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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.

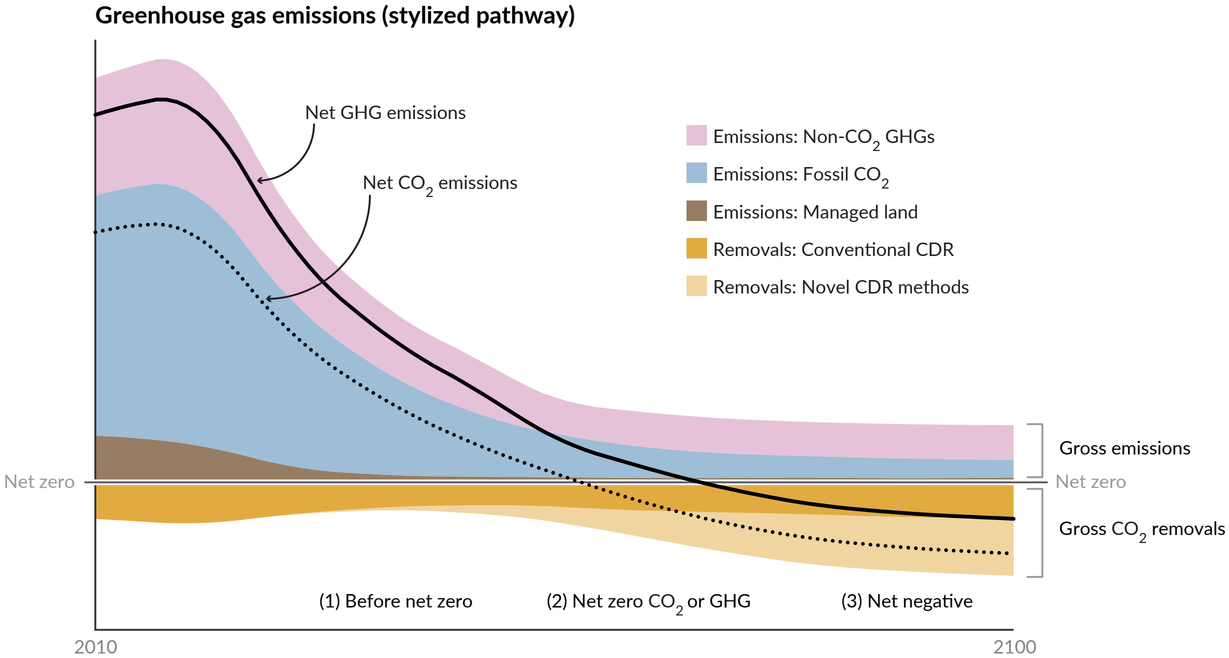

Figure 1.1 *Roles of carbon dioxide removal (CDR) in ambitious mitigation strategies, applicable at national and global levels. Basic emission and removal components of mitigation pathways, and the corresponding trajectories for both net carbon dioxide (CO_2) and greenhouse gas (GHG) emissions. (Adapted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

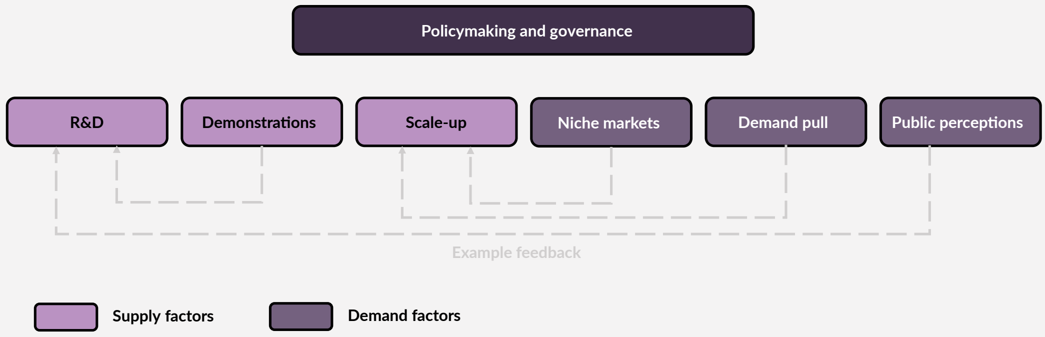

Figure 1.2 *The process of innovation on which the State of Carbon Dioxide Removal assessment is based. R&D = research and development.*

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.

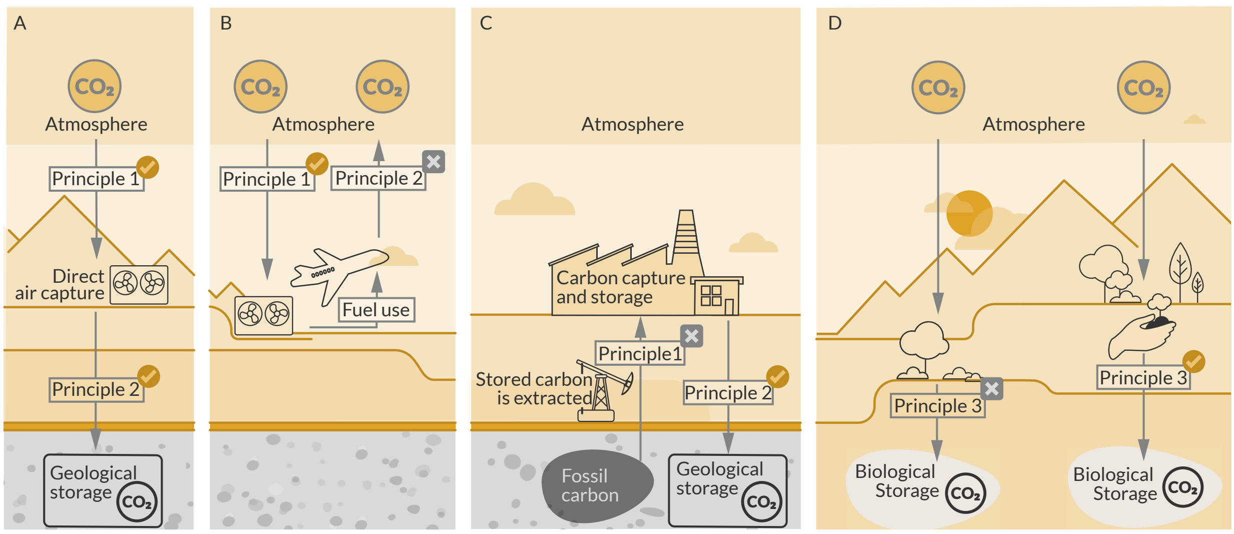

Figure 1.3 *To be defined as carbon dioxide removal (CDR), a method must capture carbon dioxide (CO_2) from the atmosphere (Principle 1) and durably store it (Principle 2) as a result of human intervention (Principle 3). An example is direct air capture with geological storage (panel A).. Several related 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.

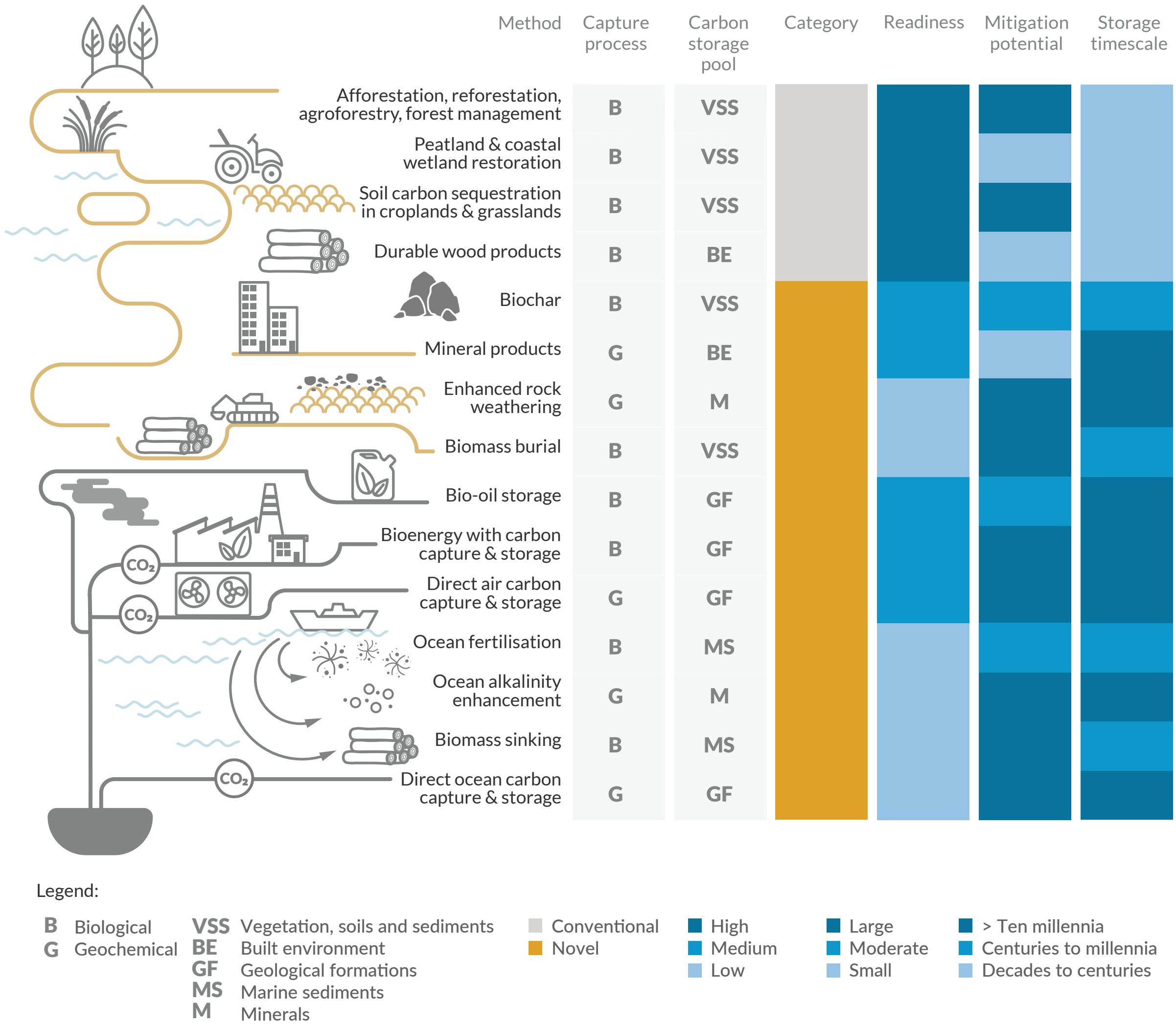

Figure 1.4 *Summary of Carbon Dioxide Removal methods, noting their respective capture process and carbon storage pool, categorization as 'Conventional' or 'Novel', their current readiness to scale (based on technology readiness levels), their maximum mitigation potential (Large: >9 $GtCO_2$/year; Moderate: 3-9 $GtCO_2$/year; Small: <3 $GtCO_2$/year), and characteristic storage timescale. (Bsed 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.


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