRV processes (e.g. enhanced rock weathering, ocean fertilization, and ocean alkalinity enhancement).
3. Existing policies that could be latterly adapted for MRV pertain almost exclusively to BECCS and DACCS, given the CCS component. The advanced market commitments highlighted in Figure 3.1 indicate that the quantity of removals planned from chemical processes such as DACCS far exceed land-based biological removal such as soil carbon sequestration, where there is a surfeit of MRV protocols.
4. Regulators will need to ensure that emergent removals such as DACCS, which largely (except for Climeworks and Carbfix) have MRV coverage through regulatory instruments, support MRV protocol development so that project developers can reliably meet demand.
5. Twenty-six of the MRV protocols relate solely to a national jurisdiction, while 44 are applicable internationally. Of the 29 entities certifying GGR activities, 15 have been developed and administered by national or supranational jurisdictions – and 10 of these provide MRV domestically only.

## Figure 5.1. Mapping of the landscape of MRV for greenhouse gas removals



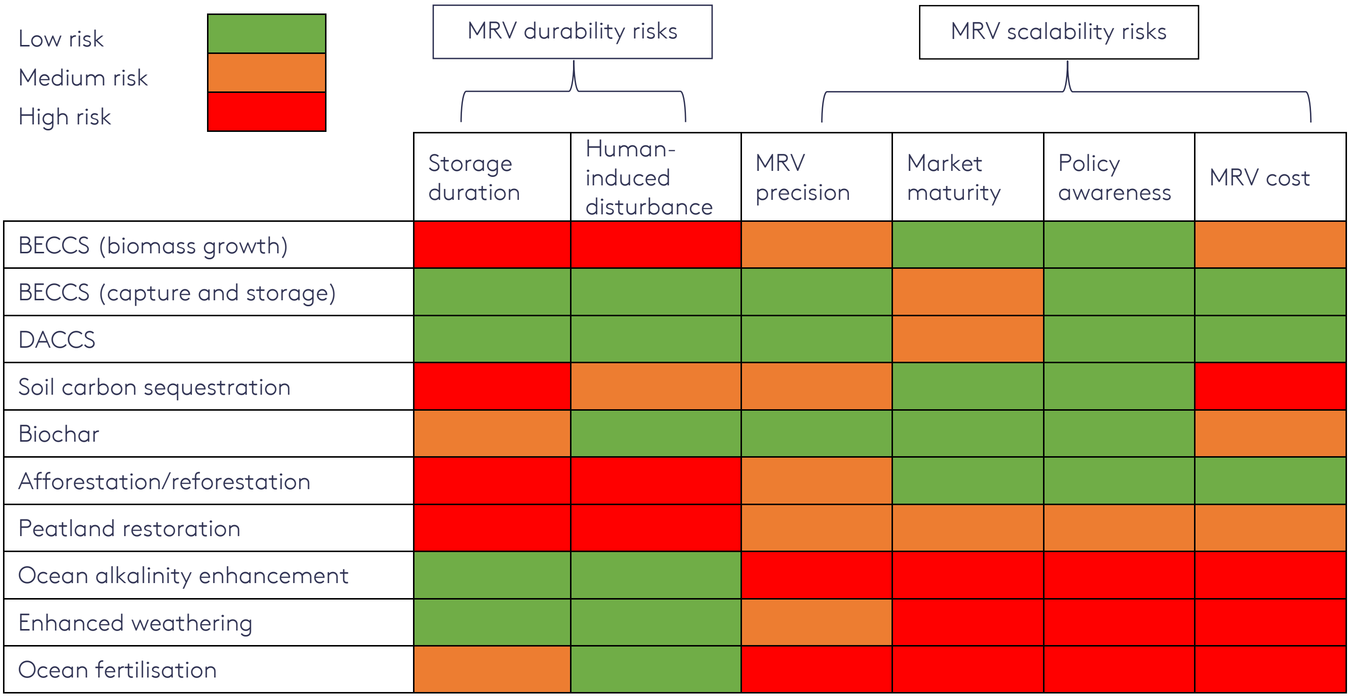

*Source: Authors' analysis of independently certified MRV protocols accessed through web search, and primary and secondary literature. Note: The mapping was compiled using the Microsoft Visio software platform. (A separate PDF download of this mapping is available from the **report landing page** along with the underlying data).*

# 6. Relative risk matrix

Based on the analysis in the previous sections and a literature review, in this section we assess risk to the adequate development and provision of MRV. Risk will change over time through research and innovation. Investing in MRV processes with a large number of risks (i.e. those highlighted in red) to reduce uncertainties will help enable the development of a broad portfolio of GGR techniques with high potential.

The colours (green, amber, red) reflect risks relative to each other, and should not be misconstrued as meaning significant absolute risks.

Figure 6.1. Relative risk matrix for MRV for greenhouse gas removal




*Source: Authors. Note: see discussion below for further elucidation on this figure. (Please see Appendix 1 for a risk matrix corrected for colour vision deficiency).*

## Durability of MRV

Evaluation of the risk associated with storage duration is based on the IPCC's assessment of the length of time carbon can be durably stored. In Figure 6.1, green denotes storage of 10,000 years or longer, amber centuries to millennia, and red decades to centuries. MRV risk is determined based on whether current MRV methods can monitor storage over the timeframes prescribed by the IPCC. Human-induced disturbance denotes the risk that a given store of carbon could be released if there is anthropogenic disturbance. It attempts to capture the extent to which carbon sinks can be reversed through malfeasance or error, irrespective of the biological/geophysical properties of the carbon sink. In practice this could denote policy changes that weaken the protection of terrestrial carbon reservoirs.

## Scalability of MRV

'MRV precision' in Figure 6.1 refers to the ability to precisely quantify the amount of carbon removed and accurately monitor this over time. The basis for this is Smith et al. (2023) and the verification confidence levels set out by Chay et al. (2022), who make a judgement on the precision of quantifying the amount of carbon removed and the existence or not of an MRV methodology. Market maturity is reflective of the landscape mapping and current state of carbon removal demand, where little activity is observed for ocean alkalinity enhancement, enhanced rock weathering and ocean fertilisation. Land-based biological processes, particularly biomass growth, soil carbon sequestration (SCS) and biochar, and afforestation, are relatively mature in comparison and significantly more MRV protocol development is occurring for these forms of GGR.

'Policy awareness' provides an indication of whether existing policies exist that could be adapted or amended to provide MRV for carbon removals. For BECCS and afforestation/reforestation there are policies that implicitly cover these technologies: for example, LULUCF for biomass growth and the sustainability criteria under the UK Renewables Obligation and Contracts for Difference subsidy regimes. Limited scope or absence of policies may pose a barrier to upscaling GGR and consequently the accompanying MRV protocols. Supposing policy support continues at pace – for example, through the design of the UK Greenhouse Gas Removal Business models, the EU Carbon Removal Certification Framework and the US Inflation Reduction Act – this should reduce overall risks associated with policy awareness. However, there is still a risk that despite the development of policy, efforts may remain concentrated on a small number of technologies rather than a broad portfolio.

Lastly, regarding 'MRV cost', there is very little reliable data. This makes it challenging to highlight where there is uncertainty or risks in various approaches or where higher MRV cost may pose a barrier to financing specific removal technologies. We have made a judgement based on the limited academic literature on storage costs, which indicates that the least expensive options involve injection of $CO_2$ into subsurface sedimentary rock (Kelemen et al., 2019), the complexity of the process (closed- vs. open-loop) and the extent to which remote sensing/technological monitoring is used instead of manual data collection. The lowest relative cost methods are the capture and storage processes for BECCS and DACCS, which require periodic monitoring at inspection wells.

Where there are technical challenges and scientific uncertainties, such as for the decay rate of different biochar feedstocks, or over how open-loop ocean methods interact with natural processes, MRV precision is understandably less than it is for mature GGR methods such as afforestation/reforestation that have access to remote sensing and strong foundational science. Other land-based biological processes such as SCS, peatland restoration and biochar are shaded amber as they involve expensive field tests during project development and throughout the life of a project. However, as these are closed-loop methods, costs are considerably less than for open-loop systems such as ocean-based GGR, where isolating $CO_2$ drawdown from background natural processes is more difficult and costly.

Comparing MRV costs for different GGR techniques is challenging. For subsurface injection and monitoring of $CO_2$ plumes, costs will be substantially higher than for more costly biological methods such as SCS. When considering what risk factors inhibit the development of MRV and the upscaling of GGR methods, cost is still significant if you are a landowner required to sample the SOC content of your soil. However, this cost is an order of magnitude lower than the cost of active seismic monitoring of $CO_2$ plumes at sea. Thus, cost is a relative MRV risk and related to the scale of actors using GGR; technical and financial barriers to entry are different across the range of GGR techniques.

# 7. Recommendations for advancing MRV for greenhouse gas removal

Because $CO_2$ removal needs to be completed by all countries, in this section we provide policy recommendations that have relevance for national policymakers. We also expand on the complexities surrounding requirements related to the development of information architecture, market design settings and minimum standards; these relate to different specified GGR stakeholders. MRV needs to be developed for national contexts, but also with cooperation in international contexts.

## Foundational science

The state of science underpinning categories of removal reflects MRV development. For example, there are well developed research foundations for biochar, afforestation and soil carbon sequestration – so MRV coverage is richer for these methods in comparison with methods that have less of a scientific foundation. Development of open-source MRV protocols for those removals that have received large advanced market commitments (i.e. DACCS) will need to ramp up to reflect this demand, thus investment in research for chemical and geochemical GGR methods is a prerequisite for better MRV here.

The landscape mapping in Section 5 above reflects supply- and demand-side dynamics, i.e. the empirical research base for a given GGR and where much of the purchasing is occurring. There are clear MRV gaps for ocean-based biological and geochemical methods when compared with land-based biological approaches. Although the foundational science is sound for these methods, research and innovation in ocean-based GGR (alongside environmental impact assessments) is needed to aid the development of MRV.

> Recommendation 1. **Government should address the fact that promising but under-researched GGR methods, such as ocean-based biological and geochemical methods, suffer from a lack of foundational science (hampering MRV development): through targeted funding for longitudinal experiments to explore the GGR potential of these methods, to create an empirical research base from which to build MRV frameworks.**

## Cost of MRV

While the anticipated total cost of different GGR techniques has been estimated and is available, the costs of MRV pertaining to specific forms of GGR is not. What MRV work is being done is often in-house and not visible externally, with its costs bundled within overall cost estimates. Where there is no MRV coverage for GGR methods, costs can obviously not be defined. Moving forward, there needs to be a legible price for different MRV processes in order to put monetary value on risk. This will be useful to those actors considering capital investments and for policymakers in particular, who will need to consider the extent of required national government support for research into, legitimation of and market demand for GGR technologies.

Moreover, publishing costs could enable the development of a cost curve that could come down over time – although publishing costs does not automatically achieve this. Better transparency would also need to be supported by policies that at least in the near-to-medium term see targeted R&D, demonstration support and demand-pull for GGR, within a well-functioning innovation system that coordinates government with GGR developers and financiers. Moves to standardise and structure buyer claims through changing norms and proposed regulation could bolster transparency and naturally lead to open-source, digitalised and transparent MRV providers being favoured. Highlighting costs may also lead to a more honest conversation about GGR, especially when comparing open-and closed-looped systems, where removing fungibility might be useful.

Policymakers need also to consider what trade-offs they are willing to make in situations where the cost of MRV is prohibitive. The scientific basis for monitoring subsurface $CO_2$ plumes has coalesced around a combination of passive and active seismic monitoring based on site-specific risk characteristics. However, policymakers need to consider how these lessons can be applied to ocean-based GGR or ERW, where there are significant evidence gaps. As an example, they could ask: How is it practicable to monitor silicate rock dust spread on agricultural land? Is it cost-effective and scientifically sound to sample $CO_2$ drawdown at years 1, 5, 10 and 20 before determining the stability of the GGR, or can a light-touch monitoring regime that utilises modelling of ERW characteristics (particle size, silicate content, soil pH, climate, etc.) and past experience provide GGR assurance? What are the trade-offs of a light-touch approach, beyond cost, in terms of sink stability against one where continuous monitoring is prescribed? In addition to this point, the MRV cost burden on smaller entities needs to be considered. Dispensation to bundle multiple smallholder MRV responsibilities with a third party or designated entity to manage these responsibilities should be an option to not limit GGR (particularly land-based biological forms) to larger entities that have the scale to handle MRV requirements.

> Recommendation 2. **R&D and demonstration support should be made available by governments to reduce costs for expensive MRV processes. Greater data-sharing between project developers, MRV providers and selling platforms should be incentivised so that market analyses are regularly published, to increase transparency. This would also highlight market risks and identify where effort is needed to reduce MRV costs.**

## Liability for GGR credits

The mapping of the MRV landscape highlights its complexity. The risk that arises from complex, opaque or overlapping protocols creates information asymmetries for buyers trying to assess MRV processes to ensure purchase quality. Clearly the complex relationship among different actors across a GGR value chain makes it important to have reliable monitoring and reporting throughout the chain that can be reconciled back to the original installation and subjected to third party verification. Such complexity means there needs to be adequate legal provisions to manage asymmetric risks allocations between buyers and sellers, should the results of MRV suggest carbon leakage or impermanence of removal.

Regulators need the ability to monitor whether MRV conditions are being met, including by updating ownership or interests in companies or land parcels with MRV liabilities. These considerations, pertaining to subsurface injection (such as in BECCS and DACCS), are explored by Mac Dowell et al. (2022), who identify the increasing likelihood that $CO_2$ injection will move beyond a 'single-$CO_2$-source-to-single-$CO_2$-sink model' to a $CO_2$ storage hub model. If $CO_2$ from multiple sources (from CCUS and GGR) is transported commonly and stored in a collective reservoir, there will be important liability implications. In this instance, the MRV liability for project developers is likely to end when pooled with other $CO_2$ in common transportation infrastructure, or when deposited into sub-surface storage sites.

Although the transport and storage model for CCUS could well apply to GGR, it is only relevant for those technologies with subsurface injection such as BECCS and DACCS. This means other land-based and geochemical removal processes are left without a formal policy framework to manage legal liability, leaving this open to buyer–seller negotiation and risk-sharing instead. Setting out the legal parameters for these types of GGR needs to be a near-term imperative for policymakers.

Historical discussions about CCS policy frameworks and forestry under the REDD framework, Kyoto Protocol and CDM provide useful context with regard to buyer versus seller responsibility. In principle, the liability for this risk could rest with either the buyer of credits (buyer-liability) or the seller of credits (seller-liability). In the latter case the host country, in effect, would assume the leakage risk. However, experience of afforestation and reforestation projects under the CDM is that a buyer-liability regime may substantially reduce demand for carbon credits generated from CCS projects. In contrast, Schwarze and Niles (2000) find that seller-liability has intrinsic advantages over other types of liability contracts. This is echoed by Mackenzie (2012), who shows that a switch from a practice of buyer- to seller-liability would improve enforcement of the contract and hence increase investment in carbon sinks.

While this context is helpful, it is important to keep in mind that the value chain for GGR is more complex than in the early 2000s. Seller-liability under previous policies was predicated on the seller being a country that could assume overall liability for a project. However, today, sellers are not countries, but either private companies supplying directly to buyers via bilateral contracts, or large platforms that aggregate and retail GGR credits from smaller developers. Indeed, currently the largest volumes of removals are concentrated on just a few selling platforms, which are also developing in-house standards and protocols (e.g. Verra, Puro.earth, American Carbon Reserve).

Extending the concept of seller-liability would imply that liability management would sit with the platforms selling GGR. This may also mitigate the risk that the organisations developing standards/protocols whose business model is reliant on accelerating GGR deployment might not be the most impartial or best judges of what constitutes good-quality GGR. Placing the liability on the selling platform may act as a driver to ensure their MRV is as robust as possible. But in practice it may not be reasonable to think of completely separate liability between the private GGR transactors (via sellers and buyers) and the country in which activities take place, since under the Paris Agreement countries with NDCs face *de facto* liability for carbon reversals from storage sites that they host – so there is seller-liability by default.

One possible solution could be to make use of insurance schemes. This could include shared responsibility whereby selling platforms have initial liability, but this is underpinned by government-backed carbon insurance schemes that they must procure. There is precedent for this in the UK government's FloodRE reinsurance scheme, which ensures flood insurance is available in high-risk areas that may be classed as uninsurable. Entering into a public–private risk-sharing agreement for GGR MRV is a pragmatic way forward, since it would be inequitable for liability arrangements to exacerbate the redistribution of benefits from public to private actors where the benefits are privatised and the risks socialised.

> Recommendation 3. **Regulators should seek to support the development of seller-liability for non-subsurface storage reservoirs such as in ocean fertilisation, afforestation and enhanced rock weathering. To ensure a fair allocation of risk between public and private entities, seller liability could be underpinned by government-backed carbon reinsurance schemes that sellers must procure.**

## MRV is being undermined by disparate actors and protocols

MRV is currently undermined by disparate actors and standards, which makes comparing removals extremely difficult. The plethora of different MRV standards could prove counterproductive. Variability in MRV protocols is preventing developers and regulators from understanding true risk, hindering progress to scale up removals. Private entities purchasing removals typically aggregate carbon removal credits from different suppliers, each of which may have its own MRV protocol. In many ways this is a result of the patchwork jurisdictional approach to incentivising and regulating GGR. For example, the EU has an economy-wide ETS and is developing a framework for certifying GGR under the Carbon Removal Certification Framework, which is happening in advance of developments in the UK and USA, and therefore differences may emerge in how MRV frameworks develop at a jurisdictional level. Discrepancies in MRV quality and design will undermine the credibility of GGR – but also, they hinder those purchasing removals from appraising their own purchases within and between supply chains. This challenge will only get worse as new market actors emerge. Regulators therefore need to ensure a degree of standardisation for interoperability across selling platforms.

> Recommendation 4. **Policymakers in the UK and other jurisdictions developing GGR strategies need to develop MRV minimum standards to ensure interoperability across selling platforms. Minimum standards should be differentiated from preferred methodologies. This could begin with identifying where in the MRV ecosystem there is**

duplication, low credibility and unnecessary complexity among voluntary and compliance MRV providers.

## An MRV regulator

There is currently no apex body to provide oversight and compliance functions for the MRV methods used to certify GGR, nor a mechanism to ensure that removals align with policy direction and contribute to carbon budgets and NDCs (Sturge et al., 2022). Flexible regulations are increasingly seen as a market enabler and important for innovation (Dechezleprêtre and Sato, 2017; Rhodes et al., 2021). The EU Governance Regulation[33] provides an example for how to coordinate a broad suite of climate mitigation policies by ensuring that strategy on energy security, decarbonisation and R&D is implemented and coordinated coherently within and between member states. However, the extent to which this is happening in other jurisdictions is less apparent.

The benefits of a laissez-faire approach in terms of allowing industry to develop GGR methods with freedom may be wasted if certain techniques are not deemed to remove $CO_2$ with the requisite permanence or within adequate safety guidelines. The role of government in this instance should be to clearly signal minimum MRV standards, for the reasons mentioned above, and to contribute to the development of global MRV standards in multilateral fora.

The Task and Finish Group report commissioned by the UK's erstwhile Department for Business, Energy and Industrial Strategy provides some useful policy recommendations (BEIS, 2021), which we echo here. The report suggests an MRV regulator should sit between project developers and the government with a remit to co-develop MRV and minimum standards for GGR. Another function could be to promote transparency through the value chain alongside development and enforcement of minimum standards so that removal providers, the purchaser, date of retirement and other pertinent project details including the level of permanence are readily available for scrutiny. Alternatively, a regulator could act as a GGR registry and host data on GGR project development, issuance and retirement. Another key task for a regulator would be to design a removal buffer pool to hedge against reversal, and explicit directives for project developers to rectify any leaks or $CO_2$ losses from subsurface reservoirs.

Precisely what a regulator would look like is, of course, still open for debate. For example, using the UK context again, would it be a standalone entity like the energy regulator OFGEM or sit within an agency such as the Department for Energy Security and Net Zero? The regulator needs to be independent, comprised of a cross-section of industry experts and endowed with statutory powers to enforce strong environmental governance.

The UK Energy Systems Catapult has schematised three options for the form a regulator could take:

1. The 'California model' – a single, economy-wide body with both MRV and administrative responsibilities
2. A simplified, single, economy-wide body with devolved administrative responsibilities through environmental agencies at sub-national level
3. A single economy-wide body with devolved and policy-specific administrative responsibilities which builds on existing MRV arrangements, utilises sector expertise and is supported by an economy-wide governance framework to ensure consistency in MRV practices. (Sturge, 2022)

Recommendation 5. Policymakers should consider regulating minimum standards for MRV. Risks exist for all GGR methods if the sector continues to develop under a light-touch regulatory regime. These risks justify stronger regulation. An MRV regulator with sufficient

[33] Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action.

powers would provide confidence that all removals are high quality. An MRV regulator would also give effect to other recommendations made above, such as 3, 4 and 6.

## Managing MRV risk

Better MRV is just one tool available to policymakers to manage durability and scalability risks relating to carbon removal. For example, Whitmore and Preston Aragonès (2022) offer three other policy approaches to mitigate the risk of removals being reversed, while also fostering GGR innovation:

1. Distinct treatment of long and short carbon cycle removals. This approach recognises that emissions from land use, i.e. biogenic methane emissions, which have a radiative forcing effect of around 15 years, are best offset or balanced by removals from land-based biological methods.
2. Pricing-in the risk of reversal by creating 'a GGR exchange rate', where fungibility is created between 1 tonne of emissions and 1 tonne of removals from different GGR methods. The risk of reversal could be set through regulation or a derivative unique to the GGR. Buffer pools could be utilised to insure against incorrect assessment of a project's reversal risk.
3. Permanent equivalence, whereby any reversal or leakage from a $CO_2$ sink must be covered by an instantaneous purchase of another removal certificate that has parity across domains such as permanence and durability. Project developers must show they have the funds at hand to match reversals. The price of a certificate would reflect the cost of the storage project, the cost of insurance or funds held, and continuing MRV.

Improving MRV across the six dimensions described above in Section 6 on the 'relative risk matrix' should be seen as part of a multi-faceted and intertemporal policy and governance framework for GGR. This includes considering separate accounting targets for GGR and conventional emissions abatement, removing perfect fungibility between GGR permits and carbon market permits, and promoting a wide range of innovation and technology-specific mechanisms to drive currently expensive, yet highly scalable MRV processes down the cost curve. Such a framework would ensure that policymakers can utilise carbon markets and other incentives appropriately to drive the development and deployment of GGR techniques without compromising near-term mitigation, and that the representation of GGR in modelled low-carbon pathways takes into account real-world incentives that will support upscaling.

Recommendation 6. Policymakers should develop a wide portfolio of GGR to manage MRV risks. This needs to be part of a broader governance framework to manage the risks of moral hazard and poor environmental integrity.

# 8. Conclusions

This report has indicated gaps in MRV readiness across the range of terrestrial and marine greenhouse gas removal methods. Without well-developed MRV, it will be difficult to upscale GGR to deliver the billions of tonnes of carbon removals that need to occur by 2025 in the lead-up to 2050.

We have identified significant MRV stratification, with many developments occurring in the voluntary carbon market for land-based biological methods, particularly soil carbon sequestration and afforestation/reforestation. For other promising methods such as BECCS and chemical methods such as DACCS, MRV is largely driven through national and international regulations. Given the large advanced market commitments for DACCS, it is imperative that privately provided MRV services can support regulatory instruments to ensure adequate supply.

MRV development risk largely lie within open-loop systems such as ocean alkalinity enhancement, enhanced rock weathering and ocean fertilisation, while durability-related risks lie with land-based biological methods vulnerable to subsequent emissions occurring, 'reversing' the removal, such as peatland restoration, soil carbon sequestration and afforestation/reforestation.

Challenges exist for public and private bodies supporting MRV development and will need to be met through greater provision of finance and incentives to develop nascent methods, alongside a carefully designed regulatory environment that stimulates GGR innovation with high integrity and durability. Coordination between GGR project developers, academia and policymakers is necessary to identify gaps in MRV coverage and risks to existing MRV methods, and to circulate knowledge.

To mitigate some of the challenges in the MRV landscape, the following is recommended: we identify a need for an MRV regulator to develop minimum quality standards and ensure MRV providers meet the required standards; nascent methods such as enhanced rock weathering and ocean-based GGR need targeted investment to develop foundational science and MRV methods; and policymakers in national and multilateral fora need to consider where legal liability for reversals and leakage sit for MRV providers and project developers, and, as the industry develops, how and to what extent removals are treated alongside other carbon market permits in voluntary and compliance mechanisms.

# Appendix 1. Relative risk matrix for MRV for greenhouse gas removal – greyscale version

- Low risk
- Medium risk
- High risk

| | MRV durability risks | | MRV scalability risks | | | |
|---|---|---|---|---|---|---|
| | Storage duration | Human-induced disturbance | MRV precision | Market maturity | Policy awareness | MRV cost |
| BECCS (biomass growth) | High risk | High risk | Medium risk | Low risk | Low risk | Medium risk |
| BECCS (capture and storage) | Low risk | Low risk | Low risk | Medium risk | Low risk | Low risk |
| DACCS | Low risk | Low risk | Low risk | Medium risk | Low risk | Low risk |
| Soil carbon sequestration | High risk | Medium risk | Medium risk | Low risk | Low risk | High risk |
| Biochar | Medium risk | Low risk | Low risk | Low risk | Low risk | Medium risk |
| Afforestation/reforestation | High risk | High risk | Medium risk | Low risk | Low risk | Low risk |
| Peatland restoration | High risk | High risk | Medium risk | Medium risk | Medium risk | Medium risk |
| Ocean alkalinity enhancement | Low risk | Low risk | High risk | High risk | High risk | High risk |
| Enhanced weathering | Low risk | Low risk | Medium risk | High risk | High risk | High risk |
| Ocean fertilisation | Medium risk | Low risk | High risk | High risk | High risk | High risk |

# References


Allan, R. P., Hawkins, E., Bellouin, N., & Collins, B. (2021). *IPCC, 2021: Summary for Policymakers*.

Anderson, K., & Peters, G. (2016). The trouble with negative emissions. *Science*, *354*(6309), 182–183.

Arcusa, S., & Sprenkle-Hyppolite, S. (2022). Snapshot of the Carbon Dioxide Removal certification and standards ecosystem (2021–2022). *Climate Policy*, 1–14.

BEIS. (2021). *Monitoring, Reporting and Verification of Greenhouse Gas Removals Task and Finish Group Report*. Department of Business Energy and Industrial Strategy. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1026994/mrv-ggrs-task-report.pdf

Berg, T., Mir, G.-U.-R., & Kühner, A.-K. (2017). *CCC indicators to track progress in developing greenhouse gas removal options* [Report for UK CCC]. ECOFYS.

Bey, N., McDonald, H., Maya-Drysdale, L., Stewart, R., Pätz, C., Hornsleth, M. N., Duin, L., Frelih-Larsen, A., Heller, C., & Zakkour, P. (2021a). *Certification of Carbon Removals—Part 1: Synoptic review of carbon removal solutions*.

Bey, N., McDonald, H., Maya-Drysdale, L., Stewart, R., Pätz, C., Hornsleth, M. N., Duin, L., Frelih-Larsen, A., Heller, C., & Zakkour, P. (2021b). *Certification of Carbon Removals—Part 2: A review of carbon removal certification mechanisms and methodologies*.

Biffis, E., Brandi, G., Lee, L., & Snavely, A. (2023). *Forestry-Backed Assets Design*. Imperial College London.

Bouckaert, S., Pales, A. F., McGlade, C., Remme, U., Wanner, B., Varro, L., D'Ambrosio, D., & Spencer, T. (2021). *Net zero by 2050: A roadmap for the global energy sector*.

Broad, O., Butner, I., & Cronin, J. (2021). *Can BECCS help us get to net zero?* https://www.ucl.ac.uk/bartlett/news/2021/jul/can-beccs-help-us-get-net-zero

Buck, H. J., Carton, W., Lund, J. F., & Markusson, N. (2023). Why residual emissions matter right now. *Nature Climate Change*, 1–8.

Budinis, S. (2022). *Direct Air Capture*. IEA. https://www.iea.org/reports/direct-air-capture

Burke, J., & Gambhir, A. (2022). Policy incentives for Greenhouse Gas Removal Techniques: The risks of premature inclusion in carbon markets and the need for a multi-pronged policy framework | Elsevier Enhanced Reader. *Energy and Climate Change*. https://doi.org/10.1016/j.egycc.2022.100074

CCC. (2020). *The Sixth Carbon Budget: Greenhouse gas removals*. Climate Change Committee. https://www.theccc.org.uk/wp-content/uploads/2020/12/Sector-summary-GHG-removals.pdf

CCC. (2022). *Voluntary Carbon Markets and Offsetting*. United Kingdom Climate Change Comittee.

Chay, F., Klitzke, J., Hausfather, Z., Martin, K., Freeman, J., & Cullenward, D. (2022). *CDR Verification Framework*. CarbonPlan. https://carbonplan.org/research/cdr-verification-methods#verification-confidence-levels-vcls

Cox, E., Spence, E., & Pidgeon, N. (2020). Incumbency, trust and the Monsanto effect: Stakeholder discourses on greenhouse gas removal. *Environmental Values*, *29*(2), 197–220.

Dechezleprêtre, A., & Sato, M. (2017). The impacts of environmental regulations on competitiveness. *Review of Environmental Economics and Policy*.

Element Energy. (2021). *Greenhouse gas removal methods and their potential UK deployment*.

Environment Agency. (2021). *A review of the evidence behind potential carbon offsetting approaches* (No. 7).

EU Commission. (2022). *Impact assessment on the Regulation establishing a Union certification framework for carbon removals* (Commission Staff Working Document SWD (2022)). European Commission. https://climate.ec.europa.eu/document/ab53e63b-4b85-4d28-ac67-6bd742506bae_en

Fajardy, M., Köberle, A., Mac Dowell, N., & Fantuzzi, A. (2019). *BECCS deployment: A reality check* (Briefing Paper No. 28; p. 14). Imperial College London.

Fankhauser, S., Smith, S. M., Allen, M., Axelsson, K., Hale, T., Hepburn, C., Kendall, J. M., Khosla, R., Lezaun, J., & Mitchell-Larson, E. (2022). The meaning of net zero and how to get it right. *Nature Climate Change*, *12*(1), 15–21.

FAO. (2011). *Assessing forest degradation. Towards the development of globally applicable guidelines* [Forest Resources Assessment Working Paper 177]. Food and Agriculture Organization.

Fawzy, S., Osman, A. I., Yang, H., Doran, J., & Rooney, D. W. (2021). Industrial biochar systems for atmospheric carbon removal: A review. *Environmental Chemistry Letters*, *19*, 3023–3055.

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., & Khanna, T. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 063002.

Global CCS Institute. (2012). *CO2 Capture Technologies: Post Combustion Capture (PCC)*. Global Carbon Capture and Storage Institute.

Green, C., & Byrne, K. A. (2004). *Biomass: Impact on carbon cycle and greenhouse gas emissions*.

Harvey, V., Guard, G., & Christie-Miller, T. (2022). *Scalability Assessment for Carbon Removal*. BeZero Carbon.

HM Government. (2021). *Net Zero Strategy: Build Back Greener*. HM Government. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf

Ho, D. T. (2023). Carbon dioxide removal is not a current climate solution—We need to change the narrative. *Nature*, *616*(7955), 9–9. https://doi.org/10.1038/d41586-023-00953-x

Höglund, R. (2020). *Removing Carbon Now* [Oxfam Discussion Paper]. Oxfam.

Honegger, M., Baatz, C., Eberenz, S., Holland-Cunz, A., Michaelowa, A., Pokorny, B., Poralla, M., & Winkler, M. (2022). The ABC of Governance Principles for Carbon Dioxide Removal Policy. *Frontiers in Climate*, *4*, 884163.

IEA. (2021). *About CCUS*. https://www.iea.org/reports/about-ccus

IEA. (2022). *CO2 storage resources and their development*. International Energy Agency. https://www.iea.org/reports/co2-transport-and-storage

IPCC. (2022). *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press. https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_FullReport.pdf

Joosten, H., Brust, K., Couwenberg, J., Gerner, A., Holsten, B., Permien, T., Schäfer, A., Tanneberger, F., Trepel, M., & Wahren, A. (2016). *MoorFutures® Integration of additional ecosystem services (including biodiversity) into carbon credits – standard, methodology and transferability to other regions*. https://doi.org/10.13140/RG.2.1.3615.7203

Kelemen, P., Benson, S. M., Pilorgé, H., Psarras, P., & Wilcox, J. (2019). An overview of the status and challenges of CO2 storage in minerals and geological formations. *Frontiers in Climate*, *1*, 9.

Khan, A., & Minor, P. (2022). A buyer's guide to high-accountability MRV. *Carbon180*.

Kivi, I., Makhnenko, R., Oldenburg, C., & Vilarrasa, V. (2022). Multi-layered systems for permanent geologic storage of CO2 at the gigatonne scale. *Geophysical Research Letters*, e2022GL100443.

Kollmuss, A., Schneider, L., & Zhezherin, V. (2015). *Has Joint Implementation reduced GHG emissions? Lessons learned for the design of carbon market mechanisms* (SEI Working Paper No. 2015–07). Stockholm Environment Institute.

Kreibich, N., & Hermwille, L. (2021). Caught in between: Credibility and feasibility of the voluntary carbon market post-2020. *Climate Policy*, *21*(7), 939–957. https://doi.org/10.1080/14693062.2021.1948384

Mac Dowell, N., Reiner, D. M., & Haszeldine, R. S. (2022). Comparing approaches for carbon dioxide removal. *Joule*.

MacKenzie, I. A., Ohndorf, M., & Palmer, C. (2012). Enforcement-proof contracts with moral hazard in precaution: Ensuring 'permanence'in carbon sequestration. *Oxford Economic Papers*, *64*(2), 350–374.

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., & Hartmann, J. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters*, *13*(6), 063001.

Mitchell, A. L., Rosenqvist, A., & Mora, B. (2017). Current remote sensing approaches to monitoring forest degradation in support of countries measurement, reporting and verification (MRV) systems for REDD+. *Carbon Balance and Management*, *12*(1), 9. https://doi.org/10.1186/s13021-017-0078-9

Mitchell-Larson, E., Mäkelä, A., Hofbauer, V., & Cohen, K. (2022). *A guide to certifying carbon removal*. Carbon Gap. https://carbongap.org/wp-content/uploads/2022/11/Carbon_Gap_White_Pater_Oct22_updateCRCF.pdf

NOAA. (2022). *NOAA Carbon Dioxide Removal Research*. National Oceanic and Atmospheric Administration. https://sciencecouncil.noaa.gov/Portals/0/Documents/Clean%20copy%20of%20Draft%20CDR%20Research%20Strategy.pdf?ver=2022-09-21-143831-560

Olesen, A. S., & Andersen, S. P. (2021). *Incentivising peatland restoration and rewetting actions through a result-based EU carbon farming mechanism*. Copernicus Meetings.

Ozkan, M., Nayak, S. P., Ruiz, A. D., & Jiang, W. (2022). Current status and pillars of direct air capture technologies. *Iscience*, 103990.

Peacock, M., Gauci, V., Baird, A. J., Burden, A., Chapman, P. J., Cumming, A., Evans, J. G., Grayson, R. P., Holden, J., & Kaduk, J. (2019). The full carbon balance of a rewetted cropland fen and a conservation-managed fen. *Agriculture, Ecosystems & Environment*, *269*, 1–12.

Rhodes, E., Scott, W. A., & Jaccard, M. (2021). Designing flexible regulations to mitigate climate change: A cross-country comparative policy analysis. *Energy Policy*, *156*, 112419.

Royal Society. (2018). *Greenhouse gas removal*. Royal Society and Royal Academy of Engineering.

Ruseva, T., Hedrick, J., Marland, G., Tovar, H., Sabou, C., & Besombes, E. (2020). Rethinking standards of permanence for terrestrial and coastal carbon: Implications for governance and sustainability. *Current Opinion in Environmental Sustainability*, *45*, 69–77.

Sanderman, J., & Baldock, J. A. (2010). Accounting for soil carbon sequestration in national inventories: A soil scientist's perspective. *Environmental Research Letters*, *5*(3), 034003.

Schwarze, R., & Niles, J. O. (2000). The long-term requirement for clean development mechanism forestry and economic liability. *The Journal of Environment & Development*, *9*(4), 384–404.

Smith, S., Geden, O., Nemet, G., Gidden, M., Lamb, W., Powis, C., Bellamy, R., Callahan, M., Cowie, A., Cox, E., Fuss, S., Gasser, T., Grassi, G., Greene, J., Lueck, S., Mohan, A., Müller-Hansen, F., Peters, G., Pratama, Y., & Minx, J. (2023). *The State of Carbon Dioxide Removal—1st Edition*.

Sturge, D. (2022). *The Case for an Economy-Wide Carbon Regulator*. Energy Systems Catapult.

Tanhua, T., Bates, N. R., & Körtzinger, A. (2013). The Marine Carbon Cycle and Ocean Carbon Inventories. In *International Geophysics* (Vol. 103, pp. 787–815). Elsevier. https://doi.org/10.1016/B978-0-12-391851-2.00030-1

Valiergue, A., & Ehrenstein, V. (2022). Quality offsets? A commentary on the voluntary carbon markets. *Consumption Markets & Culture*, 1–13.

Wang, J., Xiong, Z., & Kuzyakov, Y. (2016). Biochar stability in soil: Meta-analysis of decomposition and priming effects. *Gcb Bioenergy*, *8*(3), 512–523.

West, T. A., Börner, J., Sills, E. O., & Kontoleon, A. (2020). Overstated carbon emission reductions from voluntary REDD+ projects in the Brazilian Amazon. *Proceedings of the National Academy of Sciences*, *117*(39), 24188–24194.

Whitmore, A., & Preston Aragonès, M. (2022). *Addressing differences in permanence of Carbon Dioxide Removal*. Bellona Foundation. https://network.bellona.org/content/uploads/sites/3/2022/04/Addressing-differences-in-permanence-of-Carbon-Dioxide-Removal.pdf

Zakkour, P., Cook, G., & French-Brooks, J. (2014). Biomass and CCS-Guidance for accounting for negative emissions. In *Report for the IEA Greenhouse Gas R7D Programme, Cheltenham, UK*.

Zelikova, J., Chay, F., Freeman, J., & Cullenward, D. (2021). *A buyer's guide to soil carbon offsets* (No. 11). Carbonplan.