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Ingrid Schulte,[i] Josh Burke,[ii] Stephanie Arcusa,[iii] Leo Mercer[ii] Dianne Hondeborg[iv]

[i] *Mercator Research Institute on Global Commons and Climate Change*

[ii] *Grantham Research Institute, London School of Economics*

[iii] *Arizona State University*

[iv] *ETH Zurich*

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Kelp forests underwater. Credit: Nuno Vasco Rodrigues / Climate Visuals Countdown

Chapter 10 | Monitoring, reporting and verification

Monitoring, reporting and verifying that carbon dioxide (CO_2) has been captured from the atmosphere and stored durably is critical for growing confidence in carbon dioxide removal (CDR) and for driving growth. But the science and policy around developing robust systems for doing so is complex and in different stages of development for different CDR methods.

Key insights

- Monitoring, reporting and verification (MRV) policy differs between jurisdictions. The EU and the UK, for example, have prioritized the development of CDR standards and guidelines. In contrast, the US has focused on scaling up market-ready CDR and developing specific MRV tools for certain methods (e.g. ocean alkalinity enhancement).
- Existing MRV protocols focus predominantly on conventional CDR. MRV protocols for novel CDR methods, such as direct air carbon capture and storage and ocean alkalinity enhancement are, by contrast, only documented from 2022 onwards.
- Novel CDR methods, such as direct air carbon capture and storage, use proprietary carbon capture techniques that are often not publicly available. As the MRV protocols developed for these proprietary methods are inaccessible, it is not possible to compare them with publicly available MRV protocols.
- The MRV ecosystem consists of many overlapping protocols, which makes comparison and oversight of CDR difficult for investors and governments alike. The majority of protocols are underpinned by a common framework, however. This shared foundation brings both risks and opportunities: methodological weaknesses or incorrect assumptions in the common framework could permeate the whole MRV ecosystem; however, it can also facilitate widespread reform.

This chapter explores the concept of monitoring, reporting and verification (MRV) and how it fits into the broader CDR landscape. It then reviews recent developments in MRV policy and assesses the present state of knowledge on MRV. Finally, it summarizes the current state of MRV for different CDR methods and highlights key areas for further research.

The chapter aims to help jurisdictions developing CDR strategies to understand the complexities involved in MRV practice for different CDR methods.

10.1 Understanding MRV

Monitoring, reporting and verifying that CO_2 has been captured from the atmosphere and stored durably provides the credibility and transparency that are critical to driving growth and innovation in CDR.

Defining MRV in the context of CDR

MRV forms the foundation of any framework governing the performance of CDR activities.[4] Many notions exist of what constitutes MRV. In fact, "measurement" and "monitoring" are often used interchangeably for the "M".[428] For the purposes of this report, "monitoring" is used, and taken to include all data and information that is measured, estimated or quantified for the purposes of tracking CDR and its related impacts.

Specifically, this report defines MRV as the process of:

1. Measuring or quantifying CO_2 removals from a CDR activity and monitoring those CO_2 removals over the course of a CDR activity
2. Reporting on those removals
3. Receiving third-party verification of the removals that have been reported

These steps – which are broadly referred to as an MRV system – are realized through the implementation of greenhouse gas quantification through crediting mechanisms (processes that certify that a CDR activity has taken place) and according to predefined standards. MRV approaches are described in protocols, which this report defines as any document that outlines methods or sets quality requirements or guidelines for certification, carbon accounting, MRV or a component thereof.

Beyond this narrow definition, which focuses on MRV's carbon accounting role, there is growing interest from many actors – including governments, researchers and credit buyers – to broaden MRV parameters to include aspects such as environmental impacts (e.g. changes in biodiversity, water, soil and air quality, or land availability) and social benefits (e.g. job creation).[109,429–431] MRV of these potential co-benefits could be included within steps 1–3 above, although most crediting mechanisms currently do not do this.

Furthermore, even with robust MRV systems in place, additional governance mechanisms are needed to manage the risk of reversal (e.g. through buffer pools, "permanence periods", and "make-good" provisions).

Structures through which MRV occurs for CDR

There are several purposes for which the quantification and reporting of CO_2 removals may be undertaken, including project-, corporate- or national-level GHG inventory compilation and accounting. The two predominant structures influencing quantification and reporting

4 *The term CDR activities is used to refer to projects (i.e. where CDR is being implemented). The term CDR method is used to refer to different types of CDR (e.g. afforestation/reforestation, biochar, direct air carbon capture and storage).*

methods are (1) national greenhouse gas inventories under the UNFCCC and (2) the voluntary carbon market (VCM) methods that seek to guide project-level accounting.

Within the UNFCCC's MRV framework, all parties (i.e. countries) are required to report information on their national greenhouse gas emissions and removals. Quantification of emissions and removals from human activities, including managed land, takes place at the territorial level and is reported in various forms, including national communications, biennial update reports and biennial transparency reports. Measurement and reporting is guided by methods set forth in the *IPCC Guidelines for National Greenhouse Gas Inventories*, although parties are free to implement their own approach if they wish and if those approaches stand up to international scrutiny. The various reports are reviewed by the nationally nominated experts from the UNFCCC Roster of Experts. While IPCC guidance on greenhouse gas quantification exists for conventional CDR methods, guidance for novel CDR methods is currently lacking, other than for bioenergy with carbon capture and storage (BECCS) and biochar (see Table 10.3). Currently, MRV development for novel CDR methods is primarily happening in the VCM, at the project level. Therefore, the remainder of this chapter largely focuses on the development of MRV in the VCM.

Within the VCM, MRV is an essential component of the certification system, providing a framework for assessing CDR claims that supports the operationalization of CDR credit trading. CDR project developers must register their projects if they want to receive carbon credits for CDR. The project documents they submit for registration require plans for monitoring. The project developers follow a methodology for monitoring and quantification as well as protocols for reporting and verification developed by the greenhouse gas programme. Project developers report the project's removal, quantified relative to a baseline, to the greenhouse gas programme. An accredited third party then verifies the monitoring report, and the greenhouse gas programme certifies and issues carbon credits, which are registered on a platform that enables transfer and cancellation of credits. One potential structural deficiency within this current system is that, in some cases, a single actor can control several steps of the process, including developing the MRV framework and issuing credits, which could raise questions about oversight and impartiality.

With the CDR market developing rapidly in the VCM, the norms and practices established there will have implications for future compliance markets, for example how rules and methodologies are set. Compliance markets are government-driven markets based on policy or regulatory requirements (such as the EU Emissions Trading System). Historical experience suggests that norms and standards set in the VCM may come with significant challenges if State actors later seek to count VCM activities towards national targets. Lessons on nesting (the alignment of project-level and jurisdictional greenhouse gas accounting) from REDD+ activities may provide some useful insights here.[92]

Key challenges for MRV for CDR

Several key challenges exist for delivering robust MRV in the context of CDR. The principal objective of MRV is to assess the amount of CO_2 removed by the implementation of a specific CDR method over time. The ability to accurately quantify how much CO_2 has been removed from the atmosphere is fundamental to assessing the performance of CDR activities and to integrating CDR into climate change mitigation strategies. At the core of this is designing MRV systems that are based on the best available scientific evidence. However, significant methodological challenges remain for quantifying CDR, along with definitional questions about key concepts for the MRV of CDR (see Box 10.1).[432,433]

The MRV framework for quantifying CDR may be conceptually simple, but the practical reality is complex. The tools, instruments and protocols used to measure removals vary significantly for different CDR methods.[434] Accounting approaches are inconsistent in their handling of measurement uncertainty and issues such as storage duration and life cycle emissions. Additionally, many established MRV protocols still do not distinguish between CDR and emission reductions, including activities that avoid emissions (e.g. by protecting forests; see Chapter 4 – The voluntary carbon market, Box 4.2).[142] This lack of distinction means that removals and reductions are often included in one credit, despite the fact that removing 1 ton of CO_2 from the atmosphere has different climate impacts than preventing the emission of 1 ton of CO_2.

Furthermore, subsequent verification processes typically only consider whether MRV criteria from the applied protocol were met, not whether the rules accurately reflect atmospheric outcomes. And, owing to the absence of regulated supranational guidelines, multiple regulatory efforts are developing in parallel with fast-moving technical developments in the VCM. This is resulting in overlapping protocols for some CDR methods and incomplete MRV coverage for others.[142]

Consequently, the MRV landscape has become ever more confusing. Compounding this is the wide-ranging nature of the scientific knowledge that underlies MRV approaches. With new research constantly emerging, the challenge for policymakers, researchers and investors is to maintain a systematic overview of the evidence and to use this to improve MRV protocols. These factors highlight the need to understand the current state of MRV protocols – their scientific basis, gaps and divergence.

Box 10.1 Critical concepts that require firming up for robust MRV of CDR

Table 10.1 highlights some of the questions that are currently being debated around MRV in the context of CDR. Literature relevant to these debates can be found in Chapter 10 Technical Appendix, Table A. It will be crucial to have clear and consistent definitions and understandings of these concepts across the CDR community to ensure the robustness of MRV.

Term	Critical open questions
Durability[a]	*What storage duration can be considered "permanent"?* *What role can temporary removals play in national or corporate climate strategies?* *What removals should be fungible with one another or with CO_2 emissions?* *What level of monitoring is needed for carbon storage that has a very low of risk of reversal (e.g. subsurface mineralization)?*
Double counting[b]	*How can greenhouse gas accounting be designed across scales (e.g. nesting of voluntary removals in national accounting schemes) to prevent decreased ambition? How can measures to avoid double counting, such as "corresponding adjustments", be implemented in a just and equitable way?*
Quantification	*How can removal be quantified for open systems?* *What level of uncertainty is acceptable for different removal purposes? How should it be accounted for?*
Additionality	*What measures should be applied to test additionality?* *How can reliance on counterfactuals (e.g. scenarios considering what would have occurred had the project not taken place) be reduced?*

[a] Durability refers to the quality of being able to store carbon over time without releasing it back into the atmosphere. It is often confused with permanence, which is the length of time that stored carbon can remain sequestered.

[b] Double counting can refer to double issuance (e.g. certifying a single removal under two programmes), double use (e.g. using a credit as an offset twice), or double claiming (e.g. claiming of a removal by two entities without appropriate nesting).

Table 10.1 *Debated terminology that needs firming up for robust monitoring, reporting and verification in the context of carbon dioxide removal.*

The role of MRV in supporting CDR upscaling

Robust MRV can help governments and private sector actors overcome information gaps and asymmetries that may make it difficult for them to make investment or regulatory decisions. These issues may otherwise erode trust and confidence in CDR, halt capital investments and slow the integration of CDR into climate policy. As such, transparent and publicly accessible MRV can:

- **Be a first step in integrating CDR methods (in particular, novel CDR) into climate policies, markets and targets.**[435] To date, limited integration has occurred. This is because many countries employ a precautionary approach to policymaking, and thus it often only takes place *after* governance frameworks, including MRV, have been designed. The US is perhaps an exception as this sequencing has been inverted. Crediting CDR transforms the removed carbon into a tangible commodity that project developers can seek payment for; the transactions facilitate the exchange of credits from developer to buyer, in the case of voluntary or compliance markets, or serve as proof of delivery to receive government-funded subsidies such as the US 45Q tax credit.

- **Ensure the requirements for liability transfer are met.** Liability ownership and transfer are key components of CDR policy and governance. In the event of a reversal (where stored CO_2 is released, for example due to wildfires) or other unforeseen outcomes, it is important that there are clearly delineated remedial processes. Policymakers need to take care that liability transfers do not unfairly and prematurely redistribute risks and benefits from public to private actors. In particular, policymakers need to avoid creating an environment where the benefits in monetizing CO_2 drawdown are privatized but the risks, such as managing carbon liabilities in perpetuity, are socialized.[434] Demonstrating (most likely through MRV) that certain conditions have been met – for example, that geologically stored carbon is permanently removed and behaving in a predictable manner – is likely to be a precondition for receiving public funds.[436] Once this is the case, the ownership of the storage liability could be transferred.[5]

- **Allow stakeholders to hold project developers accountable** – for example via civil litigation and during planning approval – for their climate, public health and environmental impacts. Such accountability may also contribute to a perception that CDR is operating responsibly and help build trust and acceptance (see Chapter 6 – Perceptions and communication). A high degree of communication and adherence to responsible CDR practices by project developers may help the wider industry earn a social licence to operate and provide the preconditions on which enduring policy frameworks can be built that enhance the legitimacy of CDR for the public, governments and civil society.

- **Drive much needed investment in research and development and early- to mid-stage CDR companies.** Though novel CDR methods are at an early stage of development, there are already barriers to equal financing for different CDR methods (see Chapter 2 – Research and development).[437] Where MRV is costly, complex or deficient, it may lead to trade-offs between accuracy and cost, particularly

5 *This will likely only happen after carbon capture and storage well closure and after MRV, conducted over many years, establishes the integrity of the carbon stored.*

if there is insufficient willingness to pay for more accurate, but more expensive, MRV. These trade-offs may slow the integration of the associated CDR method into policy because some critical criteria – such as the expected durability of removal, the transparency of the crediting process and the accuracy of MRV – have not been satisfied. They may also make it difficult to generate carbon credits in voluntary markets or similar instruments (e.g. allowances within compliance markets), which is likely to be a necessary precondition for crowding-in private investment.[438] For most CDR methods based on complicated open-loop removals (where CDR is achieved by intervening in natural biogeochemical processes to stimulate CO_2 removal, such as in ocean fertilization), balancing the cost and accuracy of MRV is acute. Another reason that investment in certain CDR methods is lacking is weak transparency and credibility in those methods' accounting protocols. Investment in conventional CDR is hindered by a growing number of supply-side scandals that are ongoing in the VCM and the Kyoto Protocol's Clean Development Mechanism (see Chapter 4 – The voluntary carbon market).

- **Support learning and foundational science.** Many CDR methods are still in the early stages of development. Thus, MRV can provide a critical feedback loop to assess real-world outcomes and impacts (e.g. side effects).

10.2 The MRV policy landscape

CDR is gaining traction in policy spheres, but robust MRV systems and standards are still being designed, deliberated and negotiated.

Political momentum and signals increasingly point to the potential for CDR to be included in compliance markets (see Chapter 5 – Policymaking and governance). In the voluntary market, pledges are already being made by companies to buy CDR credits (see Chapter 4 – The voluntary carbon market). As such, it is crucial to ensure that rigorous and consistent MRV systems and standards are in place in the near future to reduce risks for investors and encourage businesses that are not currently investing in CDR to commit to purchasing removal credits.

Supranational and non-governmental developments

This section discusses approaches to codifying MRV best practice by various supranational organizations and NGOs to support the CDR industry to upscale.

IPCC methodology report on CDR technologies and carbon capture, utilization and storage

The IPCC, in early 2024, agreed on the scientific work programme for its seventh assessment cycle. For the first time, governments requested a methodology report specifically on CDR methods beyond land use, land-use change and forestry, alongside refined guidance on carbon capture and storage (CCS) and carbon capture and utilization.

The methodology report is expected to outline a framework for including novel CDR methods in national inventories and will likely guide best practice in the VCM once published, currently planned for 2027.

Article 6 of the Paris Agreement

Article 6 of the Paris Agreement provides high-level guidance for countries and businesses to pursue voluntary cooperation on climate change mitigation and adaptation. Two mechanisms under Article 6 are relevant to CDR: Article 6.2, which outlines a mechanism for trading carbon emission reduction and removal credits, and Article 6.4, which seeks to establish a centrally run crediting mechanism for project activities that reduce greenhouse gas emissions or remove CO_2 from the atmosphere.

The detailed rules for implementation of these articles were agreed at COP26. However, the implementation of these rules has not received total agreement and has been subject to refinement at subsequent COPs. At COP28, consensus was not reached on guidance for CDR methodologies (to be ultimately administered by a United Nations supervisory body) or on a definition of *carbon removal*. A framework to assess and mitigate the risk of reversals (the risk that stored CO_2 is released back into the atmosphere) was also not agreed on, nor was the duration of monitoring to ensure that storage of carbon is durable after credits have been issued.

Other gaps in MRV development also remain, such as legal and contractual considerations around transboundary CDR (e.g. where CO_2 is captured in one country, transported across a second and durably stored in a third). Currently, Article 6.2 allows countries to cooperate under loose arrangements that may be defined bilaterally and guided by methodologies from the VCM. This includes how countries set project baselines and determine additionality and what social and environmental minimum standards they apply. Whether these bespoke agreements will be robust and coherent is another question. These questions around Article 6 will continue to be revisited at meetings of the UNFCCC Subsidiary Body for Scientific and Technological Advice.

Voluntary carbon market

The Integrity Council for the Voluntary Carbon Market (ICVCM) and the Voluntary Carbon Markets Integrity Initiative (VCMI) are two established bodies that are developing guidance to advance quality considerations and best practice within the VCM. These non-governmental international frameworks aim to improve the quality of carbon credits and claims. In 2023, the ICVCM released the *Core Carbon Principles* (CCPs) after consultation with stakeholders, researchers and policymakers. The ten CCPs focus on credit supply dynamics and cover governance, accounting, additionality and robust quantification, among other things. The principles are not new; what is critical is the extent to which the CCPs are operationalized within existing standards to drive an upturn in credit quality.

The VCMI similarly released the Claims Code of Practice. The code of practice requires firms making claims based on VCM credit purchasing to set and publicly disclose a validated, science-based emission reduction target and an annual greenhouse gas emissions inventory.

In the absence of clear rule sets for Article 6.4 of the Paris Agreement, the ICVCM and VCMI guidelines may provide a foundation for national regulation of CDR. However, these standards are nascent and, in practice, the extent to which either framework provides a meaningful quality signal is unclear – this will depend on how widespread participation in these frameworks becomes.

EU Carbon Removal Certification Framework

In February 2024, the European Parliament and the Council of the European Union reached a provisional agreement to move forward with the creation of the EU Carbon Removal Certification Framework.[439] This voluntary regulatory framework aims to set out high-quality standards for certifying high-quality carbon removals, with an initial focus on DACCS and BECCS. MRV is a core element, and the framework sets out criteria for monitoring that go beyond climate impacts.

The framework differentiates between three types of carbon removal activity: permanent carbon removal, temporary carbon storage in long-lasting products, and temporary carbon storage from carbon farming (defined as practices "related to terrestrial or coastal management and resulting in capture and temporary storage of atmospheric and biogenic carbon into biogenic carbon pools or the reduction of soil emissions").[440] To be certified under the framework, CDR activities must meet criteria in four areas: quantification, additionality, long-term storage and sustainability. As a next step, certification methodologies will be developed that align with these criteria, and an EU-wide registry for carbon removals is expected to be established within the next four years.

Domestic developments

This section discusses the approach to State-led support for MRV and CDR in the UK and the US, which have developed differing approaches.

United Kingdom

In December 2023, the UK government outlined its approach to MRV for "engineered" removals,[6] based on a report commissioned by the Department for Energy Security and Net Zero.[431] Few existing MRV methodologies were deemed suitable for the UK government to endorse in their current form. The intention of the UK government is therefore to establish and define its own MRV methodology. An interim measure involves the government developing a set of quality thresholds that must be met by greenhouse gas removal (i.e. CDR) demonstrator projects funded by the government. Only projects that adhere to these thresholds and are verified by third parties will be credited.

United States

MRV development has not been a precondition to the wider development of CDR as it has been in the EU. Instead, the initial stages of the US CDR strategy focused on innovation and rapid scaling of market-ready methods through public funding under the Inflation Reduction Act and the Bipartisan Infrastructure Law (see Chapter 2 – Research and

6 *The methods under consideration were direct air carbon capture and storage, BECCS, biochar, enhanced rock weathering, ocean-based removals and carbon-negative building materials.*

development). However, purchasing rules (e.g. the Carbon Dioxide Removal Purchase Pilot of $35 million) did outline requirements for permanence, MRV and additionality. Several MRV-specific efforts are now under way to advance MRV in the US. For example, the SEA-CO_2 programme was developed by the US Department of Energy to advance cost-effective MRV for marine CDR. Similarly, a $15 million funding call was directed to the national laboratories by the Department of Energy to develop MRV best practices and technologies.

10.3 The MRV knowledge landscape

The state of knowledge on MRV is complex and in different stages of development for different CDR methods, making navigation and meaningful comparisons challenging.

To assess the state of knowledge on MRV for CDR, this report covers three elements:

- *The current MRV ecosystem*, including mapping of the number of existing MRV protocols by CDR method, by year and type of protocol, and by region
- *The state of science on MRV*, tracking the share of academic publications on MRV of CDR and reviewing MRV tools and techniques
- *Evaluations of the MRV system*, including an overview of widely used evaluation criteria and an analysis of interconnections between MRV protocols

The methods used for analysing each element are detailed in Box 10.2. The results are described in this section and summarized in a situational analysis of the overall state of MRV for individual CDR methods.

Box 10.2 Methods: Assessing the MRV knowledge landscape

Analysis of the current MRV ecosystem. Protocols are defined as documents that set quality requirements or guidelines for certification, carbon accounting, MRV or a component thereof. The overview of protocols from Arcusa and Sprenkle-Hyppolite, 2022, was taken as a starting point to collect protocols.[142] This list was updated, and additional protocols were collected through newsletters and the websites of known protocol developers. This was done separately by three researchers, and their results were consolidated. Protocols had to be published (i.e. in active use and not withdrawn) by December 2023. The start year is 2003 because this is when the earliest identified protocol was published. Protocols were not excluded based on language, but due to the search method, protocols in languages other than English are less likely to have been identified.

To qualify for inclusion, protocols had to provide guidance for CDR activities that lead to net CO_2 removals from the atmosphere, or to CO_2 removals *and* avoided emissions, or to CCS. Protocols on the latter were included because CCS facilitates CDR: methods such as direct air carbon capture and storage and BECCS are currently reliant on CCS infrastructure, which is regulated by central and local governments (e.g. Class VI wells regulated by the US

Environmental Protection Agency, and the EU CCS and Emissions Trading System directives).

Analysis of the state of science on MRV. To identify studies in the academic literature that were relevant to MRV of CDR, the platforms Web of Science and Scopus were systematically searched using a query that combined (1) a set of CDR method queries developed by Lück et al., 2024[441] with (2) a query containing key terms related to MRV. The search query was developed iteratively, and results of test queries were compared with a set of validation papers (i.e. papers of known relevance that would be expected in the search results). Literature was searched based on titles, abstracts and keywords and limited to English-language studies published before November 2023. The results were then screened for relevance using a machine learning-supported approach and based on predefined inclusion and exclusion criteria. Reporting on the systematic search results is limited to the share of relevant publications on conventional and novel CDR. While this information is not fully representative of the MRV sector, it provides a first step in understanding trends and identifying evidence gaps.

The systematic search and tracking of the literature was complemented with a traditional literature review on MRV tools and techniques. The aim of this review was to provide an overview of the current ability to measure and quantify CDR. Existing reviews identified in the search for academic literature on MRV and for reports (e.g. grey literature) on general CDR as well as individual CDR methods were synthesized. This search was complemented by expert elicitation with CDR method-specific experts.

Analysis of evaluations of the MRV system. The updated list of protocols used for the analysis of the current MRV system (described in this box) was taken as a starting point for this analysis. Thirteen other guidance documents that did not fit the definition of a protocol, but that were still relevant, were added to the 102 protocols identified in Table 10.2. The 115 standards, guidance documents and protocols for CDR were combed to identify whether they referred to another document for guidance in their development. For example, protocols might refer to their parent standard or to guidance documents like the IPCC Guidelines for National Greenhouse Gas Inventories (i.e. greenhouse gas guidance methodologies). If no other document was used, this was also noted. References to academic literature were excluded.

Current MRV ecosystem

This section presents descriptive statistics on the status of MRV protocols for different CDR methods. MRV protocol publication is described by year and country, by whether development was regulatory (developed for use in a regulated compliance scheme or developed by a jurisdictional agency) or voluntary (developed for use wholly in a voluntary market), and by whether the protocols are domestic or internationally focused. This analysis is important for tracking innovation in MRV development. A higher number of protocols is not necessarily indicative of a higher state of development or of more rigorous crediting outcomes. To the contrary, having many available protocols for a given CDR method might allow projects to choose protocols that are cheaper than more rigorous alternatives, leading to lower-quality outcomes.

A total of 102 MRV protocols were identified, which spanned 16 CDR methods. Table 10.2 depicts the number of MRV protocols per method, along with their type. There are ten protocols for geochemical CDR and ten for CCS. Sixty-six were developed in the VCM, and 36 are regulatory in nature. Fifty-nine protocols cover international CDR activity, and 43 are domestically focused (i.e. applicable to a specific subnational or national jurisdiction). Forty-seven protocols cover removal and avoidance activities.

Figure 10.1 shows the release year of protocols – focusing on initial releases to highlight the progression of protocol development – and the CDR methods to which the protocols pertain. Protocols may undergo multiple revisions over time to align with evolving scientific understanding, norms and technological advances, reflecting innovation in the sector.[7] Additionally, a higher number of protocols is indicative of more cumulative activity over time – which is one reason there are currently fewer protocols in existence for novel CDR methods than for conventional – but not necessarily a higher state of quality or rigour.

The years 2022 and 2023 saw substantial activity in the development of MRV protocols, accounting for 19% and 21%, respectively, of total development across the sample. Over the last 20 years, forestry – covering afforestation, reforestation, agroforestry and forest management – has seen the most protocol development, with 34 protocols. This is followed by soil carbon sequestration in croplands and grasslands with 21 protocols and BECCS with six protocols. Between 2003 and 2023, MRV protocols for forestry CDR methods were released in all but four years.

Direct air carbon capture and storage (DACCS) has seen MRV development in 2022, and this has focused on proprietary direct air capture technology[8] rather than CO_2 transport and storage (which is represented by the CCS column). Protocols for transport and capture were mostly established through public financing and regulation, first in 2005 and again between 2009 and 2012. This indicates that prior public investment in CCS science and the development of domestic regulations for industrial CCS have supported the current growth of the DACCS (and BECCS) industry, by allowing innovation to focus on direct air capture and use existing CCS infrastructure. It is for this reason that CCS has been included in this data set, as it directly facilitates CDR methods such as DACCS.

7 *As an example, Climate Action Reserve's US Forest Protocol has had four major revisions since its release in 2005, and the latest version was released in 2019. The European Biochar Certificate (developed by the Ithaka Institute) has had four major revisions. Unsurprisingly, older MRV protocols have been revised more than newer protocols, and this holds across regulatory and non-regulatory MRV.*

8 *Climeworks' and Carbfix's 2022 protocol for direct air capture and in situ mineralization (accredited by DNV) is an example of this type of recent innovation.*

	CDR method	Total	Voluntary	Regulatory	International	Domestic	Avoidance & removal	Removal only
Biological	Afforestation, reforestation, agroforestry, forest management	34	22	12	12	22	19	15
	Bioenergy with carbon capture and storage	6	1	5	4	2	1	2
	Biochar	5	4	1	4	1	0	4
	Bio-oil storage	1	1	0	1	0	0	1
	Biomass sinking	1	1	0	1	0	0	1
	Durable wood products	2	1	1	1	1	1	1
	Peatland and coastal wetland restoration	9	8	1	5	4	6	3
	Soil carbon sequestration in croplands and grasslands	21	15	6	15	6	11	9
	Biomass burial	1	1	0	1	0	0	1
	Ocean fertilization	0	0	0	0	0	0	0
Geochemical	Mineral products	2	2	0	2	0	1	1
Chemical	Enhanced rock weathering	4	4	0	4	0	0	4
	Direct air carbon capture and storage	1	1	0	1	0	0	1
	Direct ocean carbon capture and storage	1	1	0	1	0	0	1
	Ocean alkalinity enhancement	2	2	0	2	0	0	2
Carbon capture and storage	Fossil carbon capture and storage	10	2	8	3	7	7	1
Cross method protocol	Multiple methods	2	0	2	2	0	1	1
	Totals	102	66	36	59	43	47	48

Table 10.2 *Overview of monitoring, reporting and verification protocol development and attributes, 2003–2023. Protocols in the “voluntary” column were developed for use in the voluntary market; “regulatory” for use in a regulated compliance scheme or by a jurisdictional agency; “international” for projects in different geographies; and “domestic” for application in a specific subnational or national jurisdiction. It is also indicated whether protocols cover avoidance and removal activities or removal activities only. A higher number of protocols is indicative of more cumulative activity over time – which is one reason there are currently fewer protocols in existence for novel CDR methods than for conventional – but not necessarily a higher state of quality or rigour.*

Marine CDR methods such as ocean alkalinity enhancement had seen no development of MRV protocols by 2022, and there are still no recorded MRV protocols. The well-known challenges associated with MRV in open ocean systems (proving that CO_2 drawdown resulted from anthropogenic intervention rather than natural carbon cycling) can explain this lack of development, along with the nascence of marine CDR methods.

In the sample collected, MRV protocol development is almost wholly clustered in Europe and the US. These are also geographies where there is increasing research and funding supporting innovation and knowledge development around MRV (see the Domestic developments section in this chapter). The largest share of MRV development since 2003 is in the US, with 36 protocols released by standard developing organizations, registries and project developers. Afforestation/reforestation and soil carbon sequestration make up 58% of protocols in the US, and CCS makes up 16%. The UK has the second largest share, with nine protocols in total. However, the types of CDR method for which MRV protocols have been developed differs by country, with the UK developing (through regulation) two protocols for BECCS and the US no regulatory protocols.

In terms of geographic region, Europe (including the UK) accounts for 44% of total MRV protocol development, North America makes up 42%, Oceania 5%, Asia 4%, Latin America 3% and Africa 2%. While development of a protocol might occur in a certain jurisdiction (e.g. California), the protocol is often implemented in other geographies.

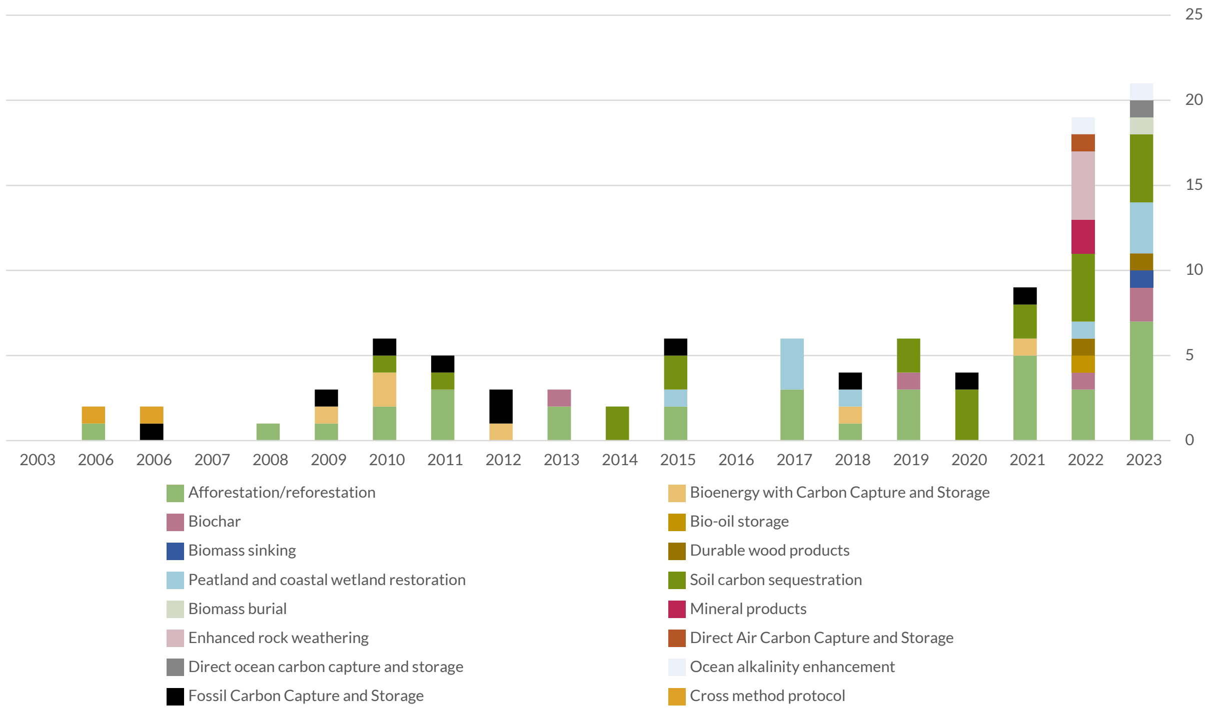

Figure 10.1 *Number of monitoring, reporting and verification protocols developed by year and CDR method, 2003–2023. Dates reflect the year of initial release.*

State of the science on MRV

Mapping and synthesizing the latest scientific development in the MRV sector is a fundamental stepping stone to designing robust crediting frameworks and policies on CDR. After searching and screening academic literature databases, nearly 2,000 studies were identified that are relevant to MRV of CDR. Over 80% of the results focus on conventional CDR, in particular aspects related to measurement and quantification. Comprehensive analysis on the content of the studies is unavailable, as the systematic review is still in progress.

In the interim, existing reports and CDR method-specific reviews give an indication of the status of measurement and quantification practices for CDR. For example, Mercer and Burke, 2023, present an overview of the foundational science underpinning MRV and the status of monitoring technologies for a range of CDR methods.[434] Ho et al., 2023, describe the status, limitations and future directions of MRV for ocean alkalinity enhancement.[442] Smith et al., 2020, review MRV for soil carbon sequestration, including the various models, data collection tools and accounting methods that are being tested or in use.[443] Similarly, Clarkson et al., 2023, describe measurement and quantification approaches for enhanced rock weathering in soil and consider solid-phase and gas-phase approaches and potential sources of uncertainty.[444]

Within the literature, there is also significant knowledge and MRV technology on the carbon storage aspects of DACCS and BECCS, as this is embedded in the industrial point source CCS sectors, but more research is needed on the direct air capture or biomass aspect of the carbon capture technological processes. This is also reflected by the trends observed in MRV protocol development (see the Current MRV ecosystem section in this chapter). Questions remain about these two methods, particularly about the cost and capture efficiency of DACCS[445–447] and, in relation to BECCS, about the values and assumptions that go into estimating the carbon stock within a unit of biomass, and how to account for biogenic emissions.[448–450]

For afforestation/reforestation, estimating CO_2 removals remains challenging owing to the difficulties and uncertainties associated with quantifying CO_2 emission fluxes from land use, land-use change and forestry activities.[432] Discrepancies remain between what is reported as anthropogenic CO_2 flux in countries' national greenhouse gas inventories and what global bookkeeping models find (see Chapter 7 – Current levels of CDR).[417] Quantification approaches are being explored by the research community to improve the reliability of estimating and distinguishing natural and anthropogenic CO_2 fluxes.[326,327,451] At the project level, MRV protocols for forestry CDR methods (e.g. afforestation/reforestation) have been the subject of significant scrutiny in recent years, in large part because of concerns around the quality of credits being generated. Sources of concern include disputed baseline setting and leakage quantification approaches, as well as challenges with maintaining the carbon stored.[452]

Select evidence on MRV tools and techniques for each CDR method is summarized in Table 10.3. The table does not assess the quality or suitability of any one approach, as appropriateness depends on the specific context. Additionally, there is debate surrounding the adequacy of using life cycle assessments and other modelling-based approaches for quantification, as they rely heavily on assumptions rather than measurements, and thus have a higher possibility of being disputed.[445]

CDR method	Measurement and quantification	Operationalisation in protocols
Afforestation, reforestation, agroforestry, forest management	Possible to directly measure CO_2 fluxes, but difficult to distinguish component due to human activity. Often calculated based on measurements of carbon stock changes (e.g. field samples, remote sensing). Emissions factors, flux measurements, or models can also be used.	National GHG inventory guidelines available Estimates differ between national inventories. and global models, due to differences in defining forest areas and distinguishing CDR from natural fluxes (see Chapter 7 – Deployment). Various regional, national and sub sectoral mandatory and voluntary methods, monitoring schemes, protocols and certifications exist, using different data sources and methods.
Bioenergy with Carbon Capture and Storage	Possible to directly measure CO_2 captured from biomass combustion and injected into storage. Emissions in feedstock production and provision can be large. CO_2 storage can be tracked through changes in pressure, temperature and composition of reservoir.	National GHG inventory guidelines available, split across sectors: i) land fluxes under AFOLU; ii) bioenergy considered carbon neutral in energy sector; iii) captured carbon under Geological Storage. In the VCM, CCS protocols can be used but do not distinguish between fossil and biogenic CO_2.
Biochar	CO_2 captured can be quantified by carbon content of biochar through sampling (proximate analysis); uncertainties in quantifying persistent fraction, new methods being developed. Emissions in feedstock production and provision can be large.	National GHG inventory guidelines include a "basis for future methodology." Voluntary, science-based MRV schemes for biochar already exist and are used, but the scope of protocols differ (e.g., on what biomass sourcing is allowed and where biochar is applied).
Peatland and coastal wetland restoration	Possible to directly measure CO_2 flux using eddy covariance or chamber systems; challenging to scale to net removals. Chamber measurement requires extrapolation into the restored area, usually using vegetation cover and water table as a proxy. Emissions of non- CO_2 gases (CH_4, N_2O) can be large.	National GHG inventory guidelines available for peatlands; other wetlands added in 2019 Supplement on Wetlands. Protocols outline a range of approaches: direct soil carbon measurements, use of emission factors, modelling.

CDR method	Measurement and quantification	Operationalisation in protocols
Soil carbon sequestration in croplands and grasslands	Possible to directly measure soil carbon fluxes; challenging to scale up to net removals e.g., due to high variability, costs. Component due to human activity is difficult to distinguish, baselines and additionality hard to establish. Measurements (field, eddy covariance/chamber, spectral) useful to parametrise models for changes over space, time.	National GHG inventory guidelines available. Protocols outline a range of approaches: direct soil carbon measurements, emission factors, modelling.
Ocean fertilisation	Not possible to directly measure captured CO_2; large uncertainties (e.g., efficiency of air-sea gas exchange). Monitoring will likely rely on tracking nutrients added to the ocean and estimating CO_2 stored by these activities.	No national GHG inventory guidelines. No protocols identified in the voluntary market.
Enhanced rock weathering	Possible to directly measure captured CO_2 via analysis of drainage waters; large uncertainties (e.g., background flux, rate of weathering, alkalinity production; amount of CO_2 lost to atmosphere).	No national GHG inventory guidelines. Protocol development in voluntary market; some require direct measurements of mineral weathering and carbon storage; others rely on modelling.
Direct Air Carbon Capture and Storage	Possible to directly measure CO_2 captured and injected into storage. Direct and indirect emissions from energy demand can be large; uncertainties remain. CO_2 storage can be tracked through changes in pressure, temperature, and composition of reservoir.	National GHG inventory guidelines available for Geological Storage; not for capture. Protocols in voluntary market can be specific to capture or include storage.
Ocean alkalinity enhancement (OAE)	Possible to directly measure captured CO_2 for equilibrated approaches, difficult for unequilibrated. Observations alone insufficient to quantify net removals; numerical simulations also required; large uncertainties and data gaps (e.g., air-sea gas exchange, ocean currents, carbonate chemistry).	No national GHG inventory guidelines. 2023 saw first releases of protocols in the voluntary market. Protocol developers outlining plans for continued research to reduce uncertainties.

Table 10.3. *Overview of MRV tools and techniques. A more detailed version is in the Technical Annex, Table B.*

Evaluations of the MRV system

To help make sense of heterogeneity among CDR standards and establish better practices, different types of evaluation are being developed (see Chapter 10 Technical Appendix, Table B for a list of these evaluations, with an indication of the criteria included and the CDR methods to which these apply). These evaluations include buyers' guides by NGOs (e.g. Carbon Credit Quality Initiative, Carbon180) and large buyers (e.g. Frontier, Shell, Microsoft); rating of carbon credits by private agencies (e.g. Calyx Global Ratings, BeZero Carbon Rating, Sylvera, Renoster); accreditation programmes by international stakeholder groups (e.g. the ICVCM's CCPs, the ICROA Accreditation Programme, the International Civil Aviation Organization's CORSIA); and academic or government research.[453–456] Evaluations, conducted at various levels (e.g. CDR standards, methodologies, projects, credits) vary depending on the evaluator. For evaluations of CDR standards, the criteria considered can cover governance (e.g. processes, transparency, independence, tracking, validation, verification), the management of impermanence (e.g. insurance, buffer pools, fixed-term crediting, discounting), the implementation of safeguards, and stakeholder engagement. Evaluations of methodologies involve assessing the methods used to quantify CO_2 removals and co-benefits as well as the adequacy of the additionality analyses, the review processes and the monitoring designs. Project- and credit-level evaluations examine technology validity, implementation, delivery risk and claims.

Each evaluator offers a different perspective on the adequacy of standards, methodologies, projects or credits and might be driven by different incentives (e.g. some have a financial stake in the evaluation). Commonalities and divergence in evaluations reflect evaluator perspectives, even within specific categories of evaluators. For example, agencies that rate credits may evaluate carbon accounting, additionality and permanence to similar depths, while diverging on how governance, co-benefits and stakeholder engagement are considered. Different perspectives can strengthen the MRV system by identifying different gaps. Commonalities can indicate consensus among actors. For criteria on which there is little general disagreement, this commonality may be a positive. For other criteria, commonality should be viewed cautiously, as there may be the possibility of confirmation bias; evaluations often emerge from the same body of literature and thought as the standards themselves. In the current situation, where the role of CDR in mitigation policy is nascent and outcomes remain uncertain, it is more critical than ever to question core assumptions.

Towards convergence

Evaluations that compare CDR standards appear to find significant differences. However, while appearing distinct, standards may actually be converging through the act of following other standards and using the same guidance documents. A standard might reference a more dominant one to bolster and legitimize its methodology. Green, 2013, showed that the Clean Development Mechanism, the ISO 14064 series, the Greenhouse Gas Protocol and the Verified Carbon Standard (Verra) were the most cross-referenced emission reduction standards.[457] Jia et al., 2023, showed that the Greenhouse Gas Protocol is the dominant corporate accounting standard.[458] For CDR standards, the analysis of evaluations of the MRV system undertaken for this report shows similar results (see Figure 10.2):

the most popular reference documents are the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, followed by the Clean Development Mechanism and then ISO 14064-2. These three are referred to (in the sense of "following the guidance of") by 67% of the reviewed standards and protocols. About a third of all standards and protocols, most of them for compliance regimes, do not refer to any other standard, for example BCarbon's Blue Carbon Living Shorelines protocol and the US Environmental Protection Agency's Class VI rules.

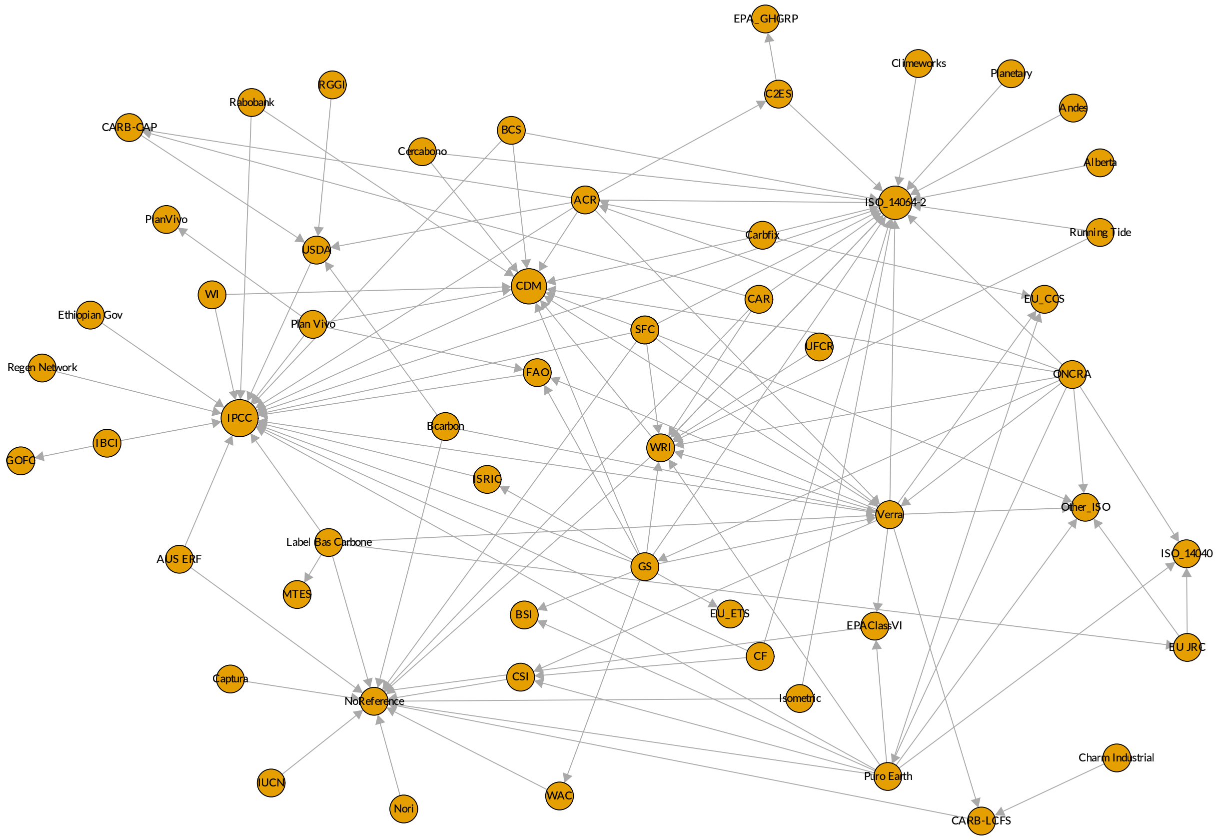

Figure 10.2 *A network forms when protocols recognize other standards or guidelines in their approach to carbon accounting. Recognition is observed as one protocol indicating in the description of their development that they followed the guidance of another document. To the 102 protocols identified in Table 10.2 were added 13 other guidance documents that did not fit the definition of a protocol. Indicated by the direction of the arrow, of the 115 standards, guidance, and protocols (lines) for CDR (incl. standards that combine avoidance and storage) analysed, 70% recognize another (including guidelines). The most popular are the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC), the Clean Development Mechanism (CDM), and International Standards Organization (ISO 14064-2). Some protocols and standards do not reference others, and are not shown in the figure. For example, the BCarbon standard has developed some protocols without guidance and others following the guidance of Verra and the US Department of Agriculture (USDA).*

This interconnection between standards has benefits and risks. On the one hand, it suggests that improvements to the dominant standards could ripple through most of the MRV system, if the derivative standards keep pace.[458] On the other hand, there is the possibility of a systemic risk derived from groupthink; for example, any inadequacies in a dominant standard could have ripple effects on the standards derived from that dominant standard. This could be a risky situation for an emerging industry to find itself in. On the upside, the industry is still nascent enough that it could distance itself more easily from any fallout than if practices were locked in.

Situational analysis: the comparative state of MRV for different CDR methods

Table 10.4 summarizes key MRV characteristics for CDR, based on the analyses in this report. Characteristics will evolve through research, innovation and policy development, so this table reflects the authors' interpretation of the current situation. The table is split into qualitative and quantitative groups, containing the metrics described below:

Qualitative metrics:

- *Ability to measure and quantify CDR*: Considers the availability of tools, equipment, technology and approaches for measuring or estimating carbon fluxes and other parameters necessary for monitoring CDR.
- *Confidence in quantification:* Takes Chay et al.'s, 2022, analysis of CDR quantification (using scientific understanding, measurement and modelling)[459] as a starting point but adapts it based on the judgment of CDR method-specific experts. In the absence of such an assessment for a particular CDR method, author judgment is applied. This metric provides insight into the uncertainty associated with quantification approaches.

Quantitative metrics:

- *Share of academic literature:* Based on results from the systematic search and screening of literature on MRV of CDR, with the caveat that quantity does not imply quality. It also does not include relevant information that may be present in grey literature.
- *Protocol coverage:* Based on the mapping of existing protocols per CDR method, with the caveat that quantity does not imply quality.
- *Protocol interconnectedness:* Network analysis of which CDR protocols refer to other CDR protocols (see Figure 10.2). Based on relative ranking and clustering of the data, higher interconnectedness indicates that more protocols for that CDR method refer to the same dominant protocol(s).
- *Regulatory oversight:* Determined by calculating the percentage of protocols that stem from regulations rather than voluntary initiatives.

	CDR method	Qualitative		Quantitative			
		Ability to measure and quantify CDR	Confidence in quantification	Share of academic literature	Protocol coverage	Protocol interconnectedness	Regulatory oversight
Biological	Afforestation, reforestation, agroforestry, forest management	Dark blue	Blue	Dark blue	Dark blue	Blue	Blue
	Bioenergy with carbon capture and storage	Dark blue	Dark blue	Light blue	Blue	Light blue	Dark blue
	Biochar	Dark blue	Dark blue	Light blue	Light blue	Dark blue	Light blue
	Peatland and coastal wetland restoration	Blue	Blue	Blue	Light blue	Light blue	Dark blue
	Soil carbon sequestration in croplands and grasslands	Blue	Blue	Blue	Blue	Blue	Blue
	Ocean fertilization	Light blue	Light blue	Light blue	White	White	Light blue
Geochemical	Enhanced rock weathering	Light blue	Light blue	Light blue	Light blue	Blue	Blue
	Direct air carbon capture and storage	Dark blue	Dark blue	Light blue	Light blue	Blue	Blue
	Ocean alkalinity enhancement	Light blue	Light blue	Light blue	Light blue	Light blue	Light blue

Table 10.4 *Authors' and experts' judgment, guided by chapter analyses, on the current state of key characteristics of monitoring, reporting and verification (MRV) of carbon dioxide removal (CDR) methods. Dark blue, blue and light blue are used, respectively, to denote higher, moderate and lower ability to measure and quantify CDR, confidence in quantification, share of academic literature on MRV of CDR, protocol coverage, protocol interconnectedness, and regulatory oversight. White indicates a value of zero.*

10.4 Outlook

Developing best practices for designing MRV policy will help build confidence in CDR as well as accelerate innovation and policy development.

The CDR landscape, and subsequent market, is developing rapidly. In the absence of global governance, stakeholders push and pull in different directions with varying degrees of influence. The result is an often disparate MRV system. Evaluations of different parts of the system can help determine knowledge gaps and future needs.

As Tables 10.3 and 10.4 highlight, there are different MRV challenges facing each CDR method. For novel CDR, more research is needed to develop and test MRV technology, including at large-scale demonstration sites. Another major gap is the current lack of IPCC greenhouse gas guidance methodologies for most novel CDR methods. Where technology is already advanced, such as with some conventional CDR, questions persist around designing flexible MRV approaches that can accommodate contextual differences and reconcile accounting differences across scales and approaches. For CDR methods in high demand, such as DACCS and biochar, developing robust MRV standards will be essential in the near term.

Across CDR methods, accuracy in accounting methods will need further investigation by researchers, particularly surrounding the availability of reliable data needed for models and life cycle assessments. As innovation in CDR continues and the sector moves towards deployment at scale, resolving these issues will be crucial.

A further critical knowledge gap across all methods is on specific MRV costs, and how these costs can be balanced with corporate needs and accuracy of quantification. Estimates are available for the anticipated total cost of different CDR methods, but the specific MRV costs within this are rarely publicly disclosed. Understanding these MRV costs is necessary to assess the uncertainty and risks associated with different CDR methods as well as the incremental cost of measurement and modelling to reduce uncertainty. Higher costs may impede financing; filling this knowledge gap could help better identify research priorities to bring down the cost of expensive MRV processes, thereby enabling a diverse range of CDR methods to be deployed.

The definition of fundamental concepts such as *permanence* remains highly contested. Even though options exist to manage different levels of permanence – such as buffer pools, ex post crediting, enhanced MRV and insurance – it may never be possible to definitively conclude that a ton of CO_2 sequestered by a biological sink, such as afforestation/reforestation, is equivalent to a ton of CO_2 captured by geochemical methods, such as ocean alkalinity enhancement or DACCS, or to a ton of fossil CO_2 not emitted in the first place. Expectations for MRV's role in addressing this challenge may thus need to be more realistic, and policy frames adapted accordingly.

Box 10.3 Limitations and knowledge gaps

This report has identified areas on which future assessments can build, including:

- *Mapping MRV protocols:* Although every care was taken to be comprehensive, the author-composed database will likely have omissions, as the landscape is evolving rapidly, and certain organizations do not make their standards publicly available. The mapping is undoubtedly biased towards removal providers that publish their MRV protocols in English. There will also be a bias towards high-income countries. The mapping should therefore be viewed as a non-exhaustive starting point that could be improved over time.
- *Assessing MRV protocols:* Due to the large landscape of MRV protocols, a systematic review of these protocols is needed to identify the different approaches in current practice, evaluate their quality and compare it to the latest science. Existing assessments of MRV protocols show a wide variety in approaches. However, a comprehensive assessment across CDR methods for all elements of MRV is still needed to better understand the quality of current CDR certification. A review of protocols that certify removals is under way, but a comparison with the current state of science is out of scope and will remain necessary.
- *Assessing the state of science of MRV:* A comprehensive overview of the current science underlying MRV systems and protocols for CDR is lacking. A systematic mapping and review of the content of the academic studies identified on MRV in CDR is under way. A challenge will be keeping the systematic review up to date, due to the fast-changing nature of the MRV landscape. As such, the review could be a useful starting point for developing a living systematic review protocol. Future reviews should also consider including grey literature, where many commentaries and assessments of MRV in practice are published.
- *Situational analysis:* The metrics used to assess the overall state of MRV for different CDR methods are limited in that they do not critically appraise the quality of MRV protocols, MRV tools and technology, or scientific research. However, the metrics still provide a useful overview of where activity and developments are happening in the MRV sector, which could be useful to track over time.
- *Extending this analysis:* This chapter did not analyse the costs of MRV due to a lack of data. There are ongoing efforts to fill this data gap. This information is essential to understanding trajectories for scaling CDR. Additionally, as compliance and voluntary markets and accompanying rules and methodologies are developed, analysis will be needed to ensure complementarity between MRV systems (e.g. via nested approaches).


THE STATE OF
Carbon
Dioxide
Removal