THE STATE OF

Carbon Dioxide Removal

A global, independent scientific assessment of Carbon Dioxide Removal

2nd EDITION | 2024

A collaboration led by Oliver Geden (German Institute for International and Security Affairs, SWP), Matthew J Gidden (International Institute for Applied Systems Analysis, IIASA) , William F Lamb (Mercator Research Institute on Global Commons and Climate Change, MCC), Jan C Minx (Mercator Research Institute on Global Commons and Climate Change, MCC), Gregory F Nemet (University of Wisconsin-Madison) and Stephen M Smith (University of Oxford)

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Foreword

As the impacts of climate change are taking place in real time across the world today, the scientific consensus is becoming increasingly clear that in addition to reducing emissions and meeting our global climate goals we will need to remove CO_2 from the accumulating pool in the atmosphere. This report provides important insights to the novice and CDR enthusiast-alike, who want to understand where CDR stands today and what challenges need to be addressed to scale the industry.

I have played multiple roles in the field of CDR, from researcher and teacher, author and speaker, to my four-year role as the Principle Deputy Assistant Secretary (PDAS) in DOE's Office of Fossil Energy and Carbon Management. In my most recent role as PDAS I assisted in shaping funding for scaling up durable removal across the broad CDR portfolio and recruiting those with expertise to do so. From piloting and demonstrating projects to moving from lab to commercial scale, in both my academic career and in government, I have worked on and seen the potential of large scale decarbonization plans that reduce the need for CDR. Nonetheless, the fact is all CDR approaches – biologic, mineral, chemical – as they scale up, will need to be coupled with accurate frameworks for measurement and monitoring, reporting, and verification (MMRV). These frameworks are essential to get right to ensure that the removals are "durable," e.g., are additional and take place on a timescale that impacts climate.

The authors of *The State of Carbon Dioxide Removal* Edition 2 report represent a diverse mix of perspectives with expertise spanning climate science, engineering, economics, and policy. The report also includes several authors with deep expertise in social science, which will be increasingly important as CDR projects move beyond R&D and toward demonstrations where they begin to grapple with the real-world challenges associated with effective community engagement and project siting. In addition, given that decarbonization efforts will be taking place in parallel to CDR, it becomes critically important to consider land, water, and low-carbon energy resources and prioritizing emissions reductions first and foremost, so that CDR scale-up does not limit the pace of overall decarbonization.

This report establishes the building blocks needed to responsibly estimate the scale of CDR achievable, in the timeframe needed, and that will exist along with other decarbonization efforts. It highlights the myriad components that will be critical as we continue building out and scaling up CDR over the next decade. CDR is no one's first choice for climate restoration - it is the contingency, the backup plan. We know we will need it, but it is still unclear what its true scale of application will ultimately become. The question of scale for requirements in 2050 is fundamentally unknowable. The true scale of CDR required will be dictated by how rapidly direct decarbonization alternatives scale, what the energy demand will be, what CDR cost reductions occur, and what barriers to future deployment will arise. Therefore, we should plan for a range of scenarios over the next decade and identify the pathways that will lead to the best options to scale CDR in the future. These pathways should include as many "no regrets" activities as possible: bringing technology to commercial demonstration, creating robust MMRV standards and technology, developing community and workforce benefit models, creating policies to incentivize demand at small but meaningful scale. This approach won't compete against mitigation approaches that are growing and gaining momentum and will give us a decade to sharpen our focus on how much CDR we will truly need to design all in efforts for effective deployment policies in the future.

How technology innovation must focus across the portfolio, where focus is needed to scale-up and what growth rates should be reasonably expected – these are all key questions that the report seeks to address. And among these crucial questions, the authors drive home the importance of communities, workers, and social impacts considerations for project development, as well as the policies that will be needed for scaling CDR while protecting against unintended consequences. At the end of the day, CDR at scale needs to include projects that take care of people, that include benefits from that flow to community members in the form of workforce development and growth, air pollution reduction, climate adaptation and mitigation, and resilience building.

If you are a newcomer to the field, this report will be a great introduction, and if you are already involved in the world of CDR, this report will ensure you are up to speed! I hope that you enjoy reading it as much as I did.

Jennifer Wilcox

Jennifer Wilcox

Presidential Distinguished Professor
of Chemical Engineering and
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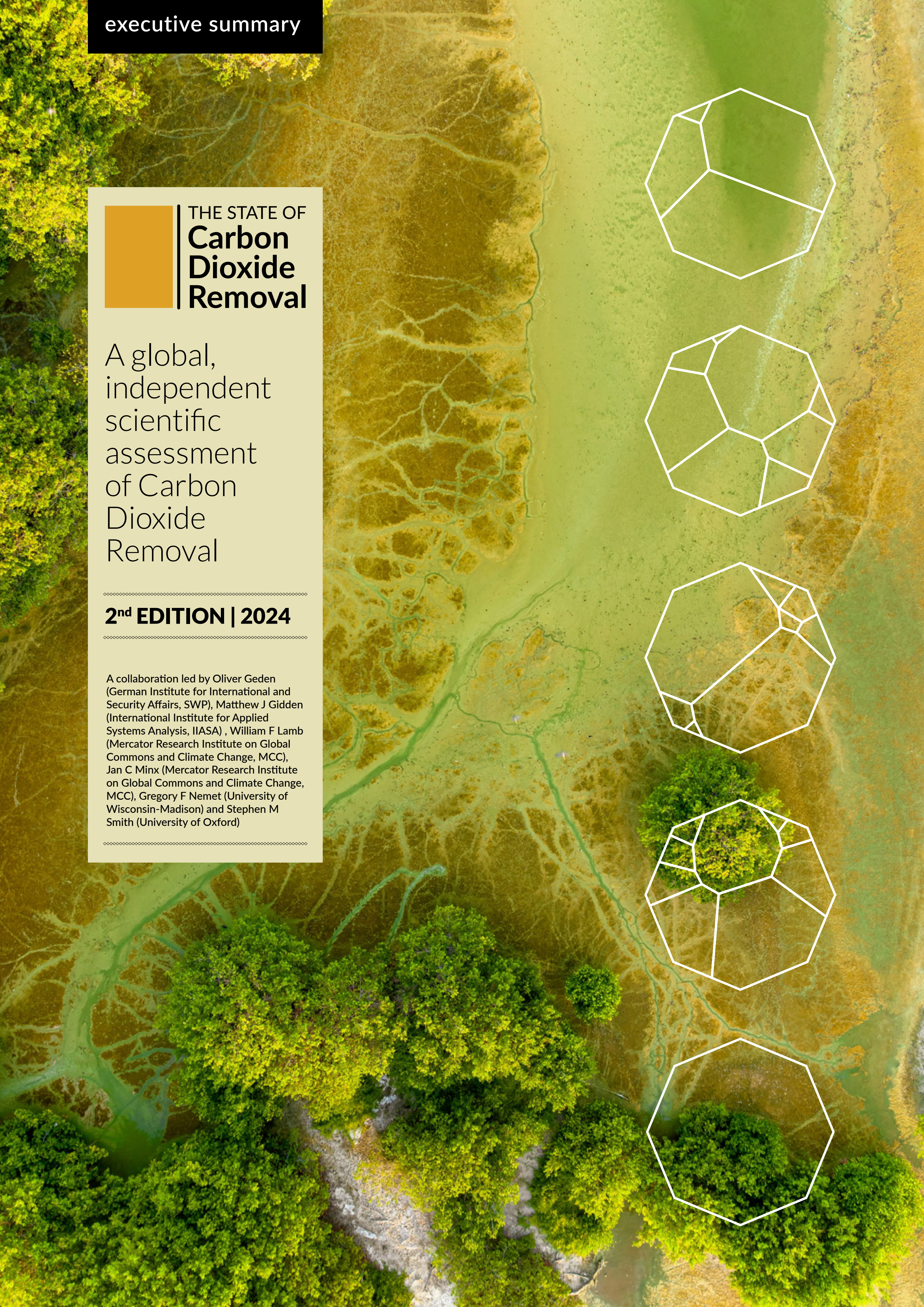
Pennsylvania



executive summary

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Executive summary

1. Meeting the Paris Agreement's long-term temperature goal requires rapid greenhouse gas emission reductions and near-term scale-up of carbon dioxide removal (CDR).

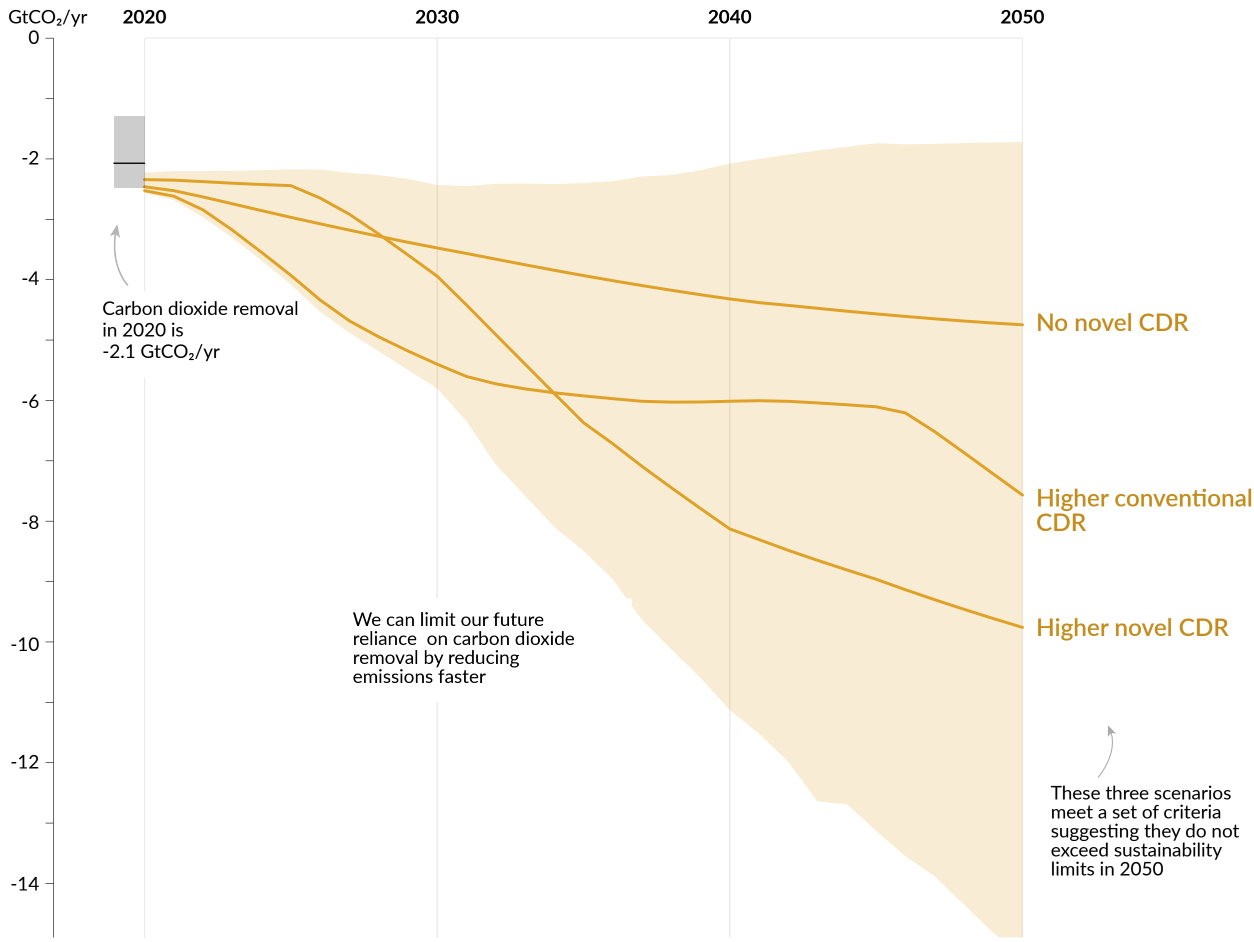
Greenhouse gas emissions continued to grow in 2023. This trend is incompatible with the Paris Agreement on climate change, regardless of how much CDR countries choose to deploy. The most important mitigation strategy in the near term is reducing emissions.

Alongside rapidly reducing emissions, *removing* carbon dioxide (CO_2) from the atmosphere is also necessary to meet climate goals. Precisely how much CDR will be needed, and where it will be deployed, depends on an array of factors, including the peak temperature reached as well as how quickly and by how much emissions are reduced.

Although the Paris Agreement states that climate change mitigation must be done "in the context of sustainable development", most scenarios do not explicitly consider social and environmental sustainability. We therefore identified a subset of scenarios that can be considered "more sustainable". Across this group of scenarios, the central range of CDR deployment is 7 to 9 $GtCO_2$ per year in 2050. The lowest scenarios reach 4 $GtCO_2$ per year in 2050. While this range is similar in 2050 to that for all below 2°C scenarios, the more sustainable scenarios cumulatively remove 170 $GtCO_2$ between 2020 and the time of net zero CO_2, compared with 260 $GtCO_2$ cumulatively in all below 2°C scenarios.

Carbon dioxide removal is a feature of all 1.5°C scenarios that meet the Paris temperature goal, in addition to reducing emissions

Carbon dioxide removal ($GtCO_2$/yr), in 2020 and in three Paris-consistent 1.5°C scenarios



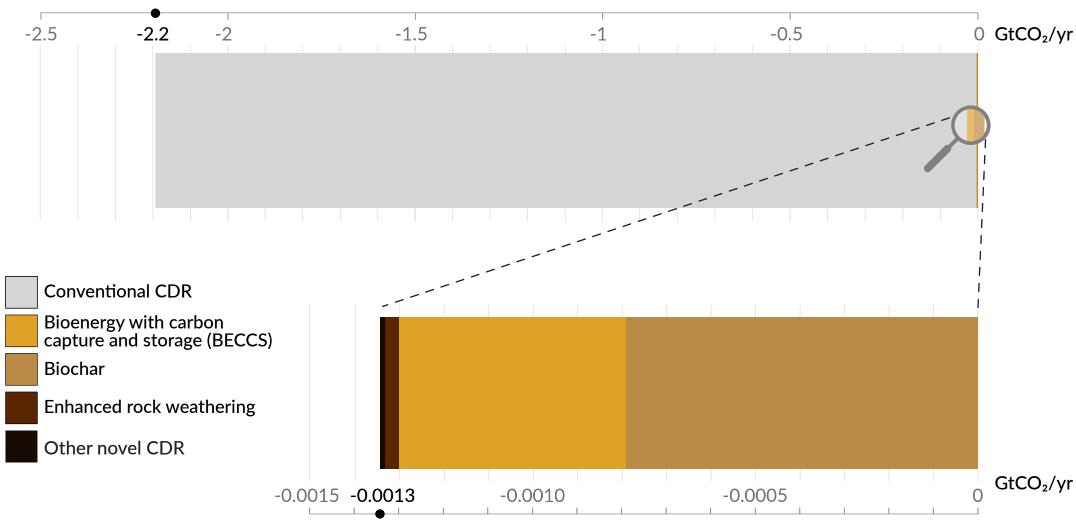
2. Some CDR deployment is occurring, albeit at a low level.

CDR is human activity that captures CO_2 from the atmosphere and stores it for decades to millennia. There are many CDR methods, which cover a variety of ways to capture and store CO_2. These methods have different levels of readiness, potential and durability. Each method has sustainability risks that could limit its long-term deployment. When deployed alongside measures to explicitly address sustainability risks, some methods can provide benefits beyond climate change mitigation.

Around 2 $GtCO_2$ per year of CDR is taking place already. Almost all of this comes from conventional CDR methods – those methods that are well established and widely reported by countries as part of land use, land-use change and forestry (LULUCF) activities – principally through afforestation/reforestation. These methods have delivered a relatively stable rate of CDR over the past two decades. Novel CDR methods – which are generally at an earlier stage of development than conventional CDR – contribute 1.3 million tons (0.0013 Gt) of CO_2 removal per year. That is less than 0.1% of total CDR, but novel methods are growing more rapidly than conventional methods, despite a downward revision in our estimates compared with *The State of Carbon Dioxide Removal* 1st edition. Of this 1.3 million tons, less than 0.6 million tons per year involves geological storage of CO_2, which represents some of the most durable forms of CDR.

Only a tiny fraction of all carbon dioxide removal results from novel methods

Total amount of carbon dioxide removal, split into conventional and novel methods ($GtCO_2$/yr)



Amount of carbon dioxide removal (CDR) is the sum of conventional CDR (2013-2022) and novel CDR (2023)

3. To scale up CDR, innovative activity needs to intensify, of which we see robust evidence.

Innovation here is broadly construed: a sequence of interconnected activities, characterized by technology push and demand-pull factors, all influenced by policymaking and public perceptions. Innovation is key to scaling up CDR, as well as to improving its sustainability, for example through increasing removal efficiency.

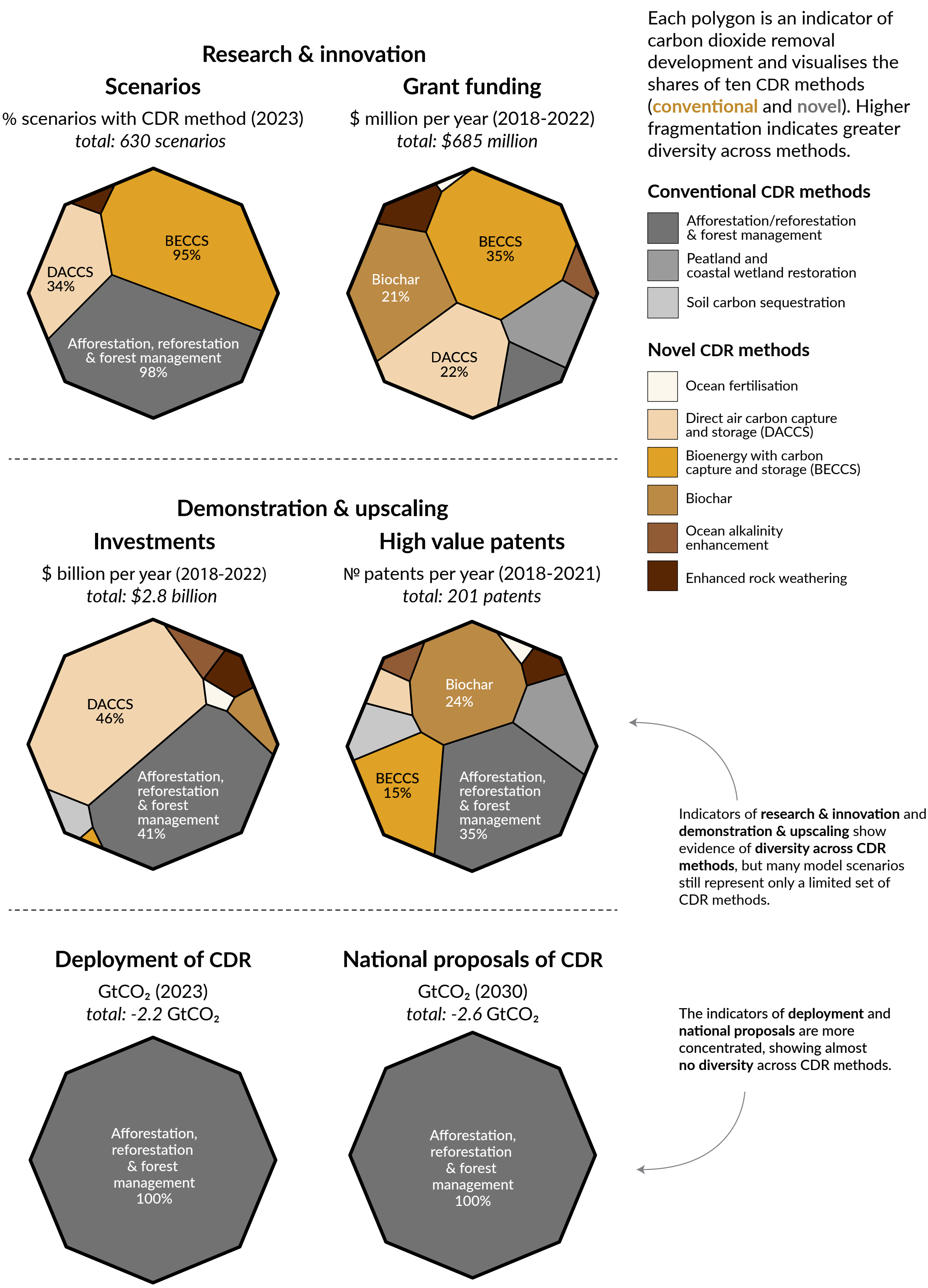
Indicators of innovation show that activity is generally intensifying, although with some recent slowdowns:

- Research: Steady growth is seen in grant funding for CDR research projects (14% per year) and publications (19% per year). Both cover an increasingly diverse portfolio of CDR methods.
- Inventions: After a period of rapid growth, patents in CDR have declined since 2010. However, patents have become more diverse and novel methods play a larger role.
- Demonstrations: Some major demonstration programmes have launched recently, in the US (the Regional Direct Air Capture Hubs programme) and at the international level through Mission Innovation.

- Startups: Investment in CDR startups has grown significantly over the past decade, outpacing the climate-tech sector as a whole – although it declined in 2023, and CDR accounts for just 1.1% of investment in climate-tech start-ups.
- Company announcements: Companies show ambition to reach, by mid-century or sooner, levels of CDR consistent with meeting the Paris temperature goal, albeit with little grounds for credibility at present.
- Market activity: The voluntary carbon market is a nascent but growing source of demand for novel CDR. Conventional CDR from afforestation saw a drop in issuances and retirements in 2023, while purchase agreements grew sevenfold for future delivery of CDR via novel methods.

Because CDR methods carry different risks and benefits, and because it is uncertain how much CDR will be needed, deploying a diverse portfolio of methods is a more robust strategy than focusing on just one or two methods. Indicators of research, invention and investment in startup companies show evidence of diversification across CDR methods. However, current deployment and national proposals for future implementation are more concentrated on a few conventional methods. In addition, many modelled mitigation scenarios still represent only a limited set of CDR methods.

Indicators of carbon dioxide removal (CDR) development show an emerging diversity of conventional and novel methods that is not yet seen in current deployment or national proposals



Deployment of carbon dioxide removal (CDR) is the sum of conventional CDR (2013-2022) and novel CDR (2023)

4. To increase CDR innovation and scale-up, policies are needed that create demand for carbon removals.

Several jurisdictions are developing policies for CDR. These are often embedded in broader policy landscapes, for example as part of agricultural and industrial policy.

We see active efforts in technology push policy for CDR as evidenced by support for:

- Research projects
- Demonstration projects
- Emerging international coordination

But demand-pull policies, which would create demand for CDR, remain weak:

- Countries' nationally determined contributions and long-term strategies submitted to the UNFCCC contain few mentions of policies that would create considerable demand for CDR.
- Monitoring, reporting and verification (MRV), which is important for facilitating transactions in CDR markets, is not fully developed at present.

While CDR is starting to get more attention from policymakers in G20 countries, the voluntary carbon market is playing a key role in scaling up CDR. This is especially true for novel methods, although these still represent only a small fraction of total market-based CDR.

International collaboration on CDR is gaining momentum, for instance through Mission Innovation's CDR Launchpad, initiated in 2022. Proactively coordinating activities, policies and expectations has been important in developing analogous technologies, such as renewables.

5. Public awareness of CDR has been rising.

To develop and deploy CDR ethically and effectively, in many jurisdictions it is crucial to understand public perceptions.

Coverage of CDR in English-language social media and news media has grown rapidly, although news media coverage peaked in 2021 and declined in 2022 and attention on Twitter/X rose only slightly from 2021 to 2022. Coverage focuses on particular methods in particular countries, for example soil carbon sequestration in Australia and direct air capture in the US.

Key factors that influence public attitudes on CDR are perceptions of "naturalness" and ecosystem impacts, along with people's underlying values and beliefs – including about climate change.

Engaging actively with a variety of publics is both an opportunity and a challenge for CDR adoption and policy. Best practices are emerging that can enable practitioners to communicate responsibly about CDR.

6. Monitoring, reporting and verification (MRV) protocols are varied, proliferating and essential for scaling up CDR.

Robust MRV provides CDR activities with credibility and transparency, which are crucial to effective voluntary carbon markets, government-created markets, regulations and national reporting. However, at present the MRV ecosystem consists of many overlapping protocols, making comparison and oversight difficult.

MRV policymaking differs among jurisdictions. For example, the EU and the UK have prioritized developing CDR standards and guidelines; the US, meanwhile, has focused on scaling up market-ready CDR and developing MRV tools for specific applications, such as marine CDR. The voluntary carbon market has played a leading role, with projects developing methods for monitoring, reporting and verifying CDR projects.

We identified 102 MRV protocols for CDR. Sixty-three percent of these are for conventional CDR, 65% are for voluntary markets, and 58% are for international activity. Forty percent were developed since 2022.

The forthcoming IPCC methodology report (on CDR methods beyond LULUCF, carbon capture and storage, and carbon capture and utilization) is expected to outline a framework for including novel CDR methods in national inventories. This framework will likely guide best practice in the voluntary carbon market and the development of national policies.

7. There continues to be a gap between the amount of CDR in scenarios that meet the Paris temperature goal and the amount of CDR in national proposals.

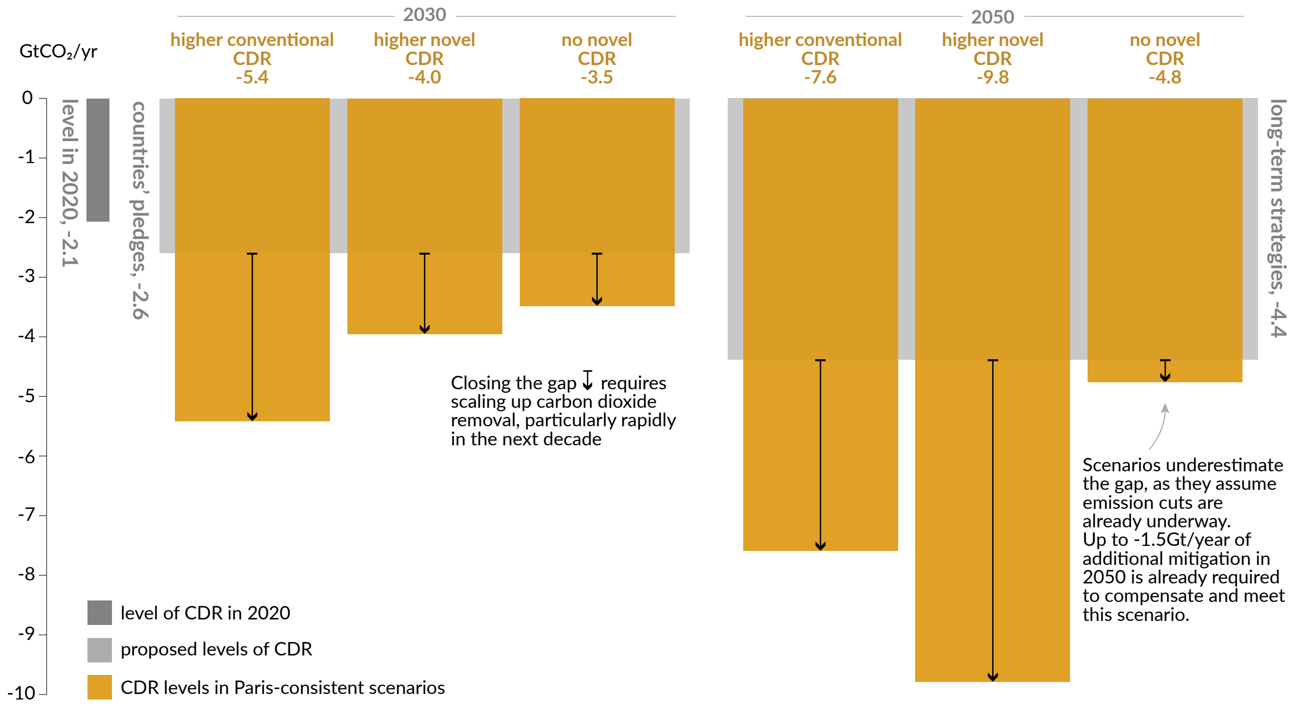
This report tracks the amount of CDR being proposed by governments, compared with the amount in scenarios that meet the Paris temperature goal. *Proposals* here includes the nationally determined contributions and long-term strategies that countries have submitted to the UNFCCC. The amount of CDR proposed falls short of what is required to meet the Paris temperature goal – this is the CDR gap. However, the CDR gap is small when the most ambitious national proposals are compared with levels in the *1.5°C with no novel CDR* scenario. The CDR gap for the three scenarios that more sustainably limit global temperature rise 0.9–2.8 $GtCO_2$ per year in 2030 and 0.4–5.4 $GtCO_2$ per year in 2050.

The actual gap is likely higher, because scenarios assume that significant emission reductions are already taking place, when in fact global emissions have continued to rise. Up to 1.5 $GtCO_2$ per year of additional mitigation through emission reductions and CDR is required by 2050 to compensate for these missed reductions in the case of the *1.5°C with no novel CDR* scenario. Meeting this additional mitigation requirement partly through CDR would imply a larger gap. There are limits, however, to CDR's capability to counteract inadequate efforts to reduce emissions.

The CDR gap can be closed by rapidly reducing emissions, scaling up a portfolio of both conventional and novel CDR methods, and explicitly integrating sustainability considerations into CDR policy. Continuing efforts to track the state of CDR – including gathering more precise and geographically disaggregated information on key indicators of CDR scale-up – can facilitate closing the CDR gap.

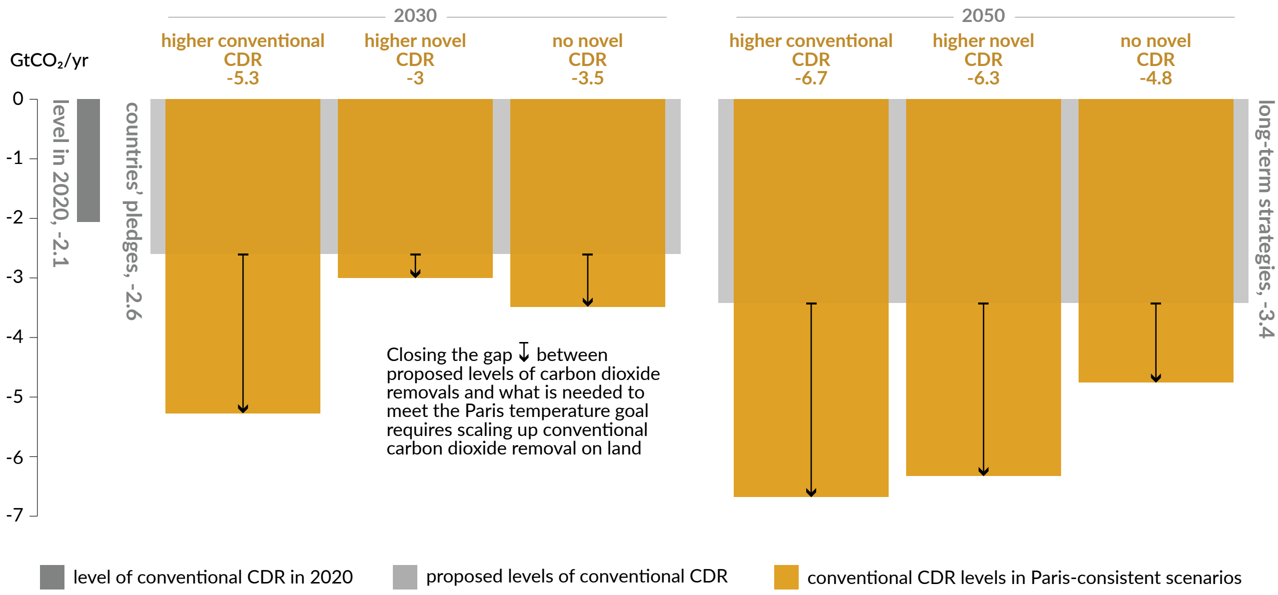
There is a ↧ gap between proposed levels of carbon dioxide removal and what is needed to meet the Paris temperature goal

Carbon dioxide removal (GtCO$_2$/yr), proposed levels compared to three Paris-consistent 1.5°C scenarios in 2030 and 2050

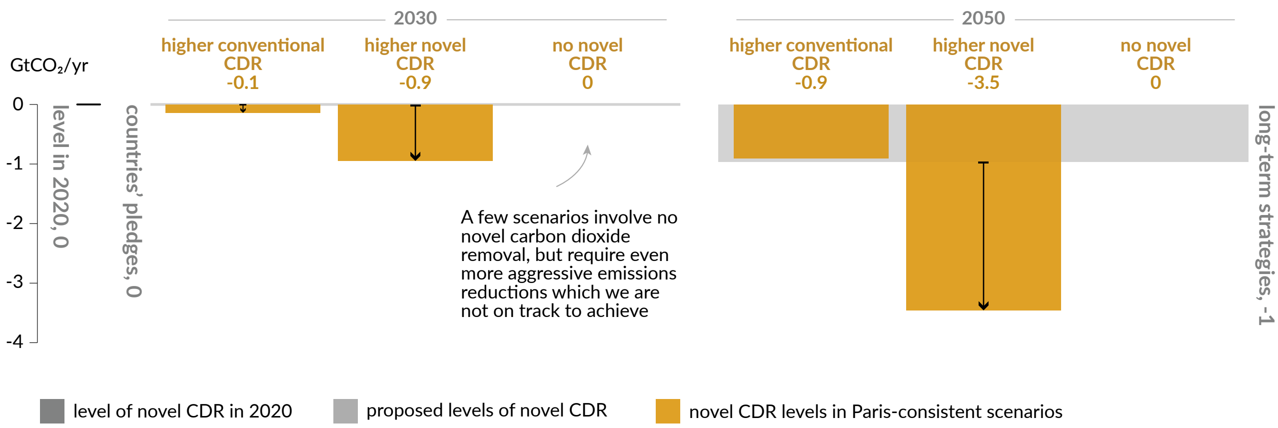


There is a ↧ gap between proposed levels of conventional and novel carbon dioxide removal and what is needed to meet the Paris temperature goal

Conventional carbon dioxide removal ($GtCO_2$/yr), proposed levels compared to three Paris-consistent 1.5°C scenarios in 2030 and 2050



Novel carbon dioxide removal ($GtCO_2$/yr), proposed levels compared to three Paris-consistent 1.5°C scenarios in 2030 and 2050



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Chapter 1 | Introduction

Carbon dioxide removal (CDR) will be necessary to limit climate change, alongside reducing emissions. This report builds on the previous edition to track CDR development, strengthen core concepts and build a community around access to reliable CDR data.

Climate change is mainly being driven by emissions of carbon dioxide (CO_2) to the atmosphere. These emissions come from human activities such as fossil fuel burning, land-use changes and industrial processes. Emissions of other greenhouse gases, such as methane and nitrous oxide, are exacerbating climate change further.

Meeting the Paris temperature goal – to limit global temperature rise to well below 2°C above pre-industrial levels and pursue efforts to limit the increase to 1.5°C – primarily requires rapid, deep and widespread reductions in emissions. CO_2 emissions have a very long-lasting effect on the climate, causing global temperature to rise and stay elevated for millennia. Halting the rise in global temperature will therefore involve bringing emissions of CO_2 down to net zero. Whereas emission reduction seeks to limit the amount of CO_2 newly released to the atmosphere, CDR involves taking previously emitted CO_2 out of the atmosphere.

This chapter sets out the purposes of this report and how CDR is defined within this assessment. It also outlines the characteristics of key CDR methods and highlights the updates and upgrades that have been made since *The State of Carbon Dioxide Removal* 1st edition, published in 2023.

1.1 Why CDR?

Alongside rapidly reducing greenhouse gas emissions, CO_2 will need to be *removed* from the atmosphere to meet climate goals.

In conjunction with deep, rapid and sustained reductions in greenhouse gas emissions, CDR can fulfil three major functions at national and global levels (see Figure 1.1):[1–3]

- In the near term, CDR can help reduce net emissions.
- In the medium term, CDR can counterbalance residual emissions to achieve net zero CO_2 or net zero greenhouse gas emissions.
- In the longer term, if removals exceed emissions, CDR can help achieve net-negative emissions. If global temperature rise exceeds acceptable levels, sustained

net-negative CO_2 emissions in conjunction with deep reductions of non-CO_2 emissions could reverse at least some of this temperature overshoot at the global level. At national levels, achieving net-negative CO_2 or even net-negative greenhouse gas emissions may be seen as a fair contribution towards the Paris temperature goal.

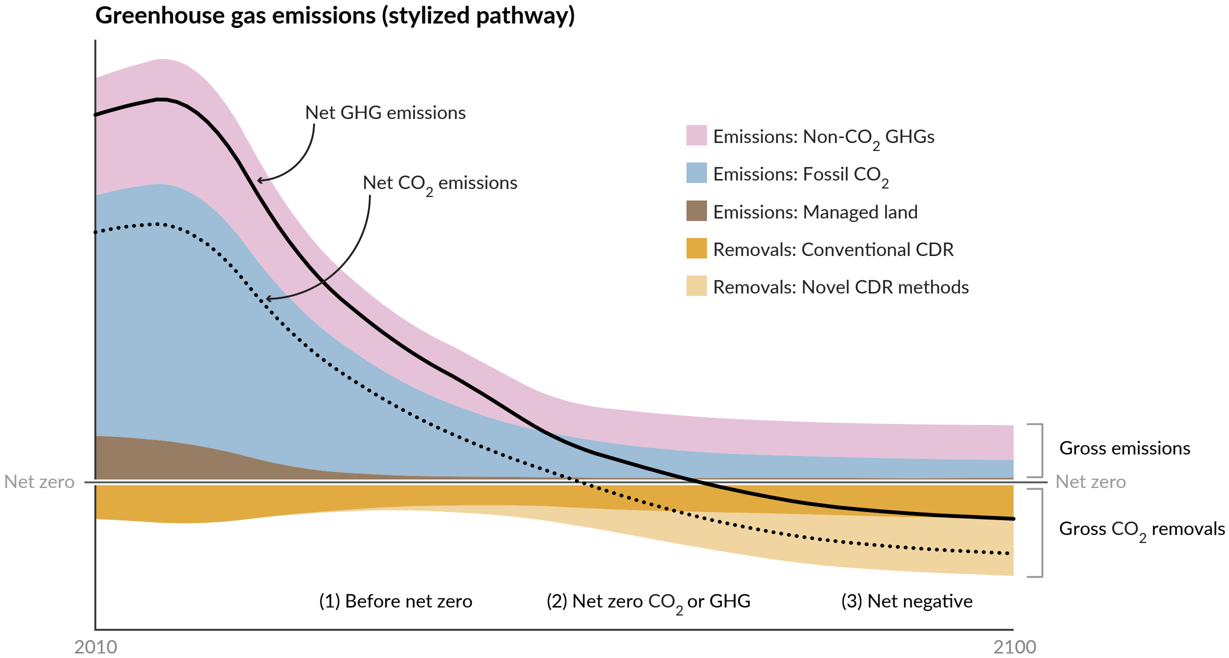

Figure 1.1 *Roles of carbon dioxide removal (CDR) in ambitious mitigation strategies, applicable at national and global levels. Basic emission and removal components of mitigation pathways, and the corresponding trajectories for both net carbon dioxide (CO_2) and greenhouse gas (GHG) emissions. (Adapted from Babiker et al., 2022.)*[4]

Methods for the removal of other greenhouse gases are being proposed in the scientific literature but are generally at a much earlier stage of development. Removing gases like methane or nitrous oxide is particularly challenging because, although powerful greenhouse gases, they are present at very low concentrations in the atmosphere.[5,6]

1.2 Purpose and scope of this report

Research, innovation, investment, policymaking and deployment related to CDR all continue to develop rapidly.

The topic of CDR continues to climb up the agendas of policymakers, investors, researchers and environmental campaigners. Consequently, information about CDR continues to increase, including academic assessments,[4,7–11] introductory books,[12] purchases of removal credits,[13,14] recommendations from business groups and consultancies,[15–18] and briefings from NGOs.[19–21]

The State of Carbon Dioxide Removal 1st edition was released in January 2023, providing a comprehensive global assessment of developments in CDR. The aim of the report was to inform and guide the further development of CDR by providing a clear, independent and authoritative assessment of available data. The response to the first edition has shown that there is indeed a need for such an assessment and for up-to-date tracking of global developments in CDR.

Since then, interest in the topic of CDR has accelerated further, including around aspects not covered in the first edition, such as voluntary markets and monitoring, reporting and verification. Many other features of the state of CDR are changing rapidly and have evolved since the first edition.

This second edition therefore continues the assessment of CDR development, based on publicly available data. Box 1.1 outlines how the report's approach has been strengthened since the first edition. In the next three chapters, the report assesses the state of CDR in terms of research and development (Chapter 2), demonstration and upscaling (Chapter 3) and the voluntary carbon market (Chapter 4). The report then examines different policy approaches and commitments by governments to develop CDR (Chapter 5) and reviews how public perceptions are evolving (Chapter 6). The subsequent four chapters look at the amount of CDR being deployed currently (Chapter 7); the amount of CDR required by pathways that meet the Paris temperature goal (Chapter 8); the *CDR gap* between current levels of CDR, government proposals and the pathways to the Paris temperature goal (Chapter 9); and emerging practices for monitoring, reporting and verification of CDR (Chapter 10).

The report aims to provide a clear, authoritative and up-to-date snapshot of the state of CDR, serving as an information resource for people making decisions about CDR and its role in meeting climate goals. Starting with this edition, the *State of Carbon Dioxide Removal* assessments will be accompanied by a freely available data portal for use by anyone with an interest in CDR (accessible via *https://portal.stateofcdr.org/*).

It remains the intention of the authors that this report be part of a continuing effort to track the development of CDR, expanding the breadth and depth of the assessment to be truly global in scope, while attentive to national differences, and building a community around making CDR data more complete, reliable and accessible.

Box 1.1 Points of departure from The State of Carbon Dioxide Removal 1st edition

To provide a coherent and comprehensive picture of the state of CDR, this edition adopts a model drawn from theories of innovation.[9] In this model, new technologies and practices evolve from a sequence of interlinked processes that feed back and build on one another (see Figure 1.2). These stages can be broadly split into factors affecting the supply of such technologies and practices (research and development, demonstration, and upscaling) and factors affecting demand (niche markets, demand pull, and public perceptions). Many of these factors are influenced by policymaking and governance.

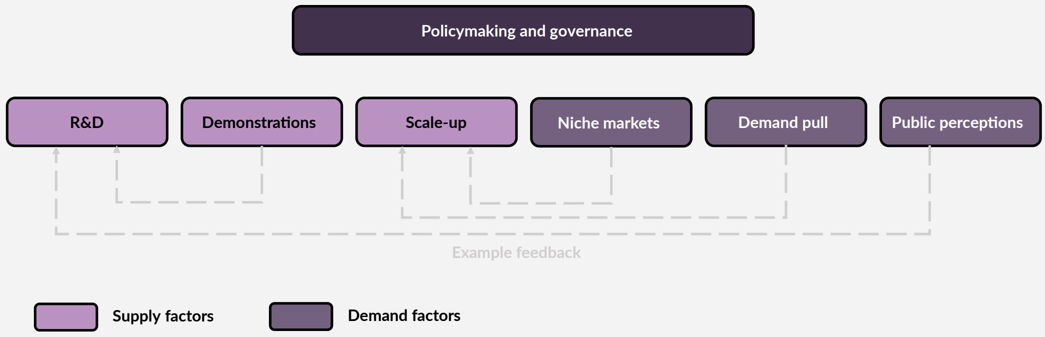

Figure 1.2 *The process of innovation on which the State of Carbon Dioxide Removal assessment is based. R&D = research and development.*

Revised chapter structure. The structure of the report has been updated to reflect this model of CDR development. The first edition contained separate chapters on research and innovation; these have now been merged. Two new chapters have been introduced: one on demonstration and upscaling and one on the voluntary carbon market (currently the predominant niche market for CDR). An extra chapter on monitoring, reporting and verification has also been introduced. Future editions may similarly include special chapters on other topics.

Core indicators. The State of CDR team has defined a comprehensive set of indicators covering important elements of the development stages for CDR and intends to continue tracking them in the coming years. These indicators cover, for example, levels of current CDR deployment, deployment targets announced by the private sector, CDR patents, public research and development funding, CDR volumes pledged or indicated in government proposals, and CDR in global mitigation scenarios. The underlying data are accessible via *https://portal.stateofcdr.org/*.

Key improvements. The first edition highlighted a number of opportunities to expand the breadth of the expert communities involved in the assessment and to improve the quality of the data and analysis. Key improvements in this second edition include:

- An expanded author team of over 50 people (compared to 26 for the first edition), covering a wider range of geographies and expertise
- Tracking of research grants as a metric for early-stage research and development investments in CDR
- Tracking of policy developments across a broader, more representative set of countries
- Analysis of public perceptions through news media as well as Twitter/X
- Improved approaches to estimating current levels of CDR, drawing on a wider range of sources and aligning with another major scientific initiative: the Global Carbon Budget
- Greater attention to sustainable development and the role of residual emissions in assessing requirements for the future scale of CDR

1.3 How this report defines CDR

CDR is human activity that captures CO_2 from the atmosphere and stores it for decades to millennia.

This report adopts the definition of CDR used by the IPCC:[22]

Human activities capturing CO_2 from the atmosphere and storing it durably in geological, land or ocean reservoirs or in products. This includes human enhancement of natural removal processes but excludes natural uptake not caused directly by human activities.

This report's definition of CDR thus follows three key principles:

- **Principle 1:** The CO_2 captured must come from the atmosphere, not from fossil sources (see Box 1.2).
- **Principle 2:** The subsequent storage must be durable, such that CO_2 is not soon reintroduced to the atmosphere (see Section 1.4).
- **Principle 3:** The removal must be a result of human intervention, additional to the Earth's natural processes.

It is important to distinguish CDR from other related terms and concepts, such as carbon capture and utilization (CCU) and carbon capture and storage (CCS). CCU and CCS share some components with some methods of CDR, but they do not necessarily result in durable net removal of CO_2 from the atmosphere (see Box 1.2). Examples of how different activities meet, or fail to meet, the principles of CDR are shown in Figure 1.3.

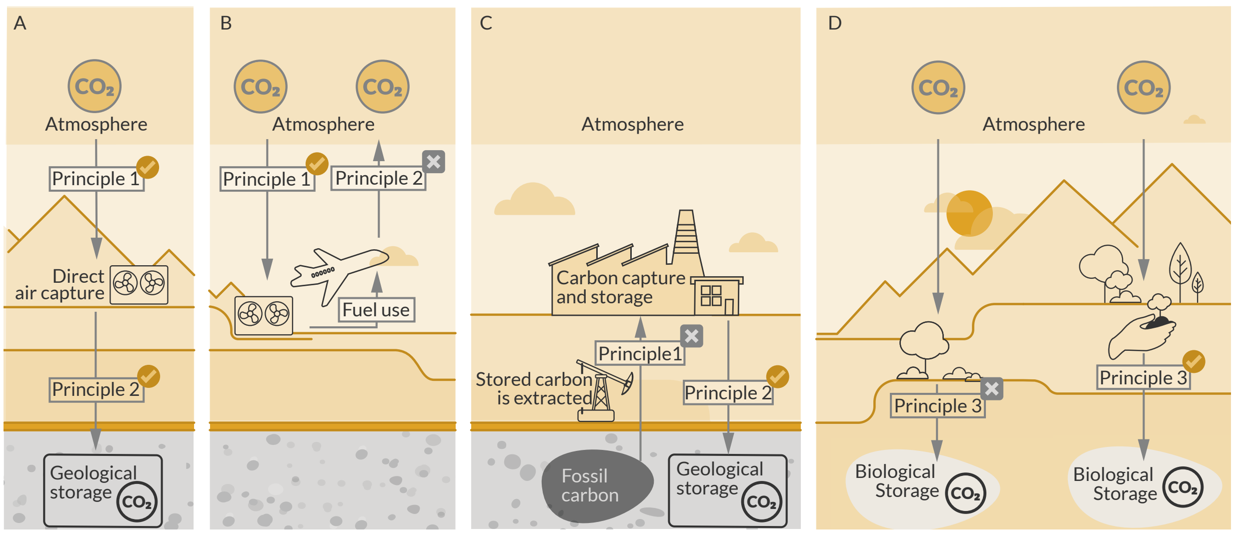

Figure 1.3 *To be defined as carbon dioxide removal (CDR), a method must capture carbon dioxide (CO_2) from the atmosphere (Principle 1) and durably store it (Principle 2) as a result of human intervention (Principle 3). An example is direct air capture with geological storage (panel A).. Several related approaches satisfy only one of these principles and hence are not CDR. For instance, direct air capture of CO_2 for use in short-lived products such as fuels does not meet Principle 2 (panel B). Capture and geological storage from sources of fossil CO_2 emissions does not meet Principle 1 (panel C). Natural processes such as tree growth can meet Principles 1 and 2, but they only meet Principle 3 and count as CDR if enhanced through human activity (panel D).*

Box 1.2 Differentiating between CCS, CCU and CDR

To count as CDR, the activity in question must capture CO_2 from the atmosphere (Principle 1) and durably store it (Principle 2). It must also be a human intervention, in addition to the Earth's natural processes (Principle 3).

Carbon capture and storage (CCS) is a set of industrial methods for the chemical capture of CO_2, the concentration of this CO_2 into a pure stream and its subsequent geological storage, meeting Principle 2. When the CO_2 comes directly from fossil fuels or minerals (e.g. limestone), this process does not meet Principle 1 and counts as an emission reduction rather than CDR. In climate policy and research, the term CCS is sometimes reserved only for such applications. CCS can, however, be applied to CO_2 streams from the combustion of biomass, from seawater, or from the air, in which case the overall process would meet both Principle 1 and Principle 2 and count as CDR. This report refers to the first form of CCS as *fossil CCS* to distinguish it from the forms of CCS that *can* count as CDR.

Carbon capture and utilization (CCU) is a set of industrial methods for the capture of CO_2 and its conversion into products. If this CO_2 comes from the atmosphere, rather than from fossil or mineral sources, then it meets Principle 1. Many of these products, however, such as carbonated drinks or fuels, store carbon only for a matter of days or months before it is released back into the atmosphere. But some products, such as concrete aggregates and timber for construction, do involve durable storage, thereby also meeting Principle 2.

1.4 CDR methods and their characteristics

There are many CDR methods, covering a variety of ways to capture and store CO_2. These methods differ in their level of readiness, sequestration potential and durability.

Each CDR method can be thought of as a particular route through the Earth's carbon cycle – capturing carbon from the atmosphere and transferring it to durable carbon pools. Each of these pools has a different characteristic timescale for how long it will store carbon. CDR methods also differ in their readiness for scaling and their biophysical or technical sequestration potential (see Figure 1.4).

Routes through the carbon cycle

CDR methods use a range of capture processes and storage pools. Between capture and ultimate storage, carbon may be converted and transferred through a number of these carbon pools. Some methods involve multiple steps, while others combine capture and storage in a single step.

CO_2 sinks

Processes that carry out the initial capture of CO_2 from the atmosphere are often referred to as *sinks*.

Biological capture. Through the process of photosynthesis, CO_2 is taken up from the atmosphere and converted into biomass. On land, this capture occurs in trees, vegetation and agricultural crops. It also occurs in aquatic habitats such as mangrove or kelp forests and seagrass meadows.

Geochemical capture. A range of non-biological chemical processes can also capture CO_2. Some of these processes already occur as part of the Earth's natural carbon cycle. For example, through weathering, certain minerals react with atmospheric CO_2 to produce either solid carbonate minerals or, in the ocean, dissolved bicarbonate. Other processes involve chemicals from human industrial activity. These can be alkaline wastes – for instance, from cement and steel production – or solvents and sorbents designed specifically to capture CO_2 and then re-release it as a concentrated stream for use or storage.

Carbon pools

Vegetation, soils and sediments. Carbon can be stored in a number of ways on land. Although much vegetation does not sequester the carbon captured in its biomass for long, trees can retain the carbon they capture for many years. Soils and sediments contain carbon in several forms, including organic carbon compounds from the residues and remains of vegetation and animals, and inorganic carbon from weathered rocks. Human interventions can enhance the amount and durability of carbon on land, for example when biomass is converted to biochar.

Marine sediments. Sediments on the floor of the deep ocean can sequester carbon away from the atmosphere on long timescales. Organic carbon is deposited onto these sediments as the remains of vegetation and animals sink to the seabed.

Geological formations. Concentrated CO_2 streams generated from chemical capture can be injected into formations such as depleted oil and gas fields, saline aquifers or reactive mineral deposits underground. Various processes then act to sequester the CO_2 in these formations, including physical trapping by impermeable rocks, dissolving of the CO_2 in water, and eventual mineralization.

Minerals. Solid carbonate minerals are generated directly by some processes of geochemical capture, such as weathering or reaction with alkaline wastes. Another form of mineralized carbon is bicarbonate, which resides dissolved in water (principally in the ocean).

Built environment. Several products used in the construction of the built environment are durable stores of carbon. Timber has been used widely as a construction material for centuries and contains the carbon captured from the atmosphere by tree biomass. Solid carbonate minerals generated through atmospheric CO_2 capture can be used in products such as aggregates, asphalt, cement and concrete.

Durability

In this report, CDR methods are defined as sufficiently durable if the carbon pool used has a characteristic storage timescale on the order of decades or more. However, this approach to what counts as CDR is not definitive. Among policymakers and scientists there is, as yet, no clearly agreed definition of durable carbon storage (see Box 1.3), and expert interpretations are expected to evolve as research continues.

Different carbon pools have very different characteristic timescales for carbon storage and different risks of reversal (i.e. re-releasing the carbon). Well-chosen geological and mineral formations offer the longest and least reversible storage. However, many other storage methods are widely regarded as valid for CDR, such as storage in trees and soils.

Box 1.3 Defining durable storage

The temperature-raising effect of fossil CO_2 emissions lasts for millennia. This is an important consideration in any effort to balance emissions and removals. Any storage for shorter than this very long timescale will only partially counterbalance fossil CO_2 emissions. Maintaining net zero CO_2 emissions – and hence halting global temperature rise – requires any residual emissions of fossil carbon to be balanced by capturing carbon from the atmosphere and storing it on the same millennial timescale.[23]

There is currently, however, neither a clear scientific basis nor a consensus among policymakers for a threshold of storage durability that should be included in the definition of CDR. Geological formations and minerals have the longest characteristic storage timescales. They are also the least susceptible to releasing CO_2 into the atmosphere as a result of human and natural disturbances. In terms of like-for-like durability, they therefore offer the closest equivalence to emissions of fossil CO_2. Storage for millennia may be the gold standard, but there are practical barriers to ensuring that projects endure for this long. Furthermore, shorter-term storage still has some value in meeting climate goals, although it is widely accepted that products which re-release carbon within a year (e.g. direct air capture to fuels, or biomass to food) are not CDR.

Existing policies by governments and voluntary standard setters have various minimum thresholds for storage, ranging from 25 years to 100 years. The IPCC Task Force on National Greenhouse Gas Inventories has been tasked to provide a methodology report on CDR, CCS and CCU during its current assessment cycle. This is expected to lead to guidance on how to account for CDR methods beyond land use, land-use change and forestry in national greenhouse gas inventories under the UNFCCC, taking differences in durability of storage into account. The *State of Carbon Dioxide Removal* assessment defines durability based on the characteristic storage timescale of the carbon pool used. A method is counted as CDR if the characteristic storage timescale is on the order of decades or more.

Figure 1.4 shows the characteristic storage timescales for different CDR methods. But the actual duration of storage depends not only on the general characteristics of the pool but also on human factors. For example, storage in soils could be reversed by a change in land use or extended through careful maintenance.

Categorizing CDR methods

The variety of processes for capturing and converting CO_2, and of options for its storage, means there are many potential methods of CDR. Figure 1.4 provides an overview of the key CDR methods considered in this report. While not exhaustive, this list is composed largely of methods that are already being deployed and/or those already analysed in the research literature. This report broadly follows the categorization and naming of methods used in the most recent IPCC assessment.[4] Whenever a specific CDR method is referred to in this report, the associated definitions and characteristics shown in this figure apply. More detailed descriptions of these CDR methods can be found in the Glossary.

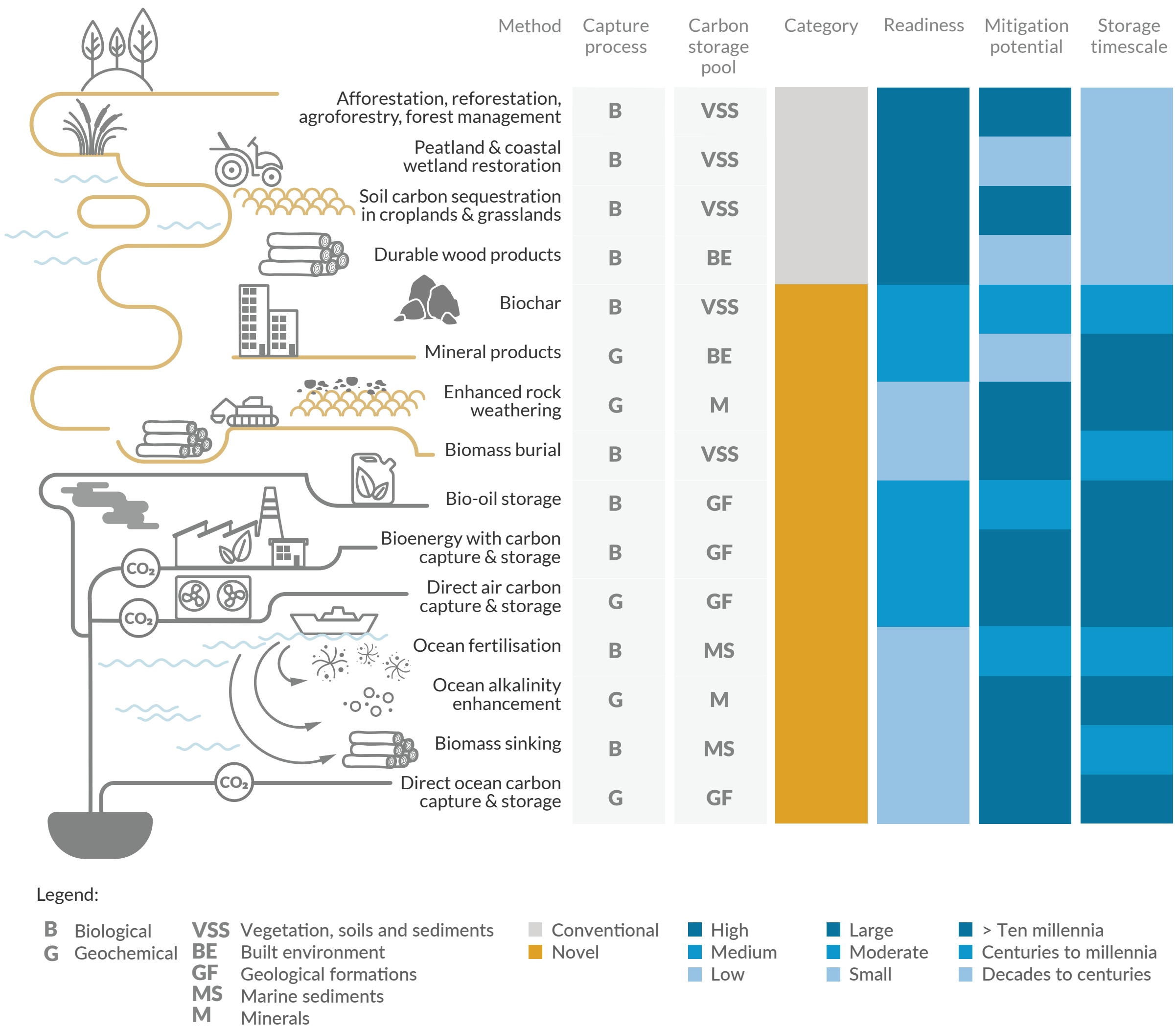

Figure 1.4 *Summary of Carbon Dioxide Removal methods, noting their respective capture process and carbon storage pool, categorization as 'Conventional' or 'Novel', their current readiness to scale (based on technology readiness levels), their maximum mitigation potential (Large: >9 $GtCO_2$/year; Moderate: 3-9 $GtCO_2$/year; Small: <3 $GtCO_2$/year), and characteristic storage timescale. (Based on Babiker et al., 2022, Bustamante et al., 2023, and Cobo et al., 2023.)*[4,24,460]

In the public debate, CDR methods are often grouped into categories for ease of reference. A common grouping is between "natural" or "nature-based" methods and "technological" or "engineered" methods. This categorization is contested, however, as well as blurred (a third "hybrid" category is frequently employed to cover methods that fall in between). There are a variety of ways in which CDR methods could be grouped, and there is as yet no universal agreement on classification. The rows in Figure 1.4 indicate different characteristics that are each useful to consider when categorizing CDR methods in different contexts, including in different parts of this report.

As in the first edition, this report refers to individual methods, where possible, or groups them by common measurable properties where necessary. The assessment continues to group CDR methods into two broad categories: conventional CDR and novel CDR. This categorization is based on a combination of the methods' characteristics: their current level of readiness for deployment, the scale at which they are currently deployed, and the type of carbon storage they employ.

Conventional CDR. This category encompasses CDR methods that are well established, already deployed at scale and widely reported by countries as part of land use, land-use change and forestry activities. The methods included in this group are afforestation/reforestation; agroforestry; forest management; soil carbon sequestration in croplands and grasslands; peatland and coastal wetland restoration; and durable wood products.

Novel CDR. This category encompasses all other CDR methods. The captured carbon is stored in geological formations, the ocean or products. These methods generally have a lower level of readiness for deployment and are therefore currently deployed at smaller scales (see Chapter 7 – Current levels of CDR). Examples of such methods include bioenergy with carbon capture and storage, direct air carbon capture and storage, enhanced rock weathering, biochar, mineral products, and ocean alkalinity enhancement.

2

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Chapter 2 | Research and development

Investments in research and development (R&D) have been increasing steadily. Although there are signs of diversification, R&D remains concentrated in a few countries and on a few carbon dioxide removal (CDR) methods. While the number of scientific publications is growing rapidly, inventive activity has been in decline.

Key insights

- The number of active third party-funded research grants on CDR has grown steadily from fewer than 50 in the year 2000 to more than 1,160 in 2022. Conventional forest-based CDR methods, soil carbon sequestration and biochar continue to dominate CDR research grants.
- The cumulative value of all research grants between 2000 and 2022 is estimated to be $2.6 (1.9–2.8) billion. Due to their larger project size, novel CDR methods such as direct air carbon capture and storage (DACCS) and bioenergy with carbon capture and storage (BECCS) receive sizeable shares of the financial support for R&D.
- Most third party-funded research grants on CDR are funded in Canada and the US. The number of research grants in non-EU European countries, such as Norway, Switzerland and the UK, are markedly higher than in the EU27, relative to the size of their populations.
- Scientific knowledge on CDR – measured as the number of research publications – has expanded more rapidly than both research funding and inventions.
- Biochar, soil carbon sequestration and afforestation/reforestation continue to dominate research publications on CDR. Over the last decade, publication output has expanded most rapidly for CDR methods such as DACCS, coastal wetland restoration, enhanced rock weathering and biochar.
- Inventions in CDR, measured as the number of international patent families, experienced rapid growth until 2011, but yearly inventions have since declined. This trend is mainly driven by lower growth in patents relating to BECCS. Yet inventions in novel CDR, particularly biochar, are playing an increasingly important role.
- Overall, R&D activities have grown steadily, with the exception of

high-value patents, and there are signs of diversification across CDR methods and geographies. However, this report continues to observe little R&D activity in ocean-based CDR or, geographically, in sub-Saharan Africa, Latin America and the Middle East.

The State of Carbon Dioxide Removal 1st edition highlighted that the pace of innovation in CDR is still modest compared with what is needed to meet the industry's own targets as well as the Paris temperature goal. Scaling up CDR in line with the Paris temperature goal will require a historic acceleration of innovation.[25,26]

Assessing innovation provides an understanding of how CDR methods are evolving, how fast they might be deployed and how costs are changing. Innovation is a process, and its sequence of stages requires multiple metrics to assess (see also Chapter 1 – Introduction).[9] However, innovation is not linear; feedback loops between these stages play an integral role.

R&D stands at the beginning of the innovation process and involves the discovery and assimilation of new scientific and technical knowledge.[9,27,28] It comprises a series of activities that span fundamental research through to applied technology development, closer to commercialization.

This chapter assesses the state of R&D in CDR using three indicators: research grants, scientific publications and patents. The indicators capture different activities and involve multiple actors, such as public funding institutions and researchers and inventors in the public and private sectors. Tracking research grants provides an input-related metric of early-stage investments in R&D that helps characterize the level of effort being made to advance CDR and drive down costs. Numbers of scientific publications and patents are output-related metrics that characterize actual R&D efforts and their efficacy in advancing the knowledge base on CDR (scientific publications) and in driving potential commercialization (patents).

2.1 Investments in R&D for CDR

The number of CDR research grants is growing steadily, investing in an increasingly diversified portfolio of CDR methods.

Awards of research grants is a new indicator in this edition of *The State of Carbon Dioxide Removal*. It comprises information on the number of funded research projects and the amount of research funding (see Box 2.1). As such, it is a metric for early-stage R&D investments in CDR and can shed light on patterns of support for different CDR methods and on how different regions invest in CDR.

There has been substantial research investment in CDR, with 3,840 research grants on CDR in this report's data set between 1991 and 2022 (this does not include research funded via institutional core budgets). These grants come from 131 funding organizations, mainly public funders such as research councils, foundations and ministries, but also philanthropic organizations. The data set shows about 1,600 receiving research organizations. Almost three-quarters of the research grants also report the value of the funding, which totals $1.9 billion. This gives an average of about $670,000 (10th to 90th percentile range: $25,000–$875,000) per project. This report therefore estimates the total third-party funding for CDR research to be about $2.6 (1.9–2.8) billion (see Box 2.1).

Grant making in CDR has grown steadily in terms of the number of projects funded as well as the total financial support provided. The number of research grants for CDR has grown from 35 active grants during 2000 to 1,160 during 2022 (see Figure 2.1a). About 74% of all research grants on CDR in the data set started within the last ten years (2013–2022). This indicates an average annual growth in active CDR research grants of 5% over the last ten years (2013–2022) and about 14% over the last 20 years (2003–2022). The annual amount of research funding spent has grown from about $5 million in 2000 to about $190 million in 2022. The average annual growth was faster for the total amount of funding than for the number of projects, at 14% over the last ten years (2013–2022) and 16% over the last 20 years (2003–2022). It is hard to determine from the data why this might be the case, but increased levels of reported funding and a decrease in project duration may contribute to the trend.

Almost 70% of all active CDR research grants between 2000 and 2022 focus on soil carbon sequestration (35%) or biochar (33%). However, research grants have been diversifying over time (see Figure 2.1b): The shares of active biochar and soil carbon sequestration projects dropped to 30% and 22%, respectively, in 2022, while shares increased for many other CDR methods, such as direct air carbon capture and storage (DACCS) (11%), peatland restoration (8%), coastal wetland restoration (7%), enhanced rock weathering (5%) and bioenergy with carbon capture and storage (BECCS) (5%).

The amount of funding in monetary terms is more evenly spread across CDR methods, as some methods are more capital-intensive than others (e.g. BECCS, DACCS).

While soil carbon sequestration and biochar receive a sizeable chunk of the allotted funding (22% and 17%, respectively), some other novel CDR methods such as BECCS (18%) and DACCS (21%) receive similar shares (despite accounting for fewer projects), driven by R&D investments in more recent years. Ocean alkalinity enhancement and enhanced rock weathering have received comparatively little early-stage R&D support. Overall, a slight trend towards diversification of CDR research funding is observable over the 20-year analysis period.

Research investments in CDR are markedly higher in Canada and the US than in the EU27. Between 2000 and 2022, 40% of all active research grants on CDR and 59% of the research funding took place in Canada or the US. There are about three times more CDR research grant years, and their total value is about twice as high, in Canada and the US than in the EU27.

In addition, some non-EU European countries, including Norway, Switzerland and the UK, jointly support almost as many research grant years on CDR as all 27 countries of the EU combined. These non-EU European country grants jointly account for about 11% of global funding support, compared with 19% for the EU27. These non-EU European countries have the highest per capita funding levels across all regions. Growth in CDR funding is also most dynamic in non-EU European countries in terms of both the number of grants and the volume of the funding. While the increase in the number of CDR grants funded in the EU27 between 2000 and 2022 was smaller than in Canada and the US, the amount of funding spent on CDR grew more dynamically. China funds many CDR projects, but the financial support reported is comparatively small. The average funding for a CDR project in China is $74,000, compared with $979,000 in Canada and the US, $1,406,000 in the EU27 and $582,000 in non-EU European countries. Factors driving these observed differences in the average size of the grants are difficult to determine and may be the result of the funding system, reporting issues or other factors.

Regions broadly follow the global trend of funding more research projects for biological CDR methods, but there are distinct patterns of specialization (see Figure 2.1c). Compared with the global average, there is a larger share of CDR research grants on soil carbon sequestration, DACCS and ocean fertilization in Canada and the US; in China, CDR research projects focus more on biochar and soil carbon sequestration. The EU27 invests in a larger share of CDR grants on BECCS and enhanced rock weathering as well as grants that deal with the broader or cross-cutting aspects of CDR (general CDR) than the global average. CDR research in Africa is more focused on biochar, afforestation/reforestation and coastal wetland restoration.

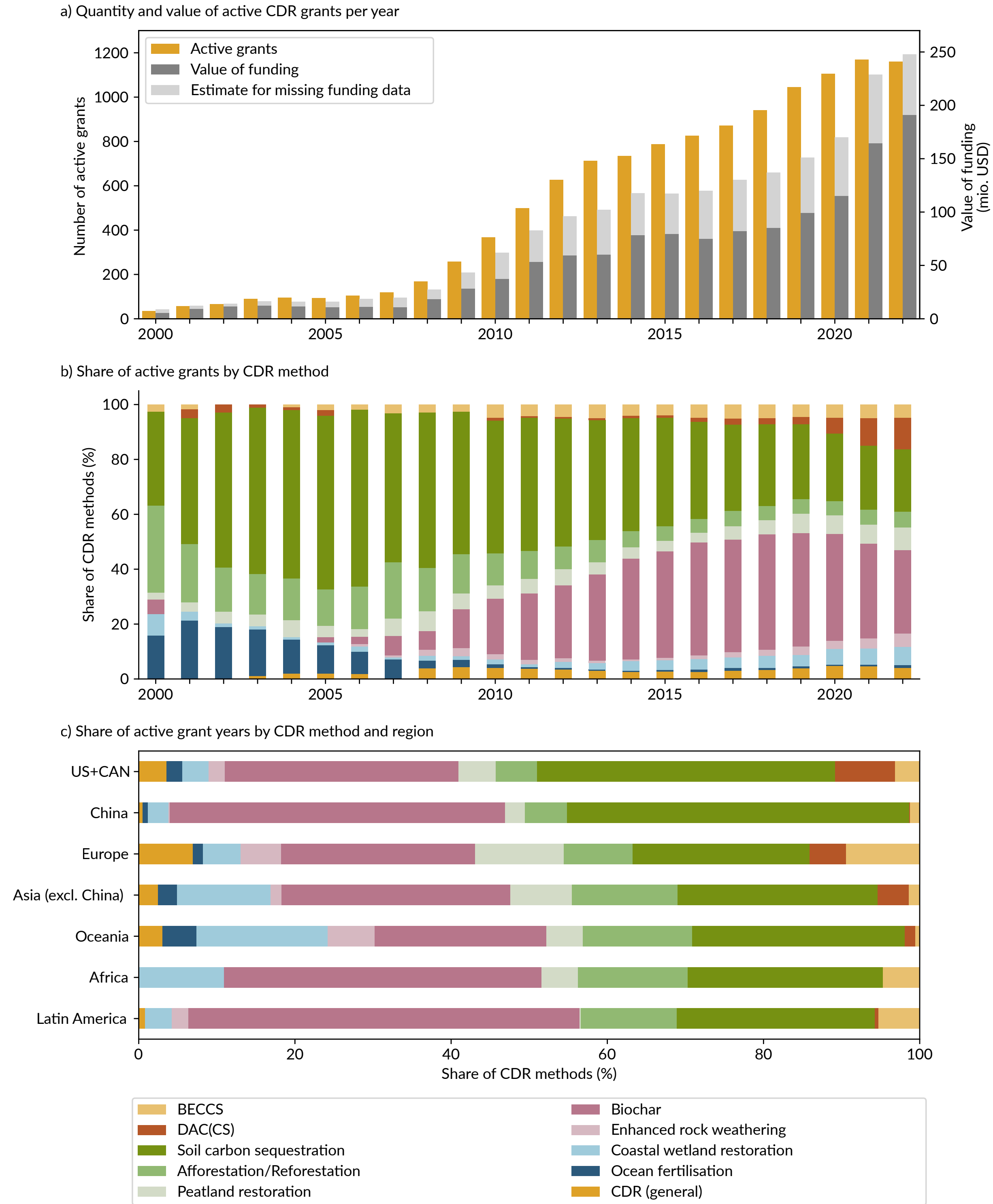


***Figure 2.1** Growth in the number and value of grants for carbon dioxide removal (CDR) research: (a) Total number of active research grants and their total value between 2000 and 2022; (b) CDR methods being researched in these grants over time as a share of the total number of all active grants; (c) CDR methods by region of funding organization as share of active grant years. BECCS = bioenergy with carbon capture and storage; DAC(CS) = direct air capture (with or without carbon storage).*

Box 2.1 Methods: Tracking early-stage R&D investments through third-party research grants

This report assesses early-stage, third-party R&D investments in CDR using data on research projects granted by funding bodies as listed in the Dimensions database.[29,30] Comprehensive keyword searches were conducted for each of the CDR methods considered to download an initial set of about 9,600 grants potentially relevant to CDR research. A machine-learning classifier (ClimateBERT based on DistilRoBERTa),[31] fine-tuned on a large set of annotated scientific abstracts, was then used to differentiate between CDR grants and grants related to CDR. A manually annotated test sample was used to evaluate this classifier, and good performance (F1-score = 0.8) was found. A multi-class model was used to annotate the CDR methods that each grant covers, which worked with moderate performance (F1-score = 0.67).

Other aspects analysed in the report – including the value of grants, the country of the funder and the receiving research organization, and the research fields – are provided directly in the Dimensions data. Data on the amount of funding were missing for 28% of the projects; these data were imputed using the average project funding and tested against CDR method-specific mean values. The 10th and the 90th percentile of the project value distribution were used to estimate a range that should reflect the uncertainties in the calculations.

While this report provides the most expansive effort to date to track early-stage third-party R&D investments in CDR, there are some important limitations (see Box 2.4).

2.2 Growth in scientific publications

Scientific publications on biochar and soil carbon sequestration continue to dominate CDR research. But publications on some other (novel) CDR methods – particularly DACCS, coastal wetland restoration and enhanced rock weathering – are increasing rapidly.

R&D comprises a series of activities to increase the stock of knowledge in a certain area and devise new applications from it. While the research grant indicators detailed in Section 2.1 focus on how early-stage R&D activities for CDR are supported across the world, this section examines indicators that try to measure R&D outputs.

The section first estimates research output on CDR as the total number of (English-language) scientific publications. While growth in scientific publications may not necessarily reflect an increase in the available knowledge, it is an indication of the interest in a field, the development of that interest over time and the opportunity for knowledge expansion. This edition of *The State of Carbon Dioxide Removal* sources the data from OpenAlex[32] – a publicly available bibliographic database – rather than the Web of Science and Scopus, as used in the first edition. The numbers here are therefore different to those in the first edition of the report (see Box 2.2). But despite the overall numbers being lower in this edition, they remain broadly comparable with the first edition in terms of the observed numbers and trends.

Overall, this report finds a large body of scientific literature on CDR of about 27,000 English-language publications between 2000 and 2022 – mostly peer-reviewed articles, working papers and books. The entire universe of scientific publications, including all peer-reviewed and non-peer-reviewed sources, could be as large as 50,000 publications.[25,33]

Publication output on CDR continues to grow rapidly. The total annual number of scientific publications on CDR increased by 19% from about 3,900 in 2021 to about 4,700 in 2022 (see Figure 2.2a). Preliminary evidence suggests that growth will continue to about 5,300 scientific publications in 2023.

Research output in 2022 was 1.4 times larger than in 2020, eight times larger than in 2010 and more than 50 times larger than in 2000, when 77 scientific studies on CDR were published. High growth rates in CDR research publications have been maintained over the last two decades. The 19% increase in publication output between 2021 (the reference point in *The State of Carbon Dioxide Removal* 1st edition) and 2022 is broadly in line with the average annual growth during the last ten years (18%; 2013–2022) and the last 20 years (21%; 2003–2022). This rate is higher than the average growth in research output on climate change as a whole[25] and the growth in active CDR research grants and associated funding over the last ten and 20 years (see Section 2.1).

Three groups of CDR methods continue to dominate the scientific literature on CDR: biochar, soil carbon sequestration and afforestation/reforestation. Their joint overall share in the scientific CDR literature has increased from about 73% during the 2000s to about 83% during the 2010s (see Figure 2.2b). This increase has been driven by the rapid growth in biochar research over the last 20 years. Hence, while publication output is growing across all CDR methods, a long-term trend towards concentration rather than diversification is evident in CDR research publications.

However, signs of diversification in more recent years indicate that this trend might be changing. The share of research publications on biochar, soil carbon sequestration and afforestation/reforestation has started to decline, from 83% in 2020 to 81% in 2022. Publication output has tended to grow faster for novel CDR methods, with some exceptions. Fast annual average growth over the last decade (2013–2022) can be observed for DACCS (26% per year) and biochar (21% per year), but also coastal wetland restoration (25% per year) – all growing faster than the CDR field as a whole (18% per year). Strong growth is also observed in research outputs for the CDR methods with some of the smallest annual publication levels. Since 2020, scientific publications on ocean fertilization have more than quadrupled, while research output on DACCS, enhanced rock weathering and ocean alkalinity enhancement has more than doubled, strengthening these less developed bodies of scientific knowledge. Looking at the diversification trend of research funding across CDR methods in Figure 2.1 (panel b), there is good reason to believe that research publications could follow a similar pattern in coming years.

Almost 50% of all CDR research publications between 2000 and 2020 are from Asia – particularly China (30% of all CDR research publications) – mainly driven by research on biochar and soil carbon sequestration. The share of CDR research publications from Europe (25%) is considerably higher than from Canada and the US (15%). The most dynamic growth patterns in CDR research publications over the last decade (2013–2022) can be observed for Africa (32% per year), China (26% per year) and the rest of Asia (30% per year), and Latin America (26% per year). Europe's growth in CDR research output (17% per year) tracks just below the average and remains higher than the rates observed for Canada and the US (10% per year). This report does not assess the quality of any of the publications.

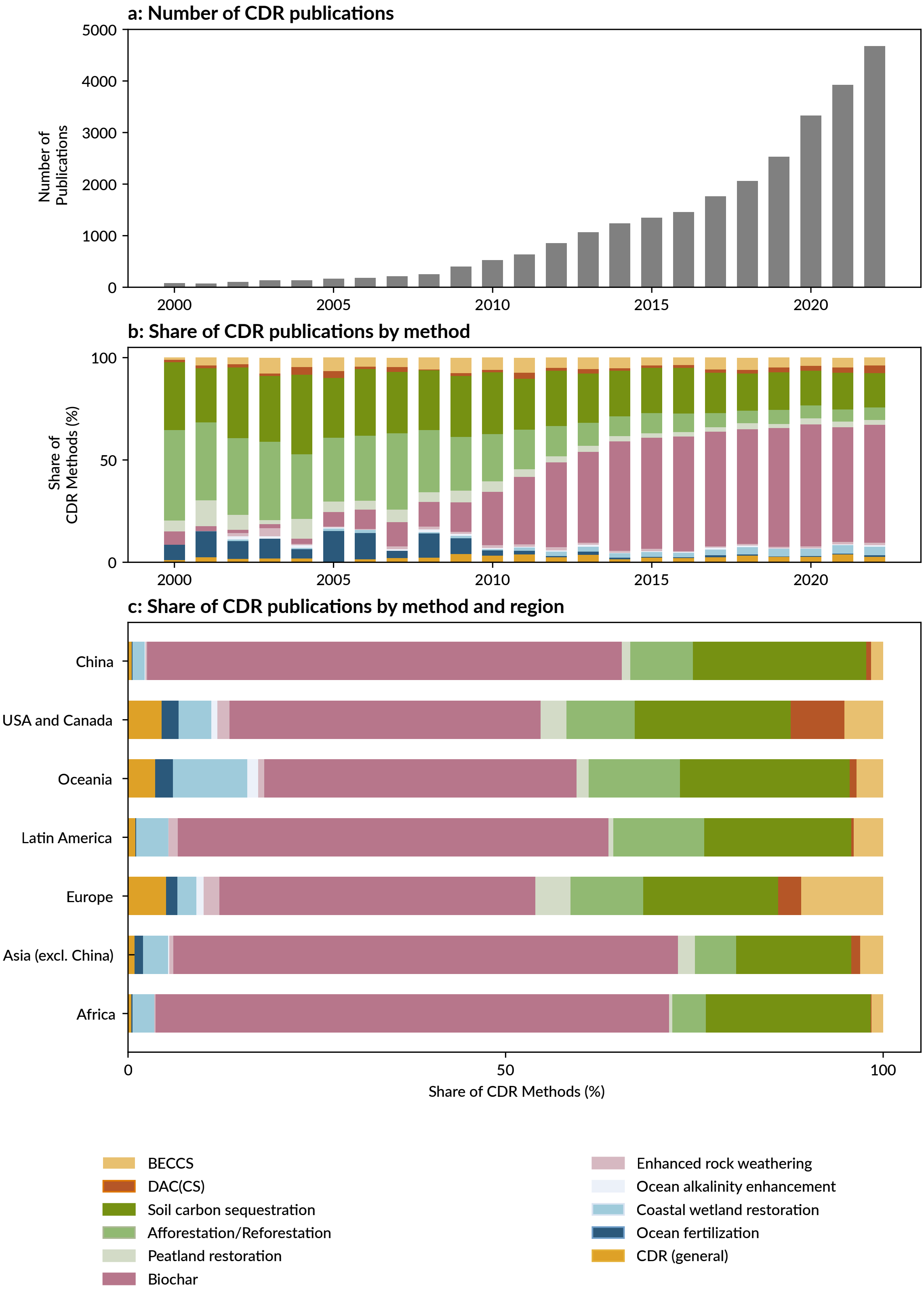


Figure 2.2 *Exponential growth in research output on carbon dioxide removal (CDR) over time: (a) Total number of scientific publications on CDR per year from 1990 to 2022 in the open-access bibliographic database OpenAlex; (b) Share of CDR methods mentioned in these scientific publications per year; (c) Share of CDR methods mentioned in scientific publications by region of first author. BECCS = bioenergy with carbon capture and storage; DAC(CS) = direct air capture (with or without carbon storage).*

Box 2.2 Methods: Tracking scientific research on CDR

This report uses an AI-based approach to identify research publications on CDR in the English-language scientific literature.[34–37] First, combinations of search terms (or search strings) were designed for each CDR method based on a comprehensive list of keywords. The search strings were then validated against a set of studies included in the IPCC Sixth Assessment Report, ensuring that these studies were returned by the literature search. Using these search strings, about 100,000 records were retrieved from OpenAlex – the largest open-access bibliographic database. The analysis in *The State of Carbon Dioxide Removal* 1st edition queried the Web of Science and Scopus. The results in the two editions are therefore not directly comparable.

For this edition, after the 100,000 records were retrieved, the title, abstract and keywords of 400–600 records per search string were manually screened and labelled with their suitability for inclusion (relevant/irrelevant) and the specific CDR method being studied. The labelled data were then used to train state-of-the-art machine-learning classifiers[31,38] to predict a total of 27,000 relevant CDR research publications as well as the CDR methods covered within them. This automated approach enables a comprehensive search for scientific literature in bibliographic databases while still ensuring a high level of precision in the identification of relevant studies. This edition identifies slightly fewer studies than *The State of Carbon Dioxide Removal* 1st edition because of using a single bibliographic database and restricting the sample to the CDR methods specifically searched for.

While the machine-learning methodology used in this report allows a more comprehensive assessment of the state of scientific research on CDR, the analysis presented here has important limitations (see Box 2.4).

2.3 Patents: Inventive activity

After a period of rapid growth, inventions in CDR have declined, but novel CDR is playing an increasingly important role in inventive activity.

Like scientific papers, patents measure the output of the invention effort but are even closer to eventual commercialization. Inventors file patents at the end of the invention process once they plan to use their invention. While this is no guarantee of eventual commercialization, it can signal the intent to progress to commercial use. A patent grants an inventor exclusive right to the new technology but forces the inventor to reveal its underlying technical process. Patent documents therefore contain detailed descriptions of the technology, which allows researchers to identify, technically categorize and measure inventive dynamics over time. Box 2.3 describes how this report uses machine learning to analyse patent data, how this methodological approach has changed since *The State of Carbon Dioxide Removal* 1st edition, and how this report addresses the limitations inherent in patent data.

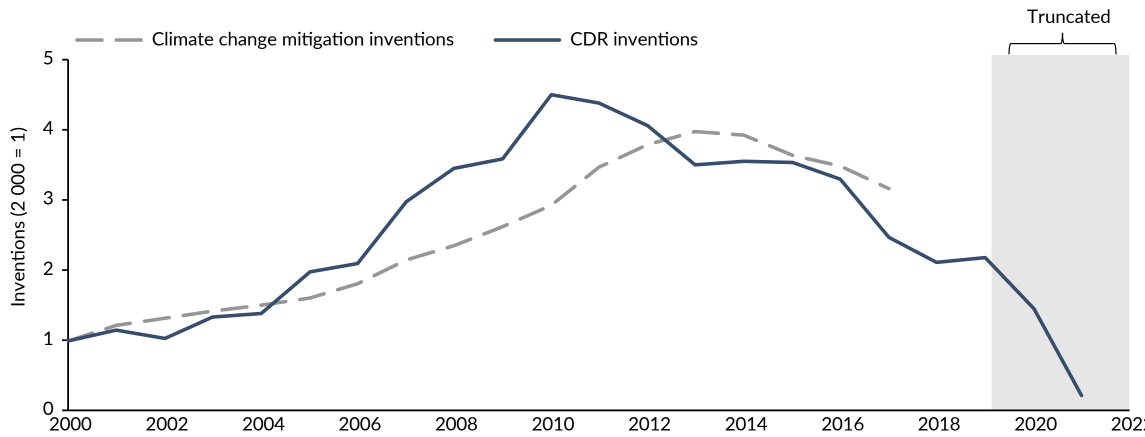
The filing of patents for CDR inventions experienced rapid growth between 2000 and 2010 but then started to slowly decrease (Figure 2.3a). The number of inventions grew fairly steadily between 2000 and 2010, with annual patent filings more than quadrupling during that period. Since 2011, there has been a moderate decline in the average number of inventions per year, but annual patent filings in 2019 were still twice the average filings in 2000. The invention trend is in line with the evolution of high-value inventions observed across all climate technologies until 2017,[39] but climate-tech inventions have rebounded recently. The decline is partly driven by a fall in patenting efforts in BECCS (fuelled by those in carbon capture and storage more broadly), potentially due to overblown expectations of its large-scale deployment in the 2000s. Macroeconomic factors, such as fossil fuel and carbon prices declining around the same time, could also have played a role, but the exact reasons are unclear.

Inventions in CDR have diversified over the last two decades, but conventional CDR (e.g. afforestation/reforestation) continues to make up a sizeable share of inventions (see Figure 2.3b). The growth in patents until 2010 was primarily driven by BECCS (with annual filings growing approximately ten times between 2000 and 2010) but also by a broader portfolio of technologies, such as biochar, enhanced rock weathering and DACCS. Despite all CDR methods having seen an absolute decline in inventions over the last decade, several novel CDR methods (apart from BECCS) have seen a relative increase in importance (in terms of share of patents). This increase is particularly striking for biochar (growing from 14% in 2010 to around 24% in 2019) and coastal wetland restoration (growing from 1% to 11% in the same period). Yet several other CDR methods have continued to play a minor role: ocean fertilization and ocean alkalinity enhancement jointly accounted for only 3% of CDR inventions during the last decade. Overall, CDR inventions constitute around 1% of all inventions of climate change mitigation technologies.[39] The patent application process and data gathering process leads to truncated data; therefore, the last three years should not be seen as representative.

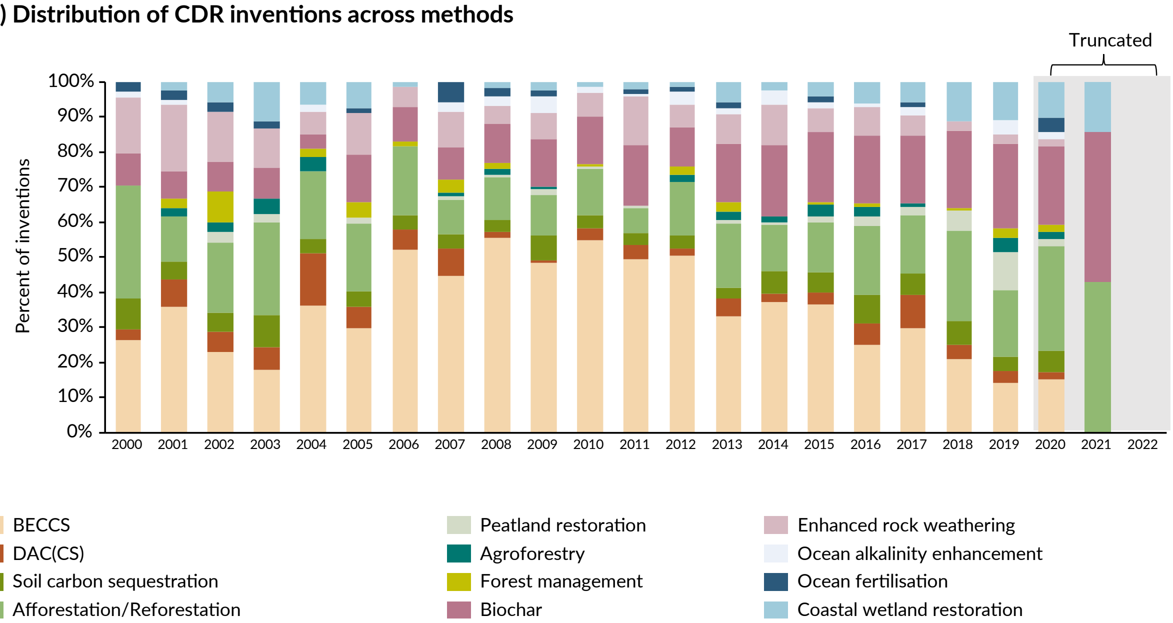
Regions show different patterns of specialization (see Figure 2.3c). Whereas Europe and Canada and the US focus heavily on inventions in BECCS (accounting for 41–48% of CDR patents in both regions), China and the rest of Asia show a greater emphasis on conventional CDR, such as soil carbon sequestration and afforestation/reforestation (together accounting for 33–39% of CDR patents in these regions). Biochar plays an important role across all regions, but it has the highest relative invention share in China (approximately 20% of all CDR inventions). DACCS is most important in Canada and the US, accounting for 7% of all CDR inventions. Coastal wetland restoration plays a more important role in China and the rest of Asia (accounting for 8–10% of CDR inventions). All other CDR methods (e.g. enhanced rock weathering, ocean fertilization) only account for approximately 10–15% of the global total of CDR inventions.

Geographically, CDR inventions are heavily concentrated in Canada and the US and in Europe. Both regions account jointly for 78% of CDR inventions, with Canada and the US featuring 44% and Europe 34% of inventions. Asia (excluding China) accounts for 12% of CDR inventions. China plays a minor role, with only 5% of all CDR inventions, but the country has recently seen increasing numbers of inventions across several CDR methods. The share of CDR patents in China is the same as its global share of climate change mitigation inventions more generally (approximately 5%).[39] Latin America, Africa and Oceania each account for less than 3% of inventions.

a) Annual patenting trends in CDR and all climate change mitigation inventions



b) Distribution of CDR inventions across methods



c) Distribution of CDR inventions across geographies (2000 - 2022)

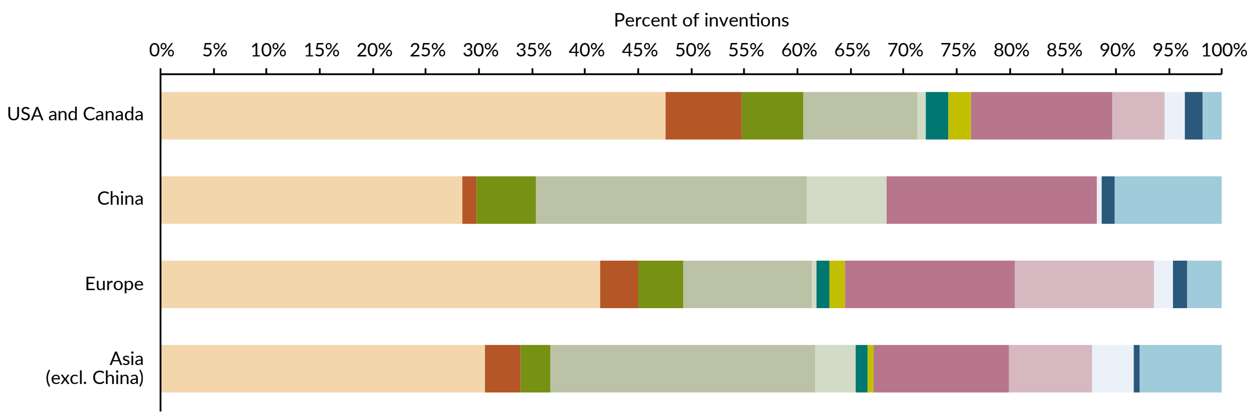


Figure 2.3 *Technological and geographic trends in carbon dioxide removal (CDR) inventions as represented by patents: (a) Annual high-value inventions in CDR and climate change mitigation inventions (from Probst et al., 2021)[39] from 2000 to 2022; (b) Share*

of high-value inventions across CDR methods; (c) Share of high-value inventions across inventor locations (i.e. where inventors currently work and live, which may be different from their country of birth). This report does not use the patenting office as a location as patents are territorial, and inventors may therefore gain patents directly in the most lucrative market (rather than their home country). The patent application process and data gathering process leads to truncated data; therefore, the last three years should not be seen as representative. Latin America, Africa and Oceania all account for 3% of inventions or less and are therefore omitted. Carbon capture and utilization and carbon capture and storage are not included, unless the underlying patent specifically refers to the use of CO_2 directly captured from ambient air or to biogenic CO_2. DAC(CS) = direct air capture (with or without carbon storage).

Box 2.3 Methods: Tracking invention in CDR

The analysis in this report applies machine learning to patent data to measure inventive activity in CDR. Patents are a common metric used in the economics and innovation literature to measure inventions.[40–42] Patent abstracts contain a detailed description of the underlying technology. Patenting activity is one measure of innovation, and one with accessible data, but innovation can also occur outside what firms choose to patent. Invention, experimentation and learning can be retained as tacit knowledge and trade secrets.

This report uses patent data from the Worldwide Patent Statistical Database PATSTAT, which the European Patent Office maintains. The database contains more than 100 million patents from 90 patent authorities and is widely used in academic and industrial research. The coverage of the data is particularly comprehensive for industrialized countries but may underrepresent certain regions of the world (e.g. Africa).

This analysis used machine learning, and specifically natural language processing, to identify and classify relevant CDR inventions. Two machine-learning classifiers were used to identify and classify CDR patents. The first, a *relevance classifier*, determines for each patent in the database whether that patent relates to a CDR method. The relevance classifier uses the supervised learning model ClimateBERT. To train the ClimateBERT model,[31] the research team manually annotated over 1,000 patents that covered all CDR methods, as well as patents not related to CDR. To ensure high-quality annotations, each patent was classified by at least two authors. Differences in individual annotations were resolved via discussion. After the relevance classifier identified potentially relevant patents, the more compute-intensive GPT-4 model[43] was used as a *technology classifier* to map each potential CDR patent to specific CDR methods. In contrast to *The State of Carbon Dioxide Removal* 1st edition, which relied on keywords and patent codes, this machine learning-based approach enabled the identification of substantially more relevant patents.

The analysis follows Probst et al., 2021,[39] in using international patent families to provide an international comparison of patenting activity. An invention is typically protected by multiple individual patents, referred to as a patent family. International patent families cover this invention in at least two jurisdictions. Monitoring international patent families – rather than simply counting individual patents – addresses two limitations inherent in patent data: the heterogeneity of patent value (i.e. some patents are very valuable, but many are not) and cross-country differences in the propensity of inventors to patent.

The analysis included all patents that could be used in the context of CDR, including technology components. However, carbon capture and storage patents were only included if they were explicitly used in the context of BECCS or DACCS. If the classifier put an invention into several categories (e.g. both afforestation/reforestation and soil carbon sequestration), the fractional counts were used to account for multi-classification (i.e. 0.5 was assigned to each technology class).

Box 2.4 Limitations and knowledge gaps

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

- The estimates of investment in CDR research projects (Section 2.1) do not reflect all research funding on CDR, as the Dimensions database only includes third-party projects and does not cover institutional funding from universities and other research institutes.
- The search strategy for research projects includes all major CDR methods but is not fully exhaustive. Most importantly, the search does not cover carbon capture and utilization with long-term storage in products, or forest management or methods that have more recently gained attention, such as direct ocean carbon capture and storage.
- The geographic coverage of the Dimensions database for tracking research grants is not fully transparent, and uncertainties remain over the scope of investments covered in some regions, such as Latin America, Africa and Asia. The same applies for the patent data from PATSTAT.
- The classification of research grants by CDR method is not performed with very high accuracy, particularly for less frequently studied CDR methods as there are fewer annotations with which to train the machine-learning classifier.
- The machine-learning methodology for searching scientific research on CDR (Section 2.2) only returns articles with English-language abstracts.
- Although OpenAlex is one of the largest bibliographic databases, covering most peer-reviewed literature and including some of the major working paper collections, it is limited in its coverage of other non-peer-reviewed studies.
- For all indicators, this machine-learning approach does not work equally well across all CDR methods and across time, which could lead to some biases in the numbers, particularly for CDR methods for which there is currently little research.
- Patents are only one measure of inventive activity, and many inventors choose to protect their inventions with secrecy rather than patents.
- This analysis uses international patent families to control for differences in patent quality, yet even within this high-quality invention group, patent quality may be highly skewed.

- While inventive activity as proxied by international patent families has been in decline, the raw number of patent filings has increased steadily. But due to concerns around patent quality, this report only shows international patent families.
- Patent data are truncated due to the application process, so the data are less reflective of inventive activity from 2020 onward.

2.4 Outlook

Innovation activity has increased and diversified across CDR methods and geographies, but some CDR blind spots remain.

Spurring innovation in CDR is essential to close the CDR gap and meet the Paris temperature goal. Early-stage R&D efforts are a prerequisite to incentivizing continued inventive activity and pushing CDR methods towards greater commercialization and upscaling. Grants, scientific publications and high-value inventions are important – although not exhaustive – metrics with which to track the innovation process. The report's findings are synthesized in Figure 2.4, which indicates distinct countries, CDR method distributions, and growth trends across the three indicators.

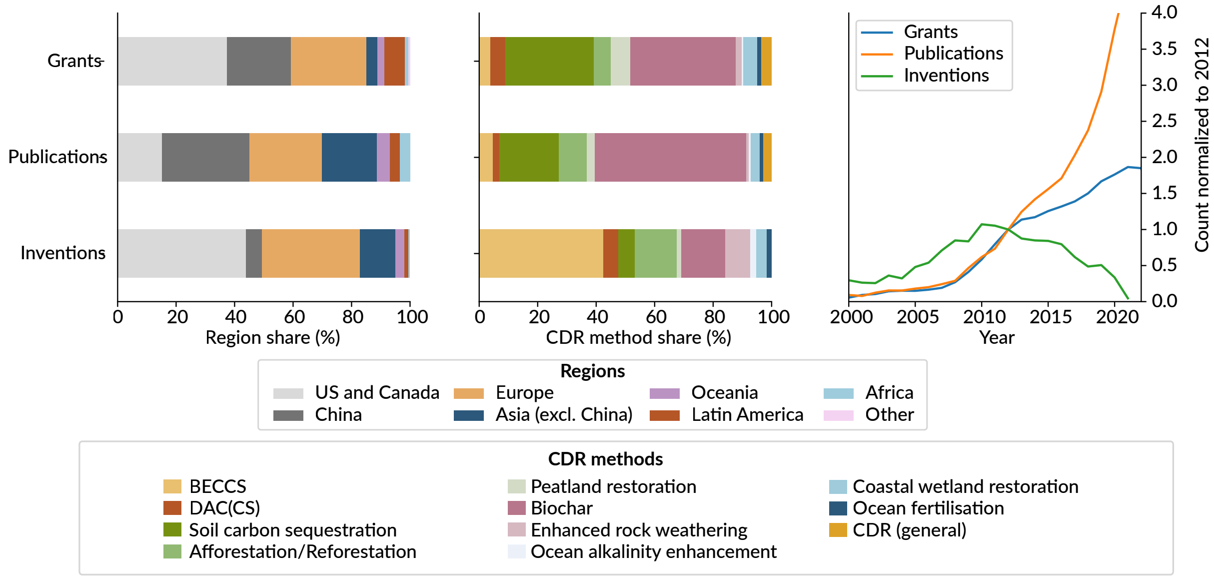


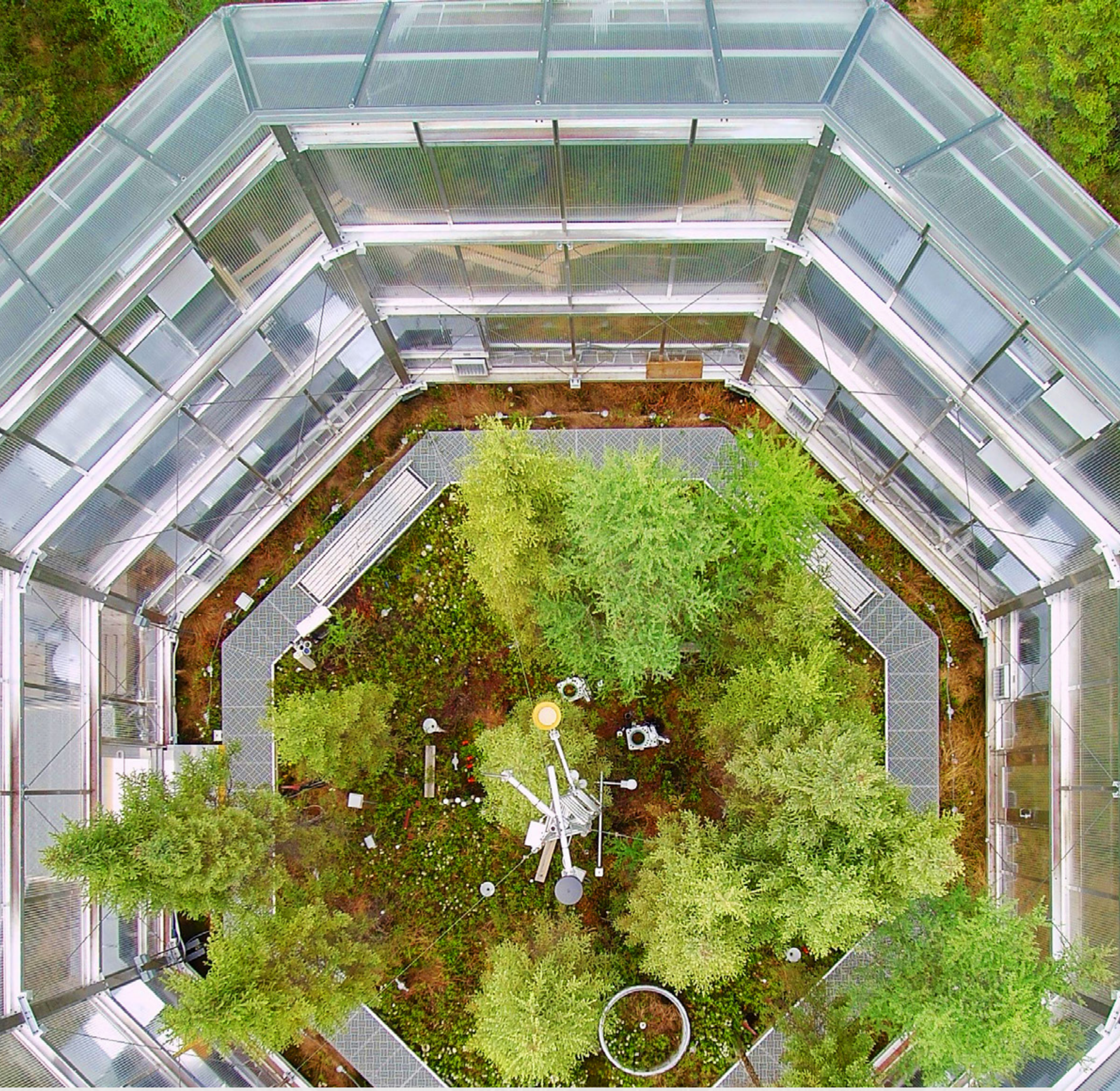
Figure 2.4 *Comparison of regions, carbon dioxide removal (CDR) methods and growth over time across three key CDR innovation metrics (research grants, scientific publications and high-value inventions). BECCS = bioenergy with carbon capture and storage; DAC(CS) = direct air capture (with or without carbon storage).*

In terms of geographic differences, three distinct R&D/innovation profiles seem to emerge, exemplified by Canada and the US, China, and Europe. These profiles are consistent, geographically, with recent research on the design of public institutions for energy innovation more generally. Like this report, that research found three different innovation models – the Asian, European and US models. Whether differences in the design of public institutions are partly responsible for different CDR innovation profiles could be an area of future research.[44]

While Canada and the US account for almost half of CDR-related grants and high-value inventions, the region's importance is less critical in the scientific publishing domain. This might indicate a more applied nature of Canadian and US grants or easier commercialization routes for Canadian and US scholars and inventors. For China, the reverse appears to be true. China produces more publications relative to grant volume but very few high-value inventions, which might indicate struggles to commercialize academic findings, possibly related to incentives for deployment. Europe, in contrast, looks relatively balanced across all three metrics. Asia (excluding China) features low levels of grants but high levels of publications and commercialization, potentially driven by private sector R&D, which is more difficult to track. Other world regions currently represent a small share of each of the three metrics. The low levels of grants in regions with little inventive activity (Africa, Latin America, and Oceania) could be a sign of inertia and indicate that the observed dynamics are unlikely to change in the foreseeable future.

In terms of CDR methods, diverging profiles can be observed across the three indicators. Grants and scientific publications are heavily focused on conventional CDR (around 40–50% relate to these methods), but novel CDR is a much stronger focus for inventions. Novel CDR methods might be easier to patent than conventional CDR methods as hardware-based technology inventions are more readily patentable than, for instance, a digital monitoring tool for carbon stores in forests.[45] Inventors might protect such inventions by secrecy rather than patents. Biochar is playing an increasingly important role across all indicators. The invention portfolio across CDR methods is more balanced than the grant and publication portfolios, indicating more diverse inventive activity relative to grants and publications.

Overall, over the last decade, a strong growth can be observed in CDR-related grants and publications, but a slowdown in inventions. The slowdown in inventions could be driven by multiple factors, such as global trends (e.g. low oil and carbon prices) or factors more specific to CDR. It is only possible to speculate on the CDR-specific reasons for the slowdown. Grants may have become less applied or may focus on novel CDR methods that are less mature, leading to a stronger increase in publication activity, but less patenting, as these methods are further away from commercialization.



Gregory F. Nemet,[i] Morgan R. Edwards,[i] Jenna Greene,[i] Lushanya Dayathilake,[ii] Zachary H. Thomas,[i] Kavita Surana,[iii] Kathleen M. Kennedy,[iv] Andrew Zaiser,[i] Benedict S. Probst[v,vi,vii]

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Spruce and Peatland Responses Under Changing Environments. Credit: ORNL, U.S. Dept. of Energy

Chapter 3 | Demonstration and upscaling

Demonstration projects, investment in new firms and expectations of growth are key to scaling up carbon dioxide removal (CDR). There is evidence of increasing activity in all three, albeit with challenges to sustaining that growth for each.

Key insights

- Rapid growth in the number and capacity of demonstration plants is observed. Notably, the US has funded a 1 million ton per year direct air carbon capture and storage demonstration plant, with another currently in negotiations.
- These US direct air capture hubs are by far the most well-funded public demonstration programme. A new initiative from Mission Innovation, the CDR Launchpad, although encompassing less funding, provides a platform for future investment and knowledge-sharing.
- Investment in CDR startups has grown rapidly over the past decade but declined in 2023 alongside a drop in overall climate-tech investment. This highlights the effect of market volatility on investments.
- Growth in novel CDR startups surpasses growth in conventional CDR startups, but CDR startups as a whole report challenges that must be overcome for companies to grow and scale.
- CDR companies and industry groups have announced capacity targets that show ambition to reach significant levels of CDR by mid-century or sooner.
- Current data to track funding – from both public and private sector entities – are sparse and incomplete. Better data are essential to understanding and managing the current CDR research, development and demonstration landscape and its outlook for the future.

The literature on innovation shows that demonstration projects and investment in new firms are central aspects of scaling up technologies from the invention phase (see Chapter 2 – Research and development) to their formative phase – between first commercialization and rapid scale-up – setting the stage for widespread adoption (see Chapter 8 – Paris-consistent CDR scenarios). This chapter tracks progress in the public funding of demonstration programmes, investment in new startups, and expectations for growth in the coming years and decades.

3.1 Emerging public demonstration programmes

Demonstration plants play a key role in derisking technologies and setting the stage for widespread adoption.

Technology innovation is often described as moving through multiple stages. Between basic and applied research (see Chapter 2 – Research and development) and widespread adoption (see Chapter 8 – Paris-consistent CDR scenarios) are demonstration projects. These projects can demonstrate a technology's performance outside of the lab and provide experimentation and learning opportunities before that technology is widely deployed. Demonstration and pilot projects are typically distinguished by their size, with *demonstration* describing larger projects. At the demonstration stage, government funding is a key component to building plants, given the uncertainties of different technologies at this scale and the opportunities for firms to learn from one another, which provides incentives for firms to follow and observe rather than build first. These projects, therefore, are critical first steps in the pursuit of widespread and effective CDR deployment. This section focuses on existing CDR demonstration plant commitments and on government programmes to fund demonstration plants.

This section also summarizes public funding measures for research, development and demonstration (RD&D). This funding falls into three categories: RD&D funding for carbon capture and storage (CCS); RD&D funding specifically for CDR; and CDR demonstration funding. Although the first category is not explicitly focused on CDR, CCS RD&D may be directly relevant to the development of CDR technologies, such as transport and storage mechanisms.

There is no centralized data source for RD&D funding for CDR methods. This analysis gathers publicly available data on funding for CCS RD&D, CDR RD&D and CDR demonstration projects to identify broad trends and estimate global funding. Although every attempt has been made to gather complete data, these data are sparse. As a result, this is a key information gathering need for the CDR community going forward, and the data gathering conducted for this analysis can serve as an initial step (see Box 3.4). The following analysis is divided into two sections, first focusing on Mission Innovation and then moving to country-specific government demonstration funding.

Mission Innovation

Mission Innovation is a key programme in spurring innovation in low-carbon energy and climate change mitigation technologies. It is an initiative of 23 countries and the EU, with an aim to drive RD&D for these technologies.[46] Mission Innovation was announced at COP26 in 2021 and includes seven key missions, one of which is CDR. Canada, Saudi Arabia and the US are the three co-leads of the CDR Mission.[47] The CDR Mission has the primary aim of spurring the development of CDR technologies that will deliver a 100 million ton net reduction in annual global carbon dioxide (CO_2) emissions by 2030. To do so, the mission focuses on three technologies: direct air carbon capture and storage (DACCS); biomass with carbon removal and storage (including bioenergy with carbon capture and storage (BECCS), bio-oil storage, biochar and other durable products from biomass); and enhanced rock weathering.

A cornerstone of the CDR Mission from Mission Innovation is the CDR Launchpad, a coalition of governments committed to accelerating CDR technology development.[48] These countries have resolved to work together to invest in CDR demonstration projects, share data and accelerate the CDR technology learning curve. Each country that is part of the CDR Launchpad has committed to:

- Support at least one CDR project with a capacity of at least 1,000 tons of CO_2 removed per year by 2025.
- Provide a portion of the $100 million in funding for CDR demonstrations and pilot projects by 2025.
- Share data and information on these CDR demonstration projects to enhance knowledge-sharing.
- Support a monitoring, reporting and verification (MRV) working group, mapping of CDR projects, and life cycle analysis case studies of CDR projects.

Mission Innovation is a platform for countries to learn from one another and set parallel goals to increase RD&D and demonstration capacity. Because the CDR Mission is relatively recent, there is not yet comprehensive data on CDR RD&D funding, and not all Mission Innovation countries have made specific commitments for demonstration funding. Estimated country-level CDR demonstration funding is shown in Chapter 3 Technical Appendix and in the country profiles presented in this report.

Five countries (Canada, Iceland, Japan, the UK and the US) and the EU are members of the Mission Innovation CDR Launchpad and have shared data on demonstration projects in their jurisdictions.[49] This data set includes 22 demonstration projects focused specifically on BECCS, direct air capture (DAC), and enhanced rock weathering (see Figure 3.1).

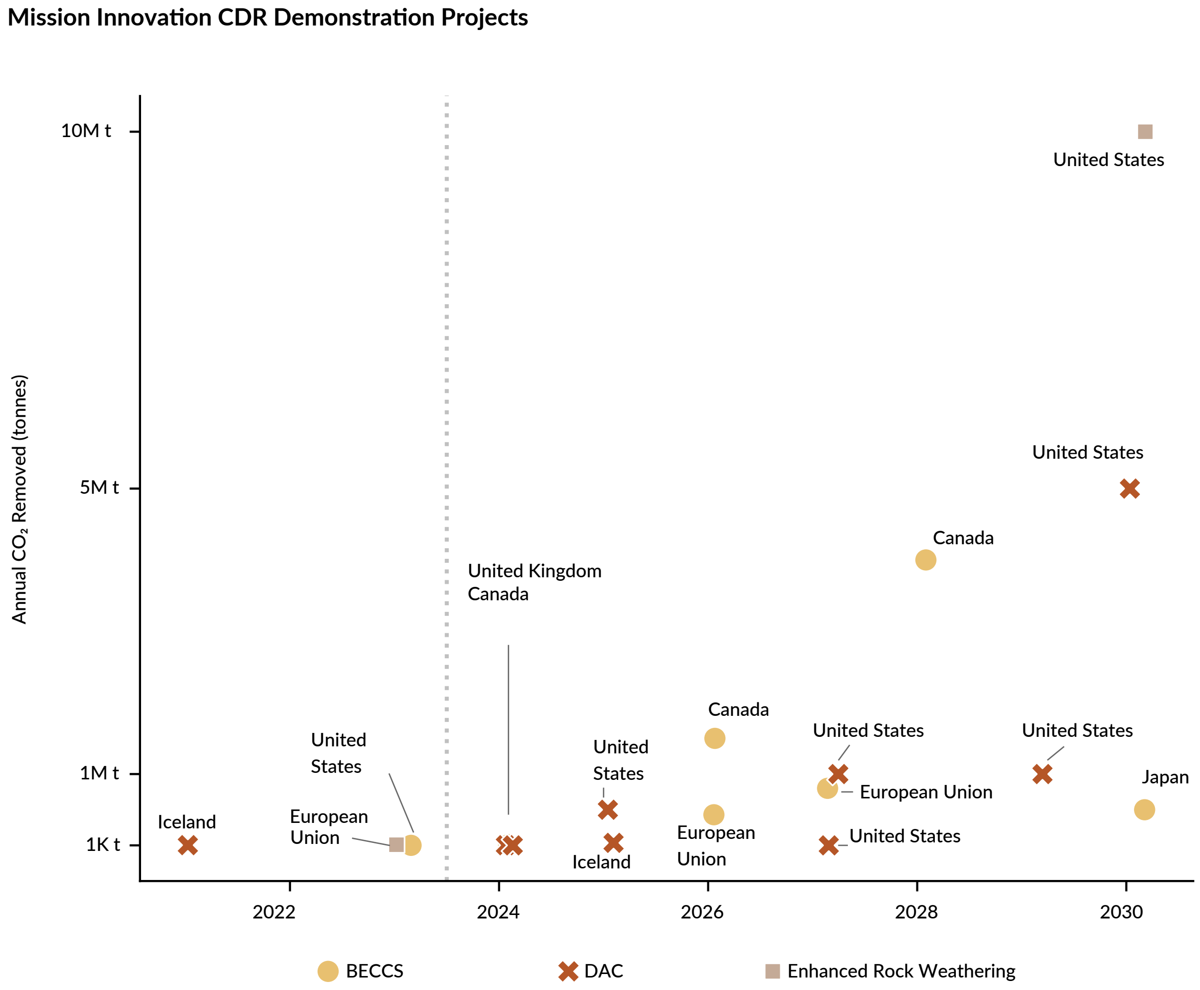

Figure 3.1 *Demonstration projects submitted by countries in the Mission Innovation CDR Launchpad. Only includes demonstration projects for which there are complete data (CDR type, annual removal capacity and year of removal capacity). For some projects, there is an initial year and capacity along with future goals. For this figure, the first year and associated capacity level are shown. The points are labelled by the country that submitted the project. These projects have not necessarily received public funding. BECCS = bioenergy with carbon capture and storage; DAC = direct air capture.*

Government funding of CDR demonstrations

Governments have approached CDR demonstration funding using diverse strategies. Documented funding for CDR demonstration projects is patchy, in part because these funding programmes include other carbon management approaches, such as carbon capture and sequestration, that are not explicitly CDR but may include CDR components. Some public data on CDR funding also exclude certain countries; for example, International Energy Agency (IEA) data exclude non-member and non-association countries.

Between 1974 and 2023, the global total of public funding for carbon capture and sequestration RD&D, as reported by the IEA, was $15 billion. However, this data set only includes 33 IEA member and association countries and the EU.[50] This figure is therefore not exhaustive of all global funding, because it only includes data from these 34 entities. This estimate also includes funding for DAC (not necessarily with storage; therefore, not necessarily CDR) and no other CDR technologies. Australia, Canada, the EU, Germany, Ireland, Japan, Norway, the UK and the US have announced public funding for CDR

RD&D, totalling $4.2 billion. Within this, Australia, Canada, the EU, Japan, Norway, the UK and the US have all funded demonstration projects, which make up $3.9 billion of this total, dominated by $3.5 billion in funding for the US Regional Direct Air Capture Hubs programme (see Box 3.1).

The remainder of this section presents profiles of government entities that have funding programmes specifically to support CDR demonstration projects: Australia, Canada, the EU, Japan, Norway, the UK and the US.[1] This section also highlights demonstration projects with public funding. Many government programmes include funding for CDR, CCS and CCU within the same programme, often under a broader carbon management strategy. Where possible, funding specifically for CDR within these programmes is distinguished.

Australia

In Australia, carbon capture, utilization and sequestration RD&D has been funded for many years through the Carbon Capture Use and Storage Development Fund and the Carbon Capture Technologies Program. The Carbon Capture Use and Storage Development Fund includes funding for up to A$25 million (US$17 million) per project for pilot and precommercial projects (demonstrations). This programme is not specifically focused on CDR but can include CDR projects.[51] One of the projects from the Carbon Capture Use and Storage Development Fund is a pilot DACCS demonstration plant operated by AspiraDAC, awarded a A$4 million (US$2.7 million) grant with an expected capacity of 365 tCO_2 per year.[52]

The Carbon Capture Technologies Program funds A$65 million (US$43 million) over eight years, from 2023 to 2031.[53] The programme specifies priority emerging carbon capture technologies, including DAC, BECCS and CO_2 utilization technologies. Through the Department of Climate Change, Energy, the Environment and Water, the National Soil Carbon Innovation Challenge is focused on measuring soil carbon sequestration.[54] The funding includes A$1 million (US$0.7 million) for 17 feasibility studies and A$39 million (US$26 million) for 13 development and demonstration projects. The Clean Energy Finance Corporation, Australia's green bank, has invested A$15 million (US $10 million) in Loam Bio, which focuses on enhancing soil carbon sequestration.[55]

Canada

The Canadian government is investing Can$320 million (US$240 million) from 2021 to 2028 in carbon capture utilization and storage RD&D through its Energy Innovation Program.[56] Eligible technologies include DAC, but the final projects are still being evaluated (as of May 2024), so the funding allocated for CDR (as opposed to CCS and CCU) is uncertain.[57]

Beyond the Energy Innovation Program, Canada is funding specific CDR demonstration projects. The Hinton Bioenergy Carbon Capture and Storage Project received Can$2.5 million (US$1.9 million) in public funding from Emissions Reduction Alberta, which is funded by the Technology Innovation Emissions Reduction Fund in Alberta.[58] Through the British Columbia Innovative Clean Energy Fund, a Carbon Engineering (a DAC company) plant that uses DAC technology received Can$2 million (US$1.5 million) for engineering

1 Programme and project funding amounts are converted from national currencies to US dollars as a common currency to calculate an estimate of global funding. Currency exchange rates are from the US Treasury in 2023. Numbers are reported to two significant figures.

and design plans.[59] This plant does not meet the storage requirement of CDR because the CO_2 is used to produce fuels. Through its Strategic Innovation Fund, the Canadian government has awarded Carbon Engineering Can$25 million (US$19 million) to design, construct and operate the Newport Innovation Centre in British Columbia (4.5 tons of CO_2 removed each day via DAC).[60] Finally, the CARBONITY biochar plant is being built with Can$11 million (US$7.8 million) of public funding through two entities: Natural Resources Canada's Investments in Forest Industry Transformation Program and Canada Economic Development for Quebec Regions.[61] This plant will be the largest capacity biochar plant in North America, and larger than any in Europe.

European Union

The EU Innovation Fund includes funding measures for CDR projects.[62] The fund began in 2020 with a goal to invest an estimated €40 billion ($44 billion) by 2030 to support the transition towards climate neutrality.

Several CCS and CCU projects have been selected through the Innovation Fund that may inform scale-up of CDR in the future. One project which counts as full CDR – a BECCS plant in Stockholm, Sweden – was awarded public funding and received €180 million ($200 million).[64] This demonstration plant is expected to remove an estimated 7 Mt of CO_2 over the first ten years of operation, which is scheduled to begin in 2026. The latest round of funding for net zero technologies opened in late 2023. At the time of writing, no projects had been selected; therefore, no funding estimate is included in this report.

Japan

Japan has invested extensively in CCS technologies, but with less of a focus on CDR.[65] The primary programme for RD&D is the Moonshot Research and Development Program, which allocates about ¥50 billion ($350 million) from 2020 to 2030 for climate technologies.[66,67] Many projects funded under this allocation are focused on methods relevant to CDR, including DAC and enhanced rock weathering. There are no upper or lower bounds for project funding under the Moonshot programme, and as no project-specific investment values are made publicly available, estimating the portion of the total funding going specifically to CDR RD&D is not possible. Beyond the Moonshot programme, the Japan Ministry of Agriculture, Forestry and Fisheries is funding a programme focused on biochar, wood-based carbon sequestration and coastal wetland restoration, up to a total of ¥16 billion ($110 million).[68] The Ministry of the Environment has also funded the capture component of the Mikawa BECCS Demonstration Plant.[69]

Norway

Norway has a dedicated national programme related to CCS RD&D, called CLIMIT.[70] The programme began in 2005 and has primarily been focused on carbon capture, storage and utilization but can also support BECCS and DACCS projects. Many of the previously funded CCS projects may have relevant lessons for CDR, especially those focused on the transport and storage of captured CO_2. Through this programme, Norsk Hydro and Climeworks collaborated on a feasibility study for a DAC plant, either stand-alone or integrated into an aluminium smelter to provide steam to the DAC unit; the study received NKr 3.5 million ($0.3 million).71 The project did not result in a built demonstration plant, however.

The Norway Ministry of Climate and Environment is funding a pilot demonstration DAC unit through Enova, a State-owned enterprise. The demonstration plant, operated by Removr, received NKr 36 million ($3.6 million) in grant funding and will capture 300 tons of CO_2 annually beginning in 2024, with a goal of expanding to 1,000 tons captured per year.[72,73] It is not clear whether the captured CO_2 is stored permanently; thus, the project is categorized as DAC rather than as CDR.

Innovation Norway, a programme of the Norwegian government, has also begun the Bionova programme, which may finance RD&D projects related to conventional CDR methods.[74] The amount of funding from this source is unclear, as funded projects and results had not been published at the time of writing.

United Kingdom

The UK funds CDR-specific RD&D programmes in addition to programmes on carbon capture utilization and storage. Approximately £32 million ($40 million) has been granted from UK Research and Innovation, a non-departmental public body, to the Greenhouse Gas Removal Demonstrators Programme, which is funding five demonstration projects encompassing several CDR technologies: biochar, enhanced rock weathering, peatland restoration, perennial biomass crops, and woodland creation and management.[75]

The Net Zero Innovation Portfolio fund, administered by the UK Department for Energy Security and Net Zero, has a programme focused on DAC and greenhouse gas removal. The funding programme is structured as a two-phase competition, with total funding of £70 million ($89 million). The first phase focused on desk-based feasibility studies. It ended in 2021, with 23 projects funded. The second phase began in 2022 and is focused on demonstration projects, with 15 projects funded. These projects are being built between 2022 and 2025, with demonstration of CDR beginning in 2025. The Department for Energy Security and Net Zero and the Department for Business, Energy and Industrial Strategy have also announced programme funding for hydrogen BECCS technologies totalling £26 million ($33 million).[76] While the UK government intends to open up CO_2 transport and geological storage in this decade, the current lack of this infrastructure means that several of these projects are progressing to capture only.

An additional £4.3 million ($5.5 million) funded six projects to capture carbon through restoration of a range of habitats, starting in 2023, through a partnership led by Natural England, a public body.[77] Innovate UK, a UK government agency, is also funding the Small Business Research Initiative competition. This competition is focused on tools and techniques for MRV for land-based greenhouse gas removal, with total funding of £1 million ($1.1 million) over two phases.[78]

United States

The US has several streams of CDR RD&D funding. The flagship CDR demonstration funding is for the Regional Direct Air Capture Hubs programme (see Box 3.1). The Carbon Negative Shot, a cross-departmental initiative of the US government, is focused on CDR and includes funding for pilots and demonstrations. The initiative recently released a Carbon Negative Shot Pilots funding opportunity announcement to complement the DAC hubs and fund small pilots for enhanced rock weathering and BECCS, recognizing that a portfolio approach is needed. This effort alone will provide $100 million over five years for demonstration projects. The funding will cover up to five small BECCS pilots, up to ten enhanced rock weathering pilots, up to five CDR testing facilities focused on CDR MRV, and up to five laboratory-scale marine CDR projects.[79]

Box 3.1 US Regional Direct Air Capture Hubs programme

The Regional Direct Air Capture Hubs programme, established in 2022 by the Biden Administration, seeks to fund four research hubs focusing on DAC. To be eligible, companies must demonstrate the ability to construct a DAC facility that can remove 50,000 tons of CO_2 per year, with a plan to scale up to 1 Mt per year.[82] This programme is funded by resources set aside by the Infrastructure Investment and Jobs Act and the Inflation Reduction Act. It is managed jointly by the Department of Energy's Office of Clean Energy Demonstrations and Office of Fossil Energy and Carbon Management. In total, the Regional Direct Air Capture Hubs programme has been authorized to grant $3.5 billion ($700 million per year over five years). The Department of Energy has not yet granted the entire funding amount, noting that it wants to allow earlier-stage companies to reach the maturity needed to become eligible for the programme before granting the entire $3.5 billion.[83]

Currently, two DAC hubs have been selected for negotiation, accounting for $1.2 billion between them.[84] Both can more accurately be described as DACCS hubs, as they sequester captured carbon in storage sites rather than using it. The first is the South Texas DAC Hub, located in Kleberg County, Texas. Jointly operated by 1PointFive (an Occidental subsidiary), Carbon Engineering and Worley, this DAC hub seeks to remove 1 million tons of CO_2 annually. This hub, in partnership with Gulf Coast Sequestration, plans to sequester this CO_2 in geological formations along the Gulf Coast. To assist the South Texas DAC Hub in its development, the Regional Direct Air Capture Hubs programme is in negotiations regarding the provision of $600 million in funding.

The second DAC hub is Project Cypress, located in Calcasieu Parish, Louisiana. Operated by Battelle, Climeworks and Heirloom Carbon Technologies, this hub is also working to remove more than 1 million tons of CO_2 annually. It will use a "saline geologic CO_2 storage site" to store carbon captured using DAC. The Regional Direct Air Capture Hubs programme has dedicated $600 million in funding for this purpose.[84]

Nineteen smaller projects are currently in negotiation with the Department of Energy, for a total of approximately $100 million. The majority of these projects are seeking funding to study the feasibility of a DAC hub prior to applying for the funding to establish one.[82]

The US Department of Energy announced $36 million to fund marine CDR MRV projects through the Advanced Research Projects Agency–Energy. The Department of Commerce and the National Oceanic and Atmospheric Administration announced $24 million to fund research on marine CDR, in part funded by the Department of Energy through the Office of Fossil Energy and Carbon Management.[80,81] The Department of Energy also announced $17 million to fund 19 early-stage research projects at colleges and universities, which may enable future demonstration projects.

Looking forward

Public demonstration programmes are increasing, both in the number of announced programmes and the capacity of the demonstration plants. However, the timelines for demonstration projects – and their subsequent upscaling phases – are uncertain due to the nascent nature of these technologies. Continued growth relies on production catalysed by the public sector via initiatives such as Mission Innovation. Mission Innovation's CDR Launchpad could become a key player in this space, serving as a platform for investment and knowledge-sharing. Furthermore, tracking funding – both from public sector entities and private sector investments – is essential to understanding the current CDR RD&D landscape and its outlook for the future. This is another role that Mission Innovation could play moving forward.

3.2 Rapid growth in investment

Investments in CDR startups have grown significantly over the past decade, outpacing the climate-tech sector as a whole.

Startups are a key part of the climate innovation landscape because they can quickly bring new products and services to market. However, they face many challenges in advancing from the demonstration stage to commercial operation and market growth.[85] Investments from the public and private sector are key to enabling startup success.[86] This analysis examines the state of investments in CDR startups through 31 December 2023, using the Net Zero Insights database (see Box 3.2).[87] The database contains 509 CDR startups, defined in this report as startups related to the capture of CO_2 from the atmosphere. Of these, 255 have received at least one investment, with 961 investors participating in 803 deals, totalling $3.9 billion, during the period 2009–2023.

Investments in CDR startups have grown dramatically in recent years. A decade ago, reported investment in CDR was low: in 2013, three startups received $4 million in two investment deals. By 2022, when total reported investment in climate-tech peaked, annual investments in CDR startups had reached 131 startups, $1.5 billion and 207 investment deals (and 2.3% of all climate-tech deals and 1.1% of dollars invested in climate-tech). However, while deals slightly increased in 2023 to 213 (with 145 startups funded), investment in CDR declined to $856 million. This decline in investment value (43%) was steeper than the decline seen in climate-tech overall (14%).

Box 3.2 Methods: Net Zero Insights database

This report uses the Net Zero Insights database to evaluate early-stage investments in CDR startups. Net Zero Insights monitors a wide range of sources to collect data on climate-tech startups and also accepts submissions from innovators and industry stakeholders. Almost all startups in the database develop climate change mitigation products or services, with a few startups focused on improving the resilience of communities to climate change (i.e. adaptation). Net Zero Insights relies on publicly available information and is published mostly in English, so it may miss some private investments or investments reported in other languages. Startups may also receive funding through instruments not included in this database (e.g. loans). Net Zero Insights shows five CDR startups that have been acquired, one of which (Carbon Engineering) reports its acquisition value as $1.1 billion.

For the analysis in this report, 1,001 potential CDR or CDR-enabling startups were identified in Net Zero Insights using the following categories: greenhouse gas capture, removal and storage; CDR; carbon capture, utilization and storage; afforestation/reforestation; and forestry. These startups were manually categorized into different CDR methods by reading the pitch and tags to look for descriptions or labels of each method: forestry CDR, DACCS, biochar, biomass burial, marine biomass sinking, enhanced weathering, BECCS, soil carbon, ocean alkalinity enhancement, coastal wetland restoration and direct ocean capture. A total of 218 companies without a specific connection to CDR, such as ordinary timber or agriculture data platforms or generic sustainability business services, were removed.

Companies that mentioned utilization or point source capture of fossil CO_2 in their pitch (or that did not specify the CO_2 source) were also removed and added to the list of enabling startups. Some CDR companies do not specify the destination of the CO_2; these companies were included in the list of CDR startups. Therefore, this analysis may include some companies that do not meet the report's definition of CDR if they use CO_2 but do not report that they do so or if they currently sequester CO_2 but later decide to use it (e.g. Carbon Engineering).

Since 2020, the CDR methods that have received the highest investor attention (based on the number of deals) are forestry CDR (38%), DACCS (23%) and biochar (14%). Enhanced rock weathering and soil carbon sequestration have also experienced rapid growth in deals, with a fourfold and twofold increase since 2020, respectively, but constitute a relatively small share of total deals. Overall, the recent trend in investment is towards more novel forms of CDR, with the share of deals in forestry CDR declining from 49% in 2020 to 30% in 2023. While deals vary in size, and thus do not always reflect trends in the flow of capital, trends in investment dollars since 2020 are similar to the trends seen in deals. For example, as well as having among the highest number of deals, DACCS and biochar are the CDR methods receiving the most funding, with $808 million to DACCS in 2022 and $234 million to biochar in 2023.

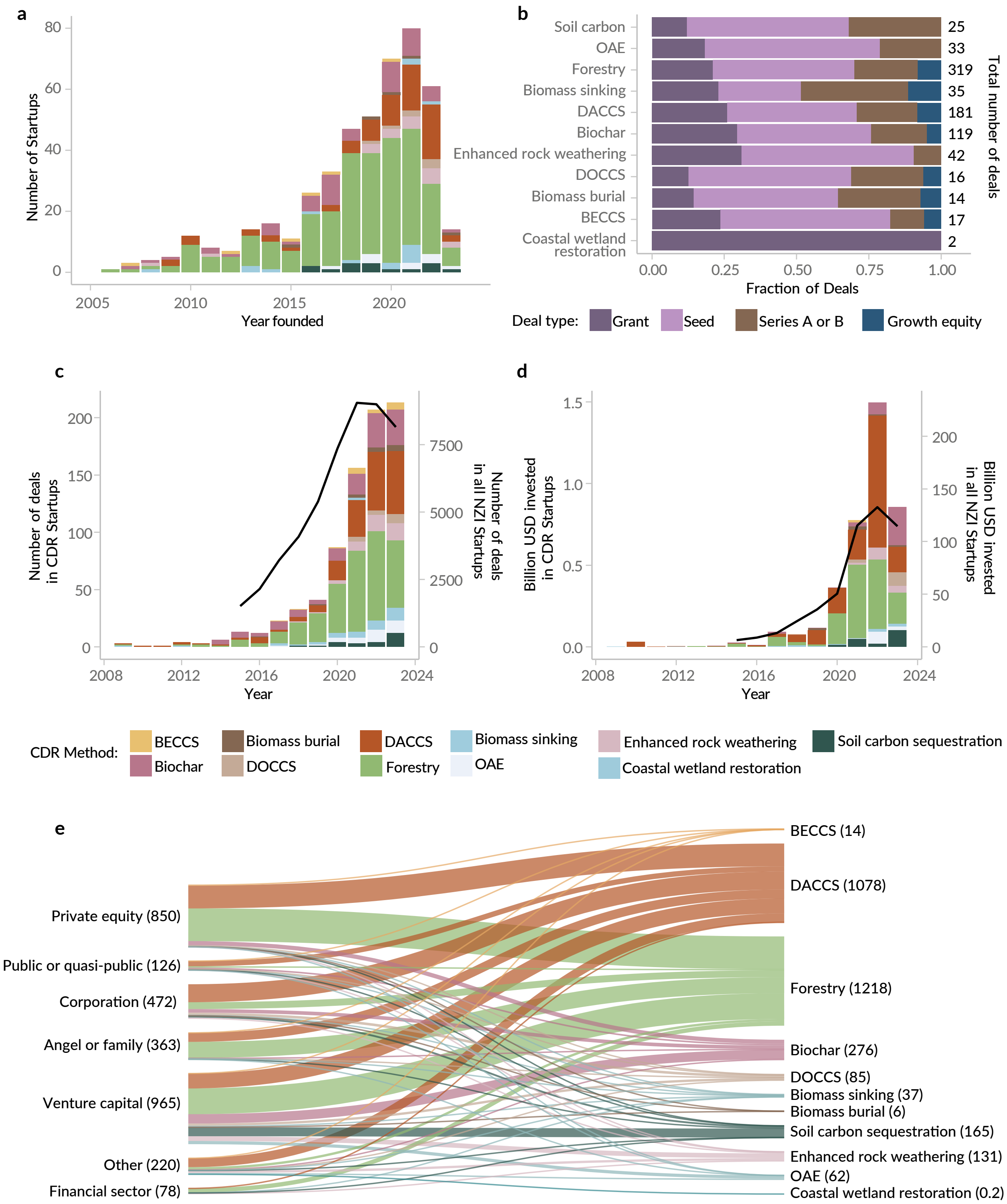

Figure 3.2 *Investment trends in carbon dioxide removal (CDR) startups from 2009 to 2023: (a) Number of startups founded in each year (509 total); (b) Proportion of deal types across CDR methods; (c) Number of investment deals in CDR startups each year (255 total startups and 803 deals, bars) and total deals for climate-tech startups (black line); (d) US Dollar value of investments in each year (208 total startups and 511 deals that report a dollar value, bars) and total investment dollars for climate-tech startups (black line); (e) Flow of investments by investor type to CDR method. BECCS = bioenergy with carbon capture and storage; DACCS = direct air carbon capture and storage; DOCCS = direct ocean carbon capture and storage; OAE = ocean alkalinity enhancement. Data source: Net Zero Insights database.*[87]

Startups receive funding in sequential rounds, beginning with grant and seed rounds that typically correspond to high technology risk or precommercial stages. They then progress to Series A and B and other equity rounds, where risks are reduced and commercial development has started. They may finally move to the growth equity stage, which tends to involve larger dollar amounts for startups seeking to expand their operations, and investors holding larger shares in these startups.[77] The distribution of investment rounds across CDR methods reflects a range of maturity (Figure 3.2b). Among CDR methods with at least ten reported deals, enhanced rock weathering is the most dependent on grants (31% of deals). Only forestry, DACCS, biochar and biomass sinking startups have received funding from later-stage growth equity rounds. However, despite the large investments in some CDR methods, such as DACCS and forestry, 71% of deals across all methods since 2020 have been grants and seeds, indicating that many new startups are still entering the space.

The funding for these investment rounds comes from a variety of sources (Figure 3.2e), with funders bringing different motivations, resources and expectations with their investments. These motivations range from financial investment returns for equity investments to strategic interests in maintaining or expanding existing businesses or pivoting to new directions. Based on dollars invested, the largest sources of funds for CDR startups from 2009 to 2023 were venture capital ($965 million; 25%), private equity ($850 million; 22%) and corporations ($472 million; 12%). This is consistent with overall funding patterns for climate-tech startups.[88] While venture capital is distributed among various CDR methods, corporate investment is largely concentrated in DACCS (52%).

Other startups are also developing technologies that could enable CDR. For example, 80 startups developing conventional CCS technologies participated in 400 investment deals from 2001 to 2023, totalling $2 billion. About half of these startups specify the destination of the captured carbon: 30 specify sequestration or storage only (68 deals and $78 million), 12 specify utilization in synthesis of low-carbon fuels or chemicals (44 deals and $174 million), and six specify utilization in curing cement (33 deals and $74 million). Five of these CCS startups report a novel carbon capture method – using algae to extract CO_2 from concentrated streams – but no investments are reported. Other enabling startups focus on CO_2 utilization and can provide early markets for captured CO_2.[89] Thirty-five startups that use a stream of CO_2 to cure cement (104 deals and $367 million) were identified, as were 92 startups that use captured CO_2 to synthesize fuels, chemicals, plastics or food (295 deals and $3.6 billion). Investments in these enabling startups follow similar growth trends to those in CDR startups.

CDR startups identify a number of pressing challenges to rapid growth. While there are no comprehensive global surveys of CDR startups, a recent survey of 40 European CDR startups highlighted challenges that are likely to extend to other regions (see Figure 3.3).[90] The surveyed startups focus mostly on DACCS, enhanced rock weathering and restoring degraded ecosystems and might therefore be less representative for other methods, such as BECCS, biochar and ocean fertilization. The startups rated the importance of bottlenecks (0 = lowest; 5 = highest) across four categories: finance, marketing and sales, product and service, and team. Each of the four categories was further divided into subcategories. The most important subcategory in each main category is shown in grey in Figure 3.3.

The surveyed startups see finance as the central bottleneck. They particularly struggle to access non-dilutive funding (i.e. grants that do not require the selling of ownership stakes in the company); dilutive funding, such as venture capital, tends to be more readily available. The challenges with non-dilutive funding relate to the speed with which funding can be acquired, rather than to availability or conditions. To acquire grants, startups need to put a full-time employee on the task, which often overstretches their budget. In addition, grants often take a year to be approved. During that time, the needs and priorities of the startup often shift, which poses problems if the funds need to be spent as originally intended. The second most pressing bottleneck reported relates to marketing and sales. Startups struggle with converting their leads into actual sales, as many buyers shy away from high prices, uncertainties in the voluntary carbon market (see Chapter 4 – The voluntary carbon market), and scientific uncertainties around MRV (see Chapter 10 – Monitoring, reporting and verification). For instance, less than 1% of companies with a science-based target have bought novel CDR and less than half of novel CDR startups have made a sale to date. These startups perceive challenges related to their product (e.g. business model or supply chains) and hiring (e.g. availability of talent, hiring, and retention) to be less pressing bottlenecks.

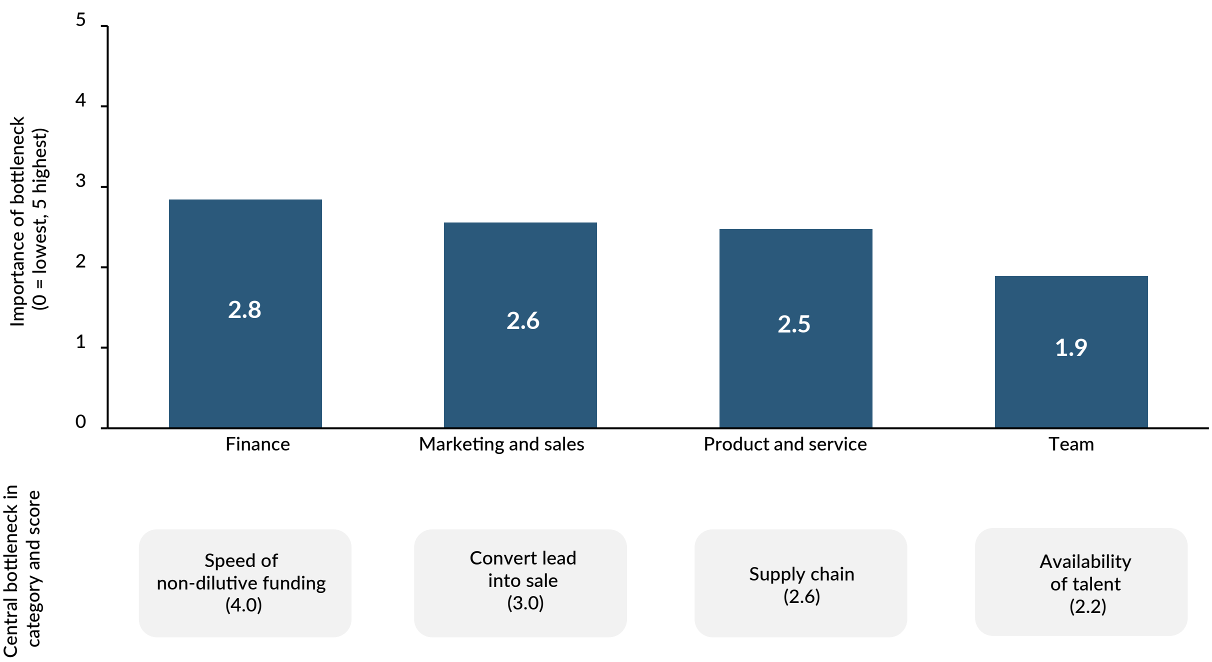

Figure 3.3 *Overview of most important bottlenecks reported by a survey of 40 European CDR startups. Data source: Akeret et al., 2023.*[90]

Box 3.3 Investment trends

The analysis of reported investments in CDR startups highlights a number of key trends:

High investor interest in DACCS. DACCS has become a primary focus for corporate and other large investors in CDR. Major CDR startups such as Climeworks and Carbon Engineering have received investments from corporations that are looking to offset emissions from their core business (e.g. Microsoft, Airbus, Chevron, J.P. Morgan). Other startups receiving high interest from corporations include those focusing on e-fuels or carbon utilization (e.g. Carbon Engineering, Prometheus, Global Thermostat) or advertising co-benefits such as water security (e.g. Avnos).

Stable interest in forestry CDR. Afforestation, reforestation and forest management – collectively called *forestry CDR* in this analysis – are more established CDR methods. Prior to 2021, forestry CDR startups attracted the majority of CDR investments. In recent years, growth in such investments has stabilized. Compared with other CDR methods, forestry CDR startups have more varied business models, reflecting a higher level of maturity. For example, 39% of forestry CDR startups offer services selling carbon credits on bespoke marketplaces, with the credits either being produced by their own technology or by another startup. These marketplaces enable startups to directly reach customers; for example, Treekly and Pachama verify and sell carbon credits for reforestation.

Emerging interest in other novel CDR. Beyond DACCS and biochar, other novel CDR methods include ocean alkalinity enhancement, enhanced rock weathering, biomass sinking, coastal wetland restoration, direct ocean carbon capture and storage, biomass burial, and BECCS. Together, startups focusing on these seven methods have participated in 52 deals from 2009 to 2023. Examples of recent startups focused on other novel CDR methods include Captura and Deep Sky (which capture gaseous CO_2 from water) as well as Seaforester and the Reef Company (which focus on coastal wetland restoration).

3.3 Company announcements for novel CDR

Announcements by CDR companies and industry groups show their ambition to reach significant levels of CDR by mid-century or sooner.

Companies have made plans and announcements for novel CDR scale-up, both in the near term (2024–2030) and the longer term (2030–2050). The announcements made for these two periods may have different levels of certainty, since companies have more concrete plans in the near term than the longer term, so this report analyses them separately. In both these analyses, the public announcements from companies should not be considered future scenarios, but rather an indication of potential market development. Some companies might not achieve the goals they have announced, some may exceed them, and additional companies will emerge and set new goals.

Projects included in the near-term analysis (2024-2030) are those under construction, in initial stages of deployment, or with publicly announced facility plans or early engineering studies. For the near term, details were gathered for projects under construction and/or in development for DACCS and BECCS (see Box 3.4). Only projects that permanently store the captured carbon or have disclosed that they have plans to do so are included. The near-term analysis is limited to these technology types because of insufficient information on the specific targets set by companies involved in biochar and enhanced rock weathering. Additionally, for emerging technologies such as biomass sinking, it is premature to make near-term predictions using company announcements, as these technologies are currently in the early stages of development.

In total, this report estimates that companies that have announced DACCS and BECCS projects may remove 118 million tons of CO_2 annually by 2030 (see Figure 3.4). BECCS companies may remove nearly 57 million tons of CO_2 annually by 2030; an increase from the current rate of 0.5 million tons per year. DACCS projects may remove 61 million tons of CO_2 annually by 2030.

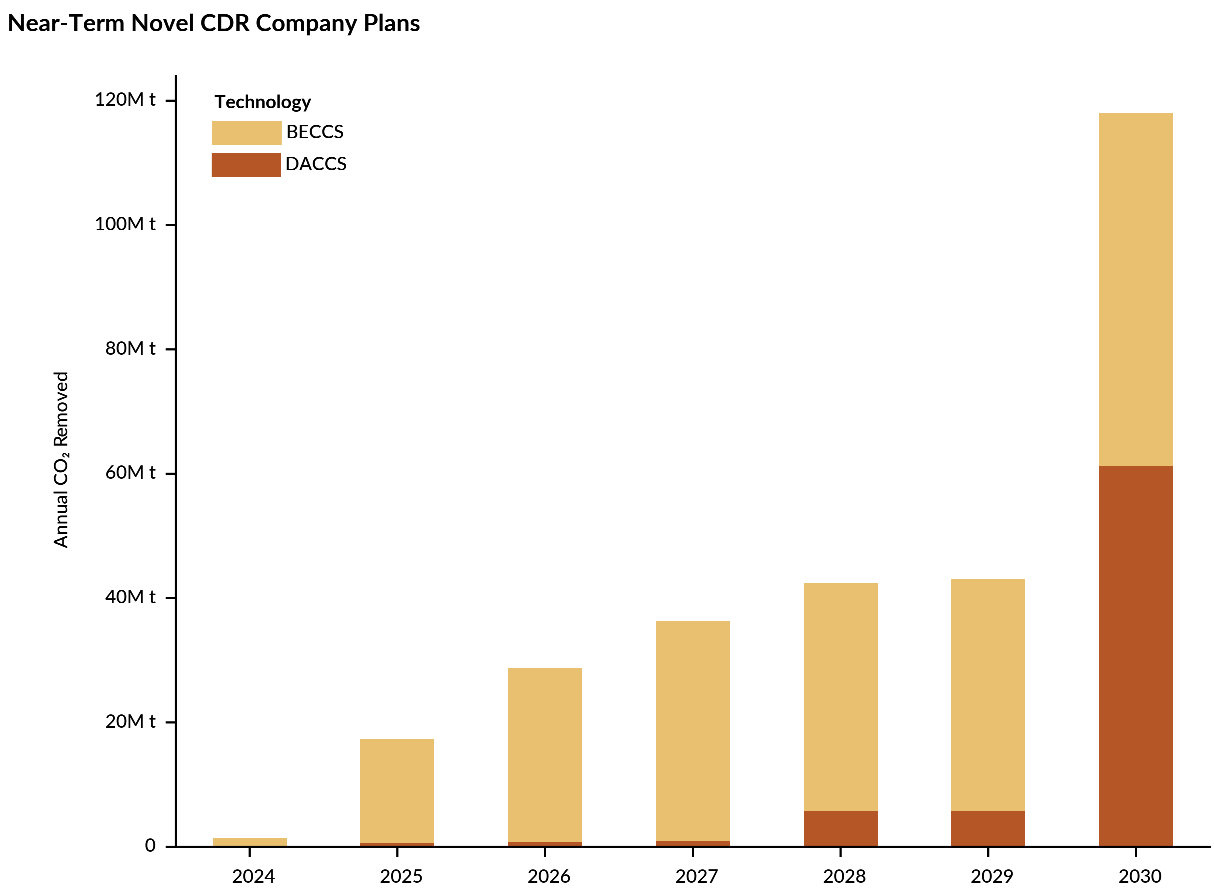

Figure 3.4 *Cumulative capacity of direct air carbon capture and storage (DACCS) and bioenergy with carbon capture and storage (BECCS) projects from 2024 to 2030. This report assumes that projects would sustain their announced annual capacities from their operational year through 2030, unless additional extensions at the same plant have been announced for the intervening period. CDR = carbon dioxide removal.*

This report supplements the analysis of short-term planned projects with an analysis of company announcements between 2030 and 2050. This longer-term analysis includes any announcement that a company has made publicly that includes both a capacity and a year. These announcements are not filtered by whether the company has begun engineering studies or made plans for specific plants. The announcements were gathered from CDR companies' websites and publicly available industry reports (see Box 3.4). Data were collected for as many companies as possible. However, this data set is not comprehensive of all CDR company plans for a variety of reasons: not all companies disclose their growth goals, and some companies may be missing despite attempts at a comprehensive inventory. Attainment of these announced ambitions is also highly uncertain, and this report includes no assessments of credibility.

Thirty-one company announcements were identified from 24 unique CDR companies and industry groups focused on novel CDR between 2030 and 2050 (Figure 3.5). These announcements span multiple CDR methods, with the majority of the individual announcements coming from DAC companies (65%); the second most prevalent method in the announcements, at 13%, was biochar.

Eleven companies have made plans for 2030, which together total 2 Gt of CO_2 removed annually. Company announcements for 2050 total 11 Gt of CO_2 removed per year, which is mostly driven by a single announcement of 8 Gt per year by 2050. This level of growth in novel CDR, from 1.3 Mt of CDR in 2023 (see Chapter 7 – Current levels of CDR) to 11 Gt in 2050, implies a compound annual growth rate of 40% per year. This growth rate is comparable to other climate-relevant technologies like solar energy and electric vehicles. Between 1975 and 2018, solar photovoltaic grew at a compound annual growth rate of 36% per year in terms of cumulative capacity, and between 2005 and 2019 electric vehicles grew at a compound annual growth rate of 80% per year in terms of cumulative number of vehicles.

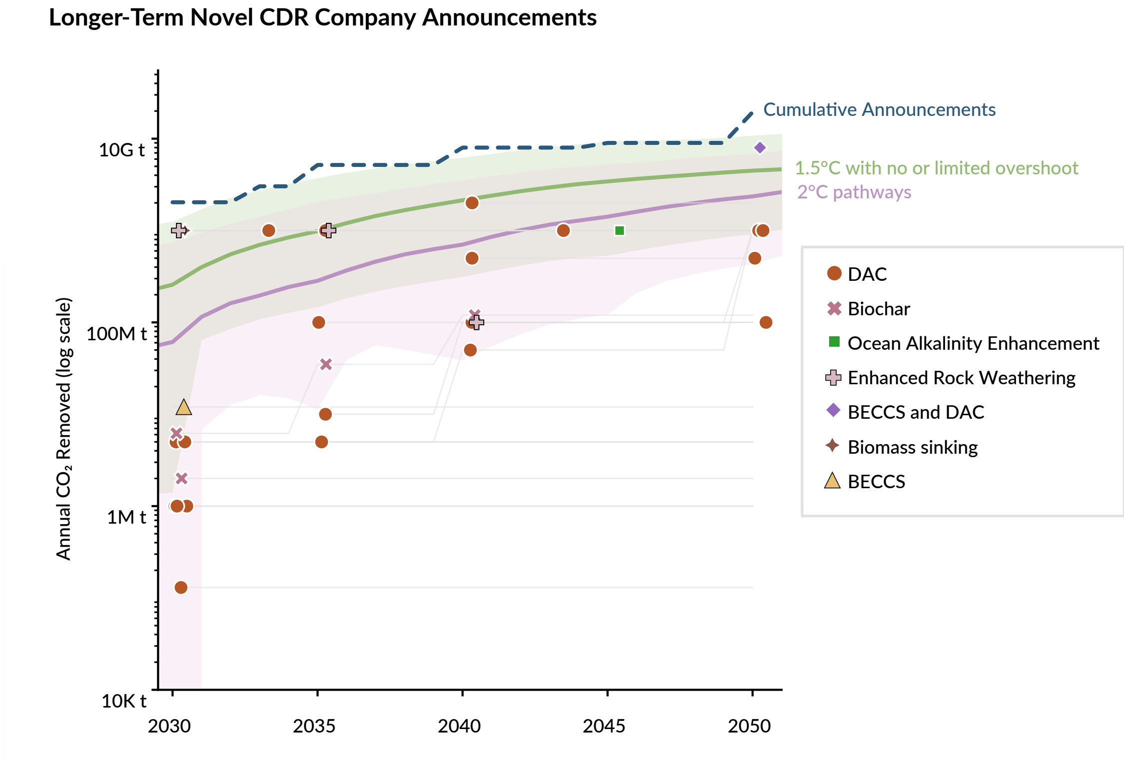

Figure 3.5 *Longer-term novel carbon dioxide removal (CDR) company announcements. Dashed lines are cumulative company announcements; points are individual company announcements; each faint grey line is one company's time series; solid lines show the median amount of novel CDR in two scenario pathways (a 1.5°C with no or limited overshoot pathway and a 2°C pathway). These scenario pathways are constructed between 2010 and 2100, but only those for 2030–2050 are shown in this chart. The shaded areas around each pathway represent the 5th to 95th percentile novel CDR in the scenarios. The companies' time series are based only on publicly available announcements. It is assumed that each company reaches the capacity of the announcement in the year of that announcement and continues at that capacity until 2050 or until the year of another, intermediate, target set by the same company, at which point their time series increases to capacity and remains flat until 2050 or a new announcement. Company announcements are not filtered by their project status or completion, so whether these announcements will be reached is highly uncertain. DAC = direct air capture; BECCS = bioenergy with carbon capture and storage.*

The cumulative amount of novel CDR announced by CDR companies is aligned with the amount of novel CDR required by two temperature scenario pathways: a 1.5°C with no or limited overshoot pathway and a 2°C pathway (see Figure 3.5). The scenarios assessed in this figure are the full set assessed in Chapter 8 (Paris-consistent CDR scenarios); therefore, there is no consideration in this chapter of whether these scenarios meet sustainability goals. Whether companies will achieve the announced amounts of novel CDR by 2050 is uncertain, but the comparison to the novel CDR required by temperature scenario pathways demonstrates the level of ambition in the novel CDR market.

Box 3.4 Methods: Short- and long-term capacity announcements

Data were gathered on near-term plans for BECCS and DACCS projects through several sources. A full accounting of these sources is included in Chapter 7 (Current levels of CDR). Planned BECCS projects include dedicated bioenergy plants, waste-to-energy plants with CCS, and cement production plants with biomass energy inputs. For these latter two types of plant, CDR volumes have been calculated by assuming that the fraction of total captured CO_2 that is attributable to biogenic sources is 50% and 10%, respectively. Together, these two types contribute less than 8% of the total planned BECCS volumes in 2030.

Data on long-term CDR company announcements were gathered by compiling a list of CDR companies and searching each company's website, along with other documents available online, for publicly announced removal levels. The list of companies came from the State of Carbon Dioxide Removal list of deployed projects, Direct Air Capture Coalition company members, companies selected for pre-purchases from Frontier (an advance market commitment funding mechanism), and a list of companies receiving investments compiled from Net Zero Insights.[79] The companies' activities span different methods of CDR but are focused on novel CDR.

Each company's website was checked for any announcement that included both a capacity and a year for its attainment. If either of these was not available, the announcement was not included. This list was supplemented with announcements found in other company documents, such as year-end presentations and conference videos available publicly online.

A time series was then constructed for each company, in which flat growth (no new capacity built) is assumed for that company unless and until a new ambition level is announced. A cumulative level for the total novel CDR capacity announcements in the market was then calculated by summing each company's time series – assuming each announcement is successfully reached by each company.

Data were gathered from as many companies as possible; however, this data set is not entirely comprehensive because not all companies disclose their CDR growth ambitions. Attainment of the targets in these announcements is also highly uncertain, and this report includes no assessments of credibility.

Box 3.5 Limitations and knowledge gaps

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

- Conducting annual surveys of national governments' public investments in CDR RD&D for several categories of CDR technology, including MRV, would be important to assess support for CDR over time. The IEA has done this successfully for energy technologies.
- Startups are often reticent to share detailed information, resulting in gaps in both investment data and technology details. Access to more detailed information about investment amounts and technology development could allow for more specific analysis of technology development trajectories and their implications.
- Company announcements, both near term and long term, can provide a useful early indicator of progress being made to close the CDR gap described in Chapter 9 (The CDR gap). Adding probabilistic information for each stage and timing can help establish a more credible range of progress.

4

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Chapter 4 | The voluntary carbon market

Despite growth in carbon dioxide removal (CDR) on the voluntary carbon market (VCM), its share of the market remains small. Future projections suggest a rapidly growing but uncertain demand for future CDR through the VCM.

Key insights

- The vast majority of carbon credits retired (used and thus no longer tradable) on the VCM relate to projects that avoid or reduce emissions, rather than remove carbon. In 2023, CDR credits accounted for less than 10% of total credits sold on the VCM.
- The market for novel CDR is nascent but growing, whereas the market for conventional CDR is more mature. Some VCM projects also adopt mixed methodologies, which generate credits from both CDR and avoided emissions.
- The number of credits issued for conventional CDR fell in 2023 from approximately 20.4 million to 13.3 million, while purchases of future novel CDR credits grew sevenfold from 600,000 to 4.6 million.
- The market plays a larger role in financing novel CDR than conventional CDR. Credits issued for afforestation/reforestation represent less than 1% of the total afforestation/reforestation CDR that occurred in 2023. By contrast, pre-purchases for novel CDR well exceeded the total amount removed through novel methods in 2023.
- The price per carbon credit is substantially higher for CDR than for other credit types. On average, credits from conventional CDR methods (which ranged from \$12 to \$16 in 2023) cost three times more than credits generated from emission reduction or avoidance projects. The average weighted price for novel CDR credits (which ranged from \$111 to \$1,608 in 2023) exceeds the price for credits from emission reduction or avoidance projects by a factor of 100.
- Despite emergent efforts to standardize and integrate CDR into compliance markets and the emerging regime under Article 6 of the Paris Agreement, there may always be a case for the VCM to exist as a niche market for CDR to facilitate innovation and experimentation and to supplement climate change mitigation efforts.

This chapter looks at the role of the VCM in expanding the deployment of CDR. The first section lays out the background of CDR in the VCM. The chapter then assesses the current state of play of CDR within the VCM and maps its future prospects.

4.1 The role of the VCM in expanding CDR

With novel CDR largely absent from government agendas, the VCM plays a key role in its deployment.

Economic theory is clear that climate change is a market failure – more precisely, the failure to take into account the external effects of emitting greenhouse gases. As long as emitting is not costly, nobody has an incentive to reduce emissions, causing damage for everyone in the world. Assigning emissions a price can help correct this market failure by internalizing the externality. This rationale is at the heart of carbon taxes and emissions trading schemes – or *compliance markets* – around the world (see Chapter 5 – Policymaking and governance). Not cleaning up the atmosphere by removing the carbon dioxide (CO_2) already emitted is presently also a market failure and thus may not occur without intervention. As a result, there is currently an undersupply of CDR, making it more difficult to meet the significant volumes of CDR required to achieve ambitious climate mitigation scenarios (see Chapter 8 - Paris-consistent CDR scenarios).

Beyond being included in national greenhouse gas inventories as part of accounting obligations, CDR has largely not been on government agendas. This is particularly true for compliance markets, with notable yet limited exceptions of CDR integration, for instance under California's emissions trading scheme. Inclusion of CDR within the VCM has thus been among the few factors contributing to CDR scale-up, especially for novel CDR. This section describes the background of CDR inclusion within the VCM.

Defining the VCM

While the VCM lacks a standardized definition, it is broadly understood as *a platform through which actors voluntarily finance projects that reduce or remove CO_2 emissions*. This report adopts a broad definition of the VCM, encompassing different types of transaction between buyers and suppliers: both those that occur via the voluntary marketplaces and those where CDR is directly procured from suppliers and publicly reported. This report explicitly includes the traditional registry-based VCM as well as niche markets that facilitate the pre-purchase of novel CDR within its definition of the VCM. This chapter considers the creation of credits in terms of their issuance (conventional CDR) or delivery (novel CDR) as well as their retirement (conventional CDR) and purchase (novel CDR). It is acknowledged that some CDR credits that buyers purchase may not be retired and could therefore also be used for compliance purposes in the future and thus may go beyond the purview of the VCM. Box 4.1 describes the VCM and how it works.

Box 4.1 How does the VCM work?

To understand CDR in the VCM, it is important to first understand the role of the VCM in climate change mitigation more broadly. The VCM is generally understood as *a platform through which actors voluntarily finance projects that reduce or remove CO_2 emissions*. The VCM is estimated to account for 2% of total carbon trade, with compliance markets (emissions trading schemes) covering the other 98%.[91] The vast majority of carbon trading is for *emission allowances* within emissions trading schemes, while the VCM only concerns carbon *credits*. Despite its small share in carbon trading overall, the VCM fulfils a role by enabling businesses to go beyond their mandatory decarbonization efforts.

Carbon credits are tradable certificates typically generated from projects developed and governed by private project developers and owners. One credit represents 1 ton of avoided, reduced or removed CO_2 or CO_2-equivalent emissions of other greenhouse gases. Such projects can occur in different sectors, such as forestry, agriculture or energy, and may come with co-benefits (e.g. improvements to biodiversity).

Carbon credits are typically *issued* (put on the market) by *registries* and *certified* according to one of several methodologies. Credits are issued after the mitigation activity has occurred; they are certified after the mitigation activity has been verified and validated by a third-party auditor (see Chapter 10 – Monitoring, reporting and verification).

A carbon crediting programme (i.e. the organization that hosts a certifiable carbon crediting standard) consists of recognized methodologies, approved third-party verifiers and an issuing registry. Carbon crediting programmes have methodologies that set the rules for different types of activity – including monitoring, reporting and verification procedures – that must be complied with for those projects to be certified as having either avoided, reduced or removed CO_2 emissions (see Chapter 10 – Monitoring, reporting and verification).

Carbon credits can be acquired directly by end beneficiaries (e.g. corporate buyers) or purchased via intermediaries (e.g. traders, brokers). Project developers and governments can also enter into bilateral *offtake agreements* and *pre-purchase agreements* with end beneficiaries, for example by arranging to sell portions of their planned future volumes of carbon credits.

Carbon credits are typically used (retired or cancelled) for voluntary or compliance purposes. After this, the credit is no longer on the market and cannot be traded anymore. However, not all credits sold end up retired, as some actors may hold on to them for future trade or use. Carbon crediting programmes allow each carbon credit to be retired or cancelled by only one single entity, to avoid the same credit being double counted in different organizational *claims*.

The largest carbon crediting programme is the Verified Carbon Standard (Verra), followed by the Gold Standard. Several other standards have also been developed, such as the Climate Action Reserve, Plan Vivo, the American

Carbon Registry and Puro.earth. In the absence of supra-organizational regulatory bodies, this array of standards has led to heterogeneity and complexity in the oversight of the VCM.

A brief history of the VCM

Although the first instances of carbon offsetting go back several decades,[92] the Clean Development Mechanism (CDM) under the Kyoto Protocol was the first international carbon market when it came into force in 2005, though crediting had already started several years before. The aim of the CDM was to assist higher-income countries in reaching their decarbonization commitments while providing access to new funding for climate change mitigation for lower-income countries. However, in the years after its launch, the CDM was the subject of severe concerns related to transparency and the overall climate impact of its projects.[93–95]

Despite these flaws, the CDM's procedures have served as a blueprint for subsequent market mechanisms, including the current VCM and the emerging market mechanisms under Article 6 of the Paris Agreement. Yet the central role that CDM methodologies have played in developing the VCM is problematic, because these methodologies have been widely documented as producing low-quality carbon credits that in some cases are also not additional to what would otherwise have occurred in the absence of such funding.[96]

Types of projects on the VCM in 2023

To calculate how much CDR is funded through the VCM, it is necessary to differentiate CDR projects – and credits – from the other kinds of projects on the market. Box 4.2 describes the different types of credit that are generated within the VCM.

The VCM today encompasses a wider range of project types than ever before: from emission reduction projects that target cookstoves and clean energy through to projects that destroy or remove greenhouse gases through various mechanisms. This range of project types is underpinned by an even more diverse suite of methodologies: some mitigation activities that are awarded carbon credits in the VCM involve only avoided emissions, emission reductions or CDR; some combine them. However, there are early signs of this changing, with registries such as the American Carbon Registry and the Verra Registry beginning to make the contribution of removal, reduction and avoidance techniques within the same methodologies clearer.[97,98]

Box 4.2 Carbon credits

Types of carbon credit. Credits tend to be *avoidance*, *reduction* or *removal* based. The distinction between activities that avoid emissions and activities that reduce emissions is not always clear, with *avoidance* and *reduction* often being used interchangeably. CDR activities, however, lower the atmospheric concentration of CO_2. As a result, their impact is determined independently of historical, current and future emission levels; conversely, avoidance or reduction projects peg their impact against a forward-looking counterfactual emission scenario.

It is not always clear which type of carbon credit projects may be generating. Some methodologies enable credits to be generated from a mix of avoidance, reduction and/or removal activities (see Chapter 4 Technical Appendix). Mixed methodologies are particularly prevalent in conventional CDR projects (e.g. forest management, sustainable agriculture) because such projects encompass activities that both reduce and avoid (as well as remove) emissions. For example, some conventional CDR projects foster practices that diminish natural disturbances – serving to reduce emissions – while also enhancing carbon storage, thereby removing CO_2.

It is also important to distinguish between *credits* and *offsets*: credits refer to the unit, and offsets refer to the specific use of the credit to compensate for existing emissions. Credits can, however, be used in many other ways, for instance as a contribution to climate change mitigation or in the form of results-based financing. Allowances issued within emissions trading schemes (described in Box 4.1) may also be considered offsets in some circumstances, although they are not credits.

Calculating the number of credits a carbon project generates. To calculate the number of credits a carbon project generates, a *baseline scenario* is required. This scenario acts as the benchmark against which the project's impact is measured. While various methods exist for establishing baselines, they typically entail using *counterfactual* assumptions, which reflect what would have occurred had the project not been implemented. This is referred to as the *business-as-usual scenario* and is predetermined within the methodologies of carbon standard setters (see Box 4.1 for a description of carbon standards). The difference between projected emissions in the business-as-usual scenario and those in the project scenario represents the *project's impact* and, consequently, the number of carbon credits it generates. Figure 4.1 illustrates how project impact is compared with the business-as-usual scenario for avoided or reduced emissions projects, versus conventional and novel CDR projects.

For *projects involving conventional CDR methods*, the project impact represents the additional number of removed tons of CO_2 compared with removal levels in the business-as-usual scenario (e.g. Verra's methodology VM0047 for afforestation, reforestation and revegetation projects).

For *projects involving novel CDR methods*, a baseline value of zero is often assumed, owing to the absence of such projects in the past (e.g. the Puro.earth methodology). The counterfactual reference scenario is subsequently based on the assumption that these projects would otherwise not be implemented (e.g. for lack of finance). However, as novel CDR projects continue to expand, this approach may undergo re-evaluations to reflect the continual evolution of methodologies for determining business-as-usual scenarios.[99]

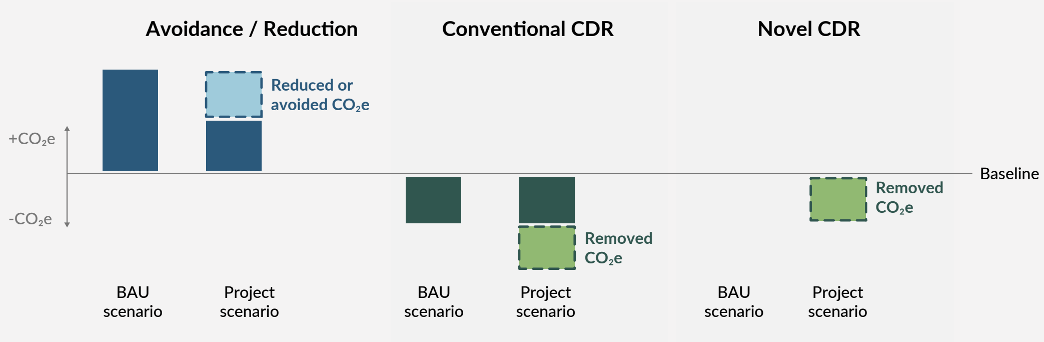


Figure 4.1 *Project impact in emission reduction projects, avoided emissions projects and carbon dioxide removal (CDR) projects on the voluntary carbon market. Avoided and reduced emissions (light blue portion of second bar in first panel: emissions that would have occurred under the business-as-usual (BAU) scenario, shown in first bar). Removed CO_2 via conventional CDR (light green portion of second bar in second panel: emissions removed on top of CDR that would have occurred under BAU scenario, shown in first bar). Removed CO_2 via novel CDR (light green portion of second bar in third panel: CDR that would not have occurred under BAU scenario, shown in first bar). Source: Walsh, forthcoming.*[100]

The like-for-like principle of using CDR credits – aligning the durability of sources with the durability of CDR. Different types of CDR credit may have differing use cases. As an example, the UNFCCC's Race to Zero campaign, among others, endorsed applying the "like-for-like" principle.[101] This principle postulates that CDR strategies must match the nature and permanence of the emissions they aim to neutralize. It posits that CO_2 originating from the long carbon cycle, such as that emitted from fossil fuels, should be sequestered in equally permanent storage (e.g. through direct air carbon capture and storage); emissions from more transient sources, such as from land-use changes or short-lived greenhouse gases, can be offset by CDR involving less durable storage (e.g. through soil carbon sequestration). Applying this principle ensures that CDR efforts align with the specific impact and lifespan of different emission types (see Chapter 1 – Introduction, for further discussion of durability).

Recent concerns about the VCM

After a rapid growth spurt in 2021–2022, the VCM was exposed to significant criticism in 2023. This included articles from *The Guardian* and *Die Zeit*, published in January 2023, which revealed that a study had shown "more than 90% of rainforest carbon credits [on the VCM were] worthless".[102] That criticism mainly related to two issues: first, the use of an inadequate baselining methodology by several REDD+ projects (see Box 4.2 for how baselines are used in VCM projects), which had resulted in an overestimation of the projects' impacts on emissions; second, questions about the additionality of the credits issued (i.e. whether they would have occurred in the absence of carbon market revenue).[103,104] Projects issuing more credits than they should has also been an issue in energy-related emission reduction projects.[105] Some VCM projects are also heavily criticized for their infringement on, or displacement of, local and Indigenous communities.[106]

These concerns and criticisms have had a tangible impact on buyers' confidence in the VCM and prompted some companies to disengage from the market entirely.[107] The concerns have also led to guidance being issued on the appropriate design of an offsetting portfolio, considering these risks.[13]

Determining quality on the VCM

The increased scrutiny of the integrity of the VCM has triggered calls for better quality control and more consistent regulation. Stakeholders in the VCM have produced various criteria for what constitutes "high-quality" carbon credits. Examples of such criteria include the Core Carbon Principles developed by the Integrity Council for the Voluntary Carbon Market and the Carbon Credit Quality Initiative's carbon credit scoring tool.

While a uniform definition of quality has yet to be established across the market, the following characteristics are most commonly used as proxies for quality: robust third-party validation and verification; robust quantification of the emission impact; high durability; additionality; and the presence of sustainable development benefits and safeguards (see analysis of 28 key stakeholder documents in Walsh, forthcoming[100]). The absence of a uniform definition of quality may have been detrimental for carbon credit sales from projects with higher environmental integrity and higher attendant price points. While various organizations – from standard setters to agencies that rate the quality of carbon credits – offer guidance and assessments of quality, many are still in the early stages of applying their frameworks to CDR credits.

In parallel, governmental bodies are ramping up efforts to establish clear standards for activities on the VCM. For example, the EU Carbon Removal Certification Framework is emerging as a voluntary framework for the certification of CDR activities. The framework defines the fundamental principles and prerequisites for certification bodies to monitor, report and verify CDR generated in Europe (see Chapter 10 – Monitoring, reporting and verification). This is based on the quality criteria defined in the EU's framework.[108] Despite several shortcomings in this framework, it can be expected to become a crucial guideline in the further development of CDR activities.

The growing importance of co-benefits

To successfully scale up CDR methods within the VCM, it will be important to gain a solid understanding of the indirect environmental and social impacts of individual CDR methods and to promote these co-benefits to buyers. CDR activities are first and foremost valued for their ability to capture CO_2 from the atmosphere and durably store it (see Chapter 1 – Introduction, for a definition of durability). But if their full potential is to be accurately assessed, their broader impact on the world also needs also be considered. Deploying CDR, especially at a large scale, can produce various environmental and socioeconomic side effects, which can be beneficial or disadvantageous to third parties (see Chapter 8 – Paris-consistent CDR scenarios).

The extent to which CDR activities trigger intended or unintended effects depends on factors such as the type of CDR, the regional and site-specific context and, importantly, the way in which the activities are governed. Measures to oversee these are commonly referred to as *sustainable development benefits and safeguards*.[109] Several authors have examined these effects in more depth, but those studies differ in underlying context and assessment framework, resulting in diverging conclusions.[110–114]

In recent years, public interest has extended beyond merely considering the direct environmental impact of CDR in favour of a broader assessment of its implications. The main carbon credit standards have produced different frameworks to better outline a project's individual contribution to sustainable development.[91] Assessments show that projects with additional co-benefits can attract higher price premiums.[115–117] Further, different stakeholders across the market have developed guidelines or set clear recommendations for buyers that consider the broader impact of carbon projects.[91] In 2023, for example, the Science Based Targets initiative launched its first framework for companies to set biodiversity targets alongside their decarbonization ambitions.[118]

These developments can be expected to further prompt buyers to factor in the presence of social and environmental co-benefits in their decision-making processes. To successfully scale up CDR methods within the VCM, it will therefore be important to gain a solid understanding of the indirect environmental and social impacts of individual CDR methods and to promote these co-benefits to buyers. To inform such decision-making, systems for monitoring, reporting and verification need to be broadened to include the non-carbon impacts of CDR activities (see Chapter 10 – Monitoring, reporting and verification).

Understanding the demand for CDR credits

A systematic understanding of the factors that drive demand for different types of carbon credit on the VCM is currently missing. Initial surveys indicate that many buyers consider quality aspects within their purchasing decision and that buyers already engaging in the CDR market are predominantly motivated by their ability to support the early development of CDR (see Section 4.3 for further profiling of existing buyers).[117,119]

Despite there being no uniformly applied definition of "high quality" when it comes to carbon credits, the increasing public scrutiny of the VCM and the growing engagement of regulatory bodies appears to have motivated buyers to shift towards higher-quality credits.[120] Other independent guidance has also been released, such as the Oxford Principles for Net Zero Aligned Carbon Offsetting,[13] the ISO Net Zero Guidelines and the Integrity Council for the Voluntary Carbon Market's Core Carbon Principles,[109] all of which provide buyers with signals as to what may constitute high-integrity credits and credible claims.

However, the lack of consistency in the terms and guidelines used across the VCM still poses challenges for efforts to increase the volume of purchases of CDR credits. Current organizational standards and schemes for ensuring quality in CDR and emission reduction projects have not been deemed sufficiently rigorous by governments – both as buyers and as regulators – resulting in the development of their own monitoring, reporting and verification methodologies (see Chapter 10 – Monitoring, reporting and verification).

The role of the VCM in supporting CDR development

The VCM has been an important, yet insufficient, provider of finance for accelerating the scale-up and deployment of CDR, as will become clear from the data presented in Section 4.2, which demonstrate the low volumes traded. However, novel CDR credits, such as for direct air carbon capture and storage, fetch high prices on the VCM. Its role is rather that of a *niche market*. These exist when early adopters display a higher-than-average willingness to pay for a technology. The high prices that novel CDR credits command in the VCM could be an indicator of this willingness (see Section 4.2).[9] Thus, according to the model of CDR development posited in Chapter 1 (Introduction), the VCM will be most important in the early stages of CDR scale-up as a niche market.

4.2 Current status of CDR within the VCM

Most of the credits generated in the VCM are for avoided emissions or emission reductions, rather than for CDR. Conventional CDR continues to dominate novel CDR in the VCM in absolute terms, despite demand for novel CDR growing more quickly.

Various estimations exist of the size of the overall VCM, as well as of the projects within it. The findings depend on the coverage of the registry from which the data are drawn[121,122] and on the project classification system used. In this report, data for 2022 and 2023 have been aggregated from the six major registries and platforms: Verra, Gold Standard, the American Carbon Registry, CDR.fyi, Puro.earth and Climate Action Reserve. Box 4.3 details the methods used to estimate the current scale and characteristics of CDR within the VCM.

Box 4.3 Methods: Estimating the scale and nature of CDR within the VCM

Source data. Data for the years 2022 and 2023 were aggregated from the six major registries and platforms: Verra, Gold Standard, the American Carbon Registry, CDR.fyi, Puro.earth and Climate Action Reserve.

Classification of projects. As described in Section 4.1, carbon credits that have been generated through CDR are not clearly differentiated within registry data from those generated through emission avoidance or emission reduction. Credits may also originate from projects that employ a mix of these methodologies (see Box 4.2). To get as clear a picture as possible of the status of CDR within the VCM, projects from registries were therefore classified based on the methodology they employ: *emission avoidance*, *emission reduction*, *novel CDR* or *conventional CDR*, in tandem with the categories of *mixed (mainly avoided)* and *mixed (mainly CDR)* (see full classifications in the Chapter 4 Technical Appendix).

The registry data for novel CDR and for conventional CDR are not directly comparable.

Novel CDR. Most of the contracts within the VCM for novel CDR are for future deliveries (meaning the actual CDR will not take place until some months or years later). The mean projected delivery time for novel CDR purchases in 2023 is three years; multi-year offtake agreements may include purchases where deliveries happen as far as 11 years in the future.[123] In the analysis, data are presented on purchase agreements for future deliveries (pre-purchases with upfront payment, or binding offtake agreements with payment on delivery) to measure demand, as well as for tons already delivered to measure supply.

Conventional CDR. In contrast, for projects involving conventional CDR only the volumes of credits issued and of credits retired are available (see Box 4.1 for definitions). Since there is very little data on potential pre-purchase for conventional CDR, and as offtake agreements are less common for conventional CDR, retirements are used here as an imperfect proxy for credit demand – alongside issuances, which measure supply.

Prevalence of project types within the VCM

The vast majority of projects on the VCM are emission reduction projects (see Figure 4.2). These projects tend to focus on decarbonizing energy or industrial systems. Of the project types that deploy a mix of methodologies (avoided emissions, emission reduction and/or CDR), *mixed (mainly avoided)* emission projects are the most common – and even more common than "pure" *avoided emissions* projects. These *mixed (mainly avoided)* projects include some types of REDD+ and forest management.

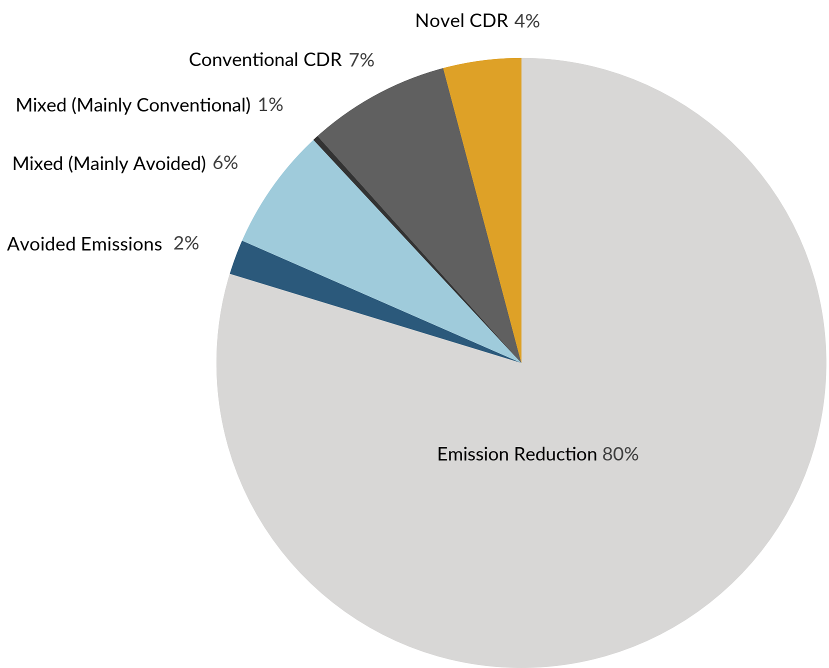


Figure 4.2 *Proportion of projects within the voluntary carbon market, 2022–2023, by project type (based on classification of project methodology). CDR = carbon dioxide removal.*

However, the prevalence of these projects in the carbon market differs considerably once the volume of carbon credits is analysed, instead of the number of projects.

As Figure 4.3 reveals, emission reduction projects dominated the VCM in both 2022 and 2023 in terms of the volume of carbon credits, both supply (measured in tons issued) and demand (measured in tons sold). These projects are followed in volume of carbon credits by avoided emissions projects and conventional CDR projects. Overall, issuances continue to outstrip retirements, resulting in a significant backlog of carbon credits from 2022 and 2023 that remain available to be retired, as well as from years prior.

2023 saw carbon credit supply decrease while demand increased, especially for CDR.

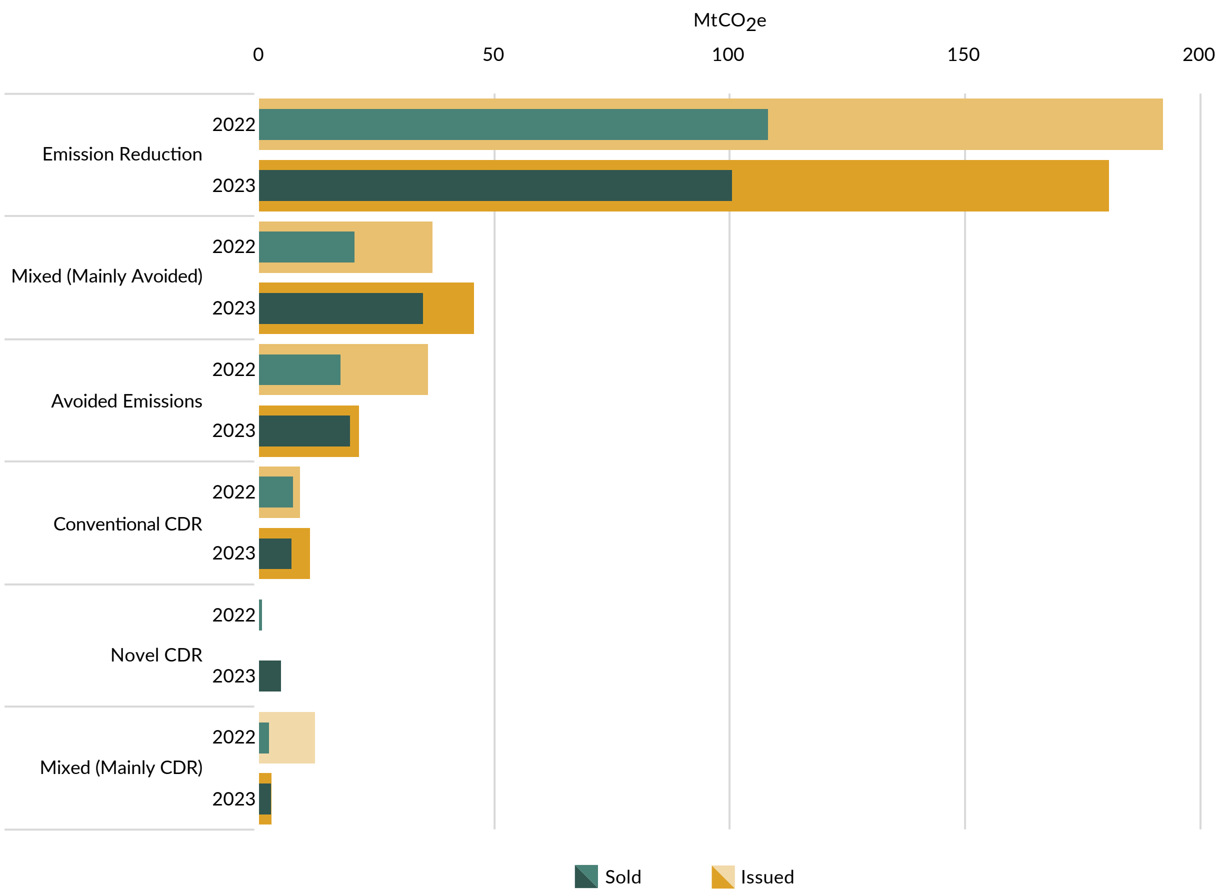


Figure 4.3 *Volume of carbon credits issued and sold on the voluntary carbon market, by project methodology type, 2022–2023. CDR = carbon dioxide removal.*

Table 4.1 breaks down the volume of credits for conventional and novel CDR in 2022 and 2023 (credits issued and sold (retired) in the case of conventional CDR, and credits issued and sold in the case of novel CDR. The results show that the VCM facilitates much more conventional CDR than novel CDR at present.

The total volume of novel CDR credits sold in 2022 – just over half a million tons – appears very small compared with the gigaton scale that may need to be reached in future (see Chapter 9 – The CDR gap). However, there has been vast growth in the VCM in 2023 – a sevenfold increase – led by large purchases by big enterprises. Microsoft, for example, purchased 3.2 $MtCO_2$.

Type of CDR credit	2022	2023
Conventional[a] CDR credits issued	20,360,212	13,255,438
Conventional[a] CDR credits sold (retired)	9,362,211	9,319,439
Novel CDR credits issued	47,905	83,180
Novel CDR credits sold	615,107	4,638,766

[a] Includes projects that adopt a mixed methodology but are mostly conventional CDR; excludes those that are mostly avoided emissions.

Table 4.1 *Estimation of carbon dioxide removal (CDR) volumes on the voluntary carbon market, 2022–2023. Issuance exclusively refers to ex post credits traded through the main offset standards. The majority of novel CDR credits are ex ante, meaning that the impact (removal activity) will occur in the future. This table reports issuances from Puro.earth, resulting in a lower volume than the overall novel CDR deliveries shown in Figure 4.4.*

There was also a significant shift in conventional CDR, which shrank in 2023 compared with its 2022 size. Another key difference between conventional and novel CDR is that most conventional CDR occurs without the involvement of carbon markets. Indeed, carbon credits issued for afforestation represent less than 1% of afforestation that occurred in 2023. The carbon market plays a more important role for the deployment of novel CDR, evidenced by the pre-purchase volume in 2023 exceeding the total amount of CO_2 removed through novel CDR methods in the same year (see Table 4.1 and Figure 4.4).

Prevalence of different CDR methods within the VCM

As Figure 4.4 shows, a much larger amount of conventional CDR (top panel) is facilitated by the VCM than novel CDR (bottom panel), the bulk of which is afforestation and reforestation. The figure also shows a surge in novel CDR tons sold between 2022 and 2023, but only a minuscule fraction of these sales has been delivered to date.

Box 4.4 reconciles the numbers on novel CDR in this section with estimates quoted elsewhere in this report.

The VCM facilitates much more conventional CDR than novel CDR at present

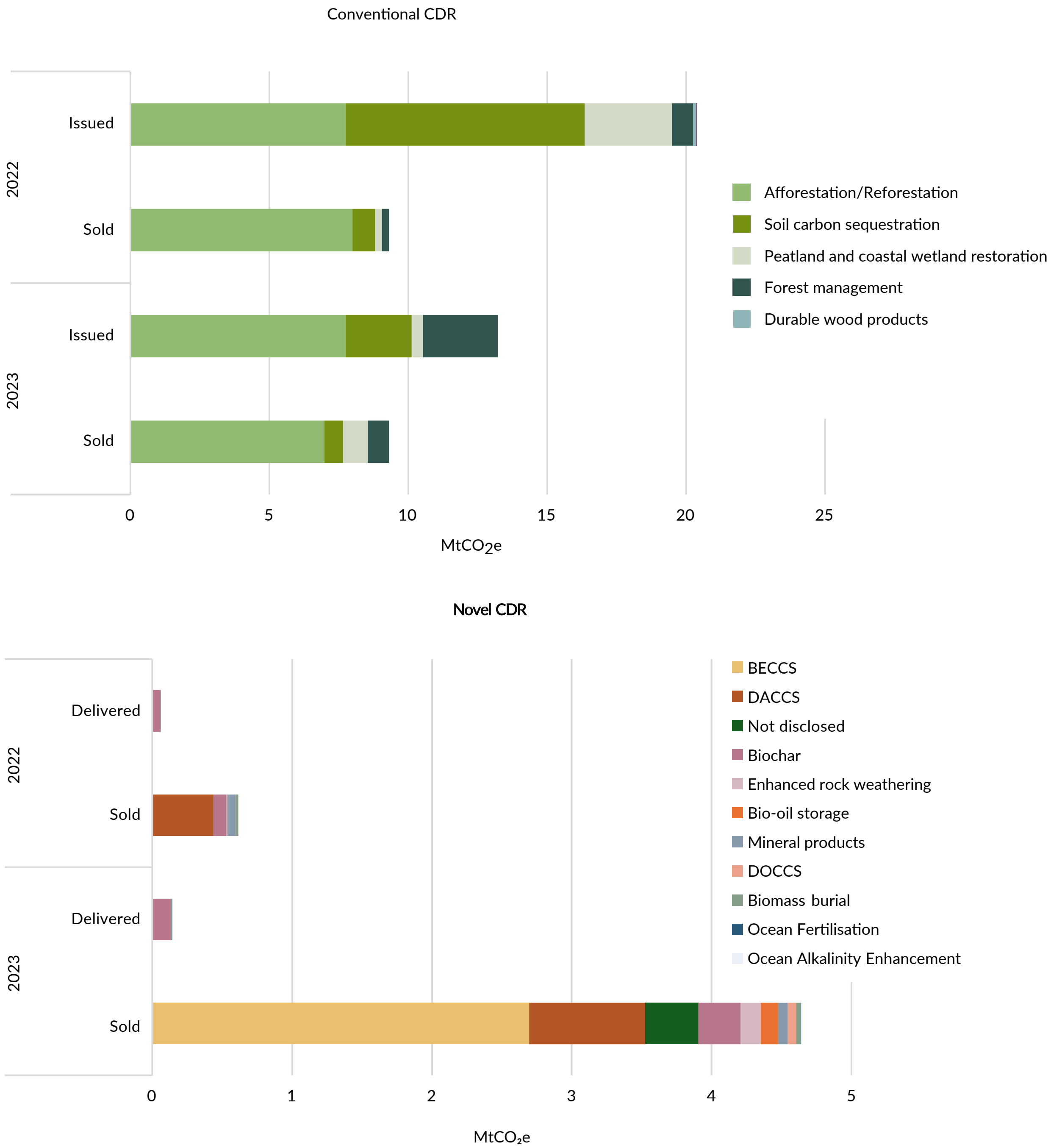


Figure 4.4 *Breakdown of the volume of carbon dioxide removal (CDR) in the voluntary carbon market (VCM) by CDR method, 2022–2023. Top panel: conventional CDR; bottom panel: novel CDR. BECCS = bioenergy with carbon capture and storage; DACCS = direct air carbon capture and storage; DOCCS = direct ocean carbon capture and storage.*

Box 4.4 The difference in estimates of current novel CDR volumes within this report

Chapter 7 (Current levels of CDR) cites 1.35 $MtCO_2$ removed via novel CDR in 2023. This chapter finds that only 139,202 tons were reported in VCM registry data as having been delivered through novel CDR in 2023. This discrepancy stems from the following:

Delivery of novel CDR outside the VCM. Most of the novel CDR by volume is occurring without the generation of associated carbon credits for trading on the VCM. The market data used within this chapter suggest that none of the removal from bioenergy with carbon capture and storage and about 17% of the removal from biochar reported in Chapter 7 were delivered as CDR credits in 2023.

Differences in methodology. Chapter 7 reports gross CDR quantities, meaning the amount of atmospheric CO_2 captured and placed in durable storage, without accounting for any emissions during the whole life cycle of the activity. In contrast, protocols for issuing VCM credits usually include at least some estimation of these emissions. Including these emissions can substantially reduce the net amount of CO_2 removal that can be claimed; for instance, the life cycle emissions of ethanol production together with bioenergy with carbon capture and storage are currently similar to, or even outweigh, the removals.[124] The exact distribution of these emissions between the CDR activity and co-products depends on the choice of allocation method.

Cost of carbon credits within the VCM by CDR method

Table 4.2 shows the prices per carbon credit for different methods of conventional and novel CDR, where the latter are an order of magnitude higher than the former. On average, credits from conventional CDR methods cost three times more than reduction or avoidance credits. The average volume-weighted price for novel CDR credits currently exceeds that of reduction or avoidance credits by a factor of 100.

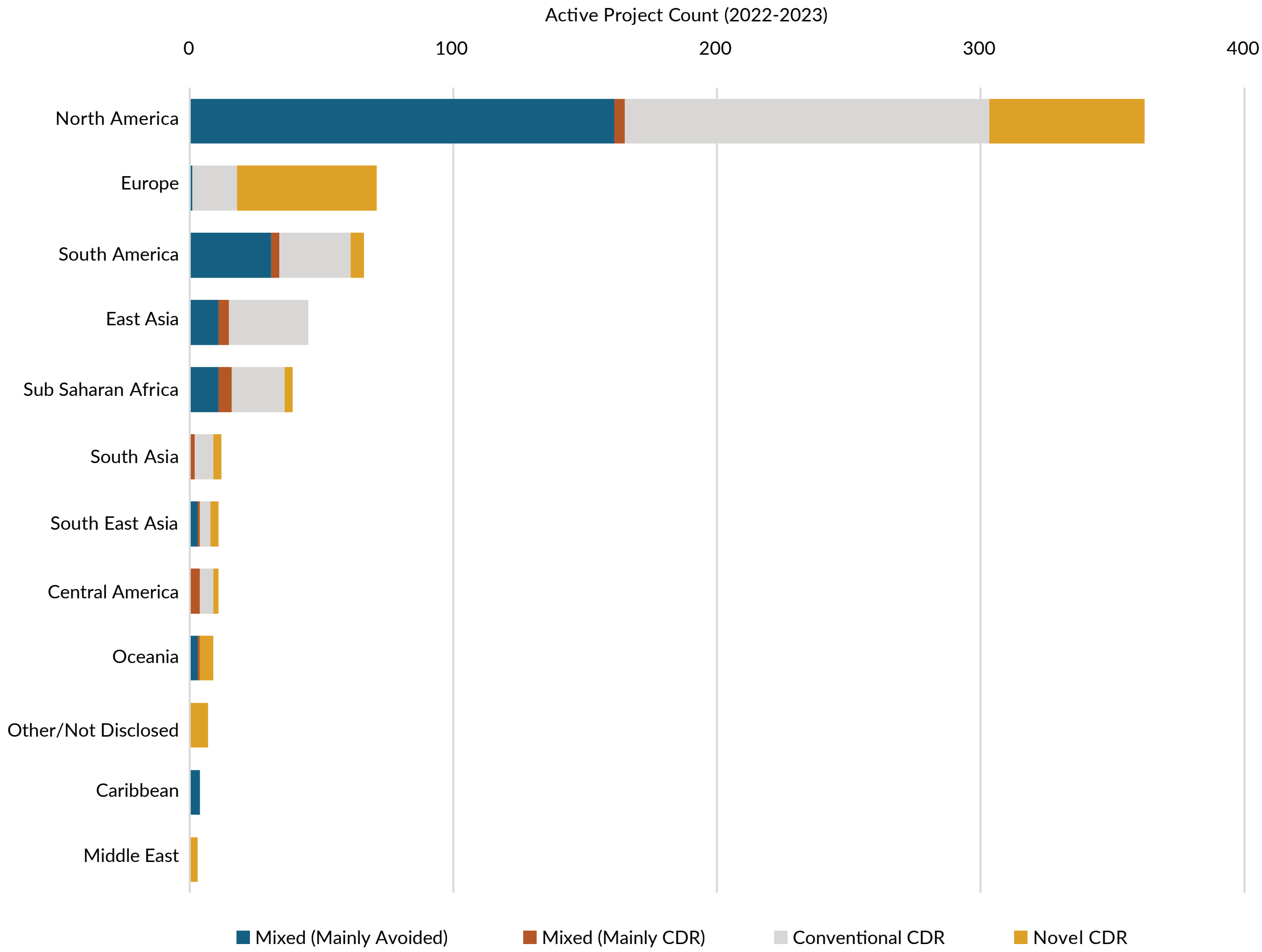
CDR method	Weighted average price ($)	
	2022	2023
Afforestation/reforestation	12	16
Bioenergy with carbon capture and storage	No data	300
Biochar	212	131
Biomass burial	92	111
Bio-oil storage	600	505
Direct air carbon capture and storage	1,261	715
Direct ocean carbon capture and storage	984	1,402
Enhanced rock weathering	434	371
Forest management	15	12
Mineral products	471	No data
Ocean alkalinity enhancement	No data	1,608
Total	303	488

Table 4.2 *Volume-weighted average price per carbon credit from transactions where the price is known, by carbon dioxide removal (CDR) method, 2022–2023. Durable wood products are not included. Data sources: CDR.fyi, 2024;[123] Ecosystem Marketplace, 2023.[116]*

Geographical distribution of CDR projects within the VCM by project type

Figure 4.5 shows the number of active projects on the VCM that either are CDR projects or have methodologies that allow for CDR (i.e. are mixed), broken down by region/country (top panel). VCM projects with the potential to generate CDR are more prevalent in the northern hemisphere than in the southern hemisphere and are especially concentrated in North America (bottom panel). This distribution of CDR potential in Figure 4.5 is largely due to the sizeable presence of forest management projects in Mexico and the US. Europe has the highest volume of novel CDR projects, which are principally biochar projects.

Active CDR* projects are distributed globally, but the majority are based in North America.



Active Project Count (2022-2023)

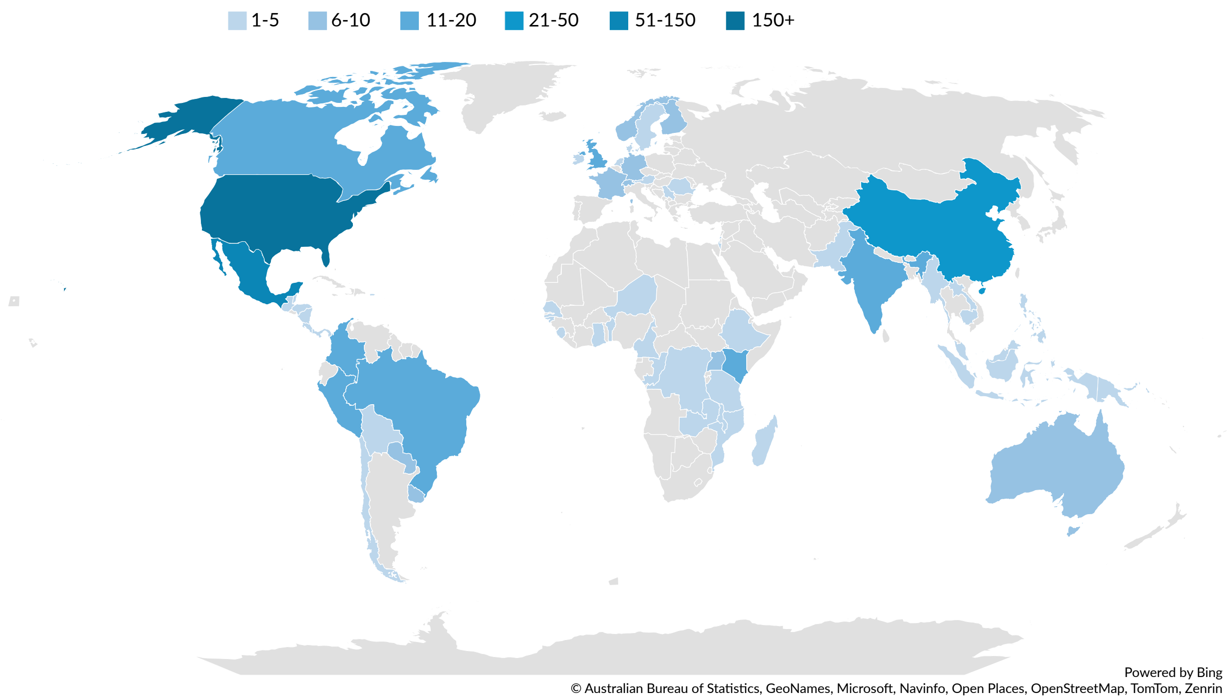


***Figure 4.5** Regional (top) and country distribution (bottom) of active carbon dioxide removal (CDR) projects in the voluntary carbon market, 2022–2023.*[91]

4.3 Future prospects of CDR on the VCM

The voluntary market for novel CDR is growing but uncertain. In the meantime, the VCM is currently leading the way in developing methods for measuring, reporting and verifying CDR projects.

As of the start of 2024, CDR is gaining increasing attention on the VCM at large. This attention has been supported by the development of new standards for novel CDR methods by the main carbon crediting programmes. It has also been promoted by revisions to existing methodologies that facilitate a clearer distinction between different credit types, thus increasing the visibility of CDR (see Box 4.2). But the increase in attention is perhaps most evident in the nascent but growing market for novel CDR, which saw a sevenfold increase in purchases during 2023.[123] This rapid development sets the scene for the analysis of the future prospects for market-based CDR.

CDR purchasers

The first step in understanding future prospects is to map who is driving the demand for CDR today. Because of the high number of credits that are purchased (retired) anonymously,[91] the visibility of corporate buyers in the VCM is patchy, and the way in which they use carbon credits is often opaque.[125] Investigations of buyer profiles and demand analyses can therefore only be regarded as an indication of the true nature of the buyer landscape.

Different assessments of the largest buyers on the VCM suggest that many of them are fossil fuel majors.[116,121,126] Therefore, doubts remain as to whether engagement in the VCM positively impacts actors' decarbonization efforts or whether it occurs alongside (and perhaps even promotes) continued high-emitting behaviours. As a result, it is important to consider not only *whether* actors are buying but also *why* they are buying.
Evidence from surveys of buyers engaging in the VCM (by purchasing reduction, avoidance or removal credits) indicates that purchase of credits is largely driven by the buyers' voluntary climate targets.[127,128] In comparison, CDR.fyi's recent survey of novel CDR buyers showed that these purchasers are driven to engage in the CDR market by their intrinsic motivation to accelerate the scale-up of the industry.[119] Transparency as to the identities of buyers of credits from novel CDR methods is higher than for buyers of conventional CDR credits. An assessment based on the number of unique buyers of novel CDR reveals that more than half of all such buyers (63%) share a background in the financial or service sector and are based in the US.[100]

VCM growth projections

Despite the recent criticism of project practices on the VCM, the volume of credits sold at the start of 2024 surpassed sales from the same period in previous years. This serves as an early indication that the VCM continues to grow.[120] Several predictions have been made of the size of the VCM in 2030 and 2050. Some predictions, such as by Bloomberg NEF, suggest that it could reach $1 trillion by 2050.[128] Other estimates are more conservative, predicting it to reach $100 billion in 2030 and $250 billion by 2050.[129] The Boston Consulting Group (2023)[115] estimates an annual demand of approximately 40–200 $MtCO_2$

for novel CDR in 2030, outstripping the announced supply of approximately 15–32 $MtCO_2$.

A crucial factor in these growth projections is the future price development of different types of credit. CDR, whether conventional or novel, tends to require more capital investment and thus attracts higher price points than credits from avoided or reduced emissions. Because of this, a more nuanced stocktake of investment, rather than an evaluation of credits sold, tends to more accurately capture the increasing willingness of buyers to support CDR projects. While CDR represents only a small portion of the total carbon credits generated through the VCM today (see Section 4.2), this proportion may shift, given parallel signals for greater demand for CDR in the coming years.[130]

Demand-side developments

Several pending developments on the demand side could also affect growth projections for the VCM. One such development is the continued operationalization of Article 6 of the Paris Agreement.[131] Article 6.4, for instance, establishes a new UNFCCC-facilitated mechanism for the validation, verification and issuance of high-quality carbon credits (see Chapter 10 – Monitoring, reporting and verification). However, the mechanism still appears several years away from operationalization, with the removals guidance being one of the most controversial elements of ongoing negotiations among the parties to the convention. As with the broader carbon market, the stringency of the multilateral rules established under Article 6.4 will heavily sway its overall effectiveness as a tool for financing CDR. A breakthrough on this could be instrumental in supporting further demand for CDR.

Another notable development is that several countries, including Colombia and South Africa, have taken steps to integrate carbon credits into compliance markets.[132] While these schemes are not limited to CDR-based credits, an overall shift from the voluntary to the compliance market setting could garner significant funding for CDR. Yet true fungibility – whether different CDR types should be treated as equivalent to emissions trading scheme units or other forms of carbon credit – remains an ongoing contention.

A continued role for markets in supporting the development of CDR

While carbon markets have been a part of the climate change mitigation toolbox for several decades, CDR remains a small part of the VCM. Conventional CDR continues to dominate novel CDR in the VCM in absolute terms, despite demand for novel CDR growing more quickly. As the VCM may not offer enough finance for scaling CDR, depending on how much will be needed, compliance markets will likely play an essential role in driving significant future demand for CDR. But as integration of CDR at scale in compliance markets is still far off, there appears to be a clear and ongoing role for the VCM in driving experimental and additional CDR in the years to come. In this way, the current VCM offers important insights for a transition of CDR into compliance markets – most notably in getting novel CDR methods tried out in practice and in leading the way in developing methods for monitoring, reporting and verifying CDR projects (see *Chapter 10*).

Box 4.5 Limitations and knowledge gaps

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

- *Differentiating CDR credits from emission avoidance and emission reduction credits on the VCM:* As the distribution of avoidance, reduction and removal credits for projects remains indiscernible in many cases, the true market size for CDR credits remains unclear.
- *Broadening monitoring, reporting and verification* to capture the non-CO_2 impacts of CDR, which is increasingly gaining importance in buyers' decisions.
- *Developing a strategy for the transition from VCM to compliance markets* to identify the role the VCM will play in scaling CDR in the future.

5

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Chapter 5 | Policymaking and governance

National-level carbon dioxide removal (CDR) policy has made some progress in supporting scientific research and demonstration for novel CDR. But there is less development in other areas where policy plays a guiding role.

Key insights

- CDR policy gained momentum in 2023, but important policy and governance ambiguities (e.g. on residual emissions) remain.
- At the international level, CDR received considerable attention at the sidelines of the COP28 negotiation process (side events, reports, launch of new cooperation); however, its presence in official negotiations was limited.
- National and subnational policies have progressed towards regulating and establishing incentives for initial novel CDR deployment projects, as well as to funding research and development.
- Safeguards against harms from improper deployment need more focus in future CDR governance.
- Case studies on Canada, China, Japan and Saudi Arabia show that CDR is embedded in broader policy landscapes (e.g. agricultural or industrial policy) which address some CDR policy needs but that dedicated CDR policies are also needed.
- A better understanding of specific national contexts can help inform and instigate new initiatives and provide opportunities for future cross-sectoral and cross-country collaborations and alliances.

The IPCC has highlighted three main roles for CDR in mitigation strategies: to reduce net emissions in the near term, to counterbalance residual emissions in the medium term, and to achieve net-negative emissions in the longer term (see Chapter 1 – Introduction). To effectively perform these functions, dedicated policies and innovative governance will be required.[133–135]

This chapter discusses both policy and governance. Governance, as defined by the United Nations Development Programme, is "the system of values, policies and institutions by which a society manages its economic, political and social affairs through interactions within and among the state, civil society and private sector".[136] Policy, by contrast, refers to specific procedures and protocols, regulations, laws, voluntary actions and other instruments enacted to achieve social goals.

5.1 The state of dedicated CDR policy

Progress is being made in the governance of research and development for novel CDR, but further policy to safeguard against potential harmful deployment and to enable public participation would be required to meet the expectations of stakeholders.

The diffusion of net zero pledges and targets in the past few years has lent momentum to CDR. But scaling up CDR will require the implementation of dedicated and actionable policy sequencing that translates this momentum into development and deployment strategies, as well as systematic integration of CDR into climate, land-use, agriculture, biodiversity, energy and industrial policy.[137–141] To become an element of ambitious mitigation strategies, it is essential that CDR policy ambitions are supported by monitoring, reporting and verification (MRV); actionable deployment incentives; transparent approaches for designating residual emissions; market integration; and near-term targets.[142–145]

Functions of governance for CDR

As important as innovation and upscaling are, effective CDR policy needs to focus on more than just those goals. Policy and governance discussions need to reflect on what this governance does for CDR and other social goals and on how this governance is embedded and linked to other governance structures in climate change mitigation and other policy areas. In particular, four functions of governance for CDR stand out: (1) enabling policy, which may include supporting CDR research and development or creating standards for MRV; (2) regulatory policy on emissions, requiring that emissions be compensated by removals; (3) policy that restricts harmful deployment, which may involve limiting fraudulent activities related to CDR or creating regulatory safeguards to protect communities and ecosystems; and (4) policy that improves decision-making, such as facilitating public deliberation or community assessment.

Current progress in these functional areas is uneven, as analysed in this chapter. The most progress is being made in support of research and innovation for novel CDR and in new initiatives to establish standards for MRV for both novel and conventional CDR. The other functions are often sidelined or ignored in new CDR initiatives at all levels of governance: international, supranational, national and, in some countries, subnational.

International CDR governance

CDR policy gained momentum in 2023 at both the international and regional scale. At the international level, CDR received considerable attention at the sidelines of the official COP28 negotiation process (side events, reports, launch of new cooperation); however, its presence in official negotiations was limited. CDR was addressed in negotiations on the guidance on carbon crediting methodologies and greenhouse gas removals under Article 6.4 of the Paris Agreement, the mechanism for voluntary cooperation based on carbon credits. The discussion included topics such as the social and environmental safeguards for removals and details of carbon accounting practices (see Chapter 10 – Monitoring, reporting and verification) and will have to be continued at future UNFCCC meetings. The failure to agree on a guidance document is a reminder of the politics inherent in multilateral CDR governance – conventional CDR having long been a highly contentious issue in the UNFCCC negotiations.[146] The final global stocktake text called for the acceleration of zero- and low-emission technologies, including a short and rather vague subparagraph on "abatement and removal technologies such as carbon capture and utilization and storage".[147]

Despite the limited progress in official UNFCCC negotiations, there are many examples of progress within the CDR landscape:

- The end-to-end integrity guidance framework from standard setters in the voluntary carbon market, which discusses the use of carbon credits to compensate for residual emissions[148]
- Mission Innovation's CDR Mission, launched in 2021 and co-led by Canada, Saudi Arabia and the US, which continues undertaking technical work on "biomass carbon removal and storage" and on "enhanced mineralization"[149,150]
- The Group of Negative Emitters, launched at COP28 by founding members Denmark, Finland and Panama, with the goal that group member countries will remove more carbon dioxide than they emit[151]
- Private sector efforts by corporate entities and registries (e.g. creating standards), which can be seen as a form of CDR governance (see Chapter 10 – Monitoring, reporting and verification)

However, when it comes to policy by governments, commitments to CDR remain vague. The official documents submitted by countries to the UNFCCC, such as long-term strategies and nationally determined contributions (NDCs), include – sometimes explicitly, sometimes implicitly – pledges or expectations for CDR.[152] Those expectations for conventional CDR have been criticized for betting too much on land and ignoring the negative impacts of using land for mitigation.[153–155] For novel CDR, the pledges are very limited, with only a few countries explicitly providing a vision and/or scope for these CDR methods (see Chapter 9 – The CDR gap). Not only are these commitments often vague, but strategies to operationalize them in national policies are often lacking. Analysis specific to a country's political, social and ecological landscape that incorporates potential policy pathways will need to be developed.

CDR policies in countries

National and EU policies have, overall, progressed towards regulating and establishing incentives for initial CDR deployment projects, as well as to funding research and development. Australia, Canada, the EU, Japan, Norway, the UK and the US have government funding programmes for CDR demonstration projects (see Chapter 3

– Demonstration and upscaling). The EU has been focused on setting up governance frameworks for CDR. One prominent development is the progress made towards the EU's Carbon Removal Certification Framework. This certification will initially be voluntary but could potentially be a tool for integrating removals into the existing climate policy architecture.[156] In the US, the focus has been on innovation and demonstration projects, for which some of the funding appropriated in prior infrastructure legislation has been released, such as $1.2 billion out of an eventual $3.5 billion for direct air capture hubs (see Chapter 3 – Demonstration and upscaling, Box 3.1). Box 5.1 contains specific updates on the country case studies included in *The State of Carbon Dioxide Removal* 1st edition.

Countries are also working out how to integrate removals into carbon market plans and policies. In India, for example, there are plans to include both removals and reductions in the planned carbon credit trading scheme, which has both compliance and voluntary elements.[157] Other countries, like China and New Zealand, have already gained some experience with trading of afforestation credits in their compliance or voluntary carbon markets. Some governments are also planning to pilot test the trading of removals between countries; for example, Sweden and Switzerland signed a declaration of intent to test how a symbolic amount of removals can be transferred.[158] This transfer will provide valuable information on how removals can be exchanged within a Paris-compliant framework.

Thus far, tangible policy progress at the national level has been mostly in funding research, development and demonstration (RD&D); most other considerations are merely at a discussion level, especially for novel CDR methods. Part of the reason for the limited progress is the complexity created by the number of sectors and technologies involved, from the ocean, soils and forest to agriculture, energy, industry and more. CDR-related policies, therefore, have to cross boundaries: between regions, between institutions, between policy objectives (e.g. food, security, adaptation, biodiversity), and more. Depending on the governance architecture in place, this cross-boundary nature can lead to synergies, but it can also lead to risks, such as political conflicts from other policy areas spilling into climate policymaking. A key example is soil carbon sequestration: Initiatives in this area could potentially lead to more sustainable agriculture or forestry. However, initiatives aiming to do so will have to deal with both climate and agricultural politics, potentially increasing the risk of backlash.

Despite this complexity, CDR is moving up the policy agenda in many countries, and actors in research, business, NGOs and advocacy are increasing their efforts to track CDR policies. While these efforts help to map the current CDR policy landscape, it should be recognized that CDR policy does not start from scratch but already exists implicitly, for example in the governance of the forestry or agriculture sectors. CDR policy is therefore developed in relation to existing policy frameworks and builds on path dependencies within other policy areas. Although there are overarching trends in policy development (several of which are discussed in this chapter), CDR policy initiatives are, by their very nature and like all mitigation policymaking, context specific. Qualitative case studies that provide insights into these specificities are therefore an important complement to exploring the state of CDR (see Chapter 9 – The CDR gap).

Ambiguity in CDR policy

More than 150 countries have proposed net zero emission targets since the adoption of the Paris Agreement.[159] It is widely recognized that achieving these targets will require scaling up CDR, supported by dedicated policy strategies, alongside reducing emissions. However, despite policy experimentation and an increase in discussions of CDR policy, important policy-related ambiguities remain. Fundamentally, the role of CDR is often not consistently specified; in other words, it is unclear whether it is intended to contribute to net emission reduction, counterbalance residual emissions, or contribute to eventually reaching net-negative emissions (see Chapter 1 – Introduction).[143] For example, there is often conflation between carbon removals and carbon offsets in both policy and corporate strategies aimed at reducing net emissions in the short term. Policy debates also often overlook the crucial difference between carbon dioxide (CO_2) sources (fossil versus biogenic or atmospheric).[25,160] While countries like Germany and Sweden, as well as the EU, are developing strategies related to residual emissions,[161–165] this is not common. The amount and type of residual emissions that need to be counterbalanced by CDR to achieve and maintain net zero emissions are still ambiguous in most countries.[143]

Without greater clarity from governments on the role of CDR in mitigation strategies, there is a risk of greenwashing or obstruction of emission reduction – a dynamic in which a promised CDR scale-up obstructs the reduction of gross greenhouse gas emissions at the rates required to achieve climate goals. Many civil society groups and academics continue to raise concerns about this risk.[166–169] If CDR is treated simply the same as a carbon offset, or if policies are not put in place to ensure that CDR is used to counterbalance only "legitimate" residual emissions,[160] CDR capacity will be used to delay abating emissions that could be addressed at their source. The current lack of specification in many strategies therefore decreases the credibility and legitimacy of CDR efforts and could hinder the most critical factor in climate change mitigation: the reduction of gross emissions.

Some jurisdictions are moving to confront the risk of greenwashing or the obstruction of phasing out fossil fuel infrastructure. For example, California's recently passed law AB 1305, Voluntary Carbon Market Disclosures, requires any carbon offsets and removals that are exchanged to specify methodologies and verification information to back up their removal claims. Another approach is to separate mitigation targets into CDR targets and gross greenhouse gas emission reduction targets. While such a separation would effectively address the issues raised above, the actual implementation would be challenging. For example, in the EU, only a limited amount of net removals from the land use, land-use change and forestry (LULUCF) sector can contribute to the achievement of the 2030 abatement target (up to 225 $MtCO_2e$). However, capping the contribution of net removals from the LULUCF sector to achieve the abatement target does not address the share of gross emissions and removals. A similar target design is being discussed for 2040,[163] which again shows that the idea of separate targets is gaining traction, but the actual implementation and clear differentiation of separate targets is both politically and administratively challenging. Such efforts tackle some of the concerns about CDR being mobilized as an offset for emission reduction, but this risk needs to be addressed at all levels and stages of policymaking, target setting, MRV schemes, deployment incentives and market integration, and within the wider policy landscape.

5.2 Tracking emerging CDR policy

As CDR policy moves from concepts and pledges to deployments on the ground, there is an opportunity to understand how CDR policies impact real-world developments and explore links with other policy domains.

An effective assessment of the current state of CDR policy needs to recognize that the policy space is rapidly evolving and that many ambiguities remain. Merely counting explicit CDR initiatives and pledges would not provide sufficient information; the assessment needs to also identify policy gaps, the politics of including CDR as part of mitigation strategies, and adverse effects that could stem from the policy's implementation.

This chapter assesses CDR policies and governance in relation to three key dimensions: (1) the overarching CDR policy architecture, (2) innovation and scaling policies, and (3) safeguards and links with other policy domains.

Overarching CDR policy architecture

Since the adoption of net zero targets, discussions about explicit CDR policy have entered the climate policy arena. Implicit CDR policy for conventional CDR, such as forestry, has been part of climate policy architectures before, but explicit CDR policy requires an overarching governance structure that defines the function of CDR in mitigation strategies. Such a structure would specify the role of removals in mitigation strategies to counterbalance residual emissions (e.g. through separate targets). In addition, it would require robust MRV schemes as well as liability mechanisms to deter the reversal of removed carbon and to ensure transparency.

Innovation and scaling policies

Given the very different technology readiness levels of CDR methods, the specific design and focus of innovation and scaling policies will differ considerably for novel and conventional CDR. Key elements in such policies will be initiatives and funding schemes for research and development, deployment incentives, and public or private procurement, as well as market integration into voluntary and/or compliance carbon markets.

Safeguards and links with other policy domains

Policy objectives beyond the carbon removed are going to shape how CDR is deployed. CDR policy intersects with many social goals: safety, environmental health, energy security, food security and more. CDR policy may thus involve policies to ensure worker or community safety, standards for environmental integrity, or policies to maximize co-benefits. It is also critical to consider that other policies (e.g. regulations concerning parts of process chains like CO_2 injection or transport infrastructure, or regulations on biodiversity protection and restoration) may shape, and are being shaped by, the output and outcome of CDR policy initiatives.

5.3 Case studies

Countries differ substantially in how and the degree to which they are turning their pledges into actionable incentives for CDR deployment – and in how they address other functions of CDR governance.

The State of Carbon Dioxide Removal 1st edition looked at the country case studies of Brazil, the EU, the UK and the US (see Box 5.1 for key updates on these countries). This edition extends the scope of the country case studies to include Canada, China, Japan and Saudi Arabia – countries that have received very little attention in the academic literature on CDR policy and governance. By systematically gathering information on the overarching CDR policy architecture, the innovation and scaling policies, and the broader policy landscape within a country, this report identifies the role of CDR in the case study country and the similarities and differences between countries in how CDR is approached as an element of climate policy. In addition, the report looks at the existing institutional architecture and policies for CDR, how they shape current CDR policy development and how they are expected to shape future CDR policy initiatives. These case studies provide snapshots of CDR policy in selected countries in early 2024, an important starting point for identifying current trends and future challenges.

Box 5.1 Case study updates from The State of Carbon Dioxide Removal 1st edition (Brazil, EU, UK, US)

The State of Carbon Dioxide Removal 1st edition looked at four case studies: Brazil, the EU, the US and the UK. This box summarizes key policy initiatives in these countries since the publication of the first edition in January 2023:

Brazil. Since the change of government in 2023 and its new emphasis on climate ambition in general, conventional CDR together with pledges to reduce deforestation have received more attention. Initiatives include the recommitment to restore 12 million hectares of land by 2030, the Tropical Forest Forever Facility launched at COP28,[170] and the Arc of Restoration programme, aimed at ecological restoration and carbon storage.[171] In addition to these developments relating to conventional CDR, possible bioenergy with carbon capture and storage applications in ethanol production are being discussed and tested as novel CDR.[172,173]

EU. CDR has continued to climb up the political agenda in the EU. In addition to the Carbon Removal Certification Framework (see Section 5.1), CDR played a key role in the recommendation for the new 2040 climate target.[163] In a strategy on industrial carbon management, the European Commission highlighted the importance of novel CDR methods.[174] More concrete steps building on this strategy, including consideration of how CDR could be accounted for and covered under the EU Emissions Trading System,[175–178] will be facilitated by the next Commission, starting in late 2024.

UK. The UK government has taken several next steps on a broad portfolio of CDR methods[179] as well as in the Developing the UK Emissions Trading Scheme consultation – an initiative that confirmed a "carbon contracts for difference" approach for novel CDR, plus integration into the UK Emissions Trading Scheme cap. Furthermore, the government aims to develop an MRV standard.[179,180] Further steps were taken to incentivize the implementation of the much-discussed bioenergy with carbon capture and storage capacity at the Drax Power Station,[181] and CDR projects can now apply to access CO_2 transport and storage networks.[182] Efforts to trial ocean alkalinity enhancement, a method the government shows less interest in, through a project funded by philanthropy in UK waters has caused local protest.[183]

US. The US has started implementing funds that were authorized in the 2021 Bipartisan Infrastructure Law and the 2022 Inflation Reduction Act, which included selecting projects for the first $1.2 billion of the $3.5 billion Regional Direct Air Capture Hubs programme, as well as releasing funds for programmes that support soil carbon sequestration and ecosystem restoration in a way that would also enhance land-based removals. In relation to CDR specifically, $24 million for marine CDR research was funded through the National Oceanographic Partnership Program in 2023. The US also announced the $35 million CDR Purchase Pilot Prize programme, enabling the purchase of CDR credits from four removal methods: direct air capture, biomass carbon removal and storage, enhanced rock weathering, and planned and managed sinks. In February 2024, the Department of Energy announced up to $100 million for CDR pilot projects and testing facilities.

Canada

Like other countries, Canada has set a target of net zero greenhouse gas emissions by 2050 and enshrined it into law.[184] Canada is exploring the roles that novel and conventional CDR methods may play in reaching net zero, with methods including bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), and CDR in the LULUCF sector being explicitly considered.[185] Overall, CDR has received increasing attention in the country in recent years, with several related policies and strategies currently under development or published, including Canada's Carbon Management Strategy,[186] Canada's Greenhouse Gas Offset Credit System,[187] and the Natural Climate Solutions Fund.[188]

Credits generated under Canada's Greenhouse Gas Offset Credit System can be used to meet compliance requirements under the country's Output-Based Pricing System, which places prices on greenhouse gas emissions, or to reach voluntary climate goals.[189] While the credit system covers both emission reductions and removals, specific protocols are to be developed for several conventional and novel CDR methods, including forest management, enhanced soil carbon sequestration and DACCS.[190]

A variety of conventional CDR methods are targeted by the country's Natural Climate Solutions Fund, consisting of the 2 Billion Trees Program, the Nature Smart Climate Solutions Fund, and the Agricultural Climate Solutions Program.[188] While the 2 Billion Trees Program, among other co-benefits, aims to contribute to climate targets via afforestation, reforestation and restoration of forest habitat,[191] the Nature Smart Climate Solutions Fund provides funding for the protection, restoration and improved management of a variety of ecosystems storing carbon, including wetlands, peatlands, grasslands and forests.[192]

In addition to these policies with a larger focus on CDR, CDR is finding its way into other parts of Canada's climate-related strategies and policies. These include Canada's Defence Climate and Sustainability Strategy 2023–2027, which states that residual emissions of real property are to be addressed using permanent CDR to meet the country's net zero goal by 2050, and Canada's 2024 budget, which highlights that the achievement of the climate goals of the country's Low-carbon Fuel Procurement Program may be aided through the procurement of CDR.

Canada is further aiding CDR scale-up by funding both research and development and pilot applications of CDR.[193] To encourage early investment in CDR, a carbon capture and utilization (CCU) and carbon capture and storage (CCS) investment tax credit is currently under development, from which CDR methods with permanent storage are expected to benefit.[193] In addition to national measures, Canada is part of international innovation initiatives relevant to CDR, including Mission Innovation, whose CDR Mission is co-led by Canada, and the Carbon Management Challenge, which is focused on accelerating the deployment of carbon management measures.[194]

Canada is also in the process of improving its regulatory framework surrounding CCS, with many of the considered measures (some of which are already published) having high relevance for CDR.[193] Among these measures is the development of relevant regulatory frameworks for carbon storage. Three of Canada's provinces have already introduced policies regulating geological CO_2 storage, addressing aspects such as liability and MRV, and further provinces are currently developing their respective regulatory frameworks for CO_2 storage,[193] usually with a focus on fossil CCS applications. By 2030, Canada's CO_2 capture capacity is projected to reach 16 Mt annually, with further increases in capture and storage capacities needed for the country to achieve its net zero target by 2050.[193]

China

As the largest emitter of current annual emissions, China plays a critical role in global climate change mitigation efforts. Its pledge to achieve carbon neutrality by 2060 has attracted considerable attention and, as in other countries, raised the profile of CDR. However, the degree to which novel and conventional CDR methods are addressed by public policy differs considerably.

Conventional CDR has already had a relatively high profile in climate policy in China. China has a long history of afforestation/reforestation programmes and efforts to enhance the carbon sink in the LULUCF sector. Although CDR has not always been the main motive for these initiatives (they may have aimed to prevent, for example, desertification),[195] recent pledges and initiatives indicate that CDR's mitigation effects are becoming more important. These projects that enhance conventional removals tend to be shaped by top-down, command-and-control regulations[196] and can have local adverse effects on ecosystems and communities.[197] New initiatives to address conventional CDR methods are linked with agriculture policy and politics.[195]

China has committed in its NDC to increase forest stock by 6 billion cubic metres from 2005 levels and mentions enhancing carbon sink capacity as one of its "Ten Key Actions for Peaking Carbon Emissions".[198] The NDC also includes a reference to "blue carbon" and mentions that in the future "carbon sink trading will be integrated into the national carbon emission trading market".[198] However, as in other countries, ensuring the quality of certificates is a challenge, especially for non-permanent CDR methods like afforestation.[199]

With respect to novel CDR, there is a large number of patents for these methods in China (see Chapter 2 – Research and development) but no systematic support or incentive system. BECCS and DACCS methods are mostly discussed in expert communities, and there are no CDR-specific policy initiatives for novel CDR. A key element of the expert debate is the increasing attention on novel CDR in national modelling.[200,201] The national government is gradually promoting the RD&D and application of CCU and CCS, mainly through the development of pilot projects, as announced in the 14th Five-Year Plan.[202,203] The country's NDC includes these technologies in a list of "carbon peak pilots".[198] To date, however, existing CCS and CCU projects are mostly associated with fossil CO_2 sources, with most projects reinjecting CO_2 for enhanced oil recovery, and therefore are not CDR projects.[204,205] In preparation for the fifth "National Key Low Carbon Technologies List", BECCS and DACCS, as well as conventional CDR and monitoring technologies, are part of the five key areas for which the government is seeking proposals.[206]

Although no specific funding for BECCS or DACCS demonstration plants could be identified in China, reports from national studies on the status of CCU and CCS indicate that innovation in DACCS and BECCS is coming to the attention of decision makers.[201,203,207,208] For example, direct air capture is mentioned in the bilateral declaration between China and the US,[209] an initiative that further raises the profile of novel CDR methods. With regard to other CDR options, biochar has been addressed in multiple research projects,[210] and different marine CDR approaches are being researched.

Japan

Japan has announced its goal of reaching net zero greenhouse gas emissions by 2050[211] and has amended the Act on Promotion of Global Warming Countermeasures accordingly. In its long-term strategy, the country identified the application of both conventional and novel CDR methods as essential to tackling unavoidable greenhouse gas emissions and reaching net zero.[212] A multi-model study suggests a CDR of approximately 100 $MtCO_2$ per year by 2050 would be necessary for a cost-effective net zero policy.[213] While the issue of carbon management is rising in Japan's policy agenda, the most prominent focus is on "carbon recycling" (i.e. CCU).[214] Rather than permanent storage of carbon or CDR specifically, the processing of captured carbon into products would be the focal point, though parts of this carbon recycling agenda are expected to be directly or indirectly beneficial for CDR.

In its NDC, Japan estimates that overall greenhouse gas removals will reach nearly 50 Mt per year by 2030. This quantity, however, represents roughly the same level of CDR as in 2013, the reference year for Japan's 2030 emission reduction target. Japan further intends to secure international emission reductions and removals cumulatively totalling 100 $MtCO_2$ per year by 2030 via the country's Joint Crediting Mechanism.[215] While removal quantities per CDR method are not yet specified in the country's NDC or long-term strategy, Japan anticipates the need for measures to enhance the forest, cropland, natural environment, and coastal and ocean carbon sinks, together with the promotion of urban revegetation and steps to further the development of DACCS.[212]

Like other countries, Japan has developed crediting schemes relevant to CDR. Both the government-managed J-Credit Scheme and the voluntary J-Blue Credit Scheme allow for the creation of CDR credits for the application of conventional CDR methods such as forest management, afforestation and coastal wetland restoration,[216–218] with the J-Credit Scheme also covering greenhouse gas emission reductions.[217,218] Credits issued under these schemes can be traded and used for offsetting purposes.[217] A methodology is now being developed for including direct air capture in the J-Credit Scheme.[219,220] In April 2024, it was announced that Japan's national emissions trading system will allow for the inclusion of CO_2 removals as eligible carbon credits in the system's voluntary first phase. The category of eligible carbon credits will include CCU, coastal wetland restoration, BECCS and DACCS.

Japan also provides funds for research and development as well as for innovation activities. CDR pilot projects can receive funding from the Green Innovation Fund, and further funding for research and development as well as pilot projects is provided via the cabinet-level Moonshot Research and Development Program,[194,221,222] whose target technologies include direct air capture, enhanced rock weathering and coastal wetland restoration.[222] As a core mission member, Japan collaborates with other countries on Mission Innovation's CDR Mission and aims to accelerate the introduction of carbon management measures under the Carbon Management Challenge.[194,223] Japan's government has also sponsored CDR road map reports through the Innovation for Cool Earth Forum, focusing on CDR methods such as DACCS, enhanced rock weathering, coastal wetland restoration and BECCS, among other themes.[224]

In recent years, Japan has also been developing CCU and CCS strategies and policies, many of which are relevant to CDR methods that rely on CCS technologies (e.g. BECCS, DACCS). However, the share of CDR-related CO_2 storage has yet to be determined for either annual or 2050 CO_2 storage targets. To address gaps and ambiguities in Japan's current legal framework surrounding CCS, the country is developing the CCS Business Act, which is expected to cover the stages of capture, transportation and storage of CO_2 and to tackle issues of storage rights, liability, monitoring and export of CO_2.[225]

Saudi Arabia

Saudi Arabia has announced its ambition to achieve net zero greenhouse gas emissions by 2060. As a major producer of fossil fuels, it has emphasized in several international forums the importance of a circular carbon economy, in which removal is one of the four key principles: reduce, reuse, recycle, remove.[226] Although the country currently has no legally binding or separate target for CDR, the government is developing a CDR strategy to prepare for the next steps in CDR policymaking.

Recent modelling suggests that a large amount of CDR would be required to achieve net zero greenhouse gas emissions: 250–371 Mt per year by 2060.[227] In addition to these modelling studies, work is under way to identify optimal locations for DACCS clusters in the country and to conduct feasibility studies for various CDR methods (notably DACCS and energy-from-waste with CCS). Recent work by the King Abdullah University of Science and Technology has evaluated the availability and suitability of CO_2 geological storage across Saudi Arabia, including in saline aquifers and depleted oil and gas fields.[228]

Some CDR-related pilot projects have emerged in the private sector, including for direct air capture. The State-owned oil and gas company Saudi Aramco, in collaboration with others, is developing the Climatree technology, a direct air carbon-capturing microalgae photobioreactor integrated with a patented CO_2 scrubber;[229] the prototype was installed at Al-Qurrayah in 2022.[230] In addition, Aramco is collaborating with Siemens Energy to develop a direct air capture test unit in Dhahran. The test facility, to be completed in 2024, will demonstrate the removal and storage of 12 tons per year of CO_2. It is expected that this will pave the way for a larger pilot plant with an annual CO_2 capture capacity of 1,250 tons.[231] In addition, Aramco and the King Abdullah University of Science and Technology are working on a CO_2 storage method, converting CO_2 into carbonate rocks.

Overall, Saudi Arabia considers DACCS the CDR option with the highest potential, and research is under way to determine its potential in the country. Saudi Arabia is one of the co-founders of the Mission Innovation CDR Mission, launched in 2021, and together with Australia is leading the development of the 2023–2026 Work Plan for the Enhanced Mineralization Technical Track, launched at COP28, covering both enhanced rock weathering as a CDR method and CO_2 injection in rock formations, which could be used for both atmospheric and fossil CO_2.[149]

In terms of conventional CDR, the Saudi Green Initiative commits to planting 10 billion trees and rehabilitating 40 million hectares of land by 2060. The National Center for Vegetation Development and Combating Desertification has been established to facilitate the tree planting. In 2023, Saudi Arabia introduced the Greenhouse Gas Crediting and Offsetting Mechanism (GCOM). It aims to allow companies and organizations to offset their emissions by purchasing credits and certificates from projects that voluntarily reduce or remove greenhouse gas emissions. The GCOM guidance acknowledges the importance of CDR and addresses the topic of permanence. Like with other accounting and offsetting schemes (see Section 5.1 on the EU Carbon Removal Certification Framework, for example), the quality of the certificates and the use cases will be important to the credibility of the scheme.

Under the GCOM framework, accounting issues for CDR methodologies would be addressed by establishing requirements and specifications for the quantification, MRV and registration of project-based emission reductions and CDR, including issues of permanence and reversal of removals. According to the government's plans, the GCOM will adapt to future changes and developments at the national and international levels, including alignment with Article 6 of the Paris Agreement.

Saudi Aramco is actively engaged in CCS and CCU projects, with fossil CO_2 sources used for enhanced oil recovery. Current work commissioned by the government includes a feasibility study for a CCS hub in the Gulf Cooperation Council countries. Saudi Arabia's target is to capture and permanently store 9 $MtCO_2$ per year by 2027, rising to 44 $MtCO_2$ per year by 2035. This capacity, built for fossil CCU or CCS, could potentially enable CDR upscaling. However, as with the other case studies, the current targets do not focus on CDR. To qualify as CDR targets, they would need to cover permanent removal from the atmosphere.

5.4 Synthesis

Conventional and novel CDR are often embedded in broader sectoral policy initiatives, but dedicated CDR policy is also needed to address both deployment and other functions of governance.

The case studies illustrated a strong focus on enabling policies for CDR, especially for research and development. Several case studies also demonstrated preparations for systems intended to facilitate the tradability of CDR credits, as well as early attempts to establish trading of conventional CDR credits. However, these credits typically represent CDR that is being used *instead of* emission reductions rather than CDR that is being used to *counterbalance* residual emissions. The case studies also show that both conventional and novel CDR are embedded in other policy fields and economic sectors. Table 5.1 summarizes the key messages from the case studies within the three dimensions outlined in Section 5.2 (overarching CDR policy architecture; innovation and scaling policies; safeguards and links with other policy domains).

	Overarching CDR policy architecture	Innovation and scaling policies	Safeguards and links with other policy domains
Canada	To reach its net zero target, Canada has recognized the need for deployment of both conventional and novel CDR. Explicit removal targets in terms of tons of CO_2 removed do not yet exist.	The government supports research and development as well as pilot CDR applications. It is currently developing CDR methodologies for its Greenhouse Gas Offset Credit System and preparing incentives including an investment tax credit and funding contracts for differences in carbon markets. Canada co-leads the Mission Innovation CDR Mission.	Conventional CDR is being tackled in policies focused on wider ecosystems, which also consider further, non-carbon benefits. Novel CDR is expected to benefit from several policies aimed at CCS and CCU, whose safeguards will also affect CDR.
China	Conventional CDR methods already have a relatively high profile, including through quantified targets and policy initiatives. The policy landscape for novel CDR is much less developed.	BECCS and DACCS are considered in the modelled pathways, but policy support for RD&D is still in its infancy and often focused on fossil CCU or CCS applications.	Large-scale afforestation, a well-established strategy, may have negative impacts on ecosystems and local communities. Conventional CDR in general is closely linked to agricultural policy and politics.

	Overarching CDR policy architecture	Innovation and scaling policies	Safeguards and links with other policy domains
Japan	So far, Japan's focus has been on conventional CDR and applying voluntary rather than compliance measures to further CDR development.	While Japan is supporting national and international CDR innovation initiatives, it is currently lacking policies targeting CDR deployment.	Japan's carbon management approach currently prioritizes carbon recycling (CCU) over CDR and CCS.
Saudi Arabia	Quantified targets and deployment initiatives exist for conventional CDR methods. A new crediting and offsetting scheme that considers novel and conventional CDR was launched in 2023. But policy for novel CDR is in the early stages.	Saudi Arabia has addressed CDR as part of its circular economy initiatives. Some pilot projects on novel CDR methods have been started in the private sector. Saudi Arabia co-leads the Mission Innovation CDR Mission.	The initiatives in novel CDR innovation are closely linked to the energy company Saudi Aramco, and research is being conducted by institutes and universities.

Table 5.1 *Key findings from case studies providing snapshots of carbon dioxide removal (CDR) policy in selected countries in early 2024.*

For conventional CDR, path dependencies, political and stakeholder networks, and the political economy of agriculture and forestry will shape the future of CDR policy. A key risk associated with the rise of conventional CDR as part of climate change mitigation strategies, as observed in the case studies, is – in addition to reversibility risks – the potential adverse impacts of its large-scale deployment on biodiversity, food security and local communities.

For novel CDR, the recent initiatives included in the case studies are closely linked to fossil CCS and CCU applications and initiatives. The emerging policies on carbon management – an umbrella term for all kinds of CCS and CCU applications, including those with fossil CCS – will shape future CDR policy. Early initiatives in the countries analysed here indicate that it will be a challenge to make sure that CCS and CCU infrastructure become an enabling factor for future large-scale CDR. The surge in CDR policy announcements and commitments and their effects on climate policy will need to be carefully assessed in the coming years. In addition to the direct risk of obstructing emission reductions, embedding CDR in wider carbon management policy initiatives poses indirect risks of confusing the different roles that these mitigation approaches can play in achieving net zero and net-negative emissions.

As CDR deployment progresses, CDR policy will continue to emerge within and be shaped by an existing landscape that includes climate, energy, industrial, agricultural, forestry, ocean and innovation policy. Each of these domains exerts an influence on what CDR policy is and will become. For example, climate policy and the existing context of policy around forestry and land use and around carbon offsets is fundamental to how markets for removals evolve. Energy policy may influence the development of particular CDR methods, such as BECCS or approaches that co-produce hydrogen. CDR policy is also linked with CCS and CCU policy in some jurisdictions. Even though the roles of CDR, CCS and CCU within a climate action portfolio differ, there can be regulatory overlap in terms of regulating geological storage, and there is often overlap in the public mind. Approaches such as soil carbon sequestration are situated within existing policy infrastructure that incentivizes conservation agriculture, marine CDR is situated within existing policies that regulate ocean activities, and so on. And policies that incentivize scientific research interact with all CDR techniques. These landscapes address some of the needs of CDR policy, but dedicated CDR policy is also required – not only for deployment but also for the other functions of governance.

Some of these governance functions – research and innovation policy, regulation that enables CDR, social safeguards, support for public deliberation and involvement in decision-making – fit better into the existing policy landscape than others. Policy focused on increasing soil carbon sequestration, for example, may further the development of MRV technologies and farmer adoption of carbon sequestering practices, but it is unlikely to address social safeguards or procurement for CDR broadly. Similarly, policy that provides public funding for direct air capture demonstration projects, which falls under industrial RD&D, tends to be dealt with in a project-level, industrial demonstration box. While direct air capture is supported by governments in this way, this leaves out governance that would deal with impacts on communities should the technology successfully scale or with how to involve the public in questions of how large a role CDR should play in responding to climate change. Dedicated CDR policy at wider scales would address these and other CDR-specific needs. And some dedicated CDR policy *is* starting to evolve in close connection with existing national mitigation strategies, as illustrated in the case studies.

Box 5.2 Limitations and knowledge gaps

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

There is limited research that maps out how sectoral policies in areas such as agriculture, industrial decarbonization, forestry, buildings and power interact with CDR development. Future assessments could systematically map this out with empirical studies.

While there have been many recent studies calling into question the efficacy of carbon offsets, there is an opportunity for further research into:

How markets for removals (rather than avoided emissions) would have similar or different challenges (around issues such as additionality, permanence, fraud, over-crediting or dispossession of communities).

Whether removals-only markets can avoid some of the challenges plaguing carbon markets.

What design features removals markets need for the best chance of success.

As technologies move from concept to demonstration to deployment, there is an opportunity to conduct comparative studies of how policy support helps companies move through the cycle and of when policy support is not the decisive factor. There is also an opportunity to conduct comparative studies of how social safeguards and public engagement – or the lack thereof – have shaped projects. Future assessments could profile cases and synthesize knowledge from them.

The emerging dedicated CDR policy landscape provides new opportunities to empirically study the political economy of CDR in international, supranational and national climate policies, in particular distributional effects, burden sharing in CDR ramp-up policies, and new forms of cooperation and alliances.

6

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Chapter 6 | Perceptions and communication

Understanding the perceptions of publics, adopters and interested parties is crucial for implementing carbon dioxide removal (CDR) and for mutual learning. The CDR perceptions literature and analyses of social media and news media coverage yield lessons for responsible communication.

Key insights

- Involving a diversity of actors in CDR is both an opportunity for mutual learning and a challenge for communication.
- A growing literature on public perceptions highlights low awareness but nuanced attitudes towards CDR methods in studied populations.
- Key factors driving public attitudes towards CDR are perceptions of "naturalness" and ecosystem impacts, along with underlying values and beliefs – including about climate change. Evidence is mixed on whether the level of perceived "moral hazard" or people's proximity to developments influence attitudes.
- Twitter/X users and news media tend to focus on particular CDR methods in particular countries – for instance, soil carbon sequestration in Australia, peatland restoration in the UK, and direct air capture in the US.
- The level of attention given to CDR on anglophone Twitter/X in 2022 was similar to that in 2021, with generally more positive sentiment towards familiar and conventional CDR methods than to other methods.
- Coverage of CDR in English-language news media has strongly increased, especially since governments started to put forward net zero targets. The news media tends to conflate CDR with avoided emissions and mitigation approaches.
- This chapter identifies seven key considerations for responsible communication about CDR, developed from lessons from public perceptions research.

This chapter combines multiple sources of evidence to understand public perceptions and communication about CDR; these sources include surveys, experiments and deliberative approaches in the scientific literature, and data from social media and news media. Section 6.1 explains the role and importance of public perceptions, and Section 6.2 presents four complementary approaches for assessing perceptions of CDR among different groups of people (see Box 6.1). Section 6.3 summarizes the outlook for this topic, including knowledge gaps and how future assessments can build on this analysis (see Box 6.4).

6.1 The role of public perceptions

Understanding public perceptions is crucial for the ethical and effective development and deployment of CDR.

Public attitudes towards new technologies can have a crucial influence on their development and deployment.[9] Perceptions of CDR methods among interested parties and the wider public will influence prospects for scaling up CDR. Publics perform several key roles: influencing policy mandates, determining whether a project has “social licence to operate” on a local and/or national scale, and providing “demand pull” for new innovations.[232–234] In addition, the public can act as a direct stakeholder in many contexts – for instance, as landowners deciding whether to take up or allow CDR initiatives on their land; as a directly impacted community; as a community of interest in support or opposition; and as providers of crucial information on local, historical and social context, which may otherwise be lacking. Publics are an essential source of knowledge for developing more effective and responsible CDR policies and methods.[235,236]

Examples of the importance of public perceptions include the genetic modification of crops and food in the EU, where early public perception research identified serious issues with public trust in political and regulatory structures – lessons that later came to be seen as “remarkably prescient” in the wake of the EU moratorium on this technology.[237] Experiences with carbon capture and storage projects around the world show that some benefited greatly from lessons learned from earlier public successes and failures.[238]

But publics are not simply a source of potential opposition; they also play a crucial enabling role, for instance as advocates or as market actors. Public perceptions should not simply be seen as the end of the innovation chain (see Chapter 1 – Introduction), nor should researchers simply ask whether people “accept” an innovation that has already been developed. Instead, the aim should be early and continual two-way communication and reflexive engagement throughout the innovation process.[239–241] Publics play crucial roles throughout this process, as well as informing the overarching social and political landscape in which CDR sits. Participatory, deliberative approaches to decision-making can help ensure that informed views from a variety of perspectives are taken into account, which in turn can improve the quality and legitimacy of decisions, as shown in US work on shale gas development, for example.[242]

Box 6.1 Multiple sets of evidence for assessing perceptions of CDR

Different techniques for assessing perceptions have specific advantages and disadvantages and are rooted in their own sets of assumptions. Section 6.2 presents four complementary approaches for assessing perceptions of CDR among different groups of people: (1) a systematic map of the scientific literature to understand the current state of evidence on different aspects of public perceptions and CDR; (2) a qualitative review of this literature to understand *why* people respond in particular ways; (3) analysis of posts on Twitter/X to understand public communication on social media and how it evolves over time; (4) analysis of news media to understand key aspects of how CDR is communicated to wider audiences.

Who is "the public"? Different approaches to gauging public perception can define *the public* in different ways, and the definitions of related categories – such as *stakeholder* and *expert* – are also not fixed. This report presents findings relating to all three of these categories, differentiating where possible, although the boundaries are frequently blurred. People also operate from different positions – for instance, *professional* actors or *civic* actors – at different times, depending on the context.[243] This report uses *interested parties* as an umbrella term to include adopters of CDR technology, CDR experts, directly affected communities, and people with a professional interest in CDR. Although this term is imperfect, it serves as an overarching term to refer to all the groups studied in the systematic review. *Adopters* refers to those adopting CDR in situations where they have some jurisdiction (e.g. landowners, farmers, community/project developers). *CDR experts* refers to those with pre-existing knowledge and opinions about CDR, such as academics, policymakers, NGOs and industry professionals.

Elicited versus non-elicited information. Elicited information is asked for or drawn out by researchers, for instance using surveys, experiments and deliberative approaches. Non-elicited information is provided unprompted, for instance in social media posts or news media articles. Elicited approaches allow the researchers to control and analyse the context and participants, but they leave the results susceptible to framing effects created by researchers in the way the topic is presented to participants. Non-elicited techniques are based on statements by people who may already have an interest in CDR, for instance as part of their job or gained from their peer group, which will impact their views. On social media it can be difficult to disentangle whether participants are experts or professional communicators, a challenge this chapter attempts to tackle with a new analysis to identify user types.

Changes since The State of Carbon Dioxide Removal 1st edition. The assessment of public perception and communication of CDR has been strengthened since *The State of Carbon Dioxide Removal* 1st edition in the following ways:

- A new systematic review of the scientific literature up to May 2023, using an extended set of keywords and machine-learning techniques to identify papers (including expert perceptions papers), distinguishing between CDR experts and the general public

- A new qualitative review of papers on public (non-expert) perceptions up to September 2023 to understand why people respond in certain ways
- Updated Twitter/X analysis to end-2022, including new data on user types and posting frequency
- New analysis of news media

Box 6.2 Methods: Evaluating the state of knowledge on CDR perceptions in the scientific literature

Systematic map of the literature. In this analysis, the English-language scientific literature was searched using two databases (Web of Science and Scopus), and all studies that evaluate perceptions of methods that capture and store carbon dioxide were extracted. A much larger body of literature was identified than in *The State of Carbon Dioxide Removal* 1st edition, due to four main factors: (1) use of more comprehensive keyword searches and machine learning to identify relevant papers; (2) extension of publication date criterion to May 2023; (3) inclusion of literature on CDR expert perceptions and media analyses on CDR; and (4) inclusion of papers that do not mention CDR explicitly but talk about methods, such as biochar applications, that are considered to lead to net removals from the atmosphere. Decisions over point (4) are particularly challenging, with blurred lines in categorizing papers as being about CDR versus about methods that may capture carbon as a co-benefit; such decisions can lead to very different findings regarding the size of the literature and have also been encountered in the CDR policy literature (see also Chapter 5 – Policymaking and governance).[244] This challenge is especially salient for methods based on the management of natural systems, such as forest management and peatland restoration.

Qualitative review. The goal of the qualitative review is to understand why public groups hold certain views about CDR. For this analysis, the English-language peer-reviewed literature was reviewed for mentions of factors driving public attitudes: that is, attributes of the respondent or project that might influence how CDR, the specific method or the proposed implementation is perceived. Conditions for deployment (i.e. under what conditions CDR methods or proposals might become acceptable) were also examined, because support for novel interventions is likely to be fragile and conditional. A systematic search was conducted for papers published before September 2023 about public groups (i.e. local communities, adopters or the general public in a particular location, but not experts), perceptions (i.e. presenting empirical data), and CDR (not including methods where the carbon sequestration is a side benefit, or carbon capture and utilization from point source emissions). The search terms used in *The State of Carbon Dioxide Removal* 1st edition were also used here (see also Waller et al., 2024[245]), and relevant papers were added if they were missed with these search terms but identified in the systematic map. The identified papers were manually coded by reading the whole paper and applying a scoring system, based loosely on the IPCC evidence/agreement scales.[246] Papers were given two scores:

Provision of empirical evidence for the factor or condition:

- 1 = yes
- 2 = no

Certainty of evidence:

- 3 = strong evidence
- 2 = mixed results (e.g. where different tests within a single paper show different outcomes, or where deliberative participants were split)
- 1 = weak or no evidence (e.g. non-statistically significant results or low effect sizes)
- −1 = the inverse relationship (where the direction of the relationship is the inverse of the expectation or hypothesis; see Figure 6.2)

6.2 Existing evidence base

Among the studied populations, people are generally cautiously supportive of CDR research and deployment, conditional on factors such as environmental safety and personal values and beliefs. Communication about CDR on Twitter/X and in news media has strongly increased over the last decade, with specific countries tending to focus on specific CDR methods.

Overview of the perceptions literature

Perceptions of CDR is a much more studied subject than was indicated by the literature review conducted for *The State of Carbon Dioxide Removal* 1st edition. This is due to the broader search criteria and more systematic methodology applied in this edition (see Boxes 6.1 and 6.2). The overview of the literature in this report includes studies on general populations, affected communities, potential adopters of CDR methods, and CDR experts (e.g. policymakers, business representatives, scientific experts), enabling the report to differentiate between different types of actors (see Figure 6.1, bottom right panel). This systematic search of the literature identified 165 English-language scientific papers on CDR perceptions.

Even though the evidence base in this report is much larger than in *The State of Carbon Dioxide Removal* 1st edition, several key conclusions from the first edition remain valid:

- The majority of publications are from Australia, Europe and North America.
- Among the studied populations, awareness of novel CDR is much lower than awareness of conventional CDR (see Chapter 1 – Introduction, for definitions).
- Support for research and deployment among studied groups is generally moderate to high, depending on the specific CDR method.

The 165 studies identified differ widely in their subject matter, data and methods used, as well as geographic location (see Figure 6.1, top and bottom left panels). This report finds evidence relating to a variety of different CDR methods. Some of the earlier studies use the broad framing of *geoengineering* without naming specific CDR methods; the more recent studies often include several CDR methods and increasingly cover novel approaches.

Alongside research on public perceptions of CDR in general populations (65 papers), this report identifies an even larger body of literature on CDR expert and adopter perceptions (89 papers). Most of the research employs quantitative methods such as surveys and survey experiments, but there are also many qualitative studies using semi-structured interviews, workshops or focus group discussions, as well as some mixed-methods approaches (see Figure 6.1, bottom right panel).

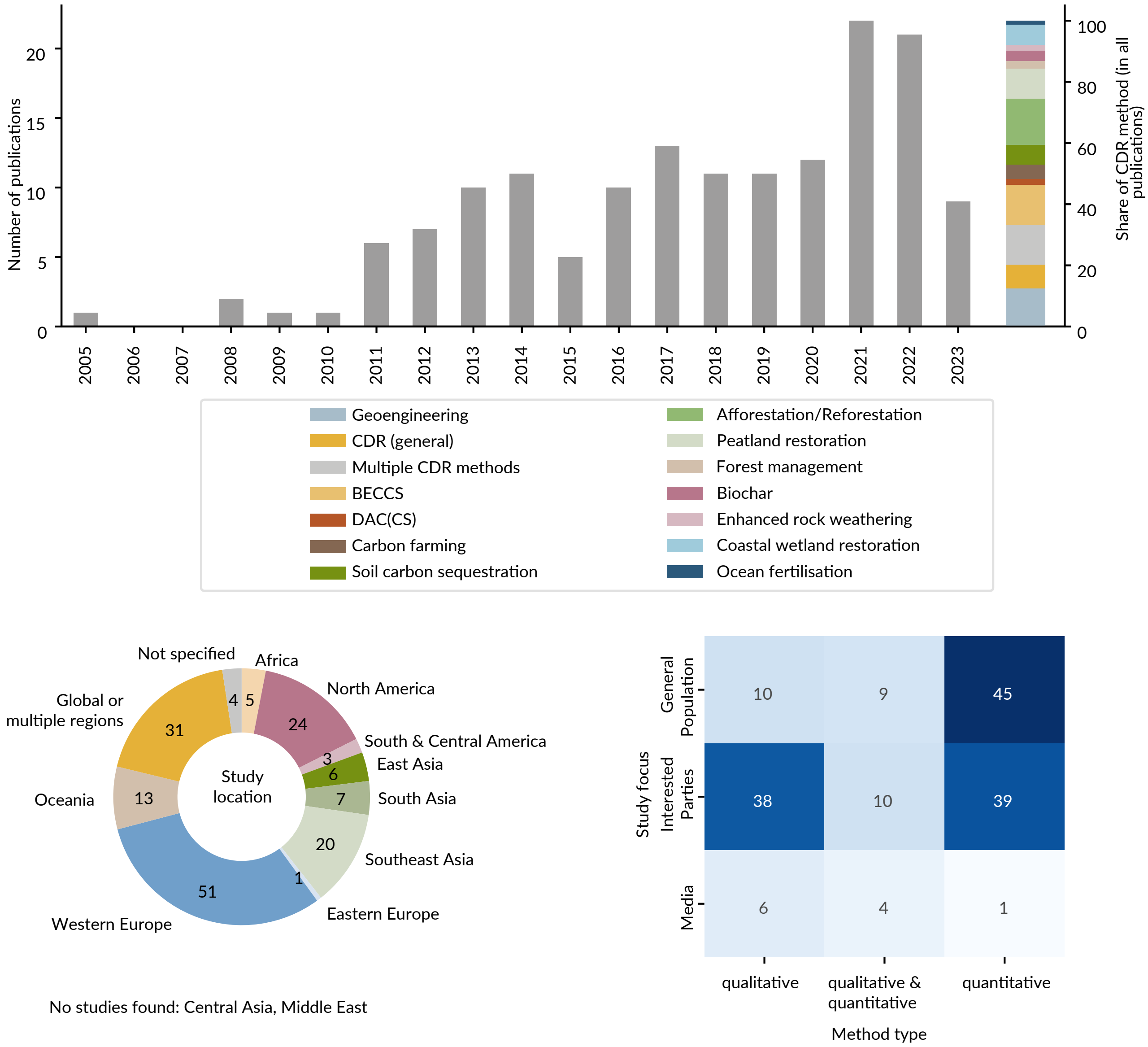


Figure 6.1 *Overview of the public perceptions literature on carbon dioxide removal (CDR) from the systematic map. Publications by CDR method and year (top), study location by region (bottom left), number of publications by study focus and method type applied in the study (bottom right). Carbon farming here refers to a cluster of CDR methods that can be applied in agriculture such as soil carbon sequestration, biochar and agroforestry. BECCS = bioenergy with carbon capture and storage; DAC(CS) = direct air capture (with or without carbon storage).*

Despite the much broader search criteria in this edition of the report, the geographic concentration in Europe and a few other countries, such as Australia and the US, remained: 62% of the studies focus on Europe, North America and the Pacific region (see Figure 6.1, bottom left panel), although the inclusion of studies on interested parties led to a higher overall coverage of regions than in the first edition. This concentration is likely driven, at least in part, by the English-language-only search strategy as well as by the concentration of authors in Western countries. In the literature on CDR experts and media, many studies do not have a specific geographic focus but are geographically constrained by language or availability of study participants.

Studies report low to moderate levels of public awareness, familiarity or knowledge about CDR. Surveys often find low familiarity with many CDR methods, with afforestation/reforestation being the most known method.[247–249] However, it is difficult to compare numbers on public awareness, familiarity and knowledge because the number of papers presenting such data is still low, and studies often measure these factors in very different ways and report aggregate results differently. An immediate implication of low familiarity is that people's opinions expressed in surveys might be very susceptible to change.

Most of the quantitative studies focus on measuring attitudes towards CDR, often using measures of support or acceptance of CDR research or deployment. CDR methods that are perceived as "more natural" get greater support among the studied populations.[248,250,251] Other important factors influencing the degree of support are perceived trade-offs and co-benefits, costs, trust in institutions, and concern about climate change; these factors are discussed further in the next section. A smaller number of studies also look at willingness to adopt or willingness to pay for CDR.[252–254] Closely related to overall attitudes are the perceived risks and benefits of CDR. While most study participants see the benefits of CDR in regulating the climate through carbon sequestration, this is not necessarily the most salient benefit to them.[255] Risks that impact the perception of CDR include technological risks (e.g. the safety of underground geological storage), environmental impacts (e.g. on biodiversity) and social impacts (e.g. on local communities).[256]

The studies researching perceptions of interested parties can be divided into two sets: one that focuses on surveying or interviewing potential adopters of conventional land-based methods such as farmers and landowners[254,257,258] and another that focuses on experts such as policymakers, delegates in climate negotiations, researchers, and industry and NGO representatives. The latter set includes studies of expert perceptions of the potential and feasibility of CDR methods[259,260] and investigations of perceptions of policy-related questions, for example on the use of bioenergy with carbon capture and storage (BECCS) in future mitigation scenarios.[261]

Factors driving attitudes and conditions for deployment

As well as understanding *what* public groups think about CDR, it is important to understand *why* they hold such views. This understanding can enable policies and projects to be crafted in ways that are more in line with public preferences and that therefore potentially have lower risk of failure. To gain such insights, this report presents a qualitative review of the English-language literature on public perceptions of CDR, expanding and updating the review presented in *The State of Carbon Dioxide Removal* 1st edition and focusing only on perceptions of the public, communities and adopters (see Box 6.1). For this reason, the corpus of literature is smaller than in the systematic map, which also included papers on expert perceptions, papers on media analysis and papers not explicitly focusing on CDR.

For the qualitative review, the more targeted corpus contains 56 papers: 32 using quantitative methods, 16 using qualitative methods and eight using a mixed-methods approach. Eleven of the new relevant papers have been published since *The State of Carbon Dioxide Removal* 1st edition. These largely represent an incremental continuation of existing knowledge, including testing whether CDR negatively impacts emission reduction efforts or intentions, via a "moral hazard" effect;[262,263] exploring the influence of climate beliefs and sense of climate urgency;[263,264] exploring preferred attributes of CDR;[265–267] and exploring how opinions change in different geographical contexts.[243,268] Direct air carbon capture and storage (DACCS) seems to be emerging as a key focus in the literature, as does new work on novel marine methods such as ocean alkalinity enhancement.[263,264] This section looks at the findings of the qualitative review to shed light on why people might form certain views about CDR (see Box 6.2).

The published literature identified 14 distinct factors driving public attitudes and 12 distinct conditions for deployment, as shown in Figure 6.2. There are many more papers exploring factors driving attitudes than exploring conditions for deployment. Survey and experiment papers tend to provide evidence on factors, whereas qualitative papers and papers on landowner uptake look at both factors and conditions. Some indicators could fall into either category; therefore, the full text of the papers was reviewed to determine how the findings are described in the paper itself. The largest body of evidence, by number of papers published, is on whether something is perceived to be "natural" or to "mess or tamper with nature", followed by whether it is perceived to have "ecosystem impacts" (including impacts on wildlife and biodiversity, as well as broader environmental impacts).

We can understand *why* publics respond to CDR in certain ways

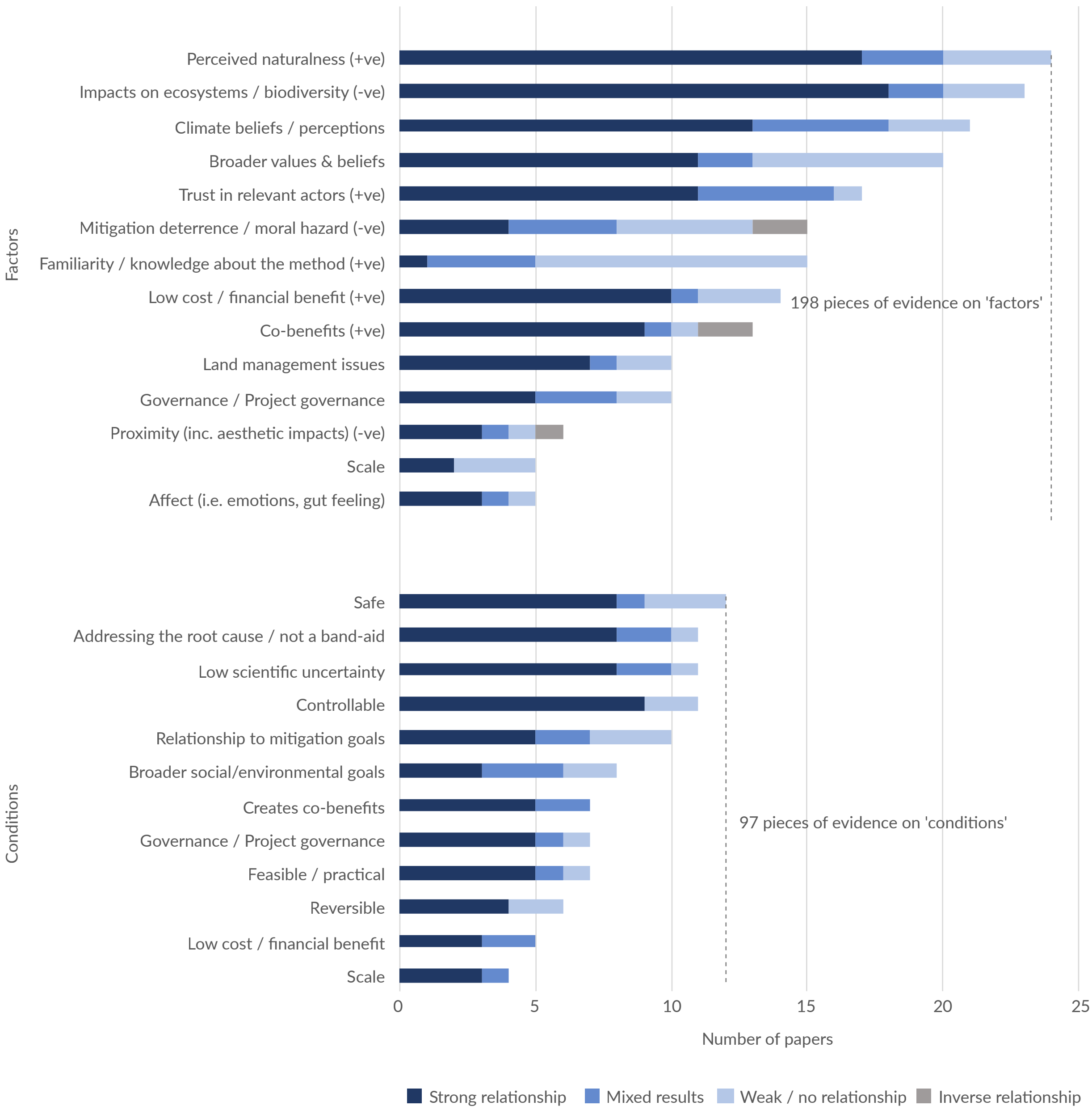


Figure 6.2 *Fourteen factors shown to drive public attitudes towards carbon dioxide removal (CDR; top) and 12 identified conditions for the deployment of CDR (bottom), from the English-language peer-reviewed literature on public perceptions (56 papers). Papers were scored according to whether they provide empirical evidence for a strong relationship between the factor or condition and public attitudes, or mixed results, or a weak relationship/no relationship, or an inverse relationship (see Box 6.2). Where appropriate, the direction of the relationship is labelled +ve (positive) or -ve (negative). Pieces of evidence = total number of papers discussing the listed factors or conditions (most papers cover more than one topic).*

The majority of papers find that these factors have a strong influence on public attitudes: CDR methods that are framed as or perceived to be more natural are more likely to be supported, and methods that have perceived detrimental impacts on ecosystems or biodiversity are more likely to be perceived negatively. Other factors often studied in the literature are values and beliefs (e.g. social identities, cultural worldviews, political affiliation), climate beliefs (e.g. belief in the urgency of climate change), and trust. For these factors, slightly more papers show mixed results or a weak relationship with public attitudes.

A large number of papers have examined moral hazard effects: the idea that CDR might negatively impact emission reduction efforts or intentions. However, the literature does not agree on whether this factor consistently drives public attitudes. Many papers provide weak or no evidence in favour of the moral hazard hypothesis, and two provide evidence for the inverse effect – in other words, learning about or deliberating CDR might in fact increase support for emission reductions.268,269 Similarly, there is low confidence on the extent to which people's knowledge of CDR or their familiarity with the topic influences their attitudes towards it. Finally, very few papers examine affect (i.e. subjective feelings, emotions) and scale (related to the type and site of activity, as well as the deployment footprint). This report also finds low confidence in people's proximity to proposed projects or developments being a factor that drives attitudes.

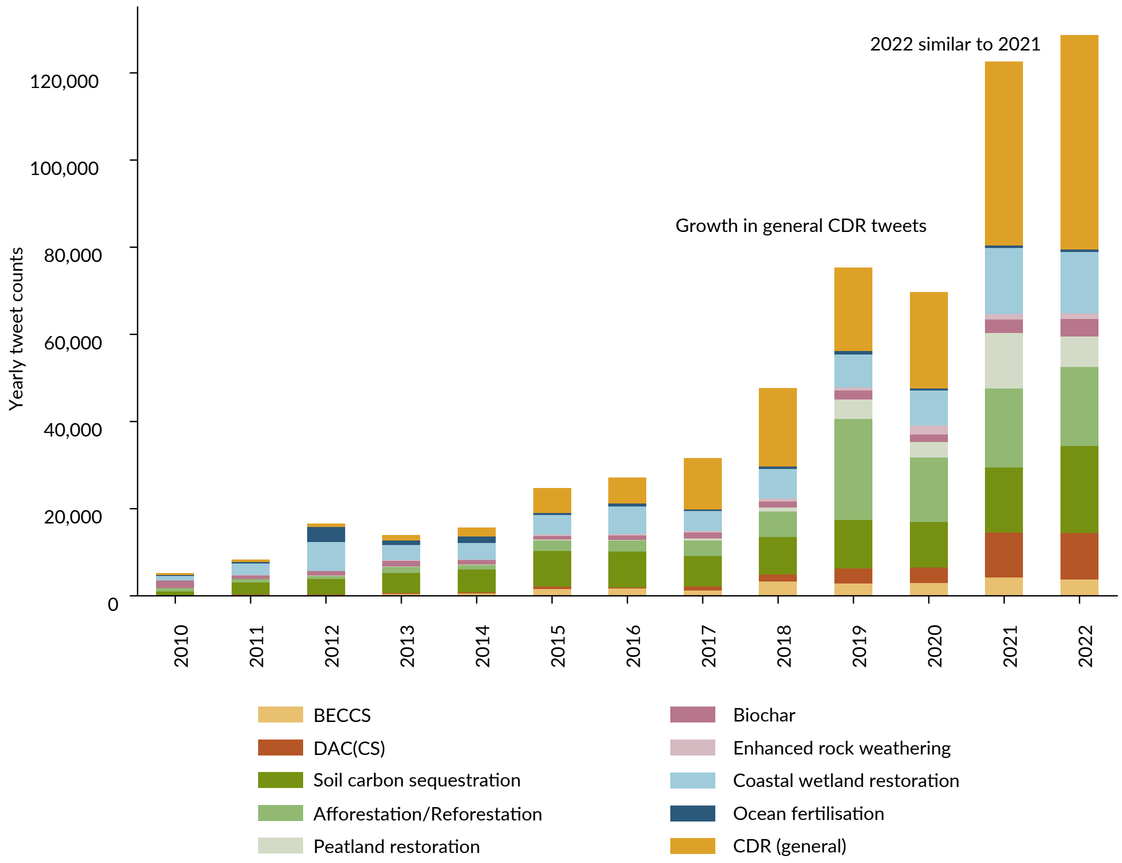
Conditions for deployment are requirements that study participants highlight as important for supporting or accepting the deployment of CDR methods. They can help develop a more nuanced understanding of how and why particular projects or proposals might become acceptable and serve as a basis for public engagement for the improvement and implementation of projects. However, fewer papers examine such conditions than look at the factors driving attitudes. The largest number of papers shows that the public wants CDR methods to be controllable, to be safe (particularly for methods involving deep geological storage), to have low scientific uncertainty, and to address the root cause of the problem. There are fewer papers on cost and profit and on co-benefits; such papers are mainly on conditions for landowner uptake of specific land-based methods.

CDR on Twitter/X

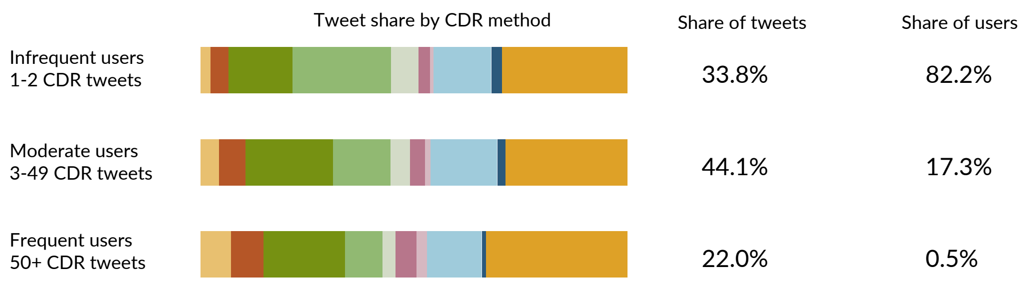
In contrast to the elicited approaches discussed in the scientific literature, social media data (i.e. non-elicited information) can be used to assess how people communicate about CDR (see Boxes 6.1 and 6.3). Twitter – now rebranded as X – is a social media platform used by many for engaging in policy-related public debates. The State of Carbon Dioxide Removal 1st edition found that English-language communication about CDR on Twitter/X grew very rapidly between 2010 and 2021,270 with brief recessions in 2013 and 2020. This edition updates the first edition analysis by extending the data to the end of 2022 and investigating what kinds of user are posting about CDR.

In the corpus of tweets analysed, the focus on different CDR methods changed gradually over the last 12 years (see Figure 6.3a). Earlier tweets mainly focused on specific CDR methods, such as soil carbon sequestration, coastal wetland restoration, ocean fertilization, afforestation and biochar. Recent years have seen an increase in the share of tweets about CDR in general, as well as an expansion to novel CDR methods such as DACCS and BECCS. Nevertheless, the bulk share of English-language tweets is still on soil carbon sequestration, coastal wetland restoration and afforestation. Twitter/X users tend to communicate more frequently about CDR methods that are more widely known: for example, afforestation is one of the most frequently mentioned CDR methods on Twitter/X and is also the most widely known CDR method according to public awareness surveys. Additional data for 2022 show little change from 2021 in attention to CDR, in terms of both absolute numbers and the relative share of different methods. General CDR and soil carbon sequestration saw an increase of a few percentage points in their shares, whereas the relative shares for peatland restoration and for coastal wetland restoration decreased slightly. But the shares of all other CDR methods remained within one percentage point of their value in 2021.

a) Growing attention to CDR on Twitter



b) Slight differences between user groups by number of CDR tweets



c) Users from different locations and of various types

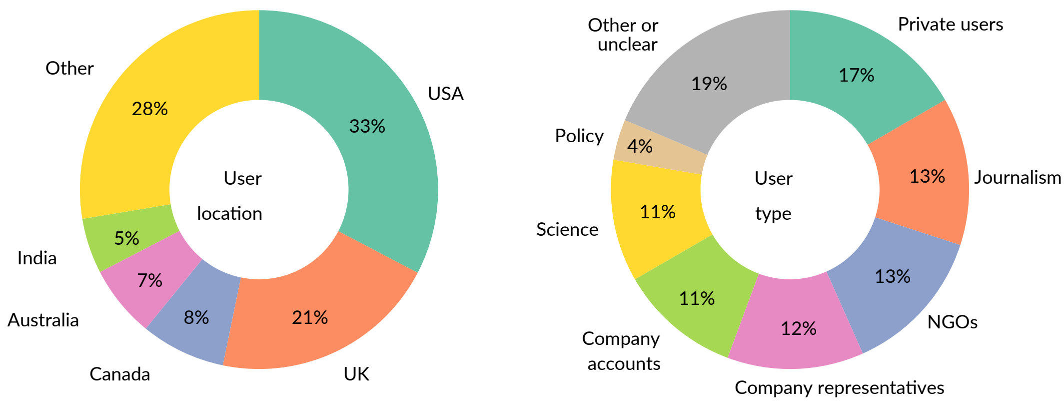


Figure 6.3 *Activity on Twitter/X related to carbon dioxide removal (CDR) by method and time, user groups by tweet frequency, share of user locations and user types: (a) Number of tweets per year and set of CDR keywords. Ocean alkalinity enhancement only resulted in very few tweets and is not reported here; BECCS = bioenergy with carbon capture and storage; DAC(CS) = direct air capture (with or without carbon storage) (b) How often users posted about CDR between 2010 and 2022 and the related shares in CDR methods, tweets and users; (c) The share of users attributable to a specific country through their self-described location (left, n = 94,096) and the shares of user types in a manually annotated sample of users (right, n = 300).*

The analysis of sentiments (i.e. whether tweets use positive, negative or neutral language) shows that across all CDR tweets positive sentiments increase over time. Tweets on biological capture methods have a positive sentiment much more often than a negative sentiment, aligning with the survey literature on perceptions.[250,251,271] Extending the analysis of tweets to 2022 reveals only small differences compared with 2021: BECCS and ocean fertilization were on average discussed more positively than before, and peatland and wetland restoration featured more prominently among both positive and negative tweets.

The above findings are robust to different subgroups of users that tweet with different frequencies about CDR (see Figure 6b and Box 6.3). There are only small deviations between subgroups: Users posting frequently about CDR post relatively more about novel CDR methods (e.g. DACCS, enhanced rock weathering, biochar, BECCS), whereas users posting only once or twice about CDR tend to post more on well-known methods such as afforestation or peatland and wetland restoration. Users posting frequently about CDR also communicate slightly more neutrally about CDR than other users. However, the general trends in attention given to CDR and sentiment towards CDR described above are valid for all subgroups with different tweet frequencies.

Different types of user are actively posting on CDR: private accounts, accounts of firms, and professionals from different fields such as business, journalism, NGOs and science (see Figure 6.3c, right). Seventeen percent of the coded users did not mention any professional activities in their self-description. The majority of accounts (60%) belong to journalists, representatives of NGOs and businesses, official company communication teams, and practitioners related to science and education, all with very similar proportions of the total. Politicians and policymakers make up only a very small percentage of users posting about CDR.

Using the self-reported location in a user's profile enabled approximately half the users in the data set to be mapped to a specific country. As only English keywords were searched to compile the data set, the strong concentration in English-speaking countries is not surprising: 70% of posts from users with an identifiable location come from Australia, Canada, the UK or the US (Figure 6.3c, left). But there are also many tweets from users located in countries such as Belgium, Chile, France, Germany, Ghana, India, Norway and Switzerland, all with shares between 5% and 1%. There are differences between countries with respect to how often users tweet about specific CDR methods and the sentiments associated with these methods. For example, users from Australia, India and the US post more about soil carbon sequestration than others. UK users post more about peatland restoration and coastal wetland restoration, while Ghanian users focus on biochar and general CDR. Across CDR methods, sentiments tend to be more negative in Australia, Canada and Germany than in India, the UK and the US.

Box 6.3 Methods: Evaluating communication about CDR on Twitter/X and in news media

CDR on Twitter/X. This analysis is based on a data set of 570,000 tweets that contain keywords specific to CDR methods or other generic CDR terms and that were posted on Twitter/X between 2010 and 2022. Only English-language tweets were included; retweets were not included. Further details on the methodology are provided in Müller-Hansen et al., 2023, and Repke et al., 2024.[270,272] The analysis used machine learning to automatically classify sentiments (i.e. the tone of the language used in tweets) as positive, negative or neutral. This classification can differ from the attitude towards CDR expressed in a tweet, as sentiment only refers to how something is said and not the position taken in the text with respect to CDR. This approach draws on well-established sentiment detection algorithms, but nevertheless has limitations; for example, algorithms sometimes struggle to detect irony. This edition of the report extends the analysis by looking more closely at the users in the data set in three ways. First, users were grouped according to how many tweets they posted on CDR topics over the entire period of the data set: those who have posted many (50+) tweets about CDR, those who have posted a moderate number (3–49), or those who have posted just one to two tweets. Second, the types of profile associated with the tweets was manually annotated by coding a sample of 300 users: 100 representative users from each of the groups identified in step 1. These annotations were used to derive estimates about the composition of the users in the data set. Third, users were assigned to different countries based on the information they provide in the “location” field of their profile using a geolocation extraction algorithm evaluated for Twitter/X.[273]

CDR in news media. For this analysis, a keyword-based search query was entered in the LexisNexis Newspapers and Wires database for nine CDR methods to identify news media articles on CDR. The search was global in coverage but restricted to English-language articles appearing both in print and online. The results were filtered to a list of 122 newspapers compiled from (1) the list of Media and Climate Change Observatory core sources[274] (a prominent compilation of sources for media studies on climate topics) and (2) a list of general interest newspapers (i.e. not specialist journals) that yielded more than 1,000 results for the CDR keywords. To eliminate false hits, a protocol for inclusion/exclusion was developed and approximately 1,500 articles were manually coded. A pre-trained classifier developed for identifying CDR methods in scientific articles was then applied[275] to predict the relevance of subsequent articles in the data set. Automatically classified articles had high precision compared to the manually coded set, but relatively low recall. As such, the initial results represent a lower bound of news media discussions on CDR. An exception to this concerns *CDR (general)*, which, as in the Twitter analysis, is a category included to capture broader discussions on CDR concepts and their role in climate policy, as opposed to specific discussions of individual CDR methods. This general category showed both low agreement between different manual coders and poor matching between the manually and automatically coded sets. This is likely due to the subjective boundary in these articles between what should be considered a discussion that "primarily" focuses on CDR (which is included in the coding scheme) versus a discussion that only "tangentially" focuses on CDR (which is excluded in the coding scheme). This report therefore does not present results for the CDR (general) category in the main figures but discusses the implications of expanding the analysis to this category. In addition, it should be acknowledged that the coverage of LexisNexis is likely incomplete and only partially overlaps with other databases such as NewsBank, ProQuest or Factavia.[276]

CDR in news media

The mass media ecosystem – newspapers, television, radio broadcasting and online news platforms – is a key source of scientific information for the general public.[277] It can influence perceptions by shaping how much coverage different topics receive and by propagating values, worldviews and opinions on a range of issues.[278–280] This section focuses on the reporting of CDR in English-language news media articles over the past three decades (1990–2021).

Much research has investigated news media portrayals of climate change, including climate denial discourses and "false balance" in reporting on the issue.[281] Similarly, studies have looked at media portrayals of emerging technologies, such as genetically modified organisms and cultured meat.[282,283] However, only a few studies have focused on reporting of CDR. The majority of these studies investigate the overarching categories of geoengineering or climate engineering, where CDR is not the main focus.[284–289] A handful of studies have dealt with CDR methods themselves or their prerequisites, covering carbon capture and storage,[290–292] BECCS[293,294] and coastal wetland restoration.[295] Given the nuances associated with CDR, including complexities such as the meaning of *net zero* and concerns that CDR could reduce incentives for emission reductions, it is surprising that few scientific studies have examined how these methods have been communicated to the general public.

This section provides a new analysis of how English-language newspapers portray specific CDR methods. Approximately 9,100 articles that discuss CDR methods were found, with the main period of media reporting starting in 2007 (see Figure 6.4).[2] A major increase in coverage occurred in 2019, peaking during October and November 2021 when a wave of countries updated their climate targets prior to COP26. Since many of these targets included net zero pledges, the resulting climate policy discourse tended to feature CDR prominently. Prior to 2019, peaks in reporting on CDR also centred on similar international events, including COP15 in Copenhagen in 2009; COP13 in Bali in 2007, where several international forestry initiatives were announced; and COP6 in The Hague in 2000, where the role of forests as carbon sinks first sparked significant debate under the UNFCCC process.

2 If the "CDR (general)" category were included, as it is in the Twitter analysis, the yielded articles would approximately double to around 18,000. However, as discussed in Box 6.3, they are excluded due to low confidence.

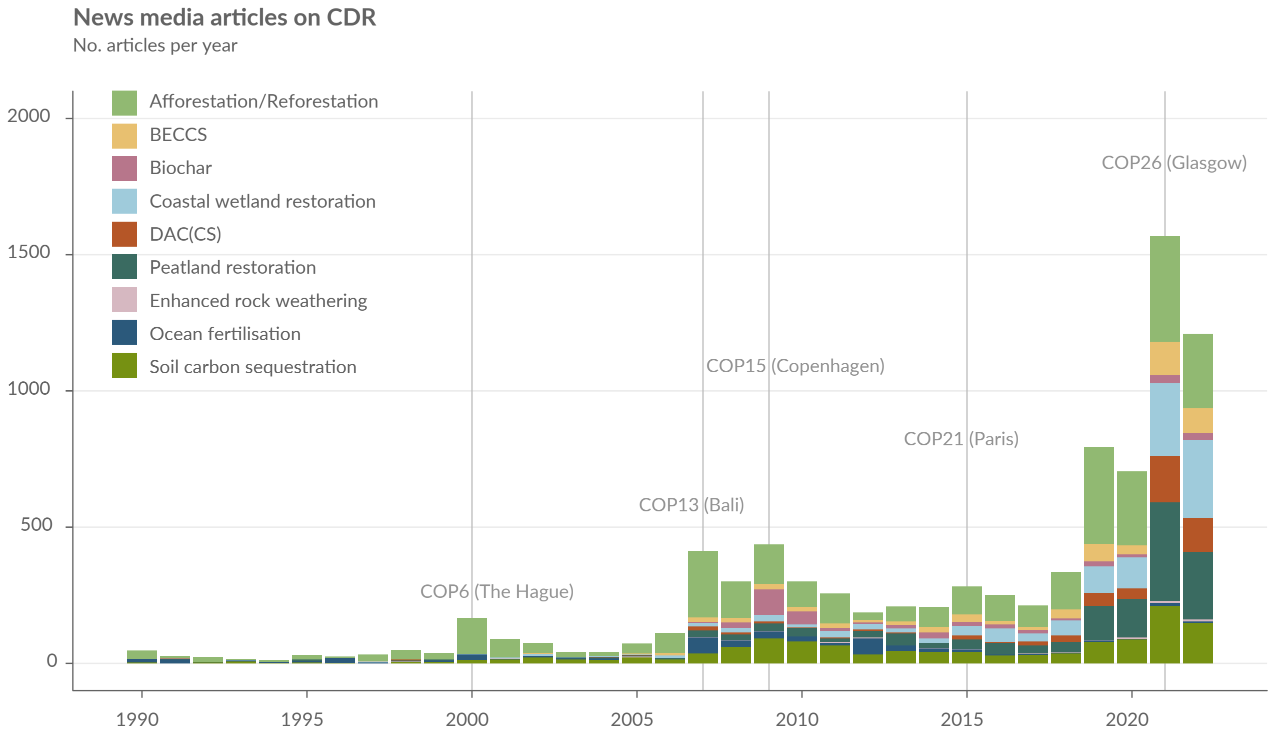
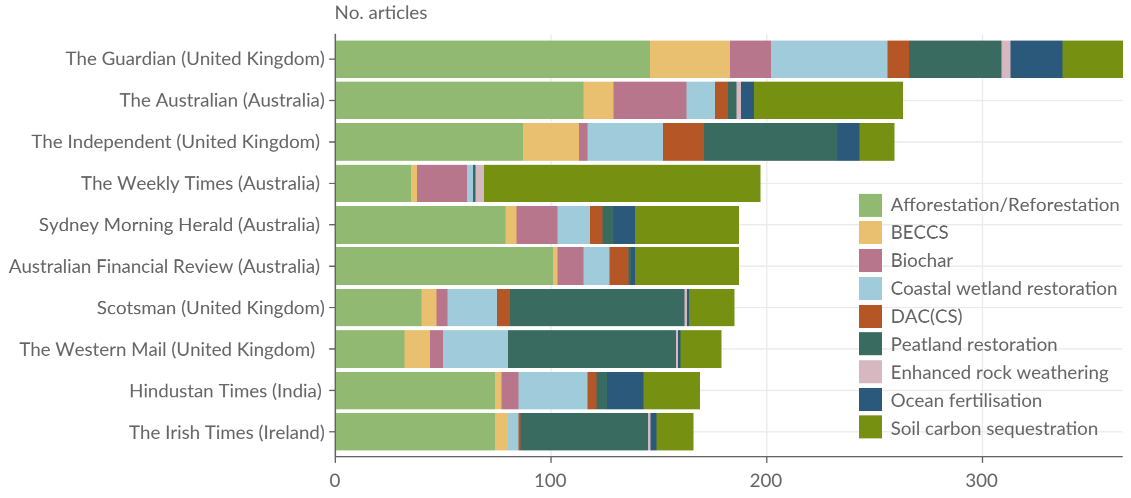


Figure 6.4 *News media articles on carbon dioxide removal (CDR) methods. Articles are double counted where they feature more than one CDR method. "CDR (general)" is excluded due to low confidence. Keyword searches for ocean alkalinity enhancement did not find any relevant articles. BECCS = bioenergy with carbon capture and storage; DAC(CS) = direct air capture (with or without carbon storage).*

Mentions of CDR in the data set are relatively concentrated in specific news media and countries. The Australian and UK press dominate coverage in this sample, accounting for eight of the top ten sources by total articles (see Figure 6.5, top panel). Soil carbon sequestration accounts for a larger share of articles than average in Australia, reflecting its higher state of integration into Australian climate policy.[244] Ecosystem restoration discourses (e.g. peatland restoration and "rewilding") are more prominent in the Irish and UK press (see Figure 6.5, bottom panel), while afforestation and coastal wetland restoration have larger shares in India and Pakistan (although this analysis only covers the English-language press in those countries).

News media articles by CDR technology and source, 1990–2021



Share of news media articles by CDR technology and source country, 1990–2021

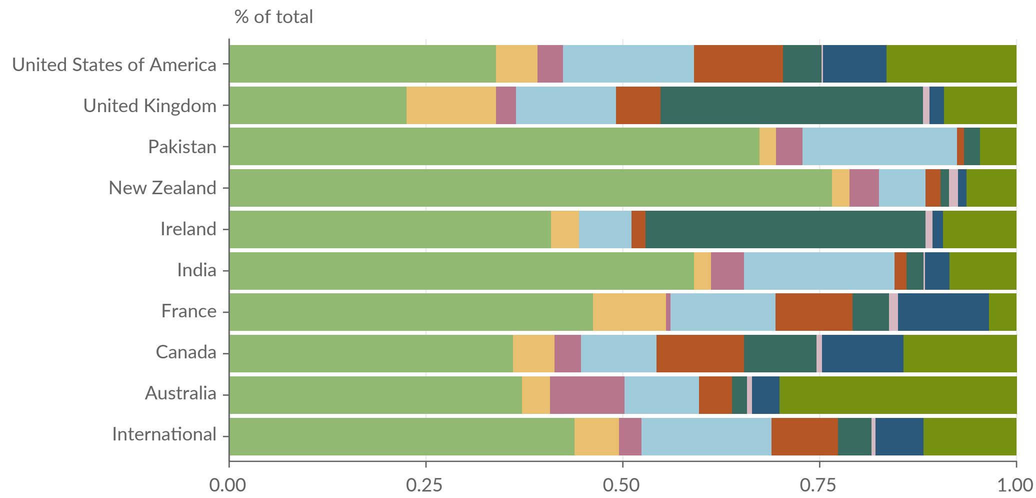


Figure 6.5 *News media articles on carbon dioxide removal (CDR) by source and location. The ten sources (top) and locations (bottom) with the highest number of hits are displayed in order. Articles are double counted where they feature more than one CDR method. The results are for English-language articles only and may not be representative of complete national media conversations on CDR. BECCS = bioenergy with carbon capture and storage; DAC(CS) = direct air capture (with or without carbon storage).*

A random sample of around 1,500 news media articles, which were read and manually coded, indicated that discussions of CDR methods tend to intersect with other concepts and mitigation approaches, including (fossil-based) carbon capture and storage, carbon capture and utilization (e.g. synthetic fuel production, biofuels), and avoided emissions (e.g. forest carbon offsets). Journalists do not necessarily distinguish between these different categories of mitigation, yet it is important to communicate the specific role of CDR as distinct from emission reduction efforts (see Chapter 1 – Introduction).

Box 6.4 Limitations and knowledge gaps

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

- Data on awareness and familiarity are still sparse and difficult to compare across studies. Very few general public questionnaires test the same measures at different time points.[301] Meanwhile, CDR expert studies are very heterogeneous and specific, and thus difficult to extrapolate to other contexts. More longitudinal research is needed to track the development of these important indicators over time.
- Future work could consider how findings and methodologies differ depending on the type of actor in question, because the small evidence base makes it difficult to draw general conclusions at present. More research is also needed on conditions for deployment, which allow public groups and adopters to positively engage with CDR.
- The scientific evidence base on CDR perceptions is still patchy in geographical terms. There are few studies, and very few lead authors, from Africa, South/Central America or Pacific countries other than Australia and New Zealand. The potential for many CDR methods is high in these regions; therefore, more knowledge about CDR perceptions in these populations is needed.
- All sections of this chapter are based on English-language data, which was noted as a limitation in *The State of Carbon Dioxide Removal* 1st edition. A more balanced assessment would include non-English sources, but this would require a large international team and dedicated funding, since local input will be essential to avoid missing vital social and cultural nuances.
- Non-elicited data from social and news media are used to provide indicators that are consistent over time. However, the restructuring of the Twitter/X platform in late 2022 must now be considered, as this saw an exodus of environmental communicators302 and a shift in the way the platform is used, creating obstacles to its future use as a consistent indicator.
- The data presented in this report suggest that there are similarities between the familiarity found in surveys and attention to CDR methods on Twitter/X. Future research should investigate the relationship between indicators derived from social media and surveys.
- Two cross-cutting knowledge gaps could be addressed in future research. First, the policy context is evolving rapidly (see Chapter 5 – Policymaking and governance), particularly with net zero targets, which are shown to greatly influence news media output. There is a need for more research linking the policy context to public perceptions in a way that views policy and public attitudes as mutually influencing and reinforcing one another rather than existing in isolation. Second, monitoring, reporting and verification is emerging as a topic of critical importance to the future of CDR (see Chapter 10 – Monitoring, reporting and verification), and it could be beneficial to link public perceptions work with this field, for instance in determining whether transparent and publicly accessible monitoring, reporting and verification processes could help build trust for CDR deployment.[303]

Strong variations were observed in the amount of critical reflection that CDR methods receive. For instance, a series of articles on DACCS plants tended not to offer a cautious appraisal of these methods, in contrast to broader and more critical pieces that introduce CDR as an overarching concept. One series of opinion articles in the Australian press frequently referred to soil carbon sequestration and biochar as methods that could advance national climate policy in place of emission reduction efforts. Other articles in the Australian press emphasized the low-carbon credentials of the cattle ranching sector, based on claims that livestock stimulate soil carbon sequestration, which has been challenged in the literature when one considers the overall climate impact of livestock.[296] These discourses no doubt dovetailed with broader contestations over climate policy in Australia, in which soil carbon sequestration was promoted by the Liberal party as a component of a policy direction comprising “technology not taxes”.[297,298] These examples highlight the risk that interest groups could leverage CDR to propagate discourses downplaying the need for ambitious climate policy and action, potentially continuing a longer tradition of climate obstruction through the mass media.[299,300] However, given the extremely limited literature on this subject, and the early stage of this analysis, it remains important to further assess the degree to which CDR discourses are exploited in the media.

6.3 Outlook

Active engagement with the general public and with interested parties is both an opportunity and a challenge for CDR. The literature on public perceptions is beginning to yield lessons for responsible communication of CDR.

Active engagement with interested parties, including the general public, presents a considerable opportunity for mutual learning. Public groups are an essential source of knowledge for developing more effective and responsible CDR policies and methods. However, communication challenges arise due to low prior awareness about CDR and the risk of spillover effects from controversies in related sectors.[304] The purpose of communicating about CDR is not to minimize opposition – or to maximize approval – but to facilitate mutual learning and informed participation in decision-making. Given persistent low levels of awareness about CDR, and the challenge of upscaling CDR to the level required to meet the Paris temperature goal (Chapter 8 – Paris-consistent CDR scenarios), developing responsible approaches for communication and engagement with the wider public and potential adopters needs to become a priority.[305]

The following seven lessons for responsible communication are derived from explicit recommendations in the perceptions literature during the time period covered by the review (noting of course that these are all English-language studies, with a distinct geographical skew):

Be careful with terminology. Pre-existing technical terms that are distinct from CDR (e.g. “carbon capture”) can confuse.[306] The term “negative” emissions can elicit unduly negative responses.[307] “Geoengineering” can spark negative sentiments.[270] Different ways of framing communication are likely to generate different public responses.[264]

Talk about CDR in context. Crucial contextual factors include the policy context,[308] different components of CDR systems,[309] the scale of CDR required domestically,[265] and the wider context of climate change mitigation and adaptation.[256,310] Communications need to be tailored to specific CDR methods and locations.[243]

Give – and receive – information about CDR. Giving information about CDR will increase awareness,[301] and providing information on scientific consensus can neutralize conspiracy theory effects in sceptical audiences.[311] Continual engagement to obtain feedback and assess public reservations is needed to progress research and development.[312]

Talk about (co-)benefits. Perceptions of benefits are a strong driver of acceptance.[249,267,313] Particularly relevant benefits may relate to long-term sustainability, environmental friendliness, controllability, cost-effectiveness and energy provision.[314,315]

Also talk about negative attributes. By identifying and deliberating negative attributes, innovation trajectories could be altered to avoid or minimize them. Salient aspects that could affect future well-being[316] include displeasing aesthetics, quick fixes, artificiality, risks and unknown effects,[301,314,317] as well as threats to emotionally and ethically significant ecological and geological systems.[315]

Do not weaken support for emission reductions. CDR should be seen as only a small part of larger efforts to tackle climate change.[256,262] Responsible communication strategies should emphasize the severity of failing to reduce emissions and should avoid framing CDR as a backup strategy or temporary “plan B” while working on more-sustainable solutions to climate change.[318,319]

Avoid framing CDR as natural (or otherwise). Perceived “naturalness” is known to increase acceptance of CDR,[320] whereas perceived “tampering with nature” is known to lower acceptance.[248] However, where the lines are drawn on what constitutes a “natural” or “unnatural” method is arbitrary and diverts attention away from the actual qualities of CDR methods.[268]

7

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Chapter 7 | Current levels of CDR

Carbon dioxide removal (CDR) is already occurring at scale. Conventional methods, principally afforestation/reforestation, currently contribute almost all CDR, although the contribution from novel CDR methods is growing.

Key insights

- The gross amount of carbon dioxide (CO_2) being moved from the atmosphere into durable carbon storage over the last decade as a result of human activity is on the order of 2,200 $MtCO_2$ per year. The uncertainties in this estimate remain large, however.
- Conventional CDR makes up over 99.9% of all current CDR. Estimates of the volumes removed vary according to the approach used. For the period of 2013–2022, models aligned with estimates of the Global Carbon Budget suggest an average of −1,860 (−1,160 to −2,230) $MtCO_2$ per year from afforestation/reforestation. Country-level data on managed forests, adjusted using vegetation models, suggest −2,010 ± 620 $MtCO_2$ per year over the same period, through both afforestation/reforestation and forest management. Both approaches agree on a slight slowdown in the rate of conventional CDR in recent years.
- The countries with the highest levels of CDR through afforestation/reforestation, averaged over 2013–2022, are (in order) China, the US, Brazil and the Russian Federation. Levels in the EU27 as a whole lie between those of China and the US.
- Conventional CDR also includes the transfer of forest carbon to durable wood products. However, some double counting with CDR through afforestation/reforestation or in managed forest exists. The transfer of carbon to durable wood products amounts to −801 $MtCO_2$ per year, averaged over 2013–2022. When the re-emission of CO_2 through the decay of existing wood products is also accounted for, the net sink from this CDR method amounts to −332 $MtCO_2$ per year over this period.
- CDR from novel methods grew from −0.66 $MtCO_2$ per year in 2021 to −1.35 $MtCO_2$ per year in 2023. Improved estimation methods mean this level is lower than that reported in *The State of Carbon Dioxide Removal* 1st edition. Significant gaps and limitations in data remain for novel CDR projects, however.
- The largest current contributions to novel CDR are from biochar (with an estimated −0.79 $MtCO_2$ per year), bioenergy with carbon capture and storage (−0.51 $MtCO_2$ per year), and enhanced rock weathering (−0.03

$MtCO_2$ per year).

- Based on available data, the country with the largest contribution to novel CDR is the US, as it hosts all bioenergy with carbon capture and storage projects that are currently operating. Methods such as biochar and enhanced rock weathering show a broader geographical spread.

This chapter brings together multiple sources of data, harmonizing them to provide a comprehensive and robust estimate of current levels of CDR. However, assessments of current CDR deployment are complex and incomplete. Key limitations and knowledge gaps are discussed (see Box 7.3).

7.1 Estimating current CDR levels

This report measures carbon removed in a given year as the amount of carbon dioxide (CO_2) moved out of the atmosphere by human activity and into a durable type of storage.

As discussed in Chapter 1 (Introduction), this report defines CDR as follows:

Human activities capturing CO_2 from the atmosphere and storing it durably in geological, land or ocean reservoirs or in products. This includes human enhancement of natural removal processes but excludes natural uptake not caused directly by human activities.

This definition establishes three primary criteria for CDR, with important implications for estimating annual CDR volumes:

Capture of atmospheric CO_2. CDR involves the removal of CO_2 from the atmosphere. The capture of fossil CO_2 at the point of emission (e.g. gas power plant) is not included in this definition.

Durable storage. The CO_2 captured from the atmosphere must be stored durably. In this report, durability is defined according to the type of carbon pool into which CO_2 is transferred. The report considers storage in the following pools to be durable: trees, wetlands, soils, biochar, durable wood products (e.g. timber for construction), mineral products (e.g. aggregates), marine sediment, ocean bicarbonate, depleted fossil fuel reservoirs, saline aquifers and mineral rock formations.

Resulting from direct human intervention. It is essential to distinguish CDR from natural carbon sinks. The land and oceans currently take up around half the CO_2 emitted into the atmosphere each year, without humans intervening to cause this uptake, and this does not count as CDR. Calculating the volumes removed through conventional CDR – through, for example, tree planting – also means excluding the component of CO_2 uptake that happens indirectly as a result of human-caused changes to environmental conditions (e.g. climate change, raised atmospheric CO_2 concentrations, nitrogen deposition).

The approach used in this report is to calculate the annual quantities of CO_2 moved out of the atmosphere by processes that meet the definition above. This means the assessment does not look at the full balance of sources and sinks over the life cycle of these CDR activities, which leads to some important caveats:

- All CDR methods involve emissions during the capture and processing of carbon. For some of the projects that make a substantial contribution to current levels of novel CDR, a full life cycle assessment suggests that these emissions are currently similar to, or even outweigh, removals (although the distribution of these emissions between the CDR activity and co-products, such as fuels, depends on the allocation method).[124] It is standard practice for emissions to be reported in national greenhouse gas inventories, allocated to the sector in which they occur. Hence, emissions from heat or electricity required for a CDR activity are reported in a country's energy sector, for instance, and not ignored. Nevertheless, any assessment of the overall effectiveness of CDR should consider these emissions as well as the removals, as given in this chapter.

- After the time of removal, and depending on the type of carbon storage, CDR methods may also involve subsequent re-release of some CO_2.[321] In the estimate presented here of carbon stored annually through wood in construction – which is among the least durable carbon pools – this is accounted for. Re-release, based on standard lifetimes of wood products, is subtracted so as to indicate the size of the net sink. For other CDR methods, however, re-release is not currently accounted for.

- By defining storage durability on the basis of the type of carbon pool rather than the actual duration of storage, the fact that some CDR activities may turn out to be more short-lived – for example because of unexpected disturbance or mismanagement – is not accounted for.

Box 7.1 outlines how the assessment approach in this second edition differs from that in the first edition.

Estimating CDR levels from conventional and novel methods

The estimated levels of conventional CDR presented in this edition depend on a combination of information from national greenhouse gas inventories (NGHGIs) and from models used in the Global Carbon Budget (GCB). The estimated levels of novel CDR are generated from a structured approach that aggregates different databases and survey information.

Conventional CDR. This report uses two independent approaches to quantify the volumes removed through *afforestation/reforestation* and in *managed forests* during the last decade (2013–2022). In both cases, models are applied to separate out the fluxes attributable to direct human intervention, consistent with this report's definition of CDR. See Box 7.2 for a further discussion of the GCB and NGHGI data sources.

The first approach uses data from the GCB. Three bookkeeping models (BLUE, H&C2023 and OSCAR) are used in the GCB to estimate gross sources and sinks of CO_2 from land use, land-use change and forestry. One component of these sinks is the CDR attributable to afforestation/reforestation – that is, from expansion of forest area due to planting or regrowth after abandonment of agricultural land. The analysis averages the three models and uses their range as an uncertainty estimate.

The second approach is based on model-adjusted NGHGI data and quantifies CDR in managed forests, which includes CDR attributable to afforestation/reforestation as well as CDR attributable to forest management of already existing forest. The NGHGI estimates of CO_2 fluxes in managed forests have been reanalysed to remove fluxes resulting from indirect human effects and other environmental changes. The size of these natural fluxes is estimated by vegetation models (see the Chapter 7 Technical Appendix for details of the modelling methodology).

Harvested wood products: This report considers that forest management contributes to CDR when biomass is transferred to durable harvested wood products (HWPs). This may not be fully additional to CDR in afforestation/reforestation or in managed forest – some double counting may exist (see Section 7.2). FAOSTAT data on the production of sawnwood and panels are used to estimate this transfer during the last decade. Since these products decay over time, some of the carbon is returned to the atmosphere. An estimate of the net changes in carbon stock in HWPs is therefore calculated as the sum of the carbon transferred into the HWP pool minus the carbon transferred back to the atmosphere via product decay.

Novel CDR. This report provides estimates of CDR levels from bioenergy with carbon capture and storage (BECCS), biochar, bio-oil storage, direct air carbon capture and storage (DACCS), enhanced rock weathering, biomass sinking, mineral products, and ocean alkalinity enhancement. Information was compiled through a systematic review and harmonization of databases from the International Energy Agency, Mission Innovation, CDR.fyi and Ocean Visions, plus surveys by the International Biochar Initiative in partnership with the US Biochar Initiative and the European Biochar Industry Consortium. This was supplemented by data gathered from company websites. Further details are given in the Chapter 7 Technical Appendix.

Box 7.1 Points of departure from The State of Carbon Dioxide Removal 1st edition

This edition of *The State of Carbon Dioxide Removal* presents different estimates than the first. These differences stem from improvements in the estimation methods as well as from actual changes in CDR activity.

Alignment with the Global Carbon Budget

- A new approach has been developed for estimating CDR from afforestation/reforestation, which aligns with the latest GCB, published in 2023. Consistent with the GCB, the estimate of CDR from afforestation/reforestation is now based on results from three bookkeeping models.
- The approach for estimating CDR from managed forests (which includes removals through afforestation/reforestation as well as from forest management) has been refined. The first edition estimated CDR from managed forests by using data reported in NGHGIs,[322] excluding emissions from organic soils. From this estimate, indirect CO_2 uptake in response to

environmental changes was subtracted, using estimates from the OSCAR model.[323] This method aligned conceptually with the GCB definition in that only fluxes directly attributable to land-use activity were counted as CDR. In this second edition, this general approach is retained to provide an estimate of CDR in managed forests, but it is even better aligned with the method used in the GCB as it estimates the induced CO_2 removal using 18 dynamic global vegetation models instead of OSCAR only.

Improved calculations

- This report provides estimates of CDR from afforestation/reforestation and managed forests no longer only as a global total but also spatially and at the country level.
- The report's estimate of carbon transfers from wood to durable HWPs includes a correction to the conversion factors used in the calculation and now also accounts for CO_2 re-release each year from the decay of these products.
- The estimate of CDR volumes from BECCS is smaller in the second edition. This now reflects the actual amounts of CO_2 removed, rather than the targets initially set by the BECCS projects. This adjustment is most pronounced for the Illinois Industrial Carbon Capture and Storage Project, which has managed to store approximately 0.42–0.52 $MtCO_2$ each year,[324] rather than its stated goal of 1 $MtCO_2$ annually.

Greater coverage of locations and methods

- Data on biochar activity in the first edition were confined to market reports within Europe, North America and bamboo plantations in China. This coverage has now been expanded significantly by drawing on new data from the International Biochar Initiative, in partnership with the US Biochar Initiative, which include data from Africa, Asia, Europe, North America, Oceania and South America. The report therefore now has a larger estimate of CDR from biochar, but this is likely still incomplete.
- The report's coverage of enhanced rock weathering has been expanded, drawing on reports from a greater number of companies. Consequently, the report's estimate of CDR levels through enhanced rock weathering is higher.
- The second edition includes new implementation options not previously captured: BECCS derived from the use of biomass in cement production combined with carbon capture and storage, BECCS derived from biological waste-to-energy conversion combined with carbon capture and storage, and ocean alkalinity enhancement.

Box 7.2 Land-use emissions and removals in national inventories

While the GCB measures emissions and removals by land-use activities in a way that is aligned with the definition of CDR in this report, NGHGIs have adopted a different scope and approach. This box describes the implications of these differences for estimating CDR volumes.

National greenhouse gas inventories. Under the UNFCCC, countries report land-related emissions and removals from human activities in their NGHGIs. The methods used to compile NGHGIs are different from the bookkeeping models used in this report and in the GCB. NGHGIs are typically based on direct observations, which cannot distinguish the CO_2 sink attributable to direct human activities from that which is attributable to indirect effects induced by human-caused changes to environmental conditions. Only the sink attributable to direct human activities can be considered CDR.

Managed land. The IPCC guidelines for NGHGIs therefore proposed the concept of *managed land* as a basis for reporting human-caused emissions and removals.[325] Managed land is land where human interventions and practices have been applied to perform productive, ecological or social functions. In most countries' NGHGI submissions, the majority of emissions and removals within managed land areas are assumed to be due to human activity – including those caused indirectly as a response to changes in environmental conditions (e.g. rising atmospheric CO_2 concentrations, climate change, nitrogen deposition).

Because of the way that NGHGIs calculate emissions and removals, countries could in theory claim greater removals by categorizing larger areas of forest land as managed, without actually changing land use. Globally, about 80% of the total forest area is reported as managed forest land in NGHGIs. Only a relatively small expansion of managed forest has occurred since the 1990s, mostly in Brazil and the Russian Federation. According to the IPCC guidelines for NGHGIs,[325] it is good practice to describe the processes that led to re-categorization when moving previously unmanaged land to the managed land category. In other words, countries should not move lands in their NGHGI categories without evidence of an actual change in the status of the land.

Global Carbon Budget. In contrast to the NGHGIs, the GCB calculates human-caused emissions and removals based on land-use activities instead of areas. It separates out changes due to environmental conditions, attributing these to natural drivers. Direct effects from human activity are estimated by bookkeeping models. These estimates are independent of the area that each country has designated as managed land.

Consequences of the NGHGI approach versus the GCB approach. The estimates in NGHGIs of the total net CO_2 sink from managed land are therefore larger than the CDR estimates in the GCB.[326] As the reasons for the discrepancy are known, it is possible to convert estimates between the two definitions (see Section 7.2).[327,328]

Estimates from NGHGIs of CO_2 fluxes in managed forests suggest net removals of around −6,500 ± 1,135 $MtCO_2$ per year over the past decade.[327] When these estimates are reanalysed to remove natural fluxes – as estimated by models – global removals are reduced to −2,010 ± 620 $MtCO_2$ per year. See the Chapter 7 Technical Appendix for details of the modelling process. These removal rates have remained stable over the last two decades (see Figure 7.1).

The different scope of NGHGIs as compared with the GCB also has implications for the alignment of NGHGIs with scenarios (see Chapter

8 – Paris-consistent CDR scenarios, Chapter 9 – The CDR gap), the measurement of conventional CDR for policy planning and net zero targets (see Chapter 5 – Policymaking and governance, Chapter 9 – The CDR gap), and for the monitoring, reporting and verification of projects (see Chapter 10 – Monitoring, reporting and verification).

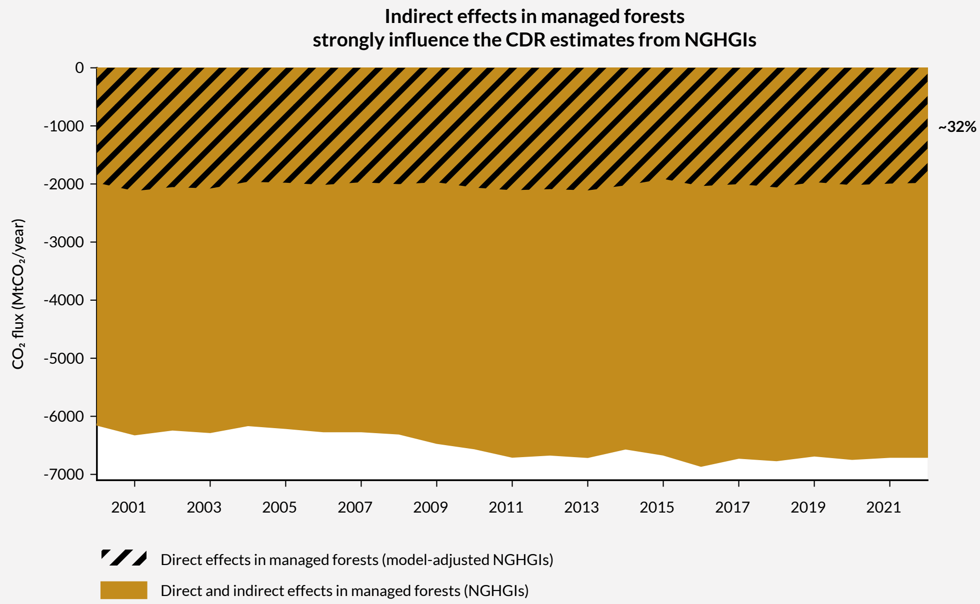

Figure 7.1 *Estimated global net carbon dioxide (CO_2) sink in managed forests from national greenhouse gas inventories (NGHGIs) (excluding emissions from organic soils) combined with modelling to factor out natural fluxes. The fluxes directly attributable to land-use activities ("direct effects", which is CDR as per the definition used in this report; black-hatched area) only account for 32% of the total average NGHGI CO_2 sink reported by countries (gold-shaded area). Countries' reported estimates include natural fluxes in response to environmental changes, as well as fluxes directly attributable to human land-use activities.*

Accounting for the relationship between CDR methods involving biomass and the atmospheric CO_2 budget

It is important to avoid double counting when estimating the CO_2 removed from the atmosphere by different CDR methods or implementation options. Depending on the method or option, the CDR refers to the time of CO_2 removal from the atmosphere or to the time carbon is transferred to a durable pool. But it may be the same carbon in both cases. This requires a choice of when in time the CDR is accounted for or else there is a risk of double counting. Several novel CDR methods (notably biochar, BECCS and bio-oil with storage) involve the biological capture of atmospheric CO_2, similar to conventional CDR, before transferring the biomass carbon into a different form of durable storage. Similarly, CDR through the transfer of biomass to durable HWPs is a conventional CDR method that involves biological capture of atmospheric CO_2 at an earlier time, where it may have been counted already under CDR through afforestation/reforestation or in managed forests.

Novel CDR derived from annual crops. If the biomass used for CDR is derived from annual crops, the crops themselves are not a durable store of carbon. This means the carbon was likely captured from the atmosphere in the same year as the transfer to durable storage, and the carbon is not otherwise counted within conventional CDR.

Novel CDR derived from woody biomass. In contrast, CDR methods that use woody biomass are transferring carbon from one durable pool to another. In this case, the most carbon was likely captured in the years preceding the point of transferral. Novel methods that use woody biomass include biochar made from woody feedstocks (which contribute about two-thirds of all biochar CDR in 2023). In principle, BECCS and bio-oil with storage could also use woody biomass; however, this report has found no current projects that do so.

For novel methods using woody biomass, this report therefore does not count CDR activity in a given year as a removal of atmospheric CO_2 in that year, but as a transfer of carbon from existing (biological) durable storage to another durable carbon pool (see Figure 7.5).

Conventional CDR through transfer of carbon to HWPs. Transfer of carbon to HWPs is considered CDR when the HWPs are durable. However, it is not entirely additional to CDR through afforestation/reforestation or CDR in managed forests:

- The woody biomass harvested for CDR may come from existing forests that have been managed over the long term. In this case, it is additional to CDR through afforestation/reforestation.
- If, however, the woody biomass comes from recently afforested or reforested areas, there will be some double counting in carbon removal between those CDR methods.

This report's estimates of carbon transfer to HWPs represent the sum of the CO_2 removed from the atmosphere during the years of biomass growth prior to harvest. Thus, the carbon removal due to transfers into long-term storage cannot be directly compared to the annual atmospheric CO_2 changes due to CDR.

Besides the issue of double counting with other CDR methods or options, it is disputable if HWPs taken from an existing forest qualify as CDR. This report defines CDR as resulting from direct human intervention. In the case of an existing forest, the carbon was removed from the atmosphere through natural processes. The CDR criterion that the removal must be attributable to human intervention thus applies only to the time of transfer to the durable carbon pool, not (or only in hindsight) to the time of the removal from the atmosphere. In the extreme case that HWPs are created from a forest that has been permanently cleared, CDR may occur through transferral to durable storage without an actual additional removal of CO_2 from the atmosphere.

7.2 Current global levels of CDR

On the order of 2,200 million tons per year of CDR is taking place already. Almost all of this comes from conventional CDR, with only an estimated 1.35 million tons per year (i.e. less than 0.1%) from novel CDR.

Current levels of conventional CDR

Estimates from the two approaches used in this assessment – model-adjusted NGHGIs and bookkeeping models – show broad agreement. Conventional CDR is currently predominantly due to afforestation/reforestation:

- ***Afforestation/reforestation.*** Annual global CDR through afforestation/reforestation amounts to −1,860 $MtCO_2$ (−1,160 to −2,230 $MtCO_2$; full range across models), averaged over 2013–2022, based on the latest GCB bookkeeping estimates (see Figure 7.2).
- ***CDR in managed forests (through afforestation/reforestation plus forest management).*** Annual global CDR in managed forests amounts to −2,010 ± 620 $MtCO_2$ per year over the same period, based on NGHGIs after indirect effects have been subtracted.

The two approaches disagree on the trend over the last 20 years, however, with bookkeeping models estimating a slight increase and adjusted NGHGIs estimating stable numbers. They do both agree on there being a slowdown in the last few years.

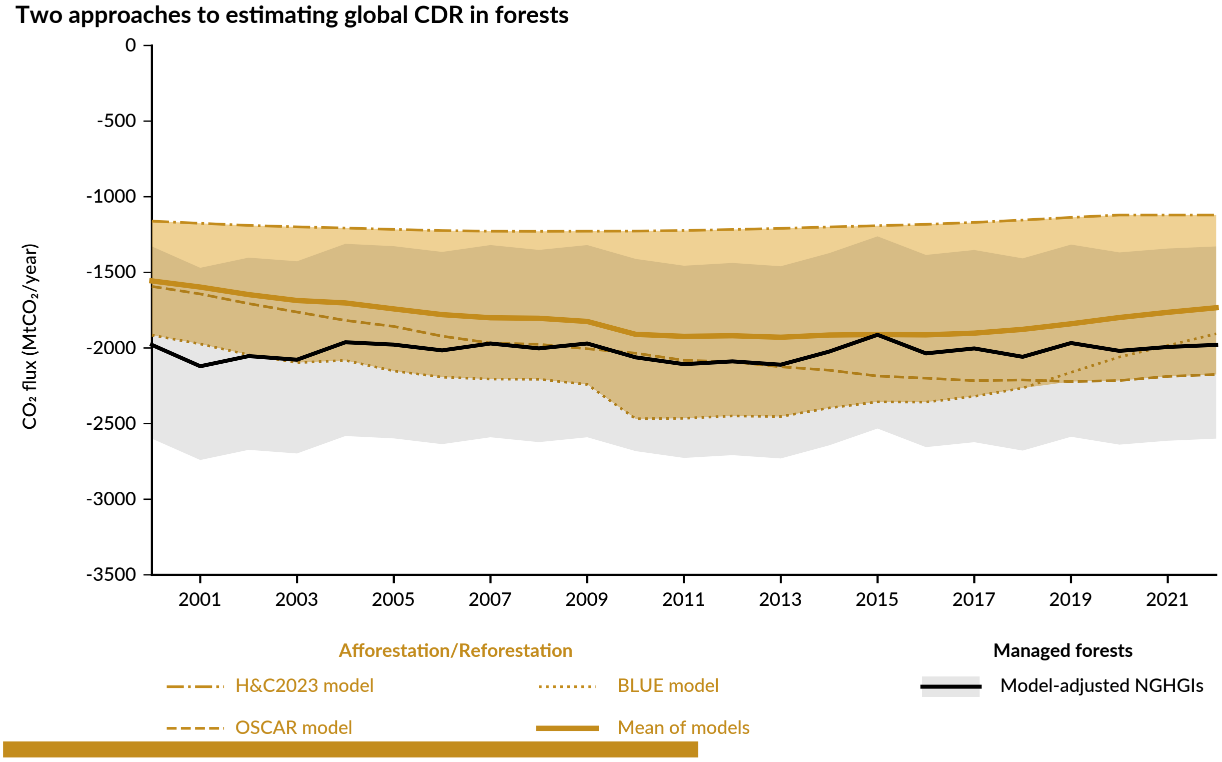

Figure 7.2 *Comparison of estimates of carbon dioxide removal (CDR) in forests. The gold lines show global CDR through afforestation/reforestation based on three bookkeeping models (BLUE, H&C2023 and OSCAR) and their mean; gold shading indicates the range across these bookkeeping model estimates. The black line denotes CDR in managed forests derived from national greenhouse gas inventories (NGHGIs), excluding emissions from organic soils, after modelled natural carbon dioxide (CO_2) fluxes have been subtracted; grey shading around the black line indicates the uncertainty in this estimate.*

At the country level, the largest CDR through afforestation/reforestation occurs in China, followed by the US, Brazil and the Russian Federation (Figure 7.3, top panel). Across the EU27 countries collectively, CDR through afforestation/reforestation falls in between that in China and the US. Together, these contribute 44% of global CDR from afforestation/

reforestation. Spatially, the largest CDR through afforestation/reforestation is found in Europe and East Asia, with substantial contributions also from several tropical regions, North America, India and parts of the Russian Federation (Figure 7.3, bottom panel). While the global-level estimates generated by the three bookkeeping models are similar, they differ more substantially at the country level.[329] The conversion between estimates based on bookkeeping models and NGHGIs also works at the country level, yet not perfectly, with country-specific reasons explaining the discrepancies in individual countries.[330]

The transfer of carbon to durable HWPs amounts to −801 $MtCO_2$ per year, averaged over 2013–2022. The net flux of durable HWPs, considering also the re-release of CO_2 through their decay, amounts to −332 $MtCO_2$ per year, averaged over 2013–2022.

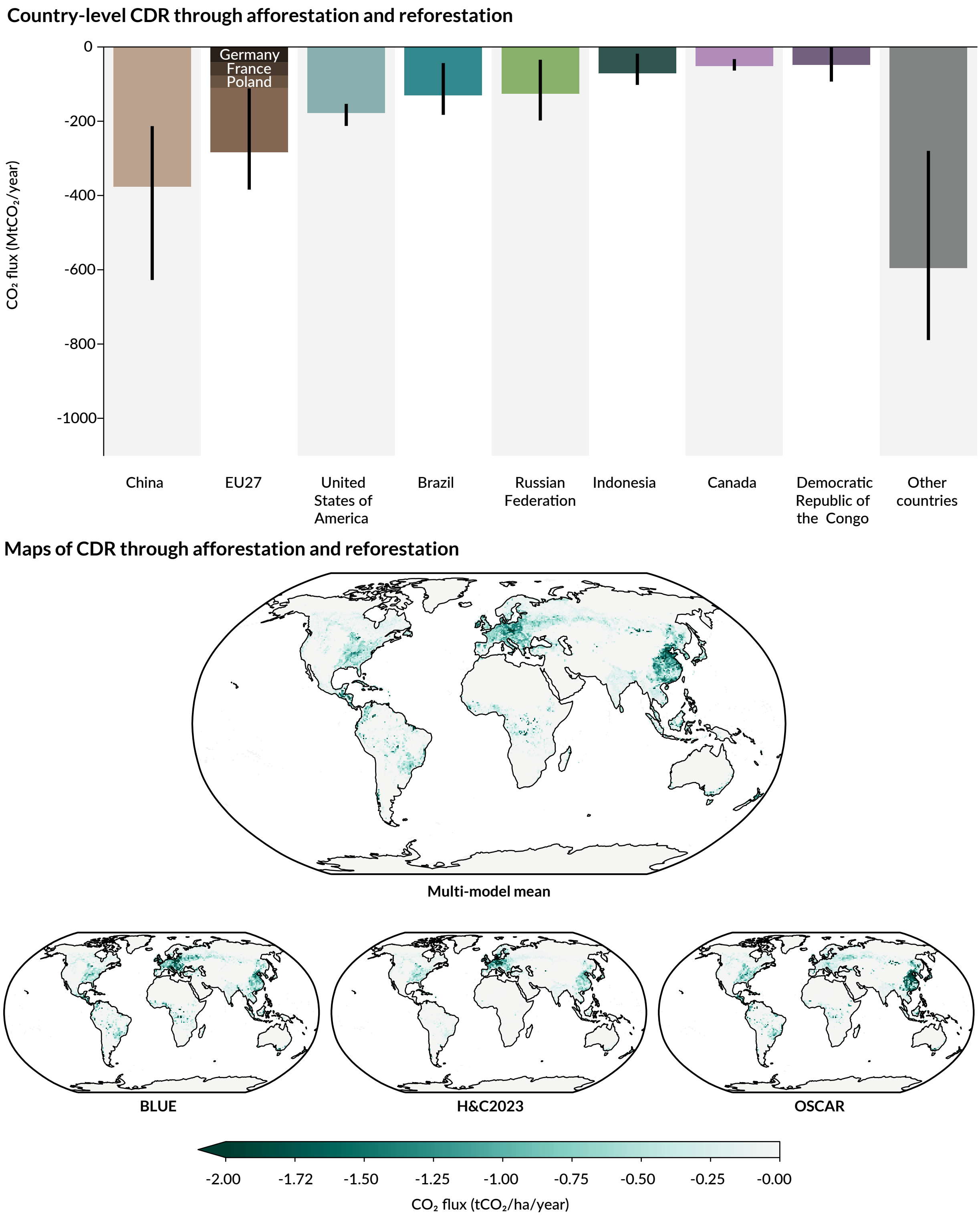

Figure 7.3 *Carbon dioxide removal (CDR) rates in forests ranked by country (and the EU27 countries collectively) (top panel) and global maps of carbon dioxide (CO_2) fluxes due to afforestation/reforestation (bottom panel). Values in both panels show averages over 2013–2022. Bars in the top panel indicate the multi-model mean of the bookkeeping models BLUE, H&C2023 and OSCAR, and whiskers represent the full spread across their estimates. Country names in the EU27 bar indicate the three EU27 countries with the largest afforestation/reforestation fluxes. The maps in the bottom panel show data for the bookkeeping models BLUE, H&C2023 and OSCAR, and their multi-model mean. BLUE provides spatially explicit data, whereas H&C2023 and OSCAR provide country-level data. The H&C2023 and OSCAR data have therefore been spatially distributed based on the CDR patterns of BLUE: for each country, the spatial pattern of the CDR flux density (i.e. flux per grid cell area) in BLUE is used, and the pattern is scaled such that the countrywide CDR estimate matches the H&C2023 and OSCAR CDR estimates in the respective country (see Schwingshackl et al., 2022, for details).*[330]

Current levels of novel CDR

In contrast to the gigaton scale of conventional CDR, the level of CDR from novel methods grew from an estimated −0.66 $MtCO_2$ per year in 2021 to −1.35 $MtCO_2$ per year in 2023 (see Figure 7.4).

The analysis shows that biochar currently provides −0.79 $MtCO_2$ per year, and BECCS −0.51 $MtCO_2$ per year. DACCS contributes −0.004 $MtCO_2$ per year, and enhanced rock weathering approximately −0.03 $MtCO_2$.

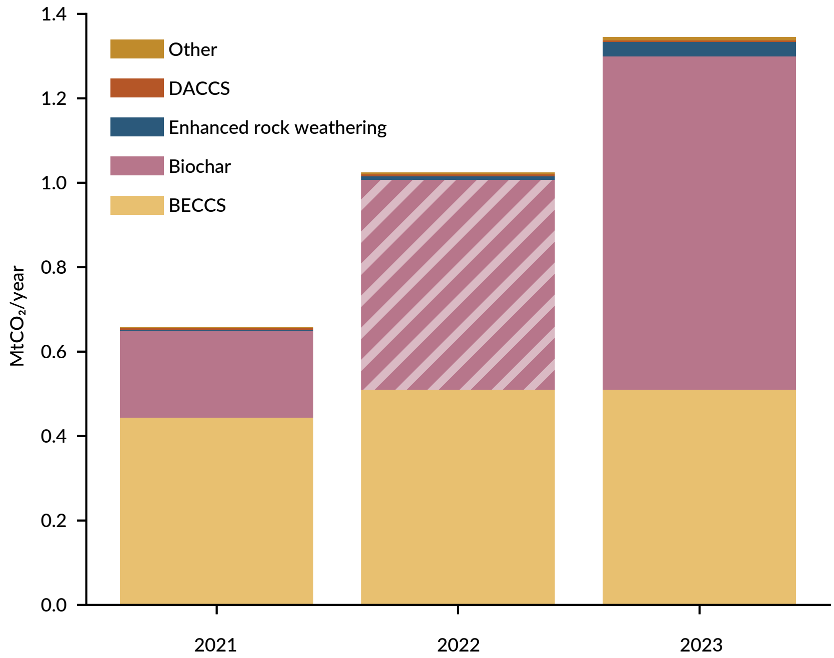

Figure 7.4 *Global carbon dioxide removal levels through novel methods. Shaded bar for biochar in 2022 represents linear interpolation from actual 2021 and 2023 data. BECCS = bioenergy with carbon capture and storage; DACCS = direct air carbon capture and storage.*

The implementation of novel CDR methods appears to remain concentrated in Europe and North America, though it is beginning to spread beyond. For BECCS, the Illinois Industrial Carbon Capture and Storage Project facility in the US is the largest and longest-running installation globally. This facility has been reaching −0.43 to −0.52 $MtCO_2$ per year from the capture of CO_2 during corn ethanol production since 2017. In 2022, another BECCS project started delivering CDR in the US: the Red Trail Energy bioethanol initiative (which reached −0.08 $MtCO_2$ in that year).[324]

Biochar has a substantially wider geographic distribution than BECCS. North America contributes an estimated 48% of the CDR from biochar; Europe follows with 17%; Asia contributes 16% and South America 11%; and Africa and Oceania contribute 8% and 1%, respectively. There was substantial growth in CDR delivered through biochar in 2023, especially in South America and Oceania, where levels increased by approximately 350 and 400 times, respectively, compared with 2021. Europe saw an estimated twelvefold increase in biochar CDR, and in Africa, removal volumes nearly tripled. These changes highlight both the rapid growth and regional variations in biochar deployment.[3]

3 *While this report draws on survey data available only for 2021 and 2023, biochar has a long-standing history.*[331]

For DACCS, the Orca facility in Iceland remains the largest operational plant globally. This facility came online in 2021 and has a capacity of 4 kt of CO_2 per year. Enhanced rock weathering is also capturing atmospheric CO_2 at the kiloton scale, although it is distributed more widely around the world than BECCS and DACCS. Companies such as UNDO, GreenSand, AgSeq and Mati have reported delivering CDR via enhanced rock weathering, with operations spread across Australia, Canada, India and the UK.

Several other novel CDR methods contribute on a smaller scale, with reported removals of just under 8 kt of CO_2 per year in removals. These novel methods include bio-oil storage, mineral products (capture of atmospheric CO_2 within demolished concrete aggregate), biomass sinking and ocean alkalinity enhancement.

A significant upswing in novel CDR is expected in the coming months. According to projections made by the International Biochar Initiative and the US Biochar Initiative, CDR from biochar is expected to reach over seven times the current deployment rate by 2025. The development pipeline also suggests a potential increase of over 2.5 times the 2023 CDR levels through BECCS and DACCS by the end of 2024. Noteworthy projects include the Blue Flint Ethanol plant in North Dakota, US, that started operations in late 2023; the Climeworks Mammoth plant in Iceland, designed to capture −0.036 $MtCO_2$ annually; and the STRATOS project by 1PointFive in Texas, US, targeting the capture of up to −0.5 $MtCO_2$ per year from mid-2025. Longer-term – but less reliable – company announcements suggest an even higher growth trajectory for novel CDR (see Chapter 3 – Demonstration and upscaling).

Figure 7.5 summarizes the current levels of conventional and novel CDR. It includes both the perspective of CO_2 removal from the atmosphere and the perspective of transfer of carbon to a durable pool. If summed together, they suggest current CDR of approximately −2,200 $MtCO_2$ per year, although how they relate to each other has been discussed in Section 7.1

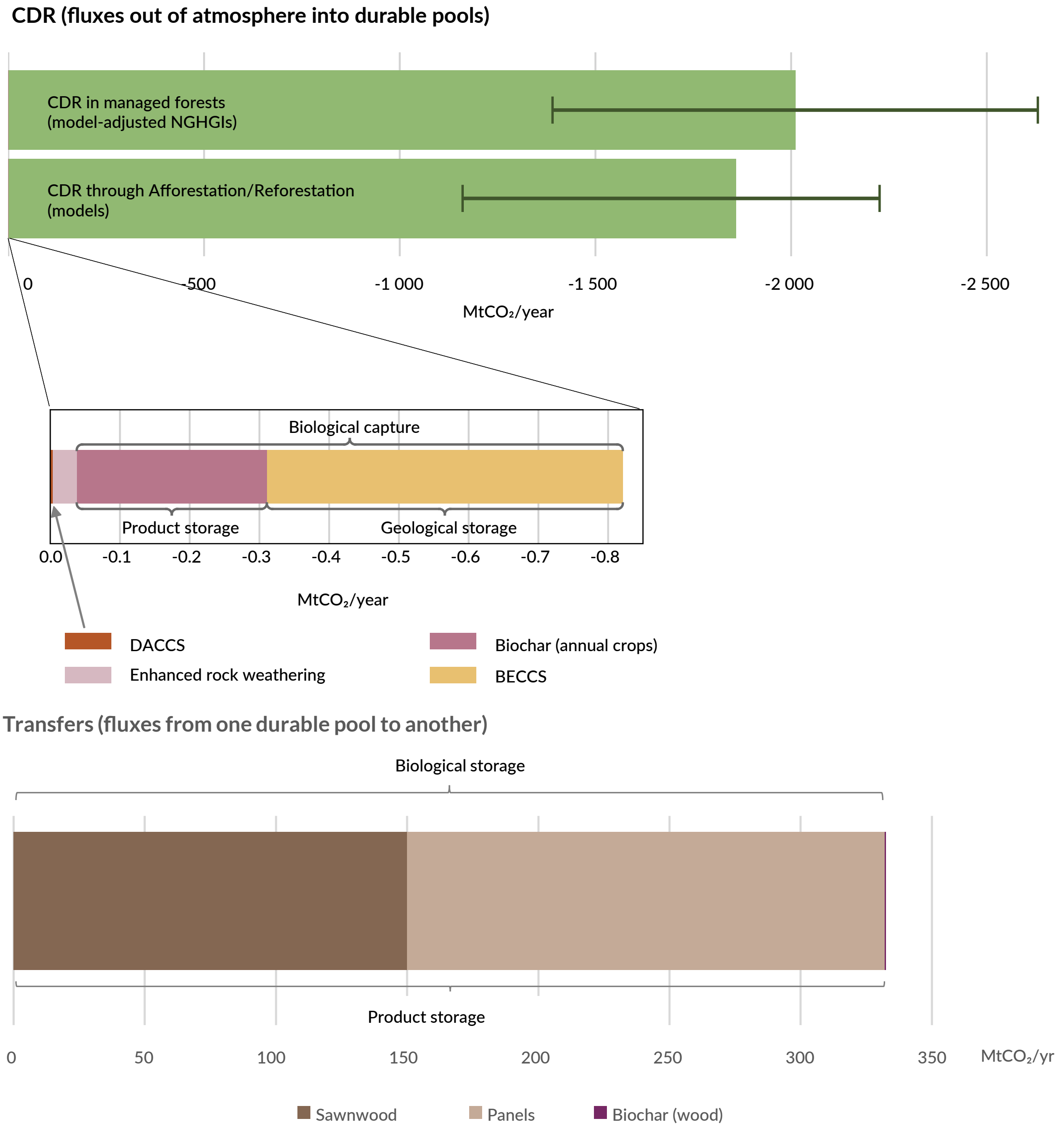

Figure 7.5 *Summary of current carbon dioxide removal (CDR) deployment, based on average levels of conventional CDR during 2013–2022 and on estimates of novel CDR in 2023. The top panel shows carbon dioxide (CO_2) moved from the atmosphere into durable storage. The middle panel shows a zoom-in for novel CDR: biochar (from annual crops), bioenergy with carbon capture and storage (BECCS), enhanced rock weathering, and direct air carbon capture and storage (DACCS). Brackets on the top and bottom of the bar indicate the capture and storage types involved (not shown: afforestation/reforestation involves biological capture and storage; DACCS and enhanced rock weathering both involve geochemical capture and mineral storage). The uncertainty bar for CDR through afforestation/reforestation in the top panel indicates the spread across the three bookkeeping model estimates. The bottom panel shows the average levels, during 2013–2022, of CO_2 recently captured from the atmosphere and transferred from one form of durable storage to another. The brackets on top indicate the origin of the captured carbon, and the brackets below indicate the final storage pool.*

Box 7.3 Limitations and knowledge gaps

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

- *Precision of afforestation/reforestation estimates:* The uncertainties in quantifying CDR due to afforestation/reforestation are substantial: the lowest and highest global estimates differ by a factor of two. A key obstacle to better constraining this number is that it is impossible to directly observe the CO_2 exchanges between land and atmosphere, or the underlying carbon stock changes, in particular in soils.
- *Distinguishing CDR from natural fluxes:* A clear separation between the effects of human activity on land and indirect responses to environmental conditions is challenging. Distinguishing between these effects requires models, but these are simplifications of complex land processes, and the input data and parameters they use have wide error margins.[332]
- *Making NGHGI and bookkeeping model estimates comparable:* The CDR estimates from model-adjusted NGHGIs and from bookkeeping models are not entirely comparable. The first includes improved management of existing forests as well as afforestation/reforestation. It may be possible to improve comparability by distinguishing between these two CDR methods in the NGHGI data, based on their "land converted to forest land" category. This would be limited to afforestation/reforestation that took place within the last 20 years, however, and would only cover certain countries.
- *Accuracy of NGHGI-based CDR estimates*: In removing the natural fluxes on managed land to derive estimates of CDR from the NGHGIs, assumptions have had to be made. These assumptions sometimes have sensitivities as large as the estimate of CDR itself. For example, country-level analysis requires a decision on how to interpret cases where the managed land appears to be a source of CO_2 rather than a sink (once the modelled natural flux has been subtracted from the NGHGI flux). These cases have been interpreted as reflecting processes like forest degradation, and hence this report has not included them as CDR.
- *Accuracy of novel CDR estimates:* The report's assessment of novel CDR levels is derived largely from self-reporting by individual (often commercial) projects. This is because almost all novel CDR methods currently lack internationally agreed approaches to monitoring, reporting and verification (see Chapter 10 – Monitoring, reporting and verification).
- *Accounting for re-release of CO_2:* Re-release of stored CO_2 is accounted for some, but not all, of the least durable CDR methods. For the estimate of carbon transfers through HWPs, emissions from decay of existing wood products are subtracted from new inputs in each given year. For the estimate of CDR levels through afforestation/reforestation, changes in durability – such as through an increasing rate of wildfires or droughts – are not considered because the bookkeeping models exclude the effects of changes in environmental conditions. The estimate of CDR in managed forests based on model-adjusted NGHGI data captures such changes to some extent. For all other CDR methods, it is implicitly assumed that all captured carbon remains stored – no re-release of CO_2 is accounted for.
- *Data gaps in tracking CDR activity:* Not all current activities that may

qualify as CDR are quantified in this report, owing to a lack of data. Among the likely largest contributors are peatland and coastal wetland restoration, agroforestry, and soil carbon sequestration in croplands and grasslands. The estimate for biochar in particular is incomplete. While the global survey data used in this report mark a significant improvement over previous data sets, these data still likely underrepresent the true scale and distribution of biochar production. Notably, the location of the survey organizers in North America may have led to higher representation in this region and lower representation in regions such as Africa, Asia and South America. This is particularly true for biochar produced for soil amendment purposes, especially in small-scale operations using portable kilns or similar setups, which may not be tracked systematically.

8

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Chapter 8 | Paris-consistent CDR scenarios

Long-term, gigaton-scale carbon dioxide removal (CDR) could be consistent with sustainability objectives if paired with ambitious emission reductions. Scenarios that are more aligned with sustainable development deploy less cumulative CDR and much less novel CDR than other mitigation scenarios.

Key insights

- On average, scenarios that limit warming to 2°C or less reduce current emissions by 34 Gt per year by 2050. A set of scenarios that are more aligned with sustainable development go further, reducing emissions by an extra 7 Gt per year, or more than 10% of today's emission levels. This report considers the more sustainable scenarios to be "Paris consistent".
- The median total levels of CDR in 2050 are similar in all scenarios that limit temperature rise below 2°C as well as in Paris-consistent scenarios with sustainability limits (7.5–7.8 Gt of carbon dioxide (CO_2) per year). The range of CDR in 1.5–2°C scenarios in 2050 is 6–10 $GtCO_2$ per year, and the range in Paris-consistent scenarios is 7–9 $GtCO_2$ per year. All scenarios assessed in this report use CDR to achieve net zero CO_2 emissions and, in some cases, net zero greenhouse gas emissions.
- Scenarios that limit global temperature rise to 1.5°C and the Paris-consistent scenarios deploy less CDR cumulatively by the time of net zero CO_2 emissions (190 $GtCO_2$ and 170 $GtCO_2$, respectively) compared to the 2°C scenarios (330 $GtCO_2$). The Paris-consistent scenarios tend to deploy more conventional CDR, whereas other scenarios deploy comparatively more novel CDR.
- Depending on future CDR is inherently risky for many reasons, and scenario evidence shows that limiting residual emissions is a more robust and sustainable strategy, and thus should be a key objective at all levels of climate policymaking.
- Novel CDR poses significant risks in terms of scalability. Some novel CDR methods have high environmental and ecosystem risks, while others have potential to generate co-benefits, but it is often difficult to determine the scale at which potential benefits outweigh potential negative impacts. Conventional CDR, when well planned and implemented with sustainability considerations, can provide significant benefits to humans and nature beyond climate change mitigation. If poorly executed, it can also

pose risks to sustainable development, such as to biodiversity and food security.

- Most scenarios continue to optimize solely for climate change mitigation and cost, too often producing unsustainable futures including very high levels of CDR that may jeopardize the attainment of other global goals. It is vital that CDR policy and strategy explicitly integrate sustainable development considerations to address risks and maximize co-benefits.

This chapter looks at the levels of CDR needed to achieve the Paris temperature goal of limiting warming to well below 2°C and striving to limit it to 1.5°C (Article 2.1a), while achieving a balance between sources and sinks of greenhouse gases (Article 4.1). The Paris Agreement also states that any response to climate change must be taken "in the context of sustainable development and efforts to eradicate poverty" (Article 2.1). Sustainability across multiple dimensions is thus paramount to delivering the mitigation goals laid out in the Paris Agreement. Section 8.1 of this chapter looks at the levels of CDR needed to achieve the Paris temperature goal in line with sustainability criteria. Section 8.2 examines the amount of residual emissions – or the remaining positive emissions that would need to be compensated by CDR to reach net zero carbon dioxide (CO_2) – that exist by sector in Paris-consistent scenarios. Section 8.3 highlights the role, risks and co-benefits of conventional and novel CDR, including areas of uncertainty in accounting for removals. Section 8.4 outlines the needs and key elements for the further development of more-sustainable scenarios.

8.1 Future scenarios

Meeting the Paris temperature goal will require strong emission reductions and the sustainable scale-up of CDR.

While the causes of anthropogenic climate change are well known to be the continued emissions of CO_2 and other greenhouse gases through fossil fuel use and land-use change, the human and economic impacts of transitioning away from current energy systems, energy consumption patterns and agricultural practices depend strongly on the national policies and strategies employed to do so. Scientists who study these different transition strategies strive to develop a consistent set of plausible assumptions about the future evolution of demographics, economic growth and technological progress, among many other factors. Techno-economic models are then used to generate quantifications of the needed energy and economy transitions consistent with these storylines. A future scenario consists of a coherent storyline of a plausible future, a wide variety of input assumptions for a model, and the output of a model. Most commonly, models called integrated assessment models (IAMs) are used to produce these scenarios in the context of climate change mitigation (see Box 8.2). This report refers to *scenarios* as the combined set of storylines, input and output of a given model framework.

The State of Carbon Dioxide Removal 1st edition assessed future CDR deployment based purely on the temperature outcomes of each provided scenario. It followed the same temperature classifications used by the IPCC, which included scenarios that limit global temperature rise to 1.5°C with 50% probability, scenarios that exceed a temperature rise of 1.5°C but then return to that level by the end of the century, and scenarios that limit temperature rise to 2°C with 67% probability (referred to by the IPCC as *C1, C2 and C3 scenarios*, respectively). The first edition went beyond assessments by the IPCC and disaggregated the total amount of conventional CDR and the total amount of novel CDR in scenarios (see Chapter 1 – Introduction, for definitions) and highlighted three illustrative scenarios to show different mitigation profiles and their trajectories (see Box 8.1).

This edition of the report builds on that previous analysis in several ways:

- Expands the scenarios assessed to include more recently published scenarios than those available in the IPCC's Sixth Assessment Report (AR6) Working Group III database
- Includes a new subset of scenarios that use sustainable development criteria
- Provides a deeper dive into the role of residual emissions and into the potential risks and co-benefits associated with conventional and novel CDR

As in the first edition, this edition refers to all 1.5–2°C scenarios as *Paris-relevant scenarios*. Whereas the first edition referred to 1.5°C (i.e. IPCC C1) scenarios as *Paris-consistent scenarios*, this edition includes a set of sustainability criteria to assess Paris consistency, among which is limiting temperature rise to below 2°C with at least 67% probability.

New for this edition of the report, all the analysis and data are provided in an open-access *State of Carbon Dioxide Removal* data portal, which will be updated for subsequent editions as new scenario evidence is made available (accessible via [https://portal.stateofcdr.org/)](https://portal.stateofcdr.org/).

Expanded scenarios

This report has collected additional scenarios from peer-reviewed publications for which data were publicly available in common data formats.[333–335] Each newly assessed scenario was provided a climate assessment (i.e. temperature pathway) consistent with approaches by the IPCC. As part of this analysis, when sufficient land-use change data were available, estimates were made for conventional CDR following the methods laid out in Gidden et al., 2023.[336] Where possible, estimates were also made for novel CDR: bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), enhanced rock weathering, and other methods (Table 8.1, Figure 8.1).

This report finds that the majority of scenarios used in the IPCC's AR6 depend on BECCS as the only novel CDR option, while newer scenarios (since AR6) are increasingly exploring future pathways that include DACCS, enhanced rock weathering and other novel methods (Table 8.1).

	Total number of 1.5–2°C scenarios (number assessed)	Number of scenarios with conventional CDR[a] (number for which CDR estimated)	Number of scenarios with novel CDR			
			BECCS	DACCS	ERW	Biochar
Scenarios in the AR6 database	*540 (407)*	*530 (407)*	*516*	*146*	*4*	*1*
New scenarios since AR6	*90 (48)*	*90 (48)*	*85*	*71*	*11*	*0*

[a] *Scenarios are considered to include conventional CDR if this value can be estimated using the methodology in Gidden et al., 2023.*[336]

Table 8.1 *Carbon dioxide removal (CDR) portfolios included in the scenarios in this assessment. AR6 = Sixth Assessment Report; BECCS = bioenergy with carbon capture and storage; DACCS = direct air carbon capture and storage; ERW = enhanced rock weathering.*

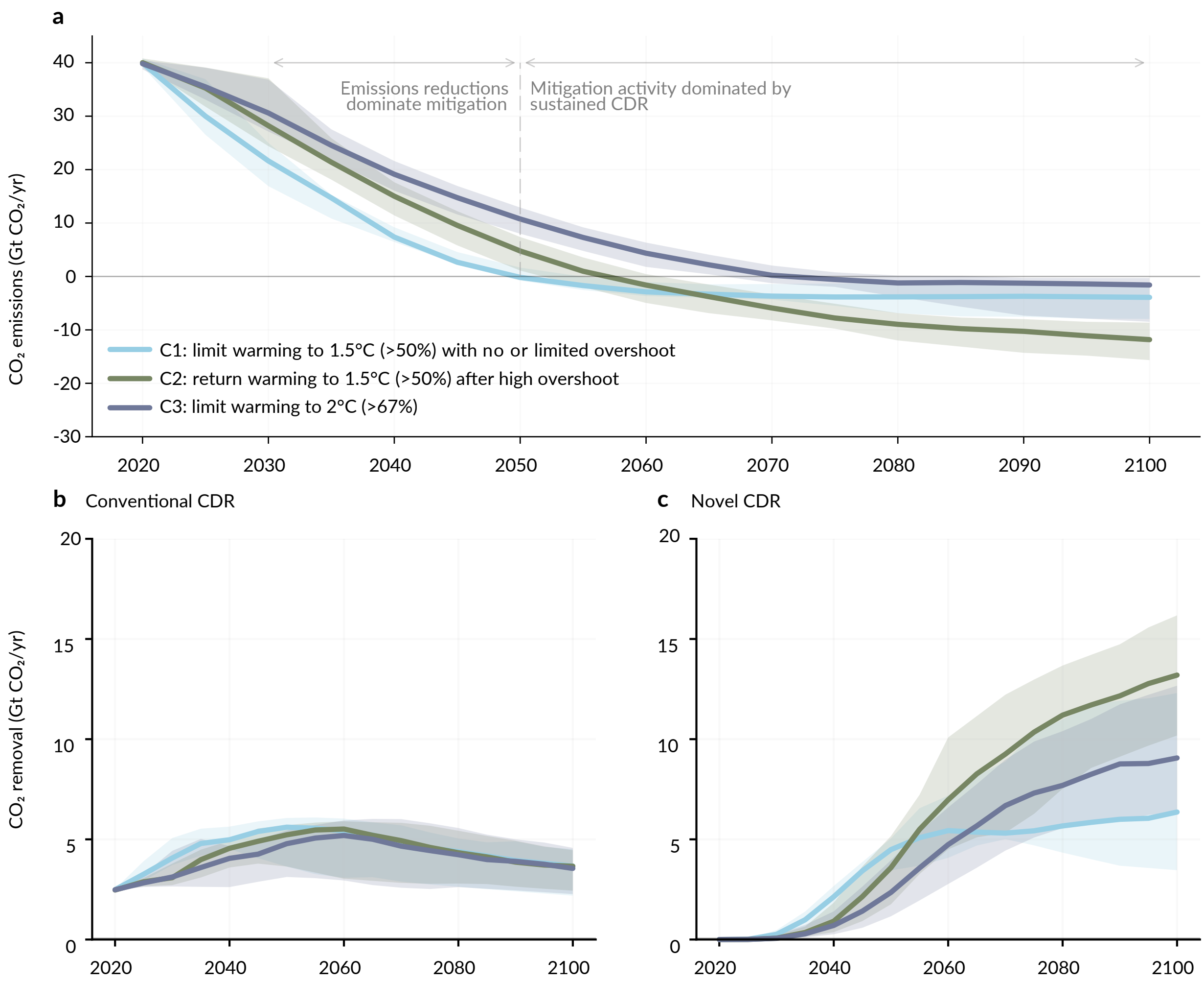

Figure 8.1 *The median and interquartile ranges of (a) carbon dioxide (CO_2) emissions and (b, c) carbon dioxide removal (CDR) values across IPCC Sixth Assessment Report scenarios and new scenarios since the Sixth Assessment Report.*

Sustainable scenarios

This analysis also looked at a subset of scenarios that are more likely than other scenarios to achieve multiple sustainable development outcomes, with the aim of better understanding how future CDR could be deployed in the context of social and environmental sustainability.

The scenarios assessed by the IPCC as well as the expanded scenarios assessed in this chapter (described in the previous section) come from the published literature, including studies from individual modelling groups and from small and large multi-model comparisons. Each study seeks to inform and further mitigation science, focusing on a specific research question. Some studies ask more general questions, such as how to bridge the gap between current nationally determined contributions and emission pathways aligned with the Paris Agreement[337] or what the cost implications are of meeting climate targets while avoiding overshooting those targets.[338] Other studies are more explicit, considering specific questions about the environmental impacts of CDR[139] or investigating how to meet different Sustainable Development Goals (SDGs), including – under SDG 13 – the 1.5°C target.[339] However, no multi-model comparison studies were found to date that systematically explore the implications of CDR deployment for meeting multiple SDGs.

Because the data provided by scenario producers are limited, it is impossible to precisely say if a given SDG is met under that scenario (and not all SDGs have explicitly quantified goals). Therefore, to identify the required subset of scenarios that are more likely to achieve multiple sustainable development outcomes, a number of criteria rooted in the sustainability literature were applied to each existing scenario (see Chapter 8 Technical Appendix). Broad conclusions were then drawn regarding CDR deployment in that subset of scenarios. The sustainability criteria considered and evaluated at the time when each scenario achieved net zero CO_2 emissions were:

- Halting deforestation and conversion of ecosystems and protecting biodiversity and ecosystem services (SDG 15)[340]
- Reducing the population at risk of hunger (SDG 2)[341]
- Limiting the increase of global energy demand while enhancing equitable access to energy (SDGs 7, 12)[339]
- Limiting reliance on energy from biomass to reduce land and water resource needs (SDGs 7, 15)[8,342]
- Keeping temperature rise well below 2°C and striving to limit it to 1.5°C (SDG 13)

Combining both temperature outcomes and dimensions of sustainability, a new "Paris-consistent" range of CDR was assessed based on this subset of more sustainable scenarios (Table 8.2, Figure 8.2). The collection of scenarios assessed does not reflect a statistical sample but rather an unstructured ensemble in which no single scenario is more likely to occur than another; however, robust conclusions can be drawn by analysing the distributions of results.343 Of the 34 scenarios that meet all sustainability criteria, ten scenarios deploy at least three CDR methods, and 24 deploy only BECCS and afforestation/reforestation.

Scenarios	2035 ($GtCO_2e$ per year [25-75th percentile])				2050 ($GtCO_2e$ per year [25-75th percentile])				At net zero CO_2 emissions ($GtCO_2$ per year [25-75th percentile])		
	Gross emission reductions from 2020	Total CDR	Conventional CDR	Novel CDR	Gross emission reductions from 2020	Total CDR	Conventional CDR	Novel CDR	Cumulative total CDR	Cumulative conventional CDR	Cumulative novel CDR
C1	30 [26, 32]	6.1 [4.9, 7.0]	4.8 [4.2, 5.5]	1.0 [0.53, 1.4]	39 [38, 42]	8.9 [7.6, 11]	5.6 [3.6, 6.1]	4.5 [3.4, 5.1]	190 [150, 260]	140 [120, 180]	51 [43, 89]
C2	21 [16, 26]	4.5 [3.5, 5.5]	4.0 [3.1, 4.5]	0.35 [0.15, 0.65]	35 [33, 39]	8.1 [6.6, 10]	5.2 [3.6, 5.7]	3.6 [1.8, 5.2]	220 [190, 250]	150 [110, 180]	64 [40, 120]
C3	19 [14, 22]	4.1 [3.2, 5.4]	3.6 [2.6, 5.0]	0.28 [0.11, 0.73]	32 [29, 34]	6.4 [5.6, 9.1]	4.8 [3.1, 5.4]	2.4 [1.2, 4]	330 [260, 440]	210 [150, 260]	140 [79, 270]
C1–C3	21 [16, 26]	4.6 [3.6, 5.9]	3.9 [3.0, 5.0]	0.43 [0.16, 0.99]	34 [30, 39]	7.5 [5.9, 10]	5 [3.3, 5.8]	3.2 [1.6, 4.6]	260 [200, 360]	170 [130, 230]	96 [48, 200]
More sustainable scenarios (within C1–C3)	31 [28, 34]	5.1 [4.6, 5.8]	4.5 [4.4, 4.9]	0.30 [0.15, 0.66]	41 [39, 43]	7.8 [6.6, 8.9]	5.7 [5.2, 5.9]	1.9 [1, 3.7]	170 [140, 210]	150 [130, 160]	22 [15, 53]
1.5°C with no novel CDR	34	3.9	3.9	0	45	4.8	4.8	0	130	130	0
1.5°C with higher novel CDR	29	6.4	3.9	2.5	43	9.8	6.3	3.5	160	110	50
1.5°C with higher conventional CDR	27	5.9	5.6	0.3	40	7.6	6.7	0.9	300	265	35

Table 8.2 *Carbon dioxide removal (CDR) and emission reductions across different scenarios (See technical annex section A8.2 for 2030 values). Cumulative values start in 2020. All values rounded to two significant digits.*

Stringent emission reductions play the strongest role in all scenarios that limit warming to 2°C or less. The 1.5°C scenarios reduce current sources of emissions compared with modelled 2020 levels by 30 (26 to 32) Gt per year by 2035 and 39 (38 to 42) Gt per year by 2050. The 2°C scenarios see emission reductions of 19 (14 to 22) Gt per year by 2035 and 32 (29 to 34) Gt per year by 2050. However, the more sustainable scenarios tend to include stronger gross emission reductions than the full scenario set, declining by 31 (28 to 34) Gt per year by 2035 and by 41 (39 to 43) Gt per year by 2050. In other words, this report's set of more sustainable scenarios further reduces sources of emissions by more than 10% of today's emission levels compared with the median of all assessed scenarios that limit warming to 2°C or less. Enhanced sectoral transformation, shifting dietary preferences, and reduced demand for products and services in certain sectors are critical components in minimizing residual emissions in these more sustainable scenarios (see Section 8.2).

Similar levels of total CDR in 2050 are seen across both the full scenario set and the more sustainable scenarios, reaching around 7.5–8 $GtCO_2$ by mid-century. However, 1.5°C scenarios and the Paris-consistent scenarios deploy less CDR cumulatively by the time of net zero CO_2 emissions (190 $GtCO_2$ and 170 $GtCO_2$, respectively) compared with the 2°C scenarios (330 $GtCO_2$). The type of CDR deployed also varies by scenario type. In general, both scenario sets see a ramping up of both conventional and novel CDR in the near term. However, by 2050 the more sustainable scenarios have a stronger dependence on conventional CDR and a relatively weaker dependence on novel CDR than the full set of scenarios. Among the more sustainable scenarios that deploy at least two types of novel CDR, BECCS contributes around 42% of total annual novel removals at the time of net zero CO_2 emissions.

Box 8.1 Focus scenarios

The State of Carbon Dioxide Removal 1st edition introduced three focus scenarios that highlighted the role of CDR: one focused on demand reduction, one on renewable energy, and one on expanding conventional and novel CDR. Each focus scenario was assessed as a 1.5°C with no or limited overshoot scenario (C1 category) by the IPCC in AR6.

While these distinctions were useful, the naming conventions were felt to detract from the message around their CDR characteristics. In any given scenario, multiple mitigation levers are used to achieve net emission reductions and limit global temperature rise. For example, the *Focus on Renewables* scenario also includes substantial dietary shifts away from meat-based diets and towards the EAT–Lancet diet[344] that includes more vegetable and plant-based proteins, among many other levers, resulting in a scenario with significantly more-sustainable outcomes.

As such, these focus scenarios have been renamed for this second edition of the report based on their CDR characteristics (2030 Total, Conventional, and Novel CDR values shown) as follows:

- Focus on Demand Reduction[345] → 1.5°C with no novel CDR (3.5, 3.5, 0 $GtCO_2$)

- Focus on Renewables[339] → 1.5°C with higher conventional CDR (4, 3, 1 $GtCO_2$)
- Focus on CDR[346] → 1.5°C with higher novel CDR (4, 3,1 $GtCO_2$)

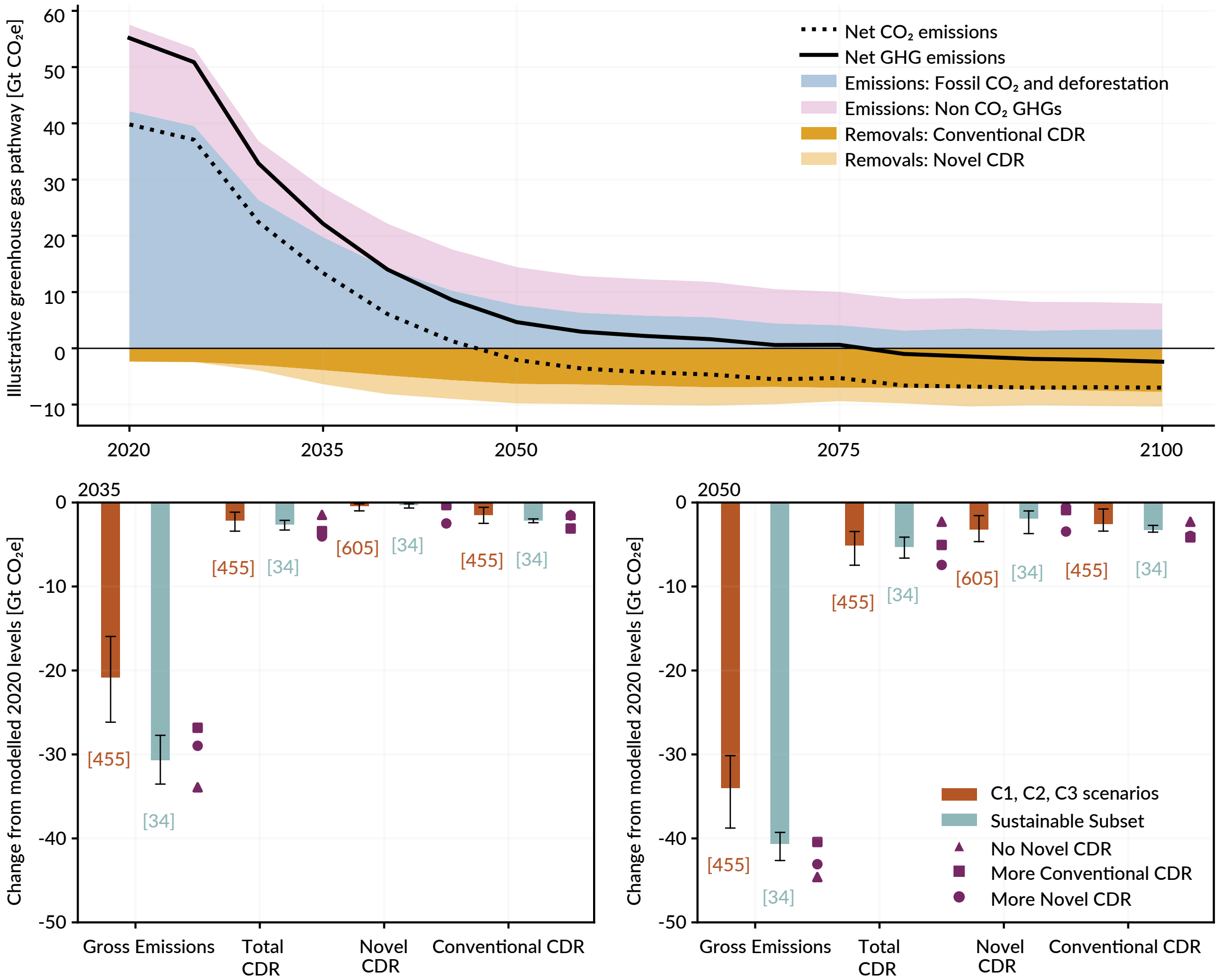

Figure 8.2 *The more sustainable scenarios see stronger gross emission reductions, more conventional carbon dioxide removal (CDR) (with potentially strong co-benefits), and less novel CDR (with potentially greater risks) by 2050. Gross emission reductions include all greenhouse gases (GHGs).*

8.2 Residual emissions across sectors

CDR counterbalances residual emissions in hard-to-transition sectors, including the agricultural and industrial process sectors. Low residual emission scenarios are most aligned with sustainability outcomes.

The scenarios assessed in this report seek to show future pathways that limit global temperature rise by reducing net CO_2 emissions, and in some cases greenhouse gas emissions, to net-negative levels. Because scenarios try to find cost-effective solutions (see Box 8.2), in some cases they can determine that it is less costly to deploy a given CDR technology than it is to further reduce emissions in a given sector. CDR thus plays three primary roles in scenarios:

- Helping draw down near-term net emissions, largely through conventional CDR

- Counterbalancing remaining positive CO_2 emissions at the time net zero CO_2 is reached, generally through strategies involving both novel CDR and conventional CDR

- Further helping draw down net-negative CO_2 emissions to achieve net zero greenhouse gas emissions by maintaining levels of conventional CDR and expanding further levels of novel CDR

Box 8.2 IAMs and scenario collections

IAMs bring together representations of multiple systems, including energy supply and demand, economies, and the environment, to study the effect of potential sociodemographic and policy futures. Scenarios generated by IAMs are one of the primary sources of scenarios in the IPCC AR6 database. IAMs use input drivers such as future trajectories of population, gross domestic product and urbanization, as well as a wealth of techno-economic assumptions. These assumptions can hew to certain narratives or storylines, for example a "middle of the road" future, or a "fossil-fuelled" future, or a "sustainability-focused" future.[347]

Different modelling teams choose different values across a wide range of assumptions, such as for technology costs, technology potential and economic discount rates. Models can also have fundamentally different structures, from least-cost or maximum-utility optimization to more simulation-based approaches, as well as fundamentally different levels of representation that focus more on the economy (e.g. computable general equilibrium) or more on fine-grained processes (e.g. bottom-up techno-economic models). Because of the diversity of approaches and assumptions, models may prefer certain types of mitigation solutions over others.[348]

IAMs are regularly used to study the range of different policy tools and the technology development needed to achieve certain policy aims. In the context of IPCC AR6, these policy aims are normally related to specified temperature outcomes governed by negotiations under the UNFCCC. However, IAMs are also used to investigate how to achieve other targets, such as the SDGs, and scenarios generated with IAMs are regularly produced without setting any specific climate target at all. Scenarios are neither predictive nor prescriptive; they are meant to show how different outcomes can be arrived at.

One must use caution when querying unstructured ensembles (or sets) of scenarios (i.e. collections of scenarios that are not coordinated to answer a specific research question), such as the IPCC AR6 Working Group III database. In many cases, scenarios submitted to the AR6 database come from structured intermodel comparison projects, in which multiple models harmonize input assumptions to answer a given research question. In the context of CDR, such projects may have included specific diagnostic scenarios, where certain CDR methods are turned on or off to study how a given climate target could be achieved if that CDR method were unavailable in the future, and the diagnostic conditions specified could affect the outcomes assessed from an unstructured scenario ensemble. In addition, these scenarios in unstructured ensembles may or may not explicitly consider other sustainability constraints, such as protecting biodiversity. Indeed, some scenarios may explicitly be designed such that they violate sustainability constraints to study what may happen in worst-case outcomes (e.g. in a fossil-fuelled future). This has led to some critique of the IPCC's assessment using scenarios generally,[349] and there are growing calls to develop better methods to perform scenario assessment.[350]

Residual emissions are the emissions that would need to be compensated by CDR to reach net zero CO_2. A precise definition of residual emissions remains elusive, as they are a future unknown quantity that depends on the success of emission reduction efforts across different sectors. Emerging evidence from national net zero strategies indicates that policymakers expect considerable quantities of residual emissions in 2050, averaging 21% of peak emissions (with a min/max range of 5–52%) in Annex I (developed) countries.[143,351] These levels have led some to question whether reduction proposals are ambitious enough and to examine the emerging politics of residual emissions.[143,168,352,353]

Residual emissions can be considered either the cumulative quantity of unabated emissions in the 21st century[354] or the annual gross emissions that are balanced by CDR once net zero CO_2 is reached. This report uses the latter definition, as it focuses attention on the specific sectors where emissions are considered hard to abate (i.e. sectors in which emission reductions level off after a transition period). This section draws from a study that examines residual emissions in the full range of IPCC AR6 C1–C3 (1.5–2°C) scenarios,[355] focusing on emission levels at the time that net zero CO_2 is reached (approximately the early 2050s for C1 scenarios, in the 2060s for C2 and in the 2070s for C3). This compilation of scenarios differs from those evaluated in Section 8.1, as it is not constrained by a set of sustainability criteria, nor does it include new scenarios since AR6.

The IPCC AR6 scenarios project considerable volumes of residual emissions, even after a period of deep reductions across sectors (see Figure 8.3). The AR6 scenarios have residual greenhouse gas emissions at the point of net zero CO_2 of 16 (13–22) $GtCO_2e$. This represents gross emission reductions of 71 (62–77) % by a median net zero year of 2066. While some scenarios subsequently continue to reduce gross emissions, potentially reaching net zero greenhouse gas emissions in the 21st century, others scale up CDR to reach those goals. Residual emissions of 13 (7.6–20) $GtCO_2e$ still remain by 2100 across the IPCC AR6 scenario ensemble. These levels are less ambitious than benchmarks in corporate net zero standards such as the International Organization for Standardization and Science Based Targets initiative standards, which arrive at net zero CO_2 in 2050 to align with a 1.5°C pathway.[355]

Scenario evidence supports the notion that residual emissions are weighted towards non-CO_2 greenhouse gases in the agricultural and industrial process sectors (see Figure 8.3).[356] The largest sources of emissions at the point that net zero CO_2 is reached in scenarios are methane emissions from livestock, CO_2 emissions from transport (including international aviation), nitrous oxide emissions from agriculture, CO_2 emissions from industrial processes (e.g. from cement and steel manufacture), and methane emissions from the waste sector. However, there is considerable variation across the scenarios, primarily driven by the type of model used and, presumably, by the underlying cost distribution of the models' mitigation options.

The precise quantity of non-CO_2 greenhouse gas emissions that would need to be compensated by CDR or removals of methane or nitrous oxide to ultimately stabilize temperatures remains uncertain.[23] The frontier of possible emission reductions is also far from explored in current scenarios, as there have been few systematic studies of low residual emission scenarios. However, scenarios at the lower end of residual emissions (e.g. less than 12 $GtCO_2e$ per year at net zero CO_2) tend to involve demand-side changes, such as dietary shifts (lowering livestock emissions) and reduced aviation demand;[339,356] achieve a deep electrification of end-use sectors;[357] or purposefully constrain CDR availability in the model, thus implementing higher-cost gross emission reductions.[358] Although there may be trade-offs to achieving such deep reductions, these strategies intersect with sustainability-oriented pathways to net zero and thus deliver significant co-benefits for social well-being and the environment. As such, limiting residual emissions and thereby lowering dependence on CDR should be considered a key objective at all levels of climate policymaking.

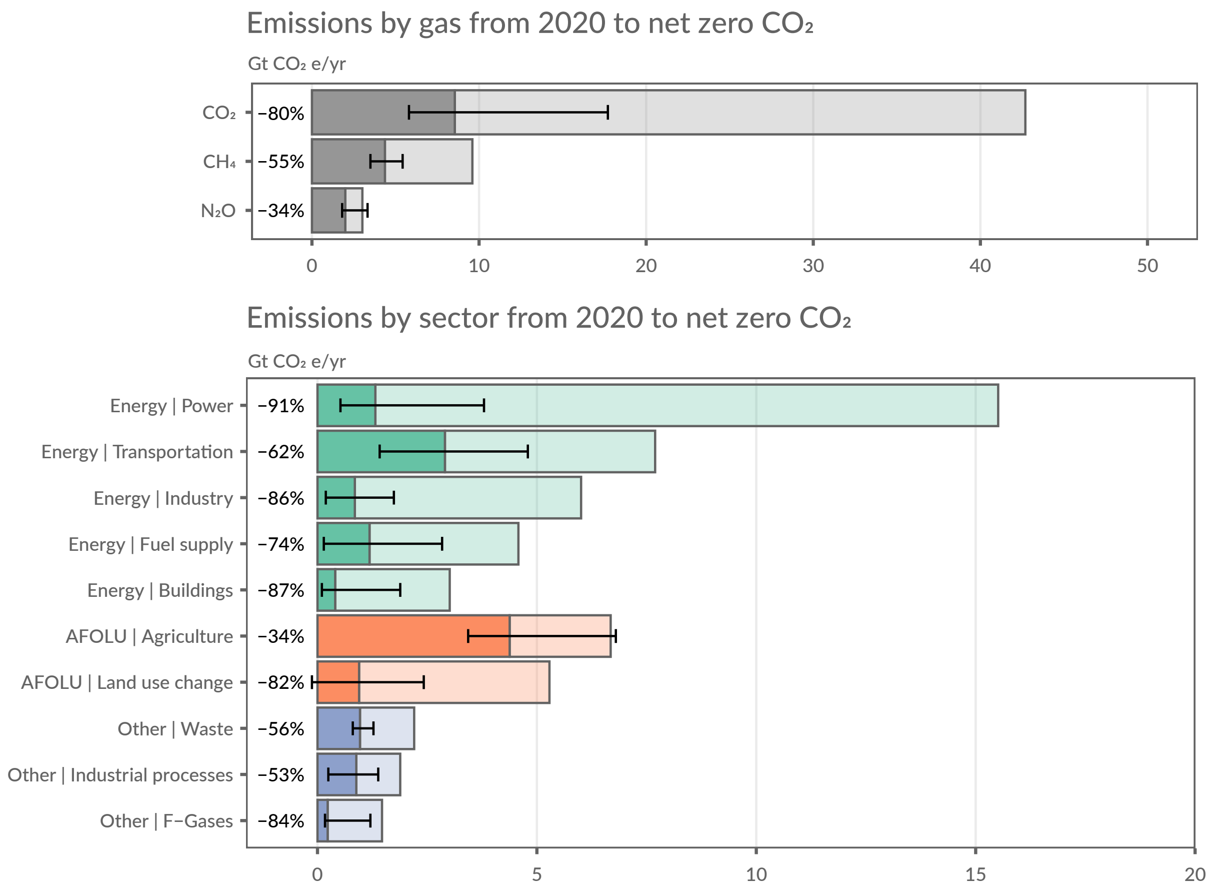

Figure 8.3 *Gross emission reductions and residual emissions in IPCC Sixth Assessment Report scenarios by gas and sector. The specific compilation of scenarios differs to those presented in Figure 8.1 and is discussed in Lamb, 2024.[355] Faded bars represent median scenario gross emissions in 2020; solid bars represent median scenario gross emissions at the point of net zero carbon dioxide (CO_2). Error bars indicate the 5th to 95th percentile of the scenario range at the point of net zero CO_2. The timing of net zero CO_2 varies by scenario but is reached between 2050 and 2055 in the assessed C1 scenarios, in the 2060s in C2 scenarios and in the 2070s in C3 scenarios. AFOLU = agriculture, forestry and other land use; CH_4 = methane; F-gases = fluorinated greenhouse gases; N_2O = nitrous oxide.*

8.3 The role and potential risks, benefits and uncertainties of conventional and novel CDR

All scenarios assessed deploy conventional CDR early on, then shift towards novel CDR later in the century. Different CDR approaches carry different potential risks and benefits, and it is highly uncertain how much CDR will be needed.

Conventional CDR measures, such as afforestation/reforestation and soil carbon sequestration, tend to be deployed in the first half of this century in scenarios that limit warming to 1.5°C and 2°C, whereas novel CDR technologies, such as BECCS or DACCS, tend to be scaled up in the latter half of the century. Early deployment of conventional CDR in scenarios is due to the relative maturity, scalability and cost-effectiveness of these methods. For instance, mitigation costs are estimated to range from –\$45 to \$100/tCO_2 for soil carbon sequestration and from \$0 to \$240/tCO_2 for afforestation/reforestation, whereas BECCS costs are projected to range from \$15 to \$400/tCO_2 and DACCS costs from \$200 to \$1,000/tCO_2.[4,359]

The potential risks and benefits of CDR approaches are also increasingly influencing their use and deployment in scenarios and in practice. Relying on CDR, especially large-scale CDR at the gigaton scale, poses social and environmental sustainability risks as well as climate change mitigation risks. However, if strategically planned and deployed, some CDR options can also provide benefits for people and nature beyond climate change mitigation.

This section discusses the role of conventional and novel CDR in scenarios, including their geographical deployment. It also outlines the potential risks and benefits of the various CDR approaches and highlights ways to avoid or reduce risks and maximize benefits.

The role of conventional CDR in scenarios

In the Paris-consistent scenarios with sustainability limits assessed in this report, conventional CDR reaches 4.5 GtCO_2 per year in 2035 and 5.7 GtCO_2 per year in 2050, cumulatively amounting to 150 GtCO_2 at the point of net zero CO_2 (Table 8.2). Methods of conventional CDR include afforestation/reforestation, forest management, soil carbon sequestration in croplands and grasslands, agroforestry, restoration of peatland and coastal wetlands such as mangroves, and durable wood products (see Chapter 1 – Introduction). To date, most of these options – with the exception of afforestation/reforestation and forest management – are not included in the IAM scenarios assessed in this report, though the newest versions of land-model components are beginning to incorporate soil carbon sequestration and peatland restoration.[340] Therefore, a large majority of the conventional CDR estimates are from large-scale afforestation/reforestation. The lack of additional conventional CDR methods in the IAMs is mainly because those methods are associated with components (e.g. land and soil management) that are themselves not yet explicitly represented in the IAMs.

Multi-model assessment[360] indicates that forested areas significantly expand at lower carbon prices (<\$50/tCO_2), while the cropland area for bioenergy crops increases at higher carbon prices (>\$100/tCO_2), largely replacing pastureland. Trade-offs and competition for land between conventional CDR and food production may be difficult to avoid without explicit consideration of sustainable food policies taken in tandem with national mitigation planning.[361,362]

The geographical deployment of conventional CDR depends on the specific method's technical potential in that location; for instance, afforestation/reforestation requires an area and climate suitable for forestation with high carbon density potential. Under mitigation pathways, afforestation/reforestation tends to be primarily implemented in Africa, Latin America, South Asia and certain developed countries.[363] Soil carbon sequestration tends to have higher potential in Africa, Asia, and some developed countries;[364] however, it is not a major CDR option deployed in assessed scenarios to date.

The scientific teams that produce scenarios are exploring ways to incorporate more conventional CDR methods, which will likely affect future assessments of CDR levels compatible with multiple sustainability goals due to their potential social and biodiversity co-benefits (see next section). For example, agroforestry and soil carbon sequestration are being considered by some models, which could potentially expand conventional CDR further. Studies show a mitigation potential of 1.1 $GtCO_2$ per year for agroforestry and of 1.8 $GtCO_2$ per year for soil carbon sequestration by 2050 at a carbon price of less than $100/$tCO_2$.[364]

Potential risks and benefits of conventional CDR

The potential risks and benefits of conventional CDR approaches are relatively well researched in the literature on ecosystem-based approaches, such as nature-based solutions, natural climate solutions, ecosystem-based adaptation, and agroecology.

All land-based interventions (including relevant novel CDR approaches) have implications for climate change mitigation, adaptation and resilience, food security, biodiversity, water quality and supply, and livelihoods and poverty, where the scale of benefit or risk largely depends on (1) the type of activity undertaken (e.g. reforestation in forest biomes versus afforestation in non-forest biomes), (2) the deployment strategy (e.g. native species in habitat corridors versus large-scale monoculture plantations of non-native species), and (3) the regional and local context (e.g. soil type, biome type, climate, land ownership and beneficiaries, competing land uses).[365]

Potential social and environmental benefits

There is increasing evidence that when well planned and deployed with explicit consideration of the local context and sustainable development outcomes, conventional CDR measures can deliver significant benefits for people and nature in addition to climate.[4] For example, community-led mangrove restoration not only sequesters carbon, it can also benefit local livelihoods, provide species habitat (including commercial fish habitat), buffer impacts from storm surge and floods, reduce pollution and improve water quality.[366] Agroforestry – or planting native fruit trees in croplands and pastures and improving soil carbon sequestration by selecting perennials and longer rooted cultivars and strategically applying compost – could improve soil health, water retention, productivity and farmer incomes, and increase resilience to heatwaves, floods and droughts.[367–371] Reforestation of degraded land that previously supported forests through community-supported natural regeneration with rewilding of native seed dispersers enhances biodiversity and provides habitat, reduces erosion and improves soil health and, depending on scale, could increase water cycling, local cooling and the resilience of the region to extreme weather.[372–374] Potential benefits from these conventional CDR approaches are therefore well positioned to contribute to the SDGs, the Global Biodiversity Framework and other global and national policy goals.[365]

Potential social and environmental risks

Conversely, poorly planned and implemented land interventions that do not adequately consider local contexts and outcomes beyond climate could have adverse effects on climate, nature and people. Potential risks include implementation of large-scale interventions (e.g. afforestation/reforestation) that compete with croplands and reduce incomes and food security;[360,375] afforestation of non-forest ecosystems, like native grasslands, to exotic monoculture plantations, reducing biodiversity and resilience to climate change, and straining water resources;[376–379] marginalization of local communities due to land grabbing and benefit capture;[380] and reduced mitigation effectiveness due to biophysical impacts from adding forests in high latitudes (e.g. albedo).[381,382]

Climate change mitigation risks

All land-based CDR approaches (conventional and novel) are vulnerable to climate impacts and reversals, which could reduce their mitigation efficacy. The capacity of land to sequester carbon over time is subject to various uncertainties, including biogeochemical, biophysical, anthropogenic and carbon accounting uncertainties, further challenging CDR estimation (see Box 8.3).

Risk mitigation strategies

To mitigate negative consequences, sustainable land-use planning and management can balance the use of land for CDR with other aspects of land-based sustainability. Through various approaches (e.g. managing scale, focusing on sustainable deployment strategies catered to local context), the benefits of CDR techniques can be optimized to achieve multiple goals, including carbon sequestration and enhancement of biodiversity, ecosystem services and livelihoods.[373] Other land-based measures, including sustainable agricultural intensification, reduced food waste, and dietary changes, can lessen the land required for food production and thus facilitate carbon sequestration through CDR, all while safeguarding food security and land sustainability.[365,383]

The role of novel CDR in scenarios

Across most of the scenarios assessed in this report, novel CDR increases to megaton scale by 2030, then to gigaton scale around mid-century and beyond. The scenarios mostly include BECCS and DACCS, with some scenarios also including enhanced rock weathering and biochar (see Table 8.1). When and how fast these technologies can be scaled up depends mainly on costs but also on technological readiness and policy.

Most of the models include large-scale deployment of BECCS in C1–C3 scenarios as it is comparatively cheap[8] and able to supply low-carbon energy, especially liquid fuels,[384] which is one part of the energy sector that is difficult and expensive to decarbonize otherwise. However, BECCS is limited by the supply of sustainable bioenergy.[8,385–388] Enhanced rock weathering is more expensive due to the extensive mining and related operations needed to produce crushed basalt rock, but little additional technological development and no carbon storage infrastructure is required. In the limited number of scenarios available, enhanced rock weathering scales up to megaton and gigaton scale around mid-century. DACCS has the highest costs and energy requirements, but also the largest potential to scale.[8] Therefore, the models invest in early upscaling to the megaton scale by about 2035, to be able to reach the gigaton scale in the second half of the century.

After mid-century, most novel CDR scales up higher than conventional CDR in the scenarios assessed (Figure 8.1). The extent of total deployment depends to a large degree on the climate policy logic[389] used to drive the scenario, for example either using a full century carbon budget, which can first be exceeded and then drawn down, or not exceeding a peak temperature, which can result in lower overall system costs and lower levels of CDR deployment.[338,390] The deployment levels of the different options then depend on each option's total potential and the options' relative competitiveness.

Enhanced rock weathering performs more efficiently in warm and humid climates and has the highest potential in Asia and Latin America.[358] BECCS needs biomass supply, thus has higher technical potential in Asia and Latin America (similar to conventional CDR), with regional distribution dependent on the modelling framework used.[384,391] However, for BECCS to be considered a CDR method, its carbon emissions must be captured and ultimately stored, requiring extensive carbon capture and storage infrastructure, which may be more prevalent elsewhere. Also, the bioenergy could potentially be traded, as is the case currently between the UK and the US, which itself can raise sustainability concerns if the biomass is sourced, for example, from existing primary forests, as has been alleged in the UK context.[392] This means biomass could be grown elsewhere but ultimately used as BECCS in a different location. However, given the low energy density of biomass, the cost and energy penalty for transportation would be higher than for fossil fuels.

DACCS shows a different geographic profile, with high deployment in regions that have high renewable energy potential in combination with high carbon storage potential. Regions with the highest DACCS deployment in currently assessed scenarios are developed countries, Asia, and the Middle East and North Africa. If DACCS is built further away from these areas, it would require extensive carbon capture and storage infrastructure, similar to BECCS.

The well-known questions and potential risks related to the sustainability (see next section) and monitoring, reporting and verification of BECCS have led the scenario literature to focus more on DACCS as a novel CDR option. However, DACCS is still expected to be one of the most expensive CDR options. Scenario evidence shows DACCS exceed the 1 $GtCO_2$ per year scale only at carbon prices above \$350/tCO_2, and sometimes far higher. DACCS also requires substantial energy inputs, which must come from carbon-free energy to maximize carbon capture efficiency and avoid environmental degradation,[393] in addition to the carbon-free energy required to support the transition of other sectors. Furthermore, carbon storage needs to be provided in potential competition with other sectors – for example, for process emissions in the cement industry – and with other CDR methods.

Potential risks and benefits of novel CDR

The IPCC provided a recent assessment of the risks and benefits of various novel CDR methods including biochar, BECCS, DACCS, enhanced rock weathering, ocean fertilization, ocean alkalinity enhancement and biomass sinking (e.g. macroalgae, seaweed).[4] Although scientific studies are continuing to emerge, large knowledge gaps remain about the effectiveness and risks of large-scale deployment of most novel CDR methods.

Potential social and environmental benefits

Novel CDR methods that store carbon geologically have the benefit of greater storage durability than conventional land-based CDR, locking in removals for as much as hundreds to thousands of years.[4] Similar to conventional CDR, some novel CDR methods also have the potential to yield social and environmental co-benefits depending on the type of activity deployed, its scale, and the local or regional context in which it is used. For example, strategically deployed biochar and enhanced rock weathering could help improve soil health and crop yields and reduce drought effects,[367,394,395] seaweed production and BECCS could contribute to market opportunities,[8] and regional ocean alkalinity enhancement could help protect coral reefs and shellfisheries from ocean acidification.[396,397] However, it is very difficult to determine the scale at which the benefits of various novel CDR technologies outweigh their potential negative impacts (outlined in the following subsections).[365]

Potential social and environmental risks

The sustainability risks of BECCS – such as increased land use and conversion, water use and fertilizer use, and their related adverse effects on food security, biodiversity and greenhouse gas emissions – have been relatively well explored and are similar to those of large-scale afforestation/reforestation covered in the section on the potential risks of conventional CDR.[349,385,387,398–403] Large-scale DACCS deployment requires volumes of sorbent bulk materials orders of magnitude larger than are produced today as well as significant energy requirements, on the order of a quarter to a third of today's global energy production.[393,404] Deploying enhanced rock weathering at scale would have a significant mining footprint, and the required rock grinding would have a significant energy and water footprint, with related potential negative impacts on biodiversity, on local water availability and quality, and on air quality.[394,405] In the scientific literature, ocean-based approaches including ocean fertilization and ocean alkalinity enhancement currently have a high risk profile due to large uncertainties related to ecosystem destabilization, feedback effects, and impacts on biodiversity.[4] Ocean alkalinity enhancement also has similar risks from mining (e.g. silicate materials) as are associated with enhanced rock weathering.[397,406]

Climate change mitigation risks

A key risk of large-scale novel CDR is scalability: that the technical, economic and political requirements and social acceptance for such levels of deployment may not be feasible or materialize in time, jeopardizing mitigation goals.[8,407,408] In particular, assumptions related to the mitigation efficiency of novel CDR methods have been challenged, in particular for BECCS (biomass yield and CDR conversion assumptions)[398,399,409,410] and DACCS and enhanced rock weathering (renewable energy use and availability assumptions).[393,404,405] In addition, models tend to assume very large capture efficiencies, on the order of 90–95%, and would overestimate the effectiveness of carbon capture and storage should these efficiencies fail to materialize in practice.

Risk mitigation strategies

The choice of feedstock (e.g. agricultural residues instead of dedicated bioenergy crops), coupled with reduced energy demand and a limited scale of deployment, can help mitigate the negative consequences of many novel CDR approaches. More research is needed to reduce the uncertainties, better understand the magnitude of risks compared with benefits, and develop strategies to mitigate the risks and maximize the benefits associated with most novel CDR.

Box 8.3 Uncertainties related to land-based CDR (conventional and novel)

The ability for land-based ecosystems to effectively remove CO_2 from the atmosphere is subject to multiple uncertainties, including physical uncertainties and accounting uncertainties. These uncertainties further emphasize that the most reliable strategy to keep temperatures within liveable limits is to reduce sources of emissions rather than depend on uncertain future sinks.

Both conventional and novel methods of land-based CDR are subject to physical uncertainties (in this case, biogeochemical and biogeophysical uncertainties) caused by imperfect understanding of how the land biosphere and its cycling of carbon and other greenhouse gases will respond to future climate change. The uncertainties are dominated by poorly constrained carbon densities (notably in soils), biospheric regrowth curves, and the fate of dead biomass. In addition, under a changing climate, disturbances such as pests, wildfires and windthrow will see changes in frequency and intensity, which in turn may reduce the durability of land carbon storage and the overall efficiency of land-based CDR. Finally, it is not clear that land-based CDR will be as effective after net zero CO_2 as it is when CO_2 emissions are net positive.[411] The estimates of future land-based CDR in this report do not account for these additional risks.

Accounting uncertainties affect current and future estimates of CDR as well as net emissions on land. As discussed in Chapter 7 (Current levels of CDR), countries and parties to the UNFCCC account for emissions and removals (together called *carbon fluxes*) in a different way in their national greenhouse gas inventories than is considered by scientific models (including the bookkeeping models assessed in Chapter 7 and the IAMs assessed in this chapter).[326] The different approaches mean that model-based results cannot be compared one-to-one with country-based accounting, presenting another layer of uncertainty. The divergent accounting practices have important ramifications for mitigation benchmarks[337] as well as for how CDR is measured, both today and in the future. Because the strength of future indirect removals is directly linked to mitigation action (strong mitigation action likely means weaker indirect removals; weak mitigation action likely means stronger indirect removals), exactly what level of future CDR is estimated depends critically on which accounting approach is used. By 2050, under current policy pathways, for example, total land-based removals increase relative to today even more so than in 1.5°C and 2°C scenarios (see Figure 8.4), whereas CDR as defined by the IPCC and in this report shows opposite trends.

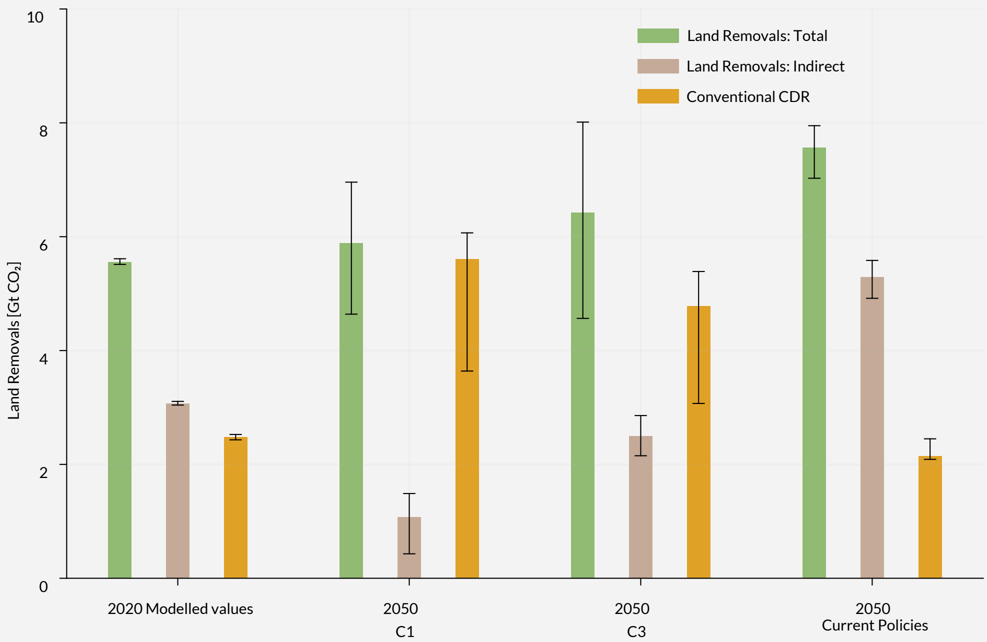

Figure 8.4 *Future levels of carbon removal differ according to which land accounting practice is used. Land-based removals (green) are those from national greenhouse gas inventories, conventional carbon dioxide removal (CDR; yellow) is from integrated assessment models, and indirect land-based removals (brown) is the difference between the two in a given scenario. Median and interquartile ranges are shown across all scenarios (the summation of conventional CDR and indirect removals does not hold for distributional values).*

8.4 Towards sustainable development pathways

CDR pathways and deployment strategies need to be aligned with the SDGs and other global goals *in addition to* significantly reducing emissions to meet the Paris temperature goal.

Countries have set ambitious global goals under the three Rio Conventions (UNFCCC, the Convention on Biological Diversity, and the United Nations Convention to Combat Desertification) and the SDGs, committing to address multiple intertwined challenges, including climate change, biodiversity, desertification, poverty, hunger and equity. These global goals provide a picture of a collective desire, which is increasingly informing private sector (e.g. Science Based Targets initiative, International Organization for Standardization, Science Based Targets Network, Task Force on Climate-Related Financial Disclosures) and subnational goals. However, scenarios, road maps and policies are frequently developed and implemented through a siloed approach, focusing on one issue (e.g. climate change).

Truly holistic perspectives are rare. Effectively meeting the global goals will require more-integrated planning and deployment that achieves multiple outcomes simultaneously and minimizes trade-offs.

As outlined in Chapter 7 (Current levels of CDR), most countries currently deploy or include plans to deploy conventional CDR. Often, those actions are prioritized as policymakers and practitioners seek other benefits beyond climate change mitigation, including to stop land degradation, enhance adaptation and resilience, and improve biodiversity outcomes (e.g. land degradation neutrality targets, SDG 13, Global Biodiversity Framework, United Nations Decade on Ecosystem Restoration). However, these country priorities are still not adequately reflected in model scenarios, including those assessed in this report.

Most scenarios continue to optimize solely for climate change mitigation and cost, too often producing unsustainable futures including very high levels of CDR that may jeopardize the attainment of other global goals. This report uses scenarios as a key line of evidence to explore more-sustainable CDR deployment, but the analysis is limited by the kind and quality of information available in scenario databases. A key future improvement in the scenario community would be to standardize variable information critical to understanding impacts across multiple SDGs, in particular in the land sector. For example, distinguishing between primary ecosystems (e.g. old-growth forests), secondary ecosystems (e.g. regrowth), and plantations could provide helpful information on risks to biodiversity and ecosystem services from land conversion associated with CDR options. Separating the extent of land area used for afforestation versus reforestation would also significantly enhance understanding of the biodiversity and water implications associated with conventional CDR. Ultimately, progress towards a larger set of scenarios that go beyond optimizing for mitigation and cost towards optimizing the delivery of globally agreed goals on biodiversity, land degradation and sustainable development would be helpful and highly relevant for policy development.

Approximately 7–9 $GtCO_2$ per year of CDR will likely be needed by 2050 to limit global temperature change consistent with the Paris Agreement. However, the most important near- and long-term action remains reducing sources of emissions to the largest extent possible. The assessment in this report shows that deploying CDR at a multi-gigaton scale could be consistent with sustainability objectives if it is paired with ambitious gross emission reductions. Scenarios that are more aligned with sustainable development tend to deploy less cumulative CDR and much less novel CDR than scenarios that are not likely to be sustainable. However, sustainability outcomes can only be attained through strategic planning and deployment of CDR that explicitly caters to regional, landscape and local contexts and is designed for multiple benefits. It is vital that CDR policy and strategy be considered in the context of sustainable development to balance benefits and trade-offs and explicitly address the associated risks.

Box 8.4 Limitations and knowledge gaps

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

- The development of a larger set of sustainability scenarios that go beyond optimizing for climate change mitigation and cost and incorporate other globally agreed goals on biodiversity, land degradation and sustainable development
- Standardization of variable information in scenarios critical to understanding impacts across multiple SDGs
- Environmental, social and economic trade-offs, including the effectiveness and risks of deploying different CDR methods across regions

9

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Chapter 9 | The CDR gap

Emission reductions continue to lag behind what is needed to meet the Paris temperature goal. There is an additional gap between national proposals for carbon dioxide removal (CDR) and scenarios that sustainably scale CDR to limit climate change.

Key insights

- Countries' nationally determined contributions propose an additional −0.05 to −0.53 Gt of carbon dioxide (CO_2) per year in conventional CDR (mostly afforestation/reforestation) by 2030, compared with 2020 levels of −2.1 (−1.5 to −2.7) $GtCO_2$ per year.
- So far, only 28 countries (counting the EU as one) have outlined their proposals for scaling CDR by 2050. If countries without proposals preserve current levels of conventional CDR, then an additional −1.9 to −2.3 $GtCO_2$ per year may be realized by 2050, compared with levels in 2020.
- Scenarios that limit global temperature rise to 1.5°C by dramatically reducing emissions while sustainably scaling CDR imply that an additional −1.0 to −2.9 $GtCO_2$ per year of CDR is needed by 2030, and an additional −2.3 to −7.4 $GtCO_2$ per year by 2050, compared with levels in 2020.
- There is therefore a *CDR gap* between national proposals and most scenarios consistent with the Paris temperature goal. However, the most ambitious proposals are close to the CDR levels required in a scenario where CDR requirements are minimized.
- The CDR gap is not a fixed quantity, but a range that reflects uncertainties and different judgments with respect to how society chooses to mitigate climate change. A critical uncertainty is how to consider the fact that global emissions did not decline in recent years, as was projected in scenarios. This implies that the CDR gap may be significantly larger than currently estimated.

Reductions in greenhouse gas emissions are not on track to meet the Paris temperature goal. This chapter investigates whether this is also the case for CDR. The first section describes the methods used to ascertain this and explains the concept of the CDR gap. Section 9.2 presents an estimate of the amount of CDR that is indicated in country proposals for 2030 and 2050. It goes on to compare this with the level of CDR required in scenarios that are consistent with the Paris temperature goal. The precise size of the gap between proposed CDR and Paris-consistent CDR is, however, dependent on several uncertain factors and assumptions, which are explored in Section 9.3. The final section looks at how the existing CDR gap can be closed.

9.1 The CDR gap concept

This report tracks the amount of CDR that countries are currently proposing compared with the amount required to meet the Paris temperature goal – this is the CDR gap.

The CDR gap is a measure of the difference between proposed CDR activities and the amount of CDR in scenarios that meet the Paris temperature goal. To calculate the CDR gap, this report estimates proposed CDR activities from country submissions to the UNFCCC describing how they will mitigate greenhouse gas emissions and reach net zero in the coming decades. The report then compares these proposed activities with the amounts of CDR in model scenarios that meet the Paris temperature goal while taking into account sustainability constraints. The report refers to these scenarios as *Paris-consistent scenarios*, as they limit warming to either below 1.5°C or 2°C in the 21st century (see Chapter 8 – Paris-consistent CDR scenarios).

The CDR gap concept is illustrated in Figure 9.1. The methods used to estimate the level of CDR that countries are proposing are described in Box 9.1, and how these estimates are then aligned with scenario data is described in Box 9.2. Box 9.3 highlights the key differences in this chapter compared with *The State of Carbon Dioxide Removal* 1st edition.

The CDR gap serves two functions: it highlights the amount of CDR required to reach the Paris temperature goal, and it facilitates tracking of progress towards this goal. This allows an understanding of how ambitious or sufficient national CDR proposals are; whether those national proposals can be achieved and with what costs; and whether countries overdepend on CDR in their mitigation strategies at the expense of deep emission reductions.

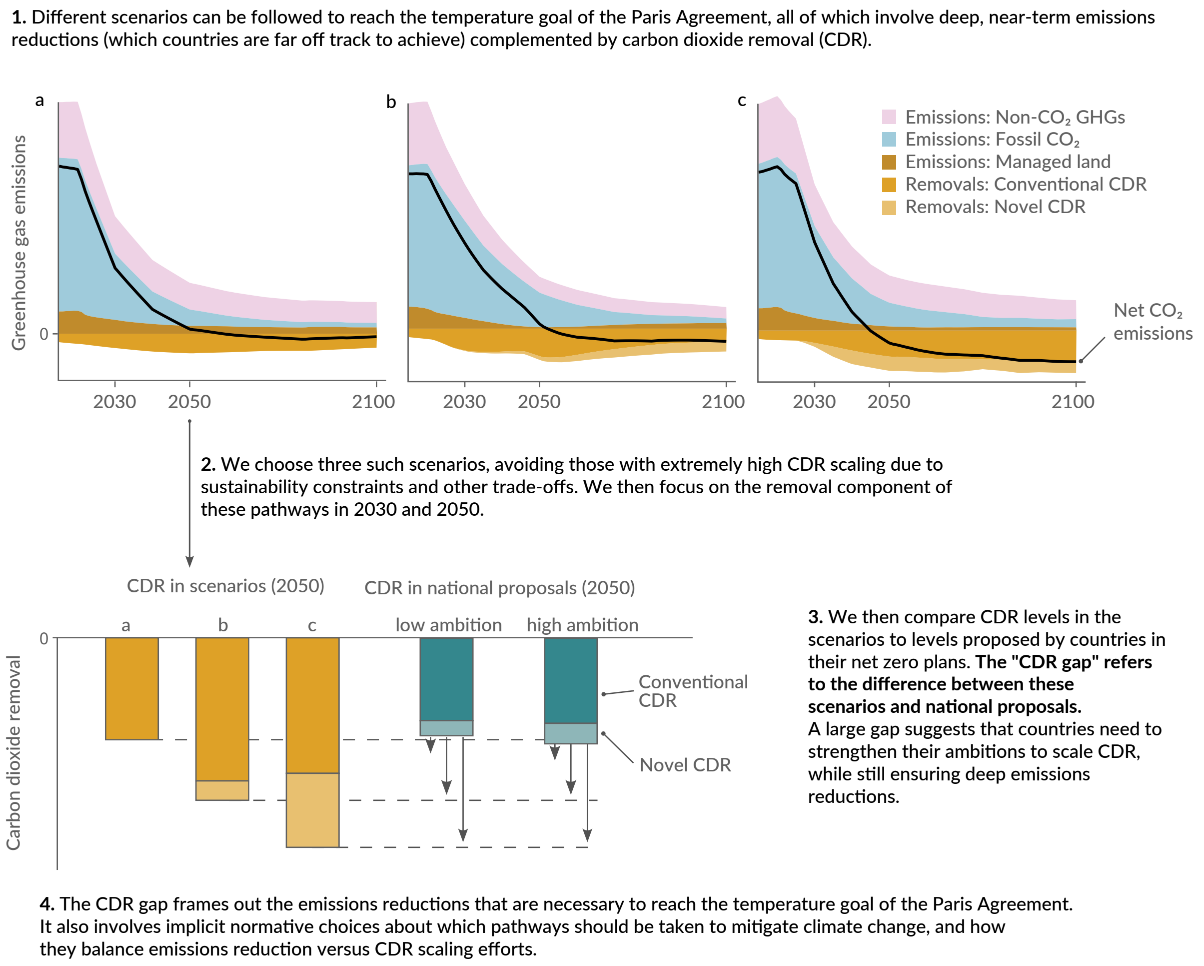

Figure 9.1 *The carbon dioxide removal (CDR) gap concept. GHG = greenhouse gas.*

Key considerations when calculating and interpreting the CDR gap

Quantifying the CDR gap involves making normative judgments about the appropriate pathway to take to mitigate climate change – notably, about how that pathway balances efforts to reduce emissions with efforts to scale up CDR. In other words, one could choose scenarios where CDR is scaled to very high levels and thereby discover a large gap when comparing these scenarios with national proposals. Conversely, one could choose scenarios with low levels of CDR and discover a smaller gap. This report addresses this, in part, by selecting three contrasting *focus scenarios* for the CDR gap analysis. Each of these scenarios represents a different pathway to reach the Paris temperature goal, with different levels and types of CDR scaling (Figure 9.1).

Scaling up CDR to very high levels would likely bring negative environmental, social and other sustainability impacts. A higher dependence on CDR in the future could also displace emission reduction efforts in the near term. A key factor in selecting the Paris-consistent focus scenarios was therefore to ensure that they sustainably scale CDR, according to the criteria established and discussed in Chapter 8 (Paris-consistent CDR scenarios). The chosen scenarios also prioritize deep and rapid emission reductions in the near term. It should be emphasized that the CDR gap is not a fixed quantity, but a range that reflects uncertainties and different judgments with respect to how society chooses to mitigate climate change.

In essence, this report compares national proposals against a set of scenarios that exhibit:

- Remaining cumulative carbon dioxide (CO_2) emission budgets that provide a 50% chance of limiting global temperature rise to 1.5°C by 2100 with no or limited temperature overshoot
- Relatively conservative levels of CDR
- High ambition in near-term emission reductions

Although this report's analysis specifically treats CDR separately from net emissions, this does not imply that the scaling of CDR methods will take place independently from other sector-based mitigation strategies. For instance, there are strong potential synergies and trade-offs between land-based CDR options, agricultural transitions and dietary shifts.[412] Similarly, scaling up novel CDR methods such as direct air carbon capture with storage dovetails with strategies to achieve a deep decarbonization of the industry and aviation sectors.[413]

Closing the CDR gap without reducing emissions will not achieve the Paris temperature goal. As such, the CDR gap, viewed in isolation, should not be misused or misinterpreted to delay emission reductions or downplay the need for such reductions. As illustrated in the three focus scenarios used in this analysis, there is a range of ways to reduce emissions; some pathways require more effort, more innovation or more societal change to reduce emissions, which can in turn lower the need for CDR. This interconnection between CDR and emission reductions at global, regional and sectoral levels is important to consider.

Types of CDR included in the gap analysis

The CDR gap analysis is oriented around the two categories of removals used throughout the report: conventional CDR and novel CDR (see Chapter 1 – Introduction, for definitions).

Conventional CDR. This refers to removals achieved through afforestation/reforestation and forest restoration, as well as other enhancements to the land sink via management of soils and vegetation (e.g. soil carbon sequestration in croplands and grasslands, agroforestry). A considerable amount of conventional CDR already occurs today, mostly through afforestation/reforestation, as documented in Chapter 7 (Current levels of CDR).

Novel CDR. This refers to methods such as direct air carbon capture with storage, bioenergy with carbon capture and storage, and biochar, which are in an early stage of development.

Both of these categories of CDR are found in the focus scenarios and in national proposals for scaling CDR. However, specific methods of CDR are represented to varying degrees. For example, afforestation/reforestation, bioenergy with carbon capture and storage, and direct air carbon capture with storage are commonly represented in the focus scenarios; in national proposals, afforestation/reforestation, forest management and soil carbon sequestration are more prevalent.[155]

Box 9.1 Methods for estimating proposed CDR

Data sources. This analysis draws on documents submitted by countries to the UNFCCC. This includes nationally determined contributions, long-term strategies, and further national documents such as biennial update reports, national communications and forest reference emission levels. Documents up to COP28 (November 2023) were included in the analysis.

Levels of proposed CDR are often not transparently reported in the UNFCCC documents.[154,155,414,415] In countries' proposals for reaching 2030 targets, novel CDR methods tend not to be included, but conventional CDR often is. However, for 2050 targets, many countries do include both types of CDR in their long-term strategies to reach net zero.

Analysis of 2030 targets. Information was compiled for 111 of 198 countries. Countries with high emissions were prioritized, while city states, small islands and arid countries with limited land-use emissions or removals were excluded. Two types of 2030 target exist, both of which are presented in the gap analysis: "conditional" targets, which would be fulfilled only with the support of other UNFCCC parties, and "unconditional" targets, for which no such conditions are described.

The analysis of conventional CDR focused on how countries reported contributions to their targets from the land use, land-use change and forestry (LULUCF) sector. Countries were grouped into three categories:

1. *Countries that provide a headline mitigation target with no specified contributions from the LULUCF sector: The analysis assumes that these countries preserve their 2011–2020 average levels of removals in the LULUCF sector.*

2. *Countries that specify the contribution of the LULUCF sector to their overall mitigation target but do not distinguish between removals and reductions in emissions relating to deforestation or land-use change: The analysis assumes that these countries preserve their 2011–2020 average proportions of removals to emissions in any changes they propose to their net LULUCF flux.*

3. *Countries that specify the contribution of the LULUCF sector as well as specific removal commitments: For these countries, the proposed removal figures were recorded. Where necessary, these figures were normalized against the country's 2011–2020 average (e.g. where commitments were given in terms of growth projections).*

For all countries, a consistent baseline of historic LULUCF emissions and removals was used, as provided by Grassi et al., 2022.[322]

Analysis of 2050 targets. Data were drawn from information compiled by Smith et al., 2022,[155] and Smith et al., 2024,[351] covering all 70 countries that have published long-term strategies. National documents are not available for all EU countries; therefore, EU-level totals were used instead, sourced from modelling studies by the European Commission.[416]

A subset of countries was identified whose long-term strategies contain scenarios that transparently describe levels of conventional or novel CDR by 2050. Countries often present a variety of scenario pathways in their long-term strategies. The national scenarios containing the least CDR are combined in the gap analysis as the "low" estimate of proposed CDR. The national scenarios with the most CDR are combined as the "high" estimate.

A key assumption was made in interpreting any overall LULUCF flux levels described in these documents. These are assumed to consist entirely of removals through conventional CDR (i.e. they are assumed to contain zero emissions from deforestation or land-use changes).

Box 9.2 Aligning proposed CDR with scenario data

As this analysis draws on national submissions to the UNFCCC to identify levels of proposed CDR, these levels align closely with inventory-based reporting conventions. Importantly, these conventions differ from those used for estimating the land-use fluxes in IPCC scenarios, which are based on the global bookkeeping model approach (see Chapter 7 – Current levels of CDR, Box 7.2).

The main difference is that inventory-based reporting typically includes CDR driven by indirect anthropogenic effects, such as rising CO_2 levels, nitrogen deposition and other climatic effects. Inventories also report a larger area of managed land than bookkeeping models. A portion of inventory-based removal estimates therefore falls outside this report's definition of CDR, as the removals are not directly human caused and, crucially, depend on the future trajectory of global emissions and environmental change.[336]

These indirect anthropogenic effects have been excluded from the proposed CDR levels for 2030 and 2050. To do so, the same conceptual approach as in Grassi et al., 2021, and the Global Carbon Budget has been followed,[417,418] as described in the Chapter 9 Technical Appendix.

Box 9.3 Points of departure from The State of Carbon Dioxide Removal 1st edition

First, the most significant change in the methodology compared with *The State of Carbon Dioxide Removal* 1st edition is extending the data set for countries' removal proposals in two ways: (1) to include all nationally determined contributions and long-term strategies published up to COP28 (November 2023) and (2) to analyse additional types of document. In a number of important cases, removal proposals are not described in nationally determined contributions but are elaborated in national communications (China, Japan), biennial update reports (Peru), long-term strategies (Chile, US), or national projections or assessments (Brazil, India).

Second, given the large volume of information missing from the long-term strategies, the gap analysis now assumes that all countries without national proposals for CDR preserve their current levels of conventional CDR up to 2050. Critical examples of this are highlighted in the results (Section 9.2), and the missing information is discussed as an uncertainty in Section 9.3.

Third, while the gap analysis uses the same three focus scenarios as in the first edition, the background range of scenarios used to contextualize the results has been adjusted. This approach follows from changes to the methodology, as described in Chapter 8 (Paris-consistent CDR scenarios), where sustainability and other screening criteria have been applied to narrow the range of scenarios depicted in this report. The three focus scenarios have also been renamed to better communicate their features:

- Focus on Demand Reduction → 1.5°C with no novel CDR
- Focus on Renewables→ 1.5°C with higher conventional CDR
- Focus on CDR → 1.5°C with higher novel CDR

9.2 The size of the CDR gap

Proposed CDR falls short of what is required in all but the most ambitious scenarios that meet the Paris temperature goal.

In this section, the estimated amount of CDR present in country proposals is described. This level is then compared with levels in scenarios that are consistent with the Paris temperature goal to inform the CDR gap assessment.

Proposed levels of CDR in 2030

If all nationally determined contributions (NDCs) were implemented, including those conditional on financial and other support, conventional CDR would slightly increase by 2030: it would provide an additional −0.53 $GtCO_2$ per year, from a baseline of −2.1 (−1.5 to −2.7) $GtCO_2$ per year in 2011–2020. If only unconditional NDCs were implemented, conventional CDR would barely change: it would provide only an additional −0.05 $GtCO_2$ per year by 2030 compared with 2020 levels.

These values are lower than those presented in the first edition of this report, which described an increase of −0.10 to −0.65 $GtCO_2$ per year by 2030. This reduction is due to the data set having been expanded to consider more national documents (see Box 9.3).

The additional −0.53 Gt per year of CDR under conditional NDCs is made up as follows:

- 55 countries describe specific changes in conventional CDR by 2030, which total −0.22 $GtCO_2$ per year.
- 31 countries do not state specific changes in CDR but describe how their overall land use, land-use change and forestry (LULUCF) fluxes will develop by 2030. The CDR levels inferred from this data account for −0.33 $GtCO_2$ per year.
- 25 countries provide no estimate of how the LULUCF sector will develop; it is therefore assumed that these countries will preserve their current level of removals.

Most of the change in removals under conditional NDCs is therefore not directly proposed by countries but has been inferred from their description of how overall LULUCF fluxes will develop by 2030.

While some countries mention novel CDR in their NDCs and national documents, none so far provide sufficient information to infer the contribution of these removals by 2030. This is mainly because countries offer only qualitative targets or group these methods within broader categories, such as fossil-based carbon capture and storage or biomass-based energy systems. The gap assessment therefore assumes no additional novel CDR is proposed by 2030.

Proposed levels of CDR in 2050

If countries implement the proposals in their long-term strategies that expand CDR the least, total CDR would increase by −1.9 $GtCO_2$ per year by 2050 from a baseline of −2.1 $GtCO_2$ per year in 2011–2020. The set of proposals with the highest amount of CDR would add −2.3 $GtCO_2$ per year compared with 2011–2020 levels.

In both cases, slightly less than half (−0.7 $GtCO_2$ per year to −0.9 $GtCO_2$ per year) of the proposed growth in CDR would be delivered through novel methods.

The range of the total proposed removals in 2050 is narrower than in the first edition of this report, which described an additional −1.5 to −2.3 $GtCO_2$ per year by 2050. This is primarily due to refinements in the methodology (see Box 9.1) rather than newly submitted or updated long-term strategies.

Only a small minority of countries provide sufficient information in their long-term strategies to infer CDR proposals by 2050, however. Of the 70 countries that had submitted a long-term strategy by COP28 (November 2023), only 28 included quantifiable levels of removals (including the EU, analysed as one country). For all other countries, it has been assumed that they are able to sustain their current levels of conventional CDR. Thus, 28 countries account for all the proposed changes in total CDR by 2050.

CDR in scenarios that sustainably scale CDR to meet the Paris temperature goal

As discussed in Chapter 8 (Paris-consistent CDR scenarios), scenarios that meet the Paris temperature goal dramatically reduce emissions in the coming decades. At the same time, these scenarios scale up CDR to gigatons of annual removals by 2050. However, there is considerable variation in the degree to which different models and types of scenarios scale up CDR. These differences are driven by several factors, including the application of sustainability constraints (e.g. on global biomass use), the speed and depth of near-term emission reductions (e.g. immediate versus delayed policy action), or the quantity of residual emissions at the point of net zero (e.g. depending on the availability of mitigation technologies or the implementation of demand-side measures).

Chapter 8 describes a set of *Paris-relevant scenarios*. This set consists of scenarios that limit global temperature rise to 1.5°C with 50% probability, scenarios that initially exceed a temperature rise of 1.5°C but then return to that level by the end of the century, and scenarios that limit temperature rise to 2°C with 67% probability. These scenarios are referred to by the IPCC as C1, C2 and C3 scenarios, respectively.

Chapter 8 also describes a subset of the Paris-relevant scenarios that are more likely to scale CDR sustainably. The Paris Agreement states that climate change mitigation must be done "in the context of sustainable development and efforts to eradicate poverty". Therefore, CDR pathways that align with social and environmental sustainability principles are more policy relevant. This subset of scenarios is known as *Paris-consistent scenarios* in this report.

In the Paris-consistent scenarios, the increase in total deployment of CDR by 2030 and 2050 is as follows:

- By 2030: total CDR deployment increases to −4.0 (−3.9 to −4.4) $GtCO_2$ per year, from a baseline of −2.1 $GtCO_2$ per year in 2011–2020. Within these near-term increases in removals, only a minority (0.12 (0.05 to 0.3) $GtCO_2$ per year) is delivered through novel CDR.
- By 2050: total deployment of CDR increases to −7.8 (−6.6 to −8.9) $GtCO_2$ per year, of which −5.7 (−5.2 to −5.9) $GtCO_2$ per year is conventional CDR and −1.9 (−1.0 to −3.7) $GtCO_2$ per year is novel CDR.

Alongside this scaling of CDR, the evaluated scenarios simultaneously reduce greenhouse gas emissions by 25 (21–28) $GtCO_2e$ by 2030 and 41 (39–43) $GtCO_2e$ by 2050. This represents a significant break with the status quo observed to date of annual increases in global emissions.

As in *The State of Carbon Dioxide Removal* 1st edition, this chapter evaluates the CDR gap against a specific set of *focus scenarios* that follow specific storylines to limit warming to 1.5°C with no or limited overshoot (known as category C1 in the IPCC Sixth Assessment Report). The deployment of CDR within these scenarios is as follows:

- ***1.5°C with no novel CDR.*** Global energy demand is rapidly reduced through improvements in the efficiency of end-use devices and service delivery. This scenario has a large contribution from conventional CDR (an increase of −2.3 $GtCO_2$ per year by 2050 compared with 2020) but purposefully does not deploy novel CDR.
- ***1.5°C with higher conventional CDR.*** A rapid supply-side transformation is implemented through the deployment of increasingly cost-competitive renewable energy technologies. This scenario also has a large contribution from conventional CDR (an increase of −4.1 $GtCO_2$ per year in 2050 compared with 2020). This is complemented by the scale-up of novel CDR (−0.9 $GtCO_2$ per year in 2050).
- ***1.5°C with higher novel CDR.*** A slower transformation of the energy supply system takes place, with an incomplete phase-out of fossil fuels in the 21st century. This scenario also has a large contribution from conventional CDR (an increase of −4 $GtCO_2$ per year in 2050 compared with 2020). This is combined with significantly more novel CDR than in the other focus scenarios (−3.5 $GtCO_2$ per year in 2050).

Within the range of sustainable scenarios evaluated in this report, *1.5°C with no novel CDR* sits just lower than the 25th percentile for total removals in 2050 (see Figure 9.2). The

1.5°C with higher conventional CDR scenario is close to the median, and *1.5°C with higher novel CDR* sits at the 75th percentile.

In addition to scaling CDR, the three focus scenarios dramatically reduce gross greenhouse gas emissions by 2030 compared with 2020 levels: by −51% in *1.5°C with no novel CDR*; by −39% in *1.5°C with higher conventional CDR*; and by −40% in *1.5°C with higher novel CDR*.

The CDR gap

The increase of CDR proposed by countries in 2030 falls short of the CDR levels required in every focus scenario, as well as levels across the broader range of sustainable scenarios. The minimum relative gap (i.e. looking only at changes from current levels, as reflected in Table 9.1) is estimated at approximately 0.5 $GtCO_2$ per year in 2030. This is the difference between the level proposed in conditional (i.e. best case) NDCs, which would increase CDR by −0.53 $GtCO_2$ per year, and the level in *1.5°C with no novel CDR*, which would increase CDR by −1 $GtCO_2$ per year. For the other focus scenarios, which have higher rates of CDR scaling in the short term, the gap increases to beyond 1 $GtCO_2$ per year.

From the limited amount of information that can be derived from countries' long-term strategies – and assuming all other countries sustain current levels of removals – the minimum gap is estimated at close to zero in 2050. This is the difference between the combined total from long-term strategy scenarios with the highest amount of CDR, which would increase CDR by −2.3 $GtCO_2$ per year, and the level in *1.5°C with no novel CDR*, which would also increase CDR by −2.3 $GtCO_2$ per year. When compared with other focus scenarios, which have higher rates of CDR scaling in the medium term, the gap widens significantly to multiple gigatons of removals per year. In absolute terms, the CDR gap is 0.9 to 2.8 $GtCO_2$ per year in 2030 (conditional NDCs) and 0.4 to 5.4 $GtCO_2$ per year in 2050 (high long-term strategies estimate), as shown in Figure 9.2.

The gap in conventional CDR

Proposals by countries to expand conventional CDR fall short of the CDR levels required in every focus scenario. Between −1.2 to −1.4 $GtCO_2$ per year of additional conventional CDR is implied in the long-term strategies by 2050. This falls short of levels in the *1.5°C with no novel CDR* scenario by at least 1.1 $GtCO_2$ per year and falls short of levels in the other focus scenarios by about 3 $GtCO_2$ per year.

The gap analysis in this report assumes that countries without a quantifiable long-term strategy preserve their existing levels of conventional CDR. These "absent" countries include Brazil, China, the Democratic Republic of Congo, and India. These are among the countries with the most significant current forest fluxes (Chapter 7 – Current levels of CDR), although they currently have minimal removals due to direct human activity, according to the adjusted inventory accounts (see Box 9.1 and Chapter 9 Technical Appendix). As most countries with quantifiable long-term strategies foresee preserving or increasing their current levels of conventional CDR, it may be that the gap starts to decrease as more countries publish long-term strategies.

The gap in novel CDR

Countries have not transparently communicated their expectations for scaling novel CDR by 2030 but do foresee deployments in their long-term strategies of between −0.7 and −0.96 $GtCO_2$ per year by 2050. There is no gap between these proposals and the *1.5°C with no novel CDR* scenario (which, as per its title, does not deploy novel CDR). However, the lower end of proposals fall short of novel CDR levels in the *1.5°C with higher conventional CDR* scenario (which has an additional −0.91 $GtCO_2$ per year in 2050) and the *1.5°C with higher novel CDR* scenario (which has an additional −3.5 $GtCO_2$ per year in 2050).

As with conventional CDR, the absence of published, quantifiable proposals for scaling novel CDR is consequential for this analysis. In particular, data are currently missing for a number of countries known to be developing road maps and policies towards deploying novel CDR, such as China, Norway and Saudi Arabia.

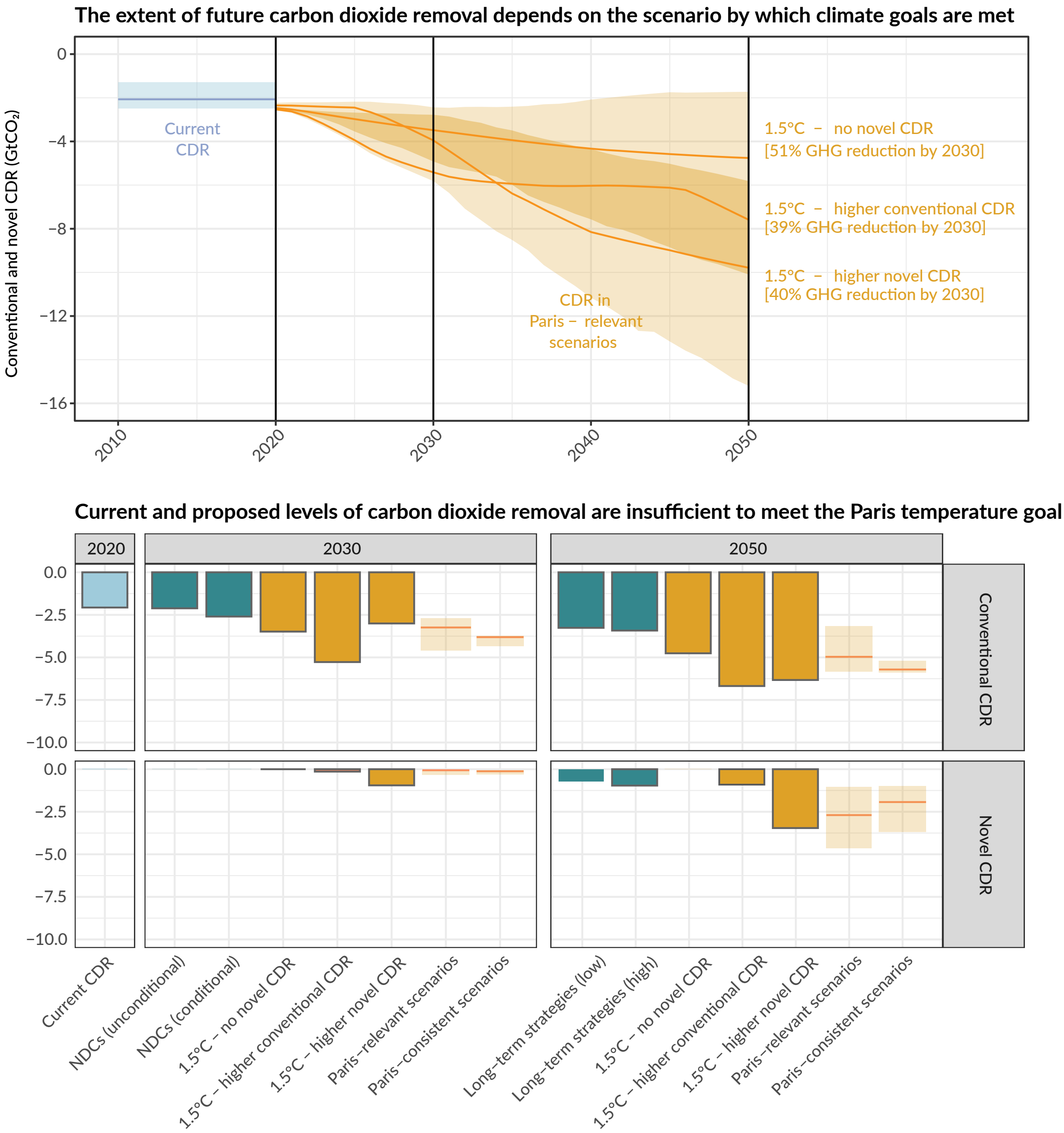

__Figure 9.2__ The carbon dioxide removal (CDR) gap. Top: current levels of CDR and levels in scenarios up to 2100. The shaded areas depict the 5th to 95th and the 25th to 75th percentiles of all Paris-relevant scenarios (categories C1–C3). The lines depict CDR levels in three Paris-consistent focus scenarios that limit warming to 1.5°C, alongside the gross greenhouse gas (GHG) emission reductions (compared with 2020 levels) required by 2030 for each. Bottom: levels of current, proposed and scenario-based CDR, split by conventional CDR and novel CDR in 2020, 2030 and 2050. Green bars depict proposed CDR levels in the nationally determined contributions (NDCs; which also include other official submissions to the UNFCCC) and the long-term strategies. Gold bars depict CDR levels in the three focus scenarios, as well as the medians and ranges (25th to 75th percentiles) of the wider set of Paris-relevant and Paris-consistent scenarios.

	Additional total CDR compared with 2011-2020 ($GtCO_2$ per year)		Additional conventional CDR compared with 2011-2020 ($GtCO_2$ per year)		Additional novel CDR compared with 2011-2020 ($GtCO_2$ per year)		Gross GHG emission reductions compared with 2011-2020 (%)	
	2030	2050	2030	2050	2030	2050	2030	2050
Paris-consistent scenarios	−1.6 [−1.4 to −1.9]	−5.3 [−4.1 to −6.4]	−1.3 [−1.3 to −1.9]	−3.2 [−2.7 to −3.4]	−0.1 [−0.1 to −0.3]	−1.9 [−1 to −3.7]	46 [39 to 53]	76 [73 to 79]
1.5°C with no novel CDR	−1	−2.3	−1	−2.3	0	0	51	78
1.5°C with higher conventional CDR	−2.9	−5.1	−2.7	−4.1	−0.14	−0.91	39	80
1.5°C with higher novel CDR	−1.6	−7.4	−0.66	−4.0	−0.95	−3.5	40	77
Nationally determined contributions[a]	−0.05 to −0.53	NA	−0.05 to −0.53	NA	0	NA	NA	NA
Long-term strategies[b]	NA	−1.9 to −2.3	NA	−1.2 to −1.4	NA	-0.7 to -0.96	NA	NA

[a] As described in Box 9.1, the nationally determined contribution analysis includes additional national documents, such as national communications and biennial update reports.

[b] Proposed CDR derived from the long-term strategies is incomplete, owing to the limited number of countries with these documents; all countries without quantifiable strategies are therefore assumed to retain current (2020) levels of conventional CDR.

Table 9.1 *Numbers behind the carbon dioxide removal (CDR) gap, reported as additional CDR compared with 2011–2020. GHG = greenhouse gas; NA = not available.*

9.3 Uncertainties

The precise size of the gap between current CDR and Paris-consistent CDR is dependent on a number of uncertain factors and assumptions.

This section discusses the CDR gap analysis in the context of ambiguities in national proposals for CDR, questions around the credibility of these proposals, current trends in conventional CDR, and uncertainties in the scenario evidence. These aspects of uncertainty suggest concrete areas of future research that could further strengthen the CDR gap evaluation (see Box 9.4).

Ambiguities in national proposals for CDR

Many countries do not clearly state their plans for scaling CDR. This applies to NDCs, long-term strategies and other national documents submitted under the UNFCCC. Of these, the long-term strategies may be the most consequential as they refer to mid-century plans, when CDR scaling becomes more urgent. The absence of clear plans adds different layers of ambiguity, which limit the CDR gap assessment.

The gap analysis assumes that countries without long-term strategies and quantifiable scenarios are able to sustain existing levels of conventional CDR. This broadly aligns with the expectations established by countries with published strategies.[143] However, as discussed in this section, it will not be an easy task even to sustain current removals.

The gap analysis finds many instances where countries do not report gross emissions and removals separately in their proposals. Many countries instead employ sectoral accounting, which follows the logic of national greenhouse gas inventories by reporting both emissions and removals within the sectors in which they occur. In the case of the LULUCF sector, the analysis assumes zero deforestation in the long-term strategies, and thus counts all net fluxes as removals. In other cases, for instance where bioenergy with carbon capture and storage is included in net reduction scenarios for the energy sector (e.g. Indonesia, Thailand), the implied removals cannot be assessed. Standardizing reporting practices across countries to avoid these issues is therefore a priority, particularly for emerging novel methods.

Emissions from international aviation and shipping are commonly excluded from the scope of national climate targets. Some countries, such as the UK, integrate these emissions into the scope of net zero targets.[419] Integration does not necessarily mean unilateral action, but it is a recognition that decarbonizing aviation and shipping globally will require new fuel and carbon management infrastructure within national borders, including novel CDR. Additionally, integration implies that further CDR would be required to offset residual emissions from these sectors (e.g. the International Energy Agency estimates approximately 210 $MtCO_2$ of emissions in 2050 for domestic and international aviation in its net zero scenarios). Nonetheless, these sectors are excluded from the CDR gap assessment, owing to the lack of scenarios from the International Civil Aviation Organization and the International Maritime Organization that transparently report gross reductions, residual emissions or implied removals.

Credibility of national proposals for CDR

What role do the NDCs, long-term strategies and other documents under the UNFCCC play in national policymaking? In other words, how credible are they as signals that countries will implement policies and ultimately scale their proposed levels of CDR?

On the one hand, these documents are key elements of the multilateral climate governance architecture. The “nationally determined” nature of the ratcheting-up mechanism was the main enabler for the adoption of the Paris Agreement. On the other hand, the extent to which these documents are embedded in national climate policymaking and reflect the state of policy planning and decision-making varies considerably. In some cases, UNFCCC processes and deadlines can have a structuring effect on national climate policymaking; in others, NDCs and long-term strategies can be a subordinate element, primarily used and written for foreign audiences and detached from national climate policies and politics. The long-term strategies in particular are primarily modelling or projection exercises with multiple scenarios rather than plans, and relevant actors may be unfamiliar with these strategies.

However, analysis of the material and data provided by countries can still provide insight into national policy developments. While the figures derived from the analysis should not be over-interpreted in their detail, the assessment of these documents provides credible ballpark numbers that help identify gaps in climate policy. See Box 9.4 for how the credibility of these plans could be further evaluated.

Current trends in conventional CDR

Recent trends in conventional CDR can give further insight into the credibility of future proposals. Figure 9.3 depicts trends in conventional CDR for the world and the top 15 countries for recent removals (averaged over 2011–2020) as calculated in this chapter (see Box 9.1). These trends are contrasted with the most ambitious proposals from the long-term strategies. These proposals total an additional −1.4 $GtCO_2$ per year in 2050 on top of the 2011–2020 baseline, assuming that countries without proposals maintain current (2011–2020) levels of removals.

Consistent with Chapter 7 (Current levels of CDR), this shows that global removals have been relatively stable over the past two decades and are currently not on track to increase by 2030 or 2050. Further, many countries are not on track to sustain current conventional CDR or to meet long-term proposals. Notable examples where removals have been decreasing over the past decades include Canada, Chile, the EU27, Mali and the Republic of Korea. In the US, removals have been relatively stable but are not on track to meet 2050 targets. China, on the other hand, has seen a large and sustained increase in removals over the past two decades.

These examples underline that even simply preserving existing land-based sinks – as assumed in this analysis – will be a considerable challenge. The recent decline of the European forest sink has been linked to decreased afforestation (i.e. land conversion to forest), increased mortality (i.e. from drought, storms, fire and disease) and, in particular, to increased harvest.[420,421] Without a significant reversal of current management practices, the EU27 will not meet its 2030 targets in the LULUCF sector. The increasingly adverse effects of climate change, including precipitation changes, heat and wildfire events, and the spread of pests such as bark beetles will further increase pressure on forest carbon sinks and likely expand the CDR gap.

Many countries are not on track to sustain conventional CDR, nor to meet long–term proposals

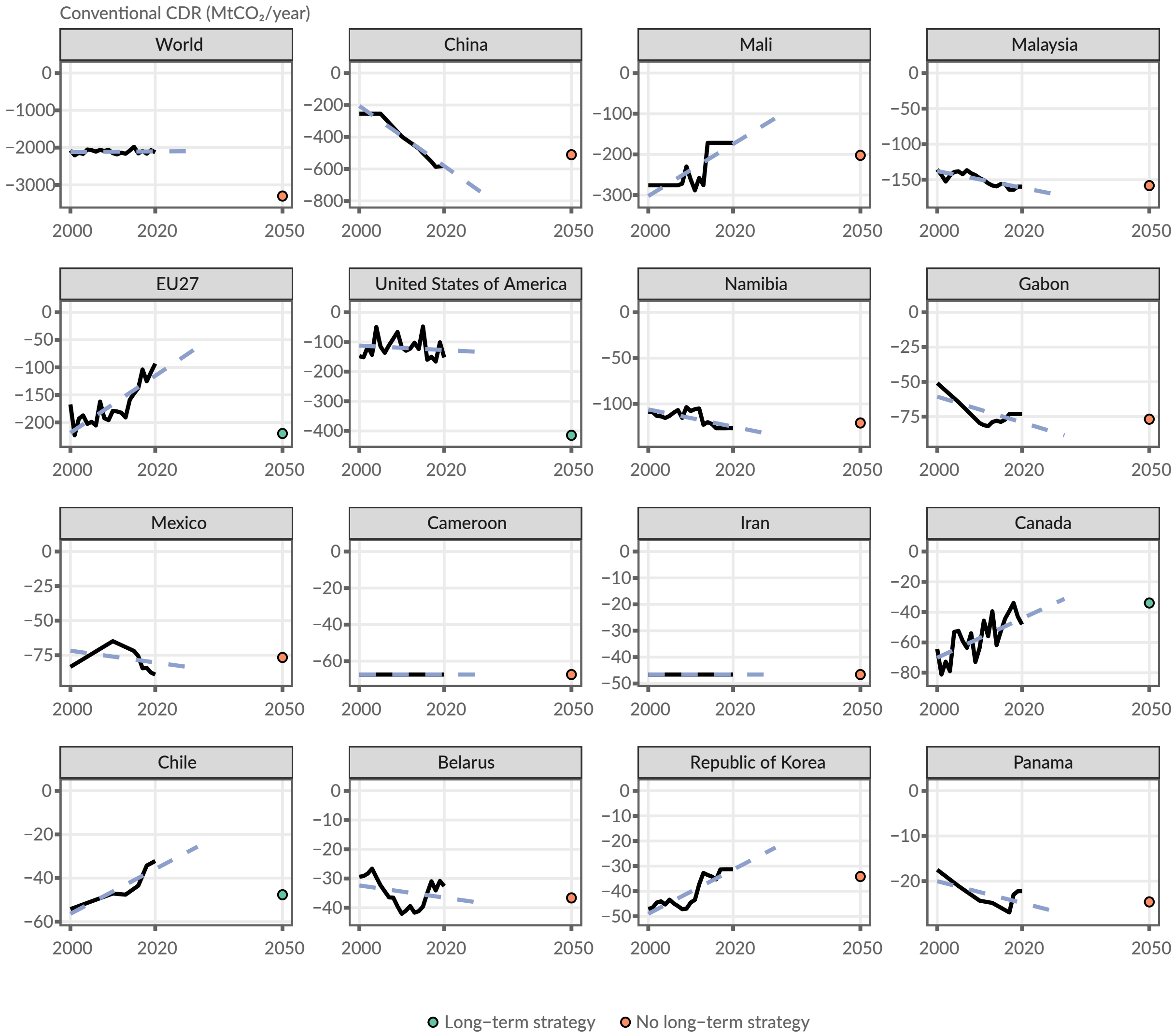

Figure 9.3 *Historic conventional carbon dioxide removal (CDR, black line) versus future proposals in the long-term strategies for the world and for selected countries. Historic conventional CDR is calculated as the sum of forest land fluxes in national inventories, excluding emissions from organic soils and harvested wood products, minus the 20-year average of natural land sinks estimated by dynamic global vegetation models for that country. Dashed lines show the linear trend up to 2030. The 15 countries with the highest decadal average removals (2011–2020) have been selected, alongside the world average. Where a country has no quantifiable long-term strategy, a target level is projected for 2050 equal to average removals from 2011 to 2020. Uncertainties in both absolute levels and trends are high, and results differ from Chapter 7 (Current levels of CDR) owing to the inventory approach used here. Data sources: National inventories from Grassi et al., 2022*[322] *dynamic global vegetation models from Friedlingstein et al., 2023.*[418]

Uncertainties in scenario evidence

The CDR gap analysis uses model scenarios to benchmark national proposals. These scenarios are subject to a number of uncertainties. A fundamental issue is that many scenarios published during the IPCC Sixth Assessment Report cycle are now relatively dated, describing pathways where emissions already peaked in the early 2020s. As a result, they do not take into account that emissions have not only failed to decrease in the past years, but have actually increased, and further eaten into the remaining carbon budget. Figure 9.4 illustrates this problem and how an *additional mitigation burden* can be quantified to estimate the effort required to get back on track to a given scenario pathway. The estimate for the *1.5°C with no novel CDR* scenario is that between 0.7 and 1.5 $GtCO_2$ per year of additional mitigation is already required to compensate for the missed emission reductions between 2020 and 2022. Since this additional mitigation could consist of either deeper reductions or the scale-up of CDR, the implication is that the CDR gap is already wider by up to 1.5 $GtCO_2$ than is depicted in the prior section.

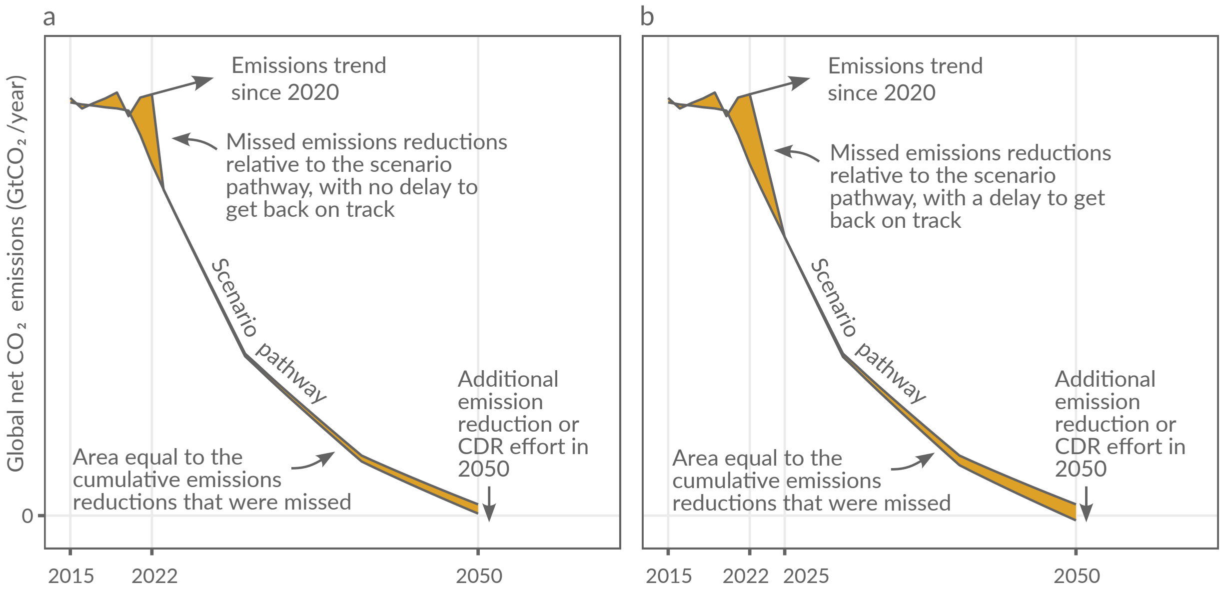

Figure 9.4 *Assessment methods for calculating the additional mitigation burden due to failed historic emission reductions relative to scenario pathways. In each panel, the amount of cumulative emissions in the top triangle (missed emission reductions) is equal to the compensated mitigation in the lower triangle. The lower triangle allows an estimate of additional mitigation at any point in time up to net zero and is calculated for each focus scenario in Table 9.2. In panel b, emissions are estimated to rejoin the scenario pathway in 2025.*

Scenario	Additional mitigation required due to missed emission reductions in 2020–2022 ($GtCO_2$ per year)			
	Without delay (Figure 9.4a)		With delay (Figure 9.4b)	
	2030	2050	2030	2050
1.5°C with no novel CDR	0.2	0.7	0.4	1.5
1.5°C with higher conventional CDR	0.1	0.3	0.1	0.4
1.5°C with higher novel CDR	0.2	0.6	0.4	1.4

Table 9.2 *Assessment of additional mitigation needed due to failed historic emission reductions relative to the scenario pathway. CDR = carbon dioxide removal.*

In addition to being out of date, scenarios do not explicitly deal with the considerable uncertainties in the climate system. Specifically, they do not take into account that estimates of climate sensitivity – the temperature response to an increase in atmospheric CO_2 concentrations – range substantially. A doubling of CO_2 concentration compared with pre-industrial levels, for example, could lead to between 1.4°C and 2.2°C of warming.[422] Accordingly, CDR requirements could be considerably larger or smaller, depending on how the climate sensitivity plays out, pointing to a potential need for a contingency CDR capacity in case of "bad climate outcomes".

Box 9.4 Limitations and knowledge gaps

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

- *Evaluating the credibility of country proposals:* What is the likelihood that countries will implement their declared policies and, ultimately, scale their proposed levels of CDR? Answering this question may involve assessing the legal basis of CDR proposals in their respective national jurisdictions,[423] tracking relevant policies as they manifest in different countries, and evaluating near-term deployments by companies (as in Chapter 3 – Demonstration and upscaling). A comparative analysis and tracking of national CDR efforts alongside emission reductions may bring further insight on the credibility of proposals, given that there is a well-developed literature on the latter.
- *Evaluating trends in current conventional CDR:* Are countries on track to preserve current conventional CDR? Answering this question will require detailed regional studies to track trends and drivers of forest fluxes, including newly planted areas, harvest levels, and losses due to drought, wildfires, pests and disease.
- *Evaluating new scenario evidence:* How does the CDR gap compare to the most up-to-date scenarios? Here, there is an important role for integrating scenarios with up-to-date historical emission estimates, as well as for scenarios that depict different levels and strategies for sustainably scaling CDR.

9.4 Closing the CDR gap

The CDR gap can be closed by dramatically reducing emissions, increasing current conventional CDR carefully through sustainable practices, and rapidly scaling novel CDR.

The analysis presented in this chapter shows that for the majority of scenarios that limit global temperature rise to 1.5°C, with no or limited overshoot, there remains a CDR gap. This gap indicates that countries need to strengthen their ambitions if the Paris temperature goal is to be met. This conclusion is consistent with assessments focusing on overall net emission reductions.[133,423–425] While it is critical for countries to prioritize near-term policies that reduce fossil fuel emissions and limit deforestation, this section focuses on the specific challenges of closing the CDR gap.

For conventional CDR, sustainably preserving and scaling these removals will require active policies to limit the impact of natural disturbances, promote sustainable land practices and prevent illegal harvests. European and boreal forests are already trending towards lower levels of removals, raising concerns that existing proposals are too optimistic.[420,421] Nonetheless, global potentials for sustainably restoring forests and delivering land-based CDR are large.[426]

Further, land management practices that would scale conventional CDR can be integrated with sustainable development and biodiversity objectives, such as those set out in the Sustainable Development Goals and the Global Biodiversity Framework.[427] Monitoring, reporting and verification will be a critical component of enhanced policy action for conventional CDR (see Chapter 10 – Monitoring, reporting and verification), as any such action should be additional, quantifiable, and in line with other social and environmental objectives.

Novel CDR presents a different set of challenges, as these methods are in an early stage of development and are not as well integrated into national policy planning. Without significant policy action in the near term to support novel CDR methods through their formative phases, it is difficult to conceive of them being able to provide gigatons of removals in the second half of the 21st century. Monitoring, reporting and verification approaches are also lagging for these methods, alongside a general lack of guidance on how to include them in national proposals under the UNFCCC. Importantly, enhanced emission reductions would reduce society's dependence on these methods and hedge against uncertainties in how fast they can scale.

Overall, this report's analysis of the CDR gap shows that, in addition to insufficient policy and action to reduce emissions, governments are planning for insufficient scaling of CDR in the coming decades. A twofold strategy that limits society's dependence on CDR through rapid and deep emission reductions while supporting and scaling CDR implementation is not a contradiction, but a necessary pathway towards successful climate policy.

10

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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.

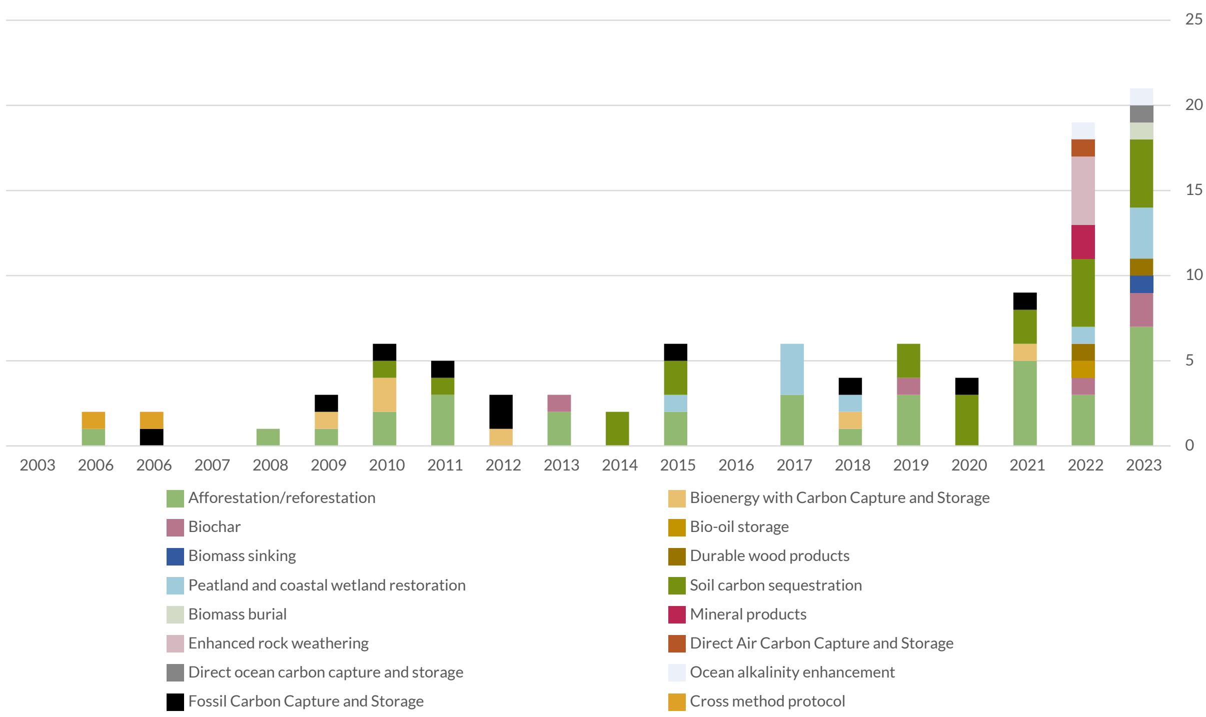

Figure 10.1 *Number of monitoring, reporting and verification protocols developed by year and CDR method, 2003–2023. Dates reflect the year of initial release.*

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.

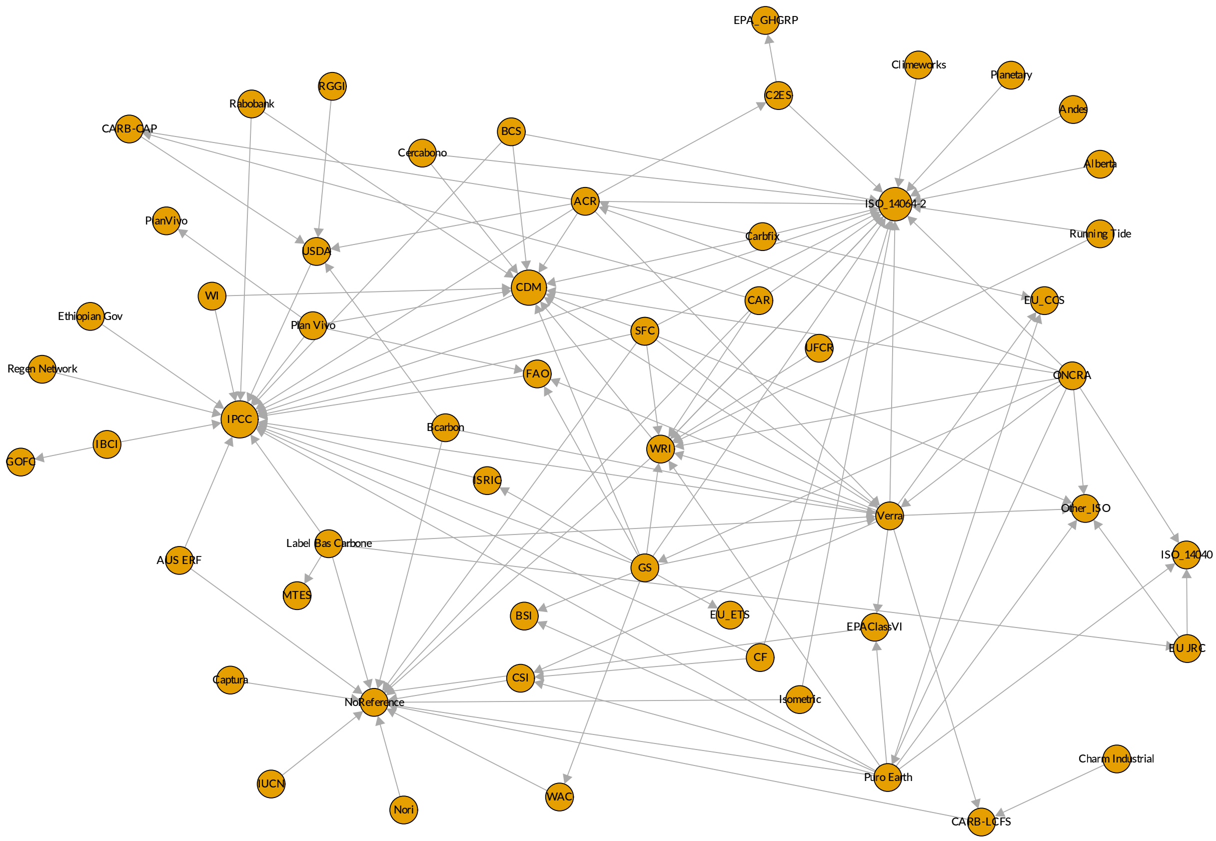

Figure 10.2 A network forms when protocols recognize other standards or guidelines in their approach to carbon accounting. Recognition is observed as one protocol indicating in the description of their development that they followed the guidance of another document. To the 102 protocols identified in 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						
	Bioenergy with carbon capture and storage						
	Biochar						
	Peatland and coastal wetland restoration						
	Soil carbon sequestration in croplands and grasslands						
	Ocean fertilization						
Geochemical	Enhanced rock weathering						
	Direct air carbon capture and storage						
	Ocean alkalinity enhancement						

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).

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Glossary

Additionality: the extent to which greenhouse gas emission reductions or removals would have occurred in the absence of the associated policy intervention or activity. An additionality test is applied in carbon credit programs to ensure that credits are not awarded for mitigation that would have occurred in the absence of the carbon credit revenue.

Afforestation: Conversion to forest of land that was previously not forest.

Agroforestry: Growing trees on agricultural land while maintaining agricultural production.

Biochar: Relatively stable, carbon-rich material produced by heating biomass in an oxygen-limited environment. Assumed to be applied as a soil amendment unless otherwise stated.

Bioenergy with Carbon Capture and Storage (BECCS): Process by which biogenic carbon dioxide (CO_2) is captured from a bioenergy facility, with subsequent geological storage.

Biomass burial: Burial of biomass in land sites such as soils or exhausted mines. Excludes storage in the typical geological formations associated with CCS.

Biomass sinking: Sinking of terrestrial (e.g. straw) or marine (e.g. macroalgae) biomass in the marine environment. To count as CDR, the biomass must reach the deep ocean where the carbon has the potential to be sequestered durably.

Bio-oil storage: Oil made by biomass conversion and placed into geological storage.

Carbon credit: A tradeable certificate representing one tonne of CO_2 or carbon dioxide equivalent (CO_2e) avoided, reduced or removed.

Note 1: The majority of carbon credits currently traded are emissions reduction credits.

Note 2: Carbon credits are commonly purchased to offset the GHG emissions of the purchasing entity. An entity can also choose to retire a carbon credit without using it as an offset.

Carbon Capture and Storage (CCS): A process in which carbon dioxide (CO_2) is captured, conditioned, compressed and transported to geological storage. This term is commonly applied in the context of fossil CO_2 emissions. To count as CDR, however, captured CO_2 must come from the atmosphere, either directly from ambient air (see DACCS) or via biomass (see BECCS) or seawater (see DOCCS).

Carbon Capture and Utilisation (CCU): A process in which CO_2 is captured and used in manufacture of products. Capture of atmospheric CO_2 for manufacture of durable products such as concrete or timber for construction is classified as CDR. Use of atmospheric CO_2 in manufacture of products that do not store carbon durably [before releasing it back into the atmosphere], such as carbonated drinks or fuels, is not considered CDR. Use of fossil CO_2 in manufacture of products is not considered CDR.

Carbon Dioxide Removal (CDR): Human activity capturing carbon dioxide (CO_2) from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes enhancement of biological or geochemical CO_2 sinks and direct air carbon capture and storage (DACCS), but excludes natural CO_2 uptake not directly caused by human activities.

Conventional CDR: CDR methods that are well established, already deployed at scale and widely reported by countries as part of land use, land-use change and forestry (LULUCF) activities. The methods included in this group are afforestation/reforestation; agroforestry; forest management; soil carbon sequestration in croplands and grasslands; peatland and coastal wetland restoration; and durable wood products.

Direct Air Capture (DAC): Chemical process by which carbon dioxide (CO_2) is captured from the ambient air. Captured CO_2 can be stored geologically (see DACCS), or used in products (see CCU).

Direct Air Carbon Capture and Storage (DACCS): Chemical process by which carbon dioxide (CO_2) is captured from the ambient air, with subsequent geological storage.

Direct ocean carbon capture and storage (DOCCS): Chemical process by which carbon dioxide (CO_2) is captured directly from seawater, with subsequent geological storage. To count as CDR, this capture must lead to increased ocean CO_2 uptake.

Durability: The capacity to store carbon over time without releasing it back to the atmosphere. In this report, carbon pools with characteristic storage timescales on the order of decades or more are classed as sufficiently durable for CDR. These include trees, wetlands, soils, biochar, durable wood products (e.g. timber for construction), mineral products (e.g. aggregates), marine sediments, ocean bicarbonate, depleted fossil fuel reservoirs, saline aquifers and mineral rock formations.

Durable wood products: Wood products which meet a given threshold of durability, typically used in construction. These can include sawnwood, wood panels and composite beams, but exclude less durable products such as paper.

Enhanced rock weathering: Increasing the natural rate of removal of carbon dioxide (CO_2) from the atmosphere by applying crushed rocks, rich in calcium and magnesium, to soil or beaches.

Forest management: Stewardship and use of existing forests. To count as CDR, forest management practices must enhance the long-term average carbon stock in the forest system.

Mineral products: Production of solid carbonate materials for use in products such as aggregates, asphalt, cement and concrete, using CO_2 captured from the atmosphere.

Monitoring, Reporting & Verification; or Measurement, Reporting and Verification (MRV): Procedures for quantification, documentation and independent review of reported GHG emissions and removals, in the context of national inventory reporting, emissions trading and voluntary claims such as carbon neutrality or net zero emissions.

Novel CDR: CDR methods that generally have a lower level of readiness for deployment and are therefore currently deployed at smaller scales. The captured carbon is stored in geological formations, the ocean or products. Such methods include Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), enhanced rock weathering, biochar, mineral products and ocean alkalinity enhancement.

Ocean alkalinity enhancement (OAE): Spreading of alkaline materials on the ocean surface to increase the alkalinity of the water and thus increase ocean CO_2 uptake.

Ocean fertilisation: Enhancement of nutrient supply to the near-surface ocean with the aim of sequestering additional CO_2 from the atmosphere stimulated through biological production. Methods include direct addition of micro-nutrients or macro-nutrients. To count as CDR, the biomass must reach the deep ocean where the carbon has the potential to be sequestered durably.

Offset (noun): A unit that represents the reduction, avoidance or removal of a ton of CO_2 or CO_2 equivalent by one entity, commonly purchased as a carbon credit, that is used by another entity to counterbalance a ton of GHG emissions by that other entity.

Offset (verb): To counterbalance a quantity of GHG emissions by retiring or canceling an equivalent quantity of carbon credits.

Note: GHG emissions of an entity can also be counterbalanced through CDR undertaken by that entity.

Paris temperature goal: The long-term temperature goal as set in Article 2 of the Paris Agreement (i.e., "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels")

Peatland and coastal wetland restoration: Assisted recovery of inland ecosystems that are permanently or seasonally flooded or saturated by water (such as peatlands) and of coastal ecosystems (such as tidal marshes, mangroves and seagrass meadows). To count as CDR, this recovery must lead to a durable increase in the carbon content of these systems.

Reforestation: Conversion to forest of land that was previously deforested.

Residual emissions: Remaining gross emissions when net-zero, and subsequently, net-negative, emissions are reached. Can apply to both net zero CO_2 and net zero GHG emissions, from local to global scales and at company or sector level. To reach net-zero emissions, the amount of CDR must equal the amount of residual emissions over a given period. To reach net-negative emissions, the amount of CDR must exceed residual emissions.

Soil carbon sequestration in croplands and grasslands: Land management changes in croplands and grasslands that increase the soil organic carbon content.

Abbreviations

AFOLU	agriculture, forestry and other land use
AI	artificial intelligence
AR6	Sixth Assessment Report of the Intergovernmental Panel on Climate Change
BAU	business-as-usual
BECCS	Bioenergy with carbon capture and storage
CAN	Canada
CCPs	Core Carbon Principles
CCS	carbon capture and storage
CCU	carbon capture and utilization
CDM	Clean Development Mechanism
CDR	carbon dioxide removal
CGE	Computable General Equilibrium
CH_4	methane
CO_2	carbon dioxide
COP	Conference of the Parties
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DAC	Direct air capture
DACCS	Direct air carbon capture and storage
DOCCS	Direct ocean carbon capture and storage
ERW	Enhanced rock weathering
EU	European Union
F-gases	fluorinated greenhouse gases
FAOSTAT	Food and Agriculture Organization Statistics
GCB	Global Carbon Budget
GCOM	Greenhouse Gas Crediting and Offsetting Mechanism
GHG	greenhouse gas
Gt	gigaton
HWP	harvested wood product
IAM	integrated assessment model
ICROA	International Carbon Reduction and Offset Alliance
ICVCM	Integrity Council for the Voluntary Carbon Market
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
Kt	kiloton
LULUCF	land use, land-use change and forestry
MRV	monitoring, reporting and verification; or measurement, reporting and verification
Mt	megaton

N_2O	nitrous oxide
NDC	Nationally Determined Contribution
NGHGI	national greenhouse gas inventory
NGO	non-governmental organization
NKr	Norwegian krone
NZI	Net Zero Insights
OAE	Ocean alkalinity enhancement
PATSTAT	European Patent Office Worldwide Patent Statistical Database
R&D	research and development
RD&D	research, development and demonstration
SDG	Sustainable Development Goal
t	ton
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USD	United States dollar
USDA	United States Department of Agriculture
VCM	voluntary carbon market
VCMI	Voluntary Carbon Markets Integrity Initiative

Throughout this report, ton is used in the sense of metric ton (i.e. 1,000 kg).


THE STATE OF
Carbon
Dioxide
Removal