THE STATE OF Carbon Dioxide Removal

A global, independent scientific assessment of Carbon Dioxide Removal

1st EDITION

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

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Foreword

The science is clear. No matter which IPCC pathway humanity will follow, holding the global average temperature increase below 1.5°C will require removing increasing amounts of CO2 from the atmosphere. Firstly, hard-to-abate greenhouse gas emissions will have to be balanced with removals in order to achieve net-zero CO2 emissions in less than thirty years. Secondly, from then onwards, vast amounts of CO2 will have to be captured from the air for many decades, cleaning up the atmosphere and returning atmospheric CO2 to climate-safe levels. At the latest by then, carbon dioxide removal (CDR) and the sustainable management of global carbon cycles will have become the major focus of climate action worldwide. In this immense global clean-up exercise, everyone will have to assume their historical responsibility.

However, CDR will not fall from heaven like manna. It will require active and urgent public policies. Novel CDR, such as direct air capture and storage, enhanced weathering and new carbon-rich materials, are still at an early stage of development and will thus require a significant push. Deployment at scale, even of well-known conventional CDR on land, will require a CO2 price incentive and an adequate regulatory framework. Without strong public governance, CDR could be implemented in a way that undercuts emission reduction efforts or harms the environment.

This report, the first of its kind, updates the world on the state of play on CDR: from research to policymaking to deployment, from scientific analysis to public perception. Not surprisingly, the scientists point their fingers at yet another yawning gap between, on one side, the scientifically assessed need and, on the other side, the lack of action on CDR along the entire value chain. The CDR gap calls for urgent action on all CDR fronts.

For me, this report points towards practical recommendations which, over the coming months, will hopefully trigger domestic and international CDR action:

I. National climate policy frameworks will have to be expanded to scale up CDR. Specific policy support will have to be created to, on the one hand, incentivise CDR, and on the other, ensure that it is done well through monitoring and good public governance.

II. At the next international climate conference in Dubai at the end of 2023 (COP28), there must be explicit acknowledgement of the magnitude of the CDR gap under the Global Stocktake, creation of a new negotiation track on CDR, clear transparency rules for national reporting of CDR and its inclusion in

Nationally Determined Contributions, and identification of international climate finance requirements for CDR, taking into account the “polluter pays” principle.

III. In parallel, public and private leaders should fast-forward practical action on CDR together – very similar to the success story I experienced in relation to renewables. Then, the creation of REN21 as an ambitious coalition in 2004 turned out to be instrumental in pushing the frontiers on renewables technology and policy, both internationally and domestically.

In the coming years, this global CDR report should continue to regularly inform policymakers on the state of progress, by systematically collecting and analysing the vast amount of data and developments in many parts of the world.

Artur Runge-Metzger

Former Director, European Commission, Directorate-General for Climate Action

Executive Summary

Scaling up Carbon Dioxide Removal (CDR) is an urgent priority, as are efforts to rapidly reduce emissions, if we are to meet the temperature goal of the Paris Agreement. Scenarios for limiting warming to well below 2°C involve removing hundreds of billions of tonnes of carbon dioxide (CO_2) from the atmosphere over the course of the century. **Drawing together analysis across several key areas, this report is the first comprehensive global assessment of the current state of CDR.**

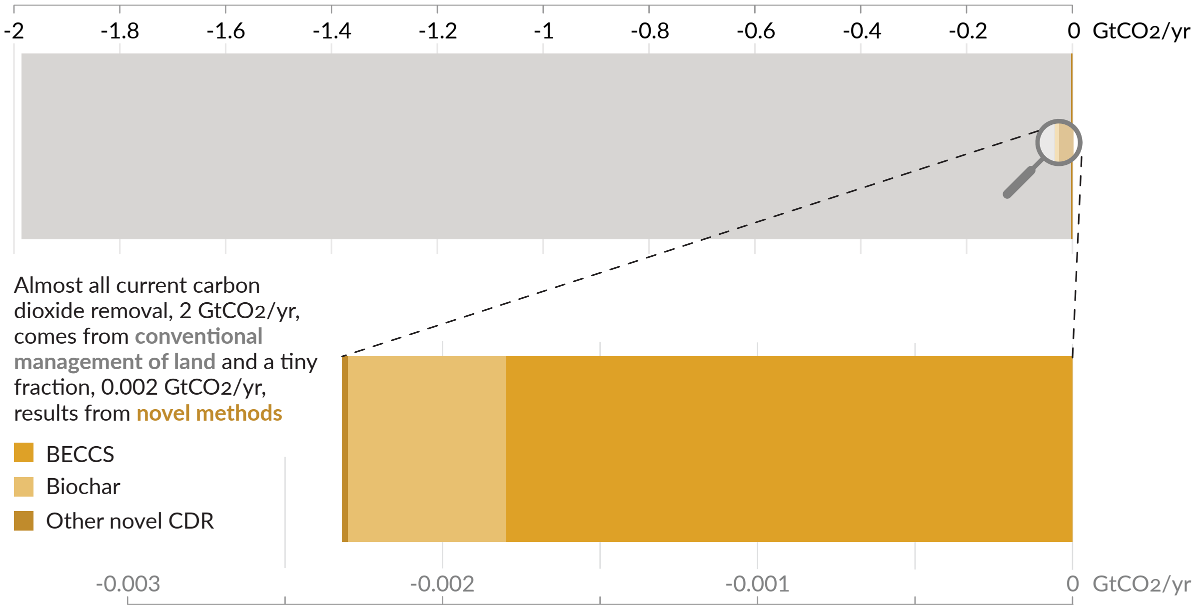
We find a gap between how much CDR countries are planning and what is needed in scenarios to meet the Paris temperature goal. The size of the "CDR gap" differs across scenarios, depending on how we choose to transform the global economy towards net-zero emissions. **However, there are currently few plans by countries to scale CDR above current levels, exposing a substantial shortfall.**

CDR involves capturing CO_2 from the atmosphere and storing it durably on land, in the ocean, in geological formations or in products. Examples include reforestation, biochar, Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS). **For the first time, this report compiles an estimate of the total amount of CDR currently being deployed around the world.**

Almost all current CDR (2 $GtCO_2$ per year) comes from "conventional" CDR on land, primarily via afforestation, reforestation and management of existing forests. Scenarios that limit warming to 1.5°C or 2°C require further increasing current forest sinks, as well as minimising emissions from deforestation. By 2050, land-based removals approximately double in 1.5°C pathways and increase by around 50% in 2°C pathways compared to 2020 levels. **In the near term, several countries plan to *maintain or slightly increase* conventional CDR on land by 2030, which is on its own a huge challenge requiring dedicated policies and management.**

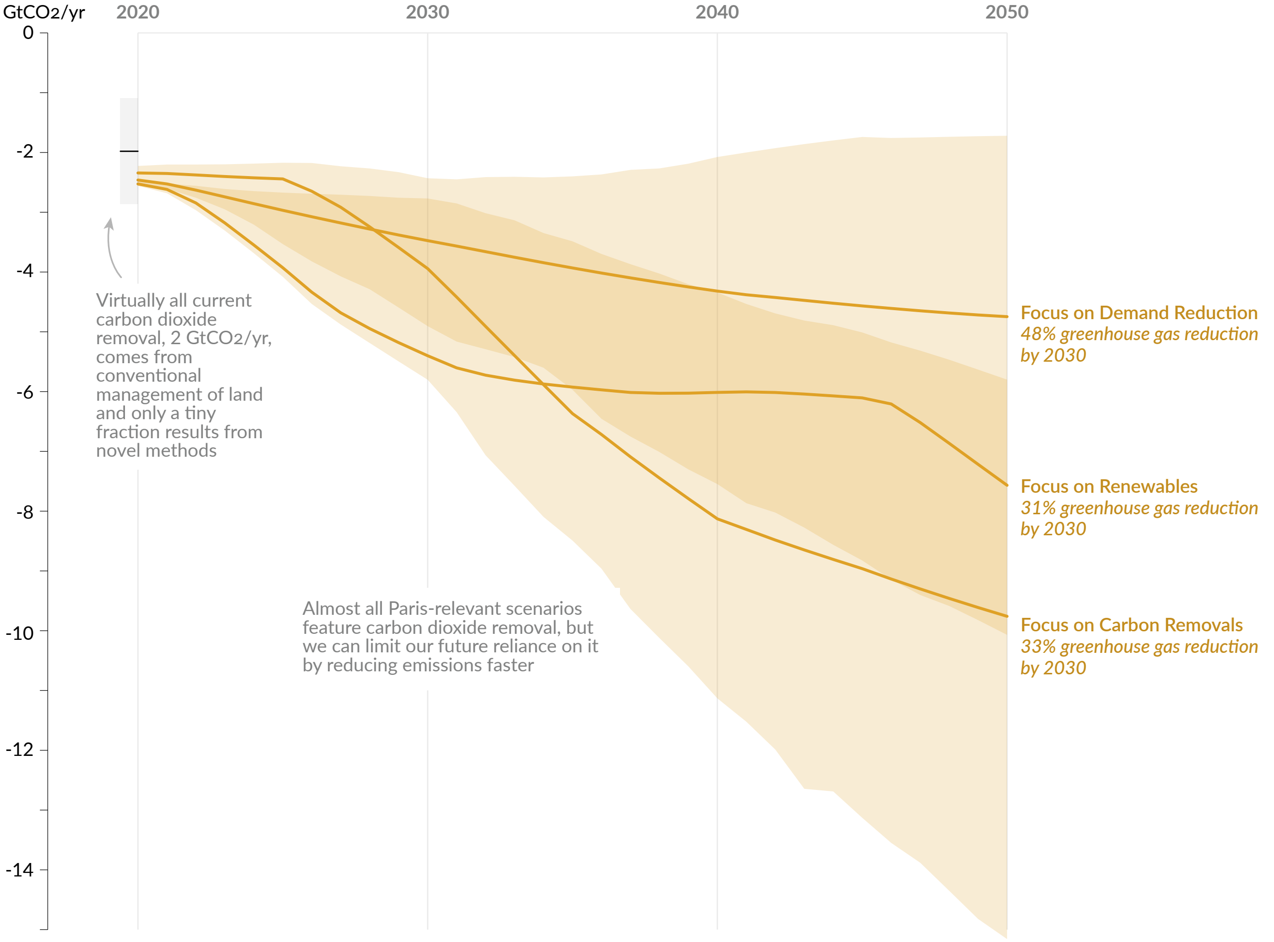
Only a tiny fraction of all current carbon dioxide removal results from novel methods

Total current amount of carbon dioxide removal, split into conventional and novel methods (GtCO2/yr)



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

Carbon dioxide removal (GtCO2/yr), in 2020 and in three Paris-consistent scenarios

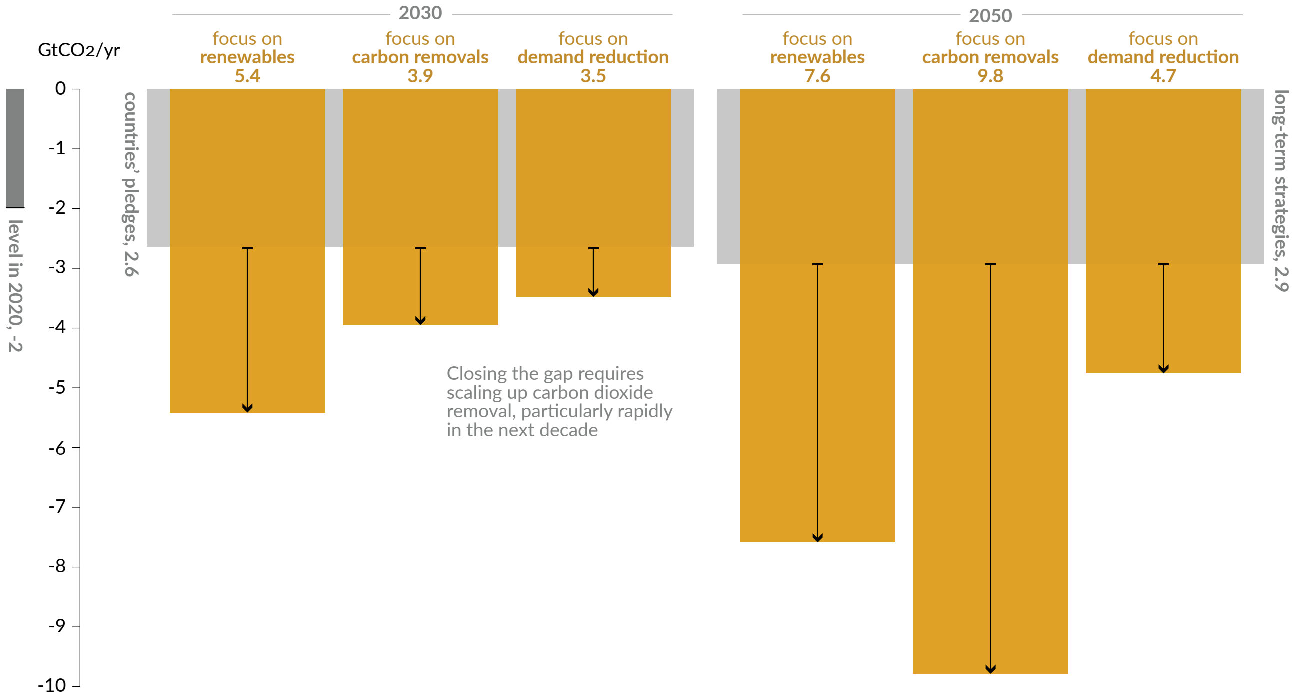


Virtually all current carbon dioxide removal, 2 GtCO2/yr, comes from conventional management of land and only a tiny fraction results from novel methods

Almost all Paris-relevant scenarios feature carbon dioxide removal, but we can limit our future reliance on it by reducing emissions faster

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

Carbon dioxide removal (GtCO2/yr), proposed levels compared to three Paris-relevant scenarios in 2030 and 2050

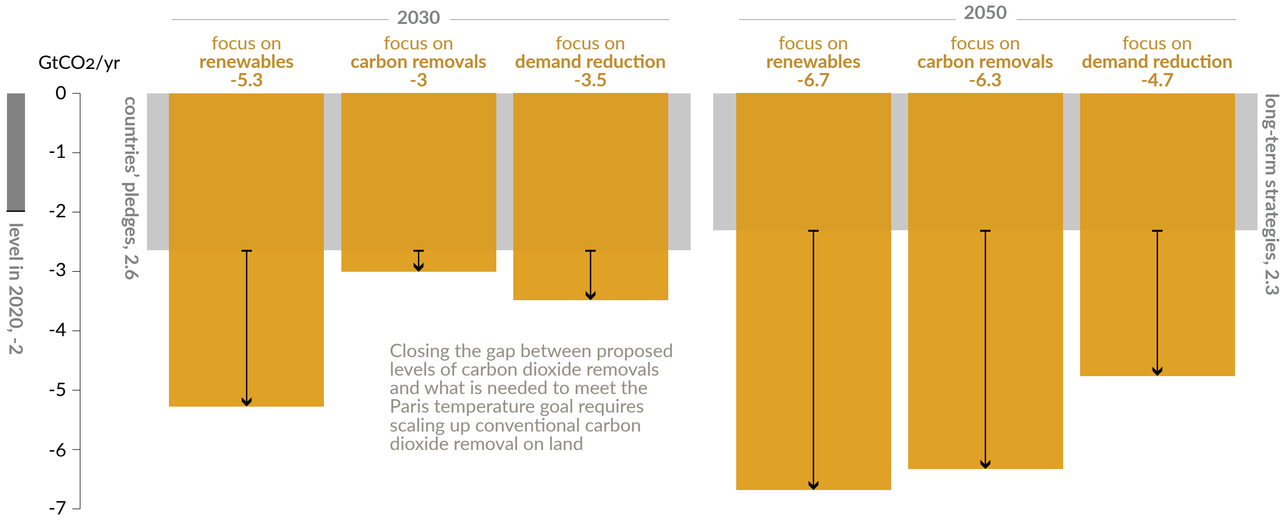


Closing the gap requires scaling up carbon dioxide removal, particularly rapidly in the next decade

Virtually all scenarios that limit warming to 1.5°C or 2°C require "novel" CDR, such as BECCS, biochar, DACCS, and enhanced rock weathering. However, only a tiny fraction (0.002 $GtCO_2$ per year) of current CDR results from novel CDR methods. **Closing the CDR gap requires rapid growth of novel CDR.** Averaging across scenarios, novel CDR increases by a factor of 30 by 2030 (and up to about 540 in some scenarios) and by a factor of 1,300 (up to about 4,900 in some scenarios) by mid-century. Yet no country so far has pledged to scale novel CDR by 2030 as part of their Nationally Determined Contribution, and few countries have so far published proposals for upscaling novel CDR by 2050.

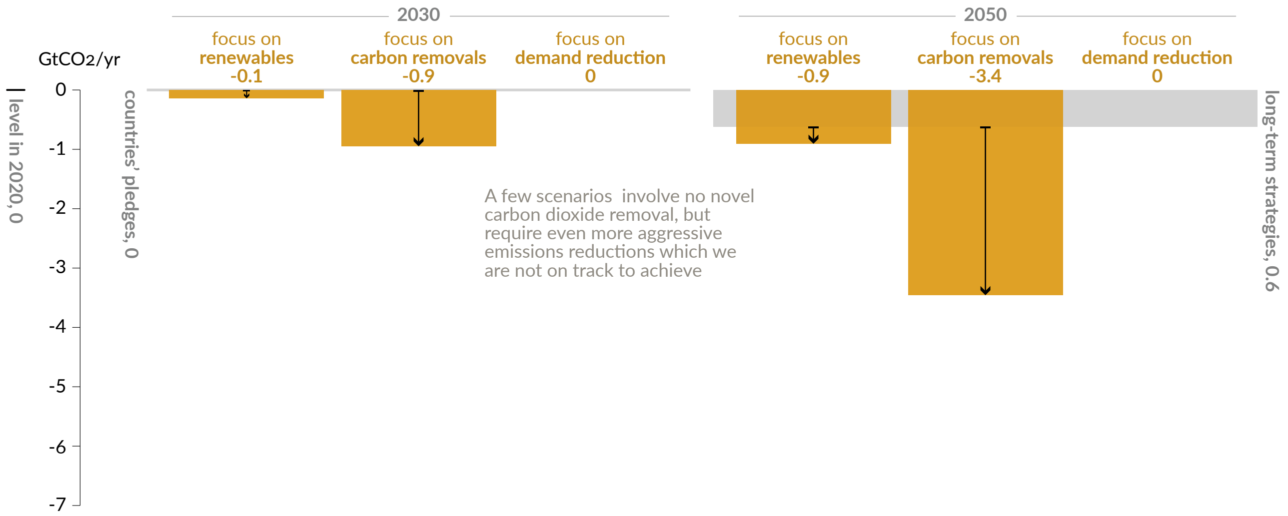
There is a ↧ gap between proposed levels of carbon dioxide removal and what is needed to meet the Paris temperature goal

A. Conventional carbon dioxide removal ($GtCO_2$/yr), proposed levels compared to three Paris-relevant scenarios in 2030 and 2050



Closing the gap between proposed levels of carbon dioxide removals and what is needed to meet the Paris temperature goal requires scaling up conventional carbon dioxide removal on land

B. Novel carbon dioxide removal ($GtCO_2$/yr), proposed levels compared to three Paris-relevant scenarios in 2030 and 2050



A few scenarios involve no novel carbon dioxide removal, but require even more aggressive emissions reductions which we are not on track to achieve

CDR is not a silver bullet, as scenarios that limit warming to 2°C or lower require deep cuts to emissions in addition to, not in place of, CDR. A few scenarios do meet the Paris temperature goal without novel CDR, but these require even more aggressive emission reductions, which we are not on track to achieve. To help manage uncertainties and risks associated with CDR at large scales, our dependence on it should be limited by reducing emissions faster.

Spurring the rapid growth in CDR necessary to close the CDR gap requires urgent and comprehensive policy support that is tailored to specific national contexts. Over 120 national governments have a net-zero emissions target, which implies using CDR to counterbalance residual emissions, but only a few explicitly integrate CDR into their climate policies. **The next decade is crucial for novel CDR, in particular, since the amount of CDR deployment required in the second half of the century will only be feasible if we see substantial new deployment in the next ten years, novel CDR's formative phase.** Yet our assessment reveals few countries have actionable national plans to develop CDR, particularly for novel methods.

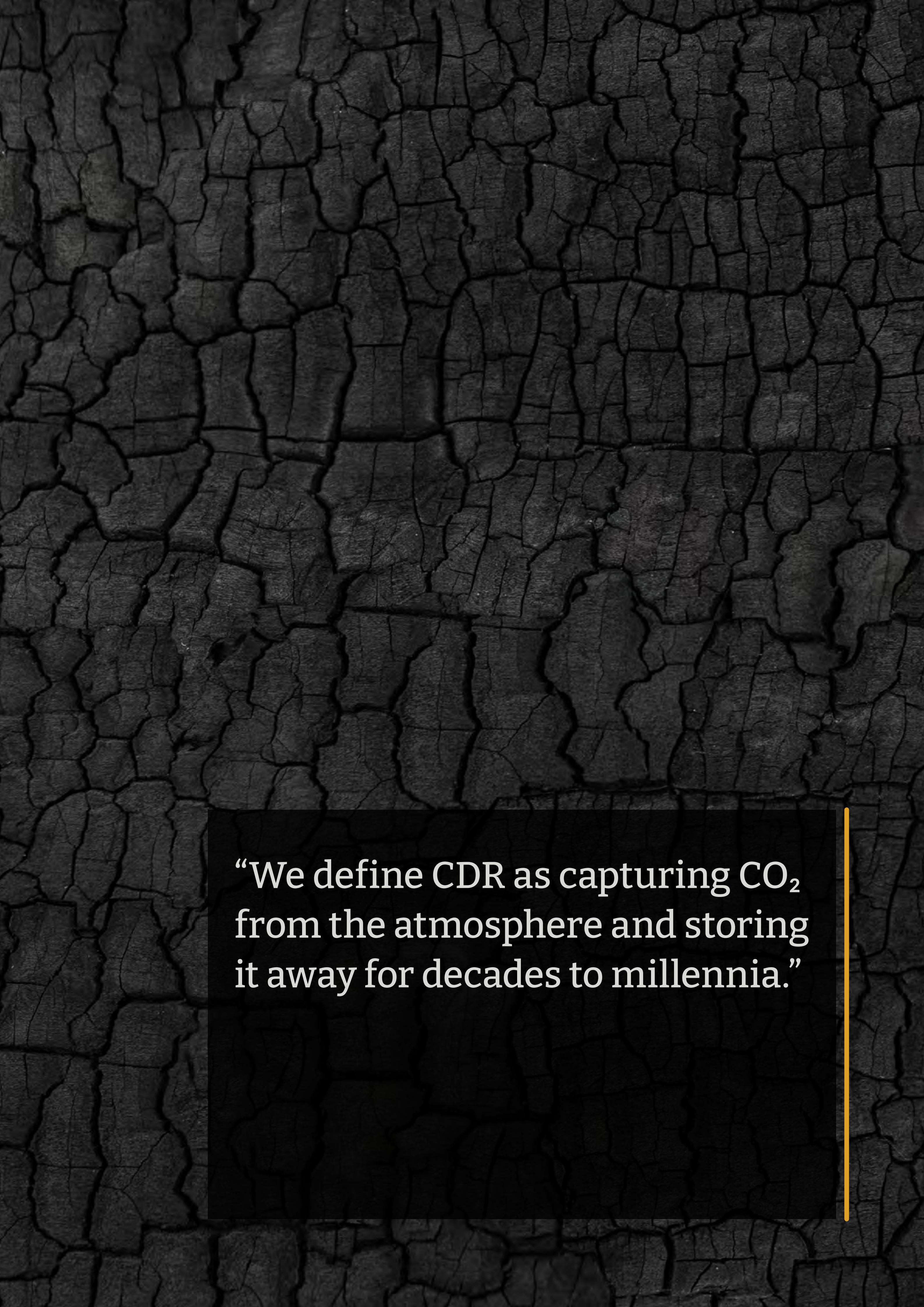
In terms of recent growth, our assessment of trends in the scientific literature, innovation and public perception of CDR reveal some interesting patterns as CDR evolves. **The peer-reviewed scientific literature on CDR is growing faster than for climate change as a whole, now consisting of over 28,000 English-language studies.** Most focus on land-based biological CDR methods such as biochar and soil carbon sequestration. Almost all are published in science and technology journals, with very few in social sciences or humanities publications, and only about a third have a specific geographic focus. This indicates a potential lack of information tailored to specific local contexts, particularly for novel CDR methods.

Innovation in CDR has expanded substantially in recent years. We see evidence of this in over $4 billion of publicly funded Research, Development and Demonstration (RD&D), a rise in patents (with China the lead country and Direct Air Capture the most patented technology) and investment in new CDR capacity totalling approximately $200 million from 2020 to 2022. **CDR is becoming more of a public talking point too, although awareness remains low relative to other aspects of climate change.** A growing number of scientific studies on how people perceive CDR indicate public support for research into CDR but raise concerns about deployment at scale. CDR methods that are familiar and often perceived as natural, such as afforestation, are viewed more favourably than others. Discussion of CDR on the social media platform Twitter is growing fast, with a trend towards more positive sentiment for all CDR methods except BECCS.

The primary policy implications of this first assessment of the state of CDR are that meeting the Paris temperature goal requires us to accelerate emission reductions, increase conventional CDR and rapidly scale up novel CDR. Actionable policy proposals, with standardised transparent reporting and involving societal deliberation, will support and shape these outcomes in a manner that acknowledges both the urgency of the challenge and issues such as policy costs, hazards and land-use conflicts.

We intend for this report to be the first in a series, continuing to track the CDR gap and providing a clear, authoritative, and up-to-date snapshot and serving as an information resource for those who are making decisions about CDR and its role in meeting climate goals. We have identified areas on which future assessments can build, including: (1) **expanding the community** of experts and data sharers to widen the knowledge, perspective and experiences that guide development of CDR; (2) **improving the availability of data** on CDR projects, plans, investment and other relevant dimensions; and (3) honing the analysis around more **complete, consistent and comparable definitions and methods.**

Twenty years ago, renewable energy was a niche sector. Today, the picture is radically different. This rapid development was enabled in part by concerted efforts to build institutions and communities for gathering and sharing information. CDR is at the start of a similar journey. We, the scientific convenors, hope that this contribution, in addition to the contributions of many others, provides similarly important guidance so that CDR too can play an important role in addressing climate change.



> “We define CDR as capturing CO_2 from the atmosphere and storing it away for decades to millennia.”

Chapter 1 | Introduction

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This report is the first independent scientific assessment tracking the global development of Carbon Dioxide Removal (CDR). This chapter sets out how we define CDR and the characteristics of key CDR methods.

1.1 Carbon Dioxide Removal in the context of climate goals

Alongside rapidly reducing emissions, we will need to remove carbon dioxide from the atmosphere to meet climate goals.

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. Meeting the Paris temperature goal (Box 1.1) requires deep and widespread reductions in emissions. While such efforts to reduce emissions prevent further CO_2 and other greenhouse gases (GHGs) from going into the atmosphere, Carbon Dioxide Removal (CDR) involves taking CO_2 out of the atmosphere that is already there.

CDR can fulfil three major functions, alongside emissions reductions. First, CDR can reduce net emissions in the near term. Second, CDR can counterbalance residual emissions to achieve net-zero CO_2 or GHG emissions in the medium term. Third, if removals exceed emissions, CDR can achieve net-negative emissions in the longer term. At the global level, net-negative CO_2 emissions could reverse at least some overshoot, where global temperature increase exceeds acceptable levels.[1]

Box 1.1 Climate goals

Through the Paris Agreement, countries have together set quantifiable goals to reduce (or “mitigate”) climate change. The principal goal is defined in terms of temperature:

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.

In support of this long-term temperature goal, the Paris Agreement further sets out a goal for emissions and removals:

to achieve a balance between anthropogenic [i.e. human-caused] emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty.

This balance of emissions and removals from human activity is often referred to as "net-zero emissions". Over 120 countries have now pledged their own domestic net zero targets (see Chapter 5 – Policymaking), as have many companies.[2]

Net-zero emissions targets, including the target in the Paris Agreement, are usually applied to a basket of greenhouse gases rather than to CO_2 alone. In the case of a greenhouse gas target, the definition of net zero requires a way to compare the emissions and removals of the different gases. Depending on the way chosen, net zero may involve different balances of greenhouse gases and hence may lead to global temperature decreasing, or even continuing to increase, over subsequent decades.

For ease of readability, in this assessment we refer to the long-term temperature goal in the Paris Agreement (well below 2°C above pre-industrial levels, pursuing efforts to limit the increase to 1.5°C) as "the Paris temperature goal" but use more specific terminology where necessary.

1.2 Purpose and scope of this report

Drawing together analysis across several key areas, this report is the first step towards a global assessment of the state of CDR.

The topic of CDR is moving rapidly up the agendas of policymakers, investors, researchers and environmental campaigners. Consequently, information about CDR is increasing, including academic assessments[3–5], introductory books[6,7], data on CDR startups, purchases of carbon removal credits[8], recommendations from business groups[9] and briefings from NGOs[10].

Yet, to date, there are still major limitations in information regarding CDR:

- Despite growing recognition that CDR needs to be scaled, there is no current global effort to quantify the **amount of CDR currently deployed**, and **whether it is on track** to meet the Paris temperature goal.
- Information on CDR is **highly dispersed**, often gathered using inconsistent definitions and methods, and without regular updating to keep pace with developments.
- Growing **political and private sector interest** in CDR makes it crucial to establish an **independent and scientific assessment** of the state of CDR and the size of any gap to be closed.

This report is the first such assessment. Based on publicly available data, we assess CDR development in several key areas. In the first three chapters we assess CDR in terms of scientific research (Chapter 2), innovation (Chapter 3) and public perception (Chapter 4). Then, we examine different policy approaches and commitments by governments to develop CDR (Chapter 5). The subsequent three chapters look at the amount of CDR being deployed now (Chapter 6), the amount required in pathways that meet the Paris temperature goal (Chapter 7) and the gap that exists between current deployment, government pledges and these pathways (Chapter 8). Finally, we highlight future directions for improving and deepening this assessment (Chapter 9).

It is our intention that this report is the first in a series: continuing to track the CDR gap, expanding the breadth and depth of the assessment to be truly global in scope, and building a community around making CDR data more complete, reliable, accessible and inclusive. We intend this report to provide a clear, authoritative and up-to-date snapshot, serving as an information resource for people making decisions about CDR and its role in meeting climate goals. In addition, we intend that future assessments will be accompanied by a freely available data portal for use by anyone with an interest in CDR.

1.3 What we mean by CDR

We define CDR as capturing CO_2 from the atmosphere and storing it away for decades to millennia.

For the purposes of this assessment we adopt the definition of CDR used by the Intergovernmental Panel on Climate Change (IPCC)[11]:

> *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.*

Our 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). The removal activity may capture atmospheric CO_2 directly or indirectly, for instance via biomass or seawater.

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 Earth's natural processes.

It is important to distinguish CDR from other related terms and concepts, such as Carbon Capture and Utilisation (CCU), and Carbon Capture and Storage (CCS). While they share some components with CDR, they do not necessarily result in durable net removal of CO_2 from the atmosphere (Box 1.2). Examples of how different approaches meet, or fail to meet, the principles of CDR are shown in Figure 1.1.

Box 1.2 Differentiating CCS, CCU and CDR

To count as Carbon Dioxide Removal (CDR), a method must be an intervention which captures CO_2 from the atmosphere (Principle 1) and durably stores it (Principle 2).

Carbon Capture and Storage (CCS) is a set of industrial methods for the chemical capture of CO_2, concentration of this into a pure stream and its subsequent geological storage. Where the CO_2 comes directly from fossil fuels or minerals (for example, limestone), this process does not meet Principle 1 and counts as an emissions reduction rather than CDR. Indeed, the term CCS is sometimes reserved only for these applications. CCS can, however, be applied to CO_2 streams generated using biomass or directly from the air, in which cases the overall process meets both Principle 1 and Principle 2, and counts as CDR. In this assessment we refer to "fossil CCS", where necessary, to distinguish this from CCS as a component of CDR methods.

Carbon Capture and Utilisation (CCU) is a set of industrial methods for the chemical capture of CO_2 and its conversion into products. These products can include carbonated drinks, fuels, plastics and aggregates. If this CO_2 comes from the atmosphere, then it meets Principle 1. Many of these products, however, last only a matter of days or months before the carbon is released into the atmosphere. Only some involve durable storage, thereby meeting Principle 2. Furthermore, if the captured CO_2 comes from fossil or mineral sources, this again counts as a (temporary) emissions reduction rather than CDR.

Carbon Dioxide Removal (CDR) must involve both capture of CO_2 from the atmosphere and durable storage, whether in a useful product or another carbon reservoir. Not all CCS and CCU methods involve CO_2 removal from the atmosphere or lead to durable storage.

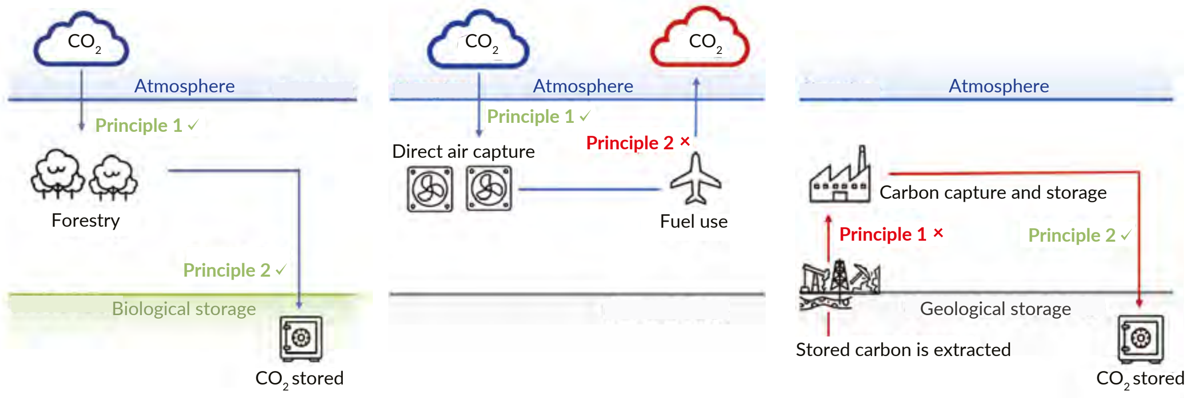


Figure 1.1. *To be defined as Carbon Dioxide Removal (CDR), a method must capture CO_2 from the atmosphere (Principle 1) and durably store it (Principle 2). An example of a method which satisfies both principles, and hence qualifies as CDR, is afforestation/reforestation (left). There are several approaches that satisfy only one of these principles, and hence are not CDR, but which count as Carbon Capture and Utilisation (e.g. Direct Air Capture to fuels (middle) or as fossil Carbon Capture and Storage (right). Source: Zero Emissions Platform (2020)*[12].

1.4 Building blocks of CDR

There are different ways to capture CO_2 from the atmosphere and different ways to store it. Some means of storage are longer-lasting and less vulnerable to reversal than others. Individual CDR methods can be thought of as different routes through the Earth's carbon cycle – capturing carbon from the atmosphere and transferring it to a durable carbon pool (see section below, Box 1.3 and Figure 1.2).

Routes through the carbon cycle

CDR methods encompass a range of capture processes and storage pools. Processes which carry out the initial capture from the atmosphere are often referred to as *sinks*. Between capture and ultimate storage, carbon may be converted and transferred through a number of carbon pools. Some methods involve multiple steps, while others combine capture and storage in a single step.

Capture processes

Biological capture. Through the process of photosynthesis, CO_2 is taken up from the atmosphere by trees, crops and aquatic biomass such as kelp and seagrasses.

Geochemical capture. A range of minerals can bind atmospheric CO_2, as can alkaline waste materials from construction and industry. The CO_2 is bound in the form of solid carbonate (which can be used as a product, such as aggregates) or dissolved bicarbonate, both of which are durable carbon pools.

Chemical capture. CO_2 can be captured directly from air using chemical solvents and sorbents designed to re-release it as a concentrated CO_2 stream for use or storage.

Storage processes

Biological storage (on land and in oceans). While annual plants do not retain carbon durably, trees can retain their carbon for decades, centuries or more. Soils and wetlands are a further store of carbon, derived from compounds exuded by roots and dead plant matter. In the oceans, aquatic biomass may sink to the ocean floor and become marine sediment. Carbon can be retained durably in these ecosystems, especially if managed carefully to reduce disturbances.

Product storage. Many carbon-based products do not constitute durable storage. However, construction materials and biochar (a carbon-rich material produced by heating biomass in an oxygen-limited environment) can store carbon for decades or more. These carbon-based products can be made from conversion of harvested biomass (in the cases of biochar and wood in construction), from concentrated CO_2 streams or even from CO_2 from ambient air (in the case of aggregates).

Geochemical storage. Concentrated CO_2 can be stored in geological formations, using depleted oil and gas fields or saline aquifers, or reactive minerals such as basalt. Geochemical capture leads directly to long-term storage of CO_2 in the form of carbonate minerals or bicarbonate in the ocean.

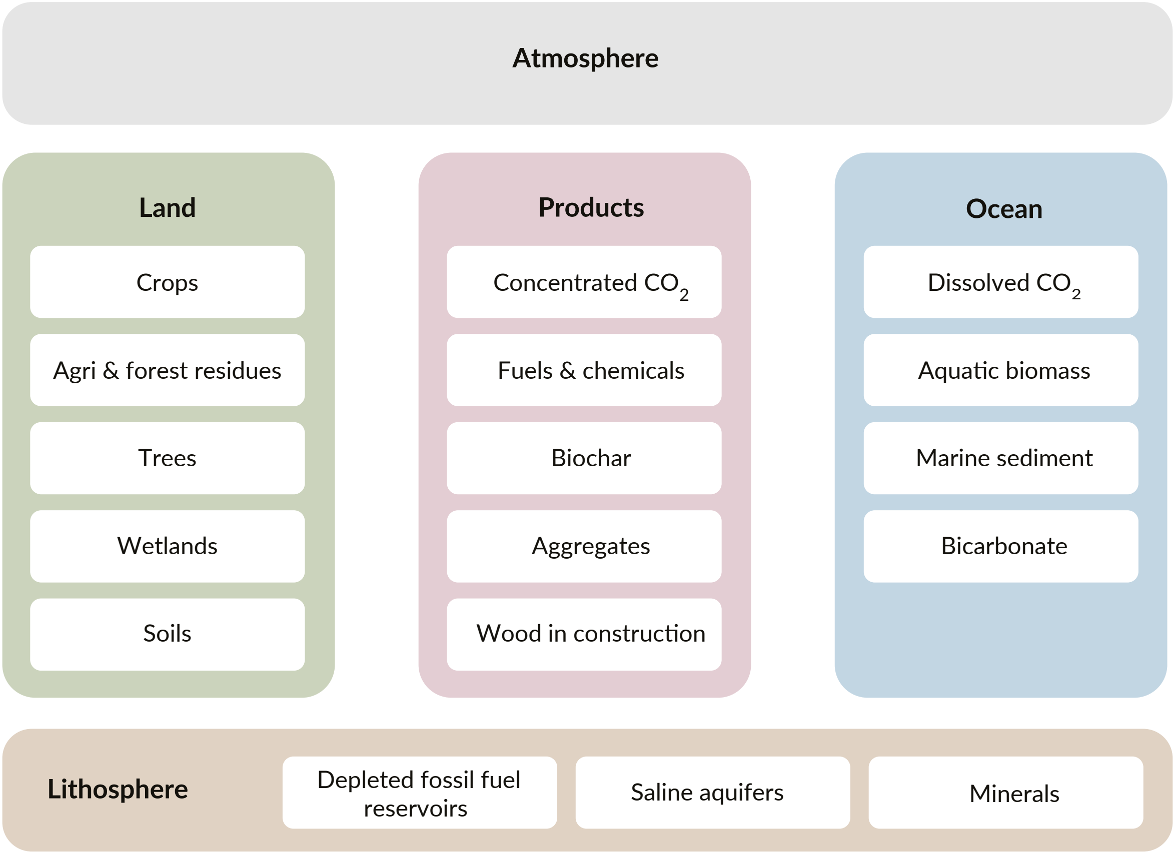


Figure 1.2. *The global carbon cycle consists of five main carbon reservoirs: the atmosphere, land, products, ocean and lithosphere (geological formations). Within each reservoir there are various carbon pools (indicated in each reservoir) whose characteristics vary in terms of storage capacity and durability. Carbon Dioxide Removal methods transfer* CO_2 *from the atmosphere into other durable pools within the global carbon cycle.*

Durability

Different carbon pools have very different characteristic timescales for storage and risks of reversal, and there is no clearly agreed definition of durability (Box 1.3). Well-chosen geological and mineral formations offer the longest and least reversible storage. Nevertheless, choosing to include only these methods excludes others widely regarded as valid CDR, such as those that store carbon in trees, biochar and soils.

In this assessment we choose to define CDR methods as sufficiently durable if the carbon pool used for storage has a characteristic timescale on the order of decades or more. The list of CDR methods that we have included in this assessment matches that used by the IPCC[13], including wood products used in construction such as panels and sawnwood (Table 1.1). These construction products characteristically store carbon for decades after having captured it during tree growth[14]. Furthermore, at the end of their use as products, the carbon could be transferred to another more durable store, for instance if used for Bioenergy with Carbon Capture and Storage (BECCS).

It should be kept in mind that our approach to what counts as CDR is not definitive – we expect that expert interpretations will evolve as research continues.

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[15]. Maintaining net-zero emissions – and hence halting the global temperature increase – requires any residual emissions of fossil carbon to be balanced by storage on the same millennial timescale[16].

There is currently no clear scientific basis for a threshold of durability to define Carbon Dioxide Removal (CDR), nor consensus among policymakers. Despite storage for millennia being the gold standard, there are practical barriers to assuring projects for this long. Furthermore, shorter-term storage still has some value for meeting climate goals, although it is widely accepted that products which re-release carbon within a year (such as 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 up to 100 years, sometimes with discounted credits issued for shorter thresholds[17,18].

Figure 1.3 shows the characteristic storage timescales of various carbon pools. The actual duration of storage depends not only on the characteristic timescale of a pool but also on human factors: storage in soils can be ended by a change in land use but can also be extended through careful maintenance. Geological formations (saline aquifers, depleted oil and gas fields, and minerals) have the longest characteristic timescales and are least susceptible to releasing CO_2 into the atmosphere as a result of human and natural disturbances. They are therefore most able to provide a like-for-like balance to emissions of fossil CO_2.

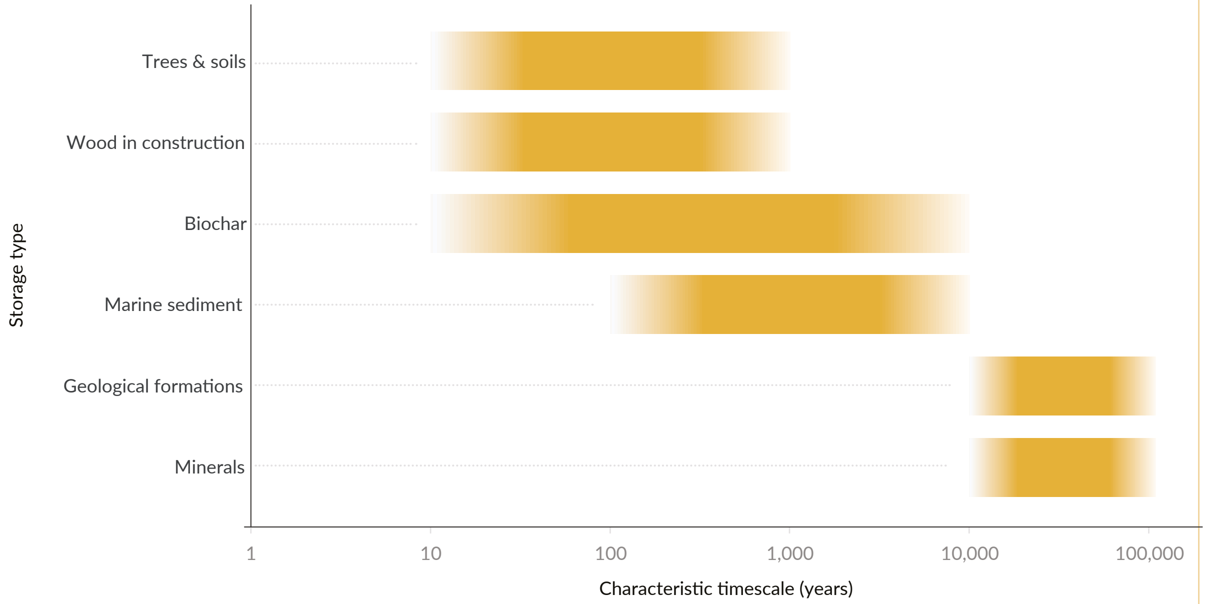


Figure 1.3. *The durability of different carbon storage pools ranges from decades to tens of millennia. Note that these timescales are indicative, assuming no premature disturbance. Source: IPCC WG3 AR6 Chapters 7 & 12*[13,19].

In this assessment we define durability based on the characteristic timescale of the storage pool used. We count a method as CDR if the characteristic timescale of storage is on the order of decades or more.

1.5 CDR methods in this assessment

What counts as CDR will continue to evolve as methods develop, research continues and key definitions are agreed.

The variety of capture and conversion processes and storage options means there are many different potential CDR methods. Table 1.1 provides a list of methods based largely on the research literature summarised by the most recent IPCC assessment[13]. As well as providing the method names we use throughout the report, the table summarises the specific route through the carbon cycle that each method employs; its stage of development (or Technology Readiness Level, TRL); its estimated costs at scale; its mitigation potential (the maximum potential to both remove atmospheric CO_2 and displace emissions in 2050 – by replacing emissions-intensive products and processes – considering biophysical and technological limits but not economic, environmental, socio-cultural or institutional constraints); its key potential hazards and co-benefits; and the feasibility of monitoring, reporting and verification (MRV). Based on this review of the research literature, aspects of many CDR methods are highly uncertain. This is particularly true for the mitigation potential and costs of methods at lower TRLs, as illustrated by the wide ranges provided in Table 1.1. Furthermore, MRV of the net carbon removal can be challenging, and hazards and co-benefits can be highly context-specific, particularly for methods involving the land and ocean.

We use this set of CDR methods as a template throughout the assessment, but two caveats should be kept in mind:

- While based on a comprehensive survey of the scientific literature, it is not a fully complete set, even in the present day. For instance, in our analysis of innovation (Chapter 3) and deployment (Chapter 6) we note the use of an additional method, converting biomass to bio-oil injected into geological storage. Over time, we expect more CDR methods to develop.

- Not all the analyses we draw from include all these methods on a consistent basis. For instance, the methods used to analyse innovations (Chapter 3) focus on components such as Direct Air Capture, rather than on full CDR systems. This reflects the current lack of consistent approaches across the expert community. In the chapters that follow, we make clear which are included.

Given the number of CDR methods, they are often grouped into categories for ease of reference. A common grouping is between "natural" methods and those that are "technological" or "engineered"[20] This categorisation is contested, however, and blurred (a third "hybrid" category is frequently employed to cover methods in between)[21]. Methods which protect, restore or manage ecosystems while delivering other benefits are termed "nature-based solutions" by some[22], while methods which involve a variety of biomass uses coupled to durable storage have been called "biomass carbon removal and storage (BiCRS)" by others[23]. There are a variety of ways in which CDR methods can be grouped, and no single agreed way – indeed, different groupings may be useful in different contexts.

In this assessment we refer to individual methods, where possible, or group them by common measurable properties if necessary. In comparing current CDR deployment with future commitments and scenarios, we group CDR methods into two broad categories, "conventional CDR on land" and "novel CDR". This is based on a combination of their current level of readiness, the scale at which they are currently deployed, and the type of carbon storage they employ:

Conventional CDR on land: Methods that both capture and store carbon in the land reservoir. They are well-established practices already deployed at scale (TRL 8–9) and widely reported by countries as part of their Land Use, Land Use Change and Forestry (LULUCF) activities. The methods we include in this group are: afforestation/reforestation; soil carbon in croplands and grasslands; peatland and wetland restoration; agroforestry; improved forest management; and durable Harvested Wood Products. While the latter stores carbon in the product reservoir, we include it here because it is already deployed at scale and the carbon remains as biomass.

Novel CDR: All other methods, storing captured carbon in the lithosphere (geological formations), ocean or products. Generally at a TRL below 8–9, these methods are currently deployed at smaller scales (see Chapter 6 – Deployment). Examples include BECCS, Direct Air Carbon Capture and Storage (DACCS), biochar and ocean alkalinisation.

In future assessments we aim to improve the consistency of categorising methods and incorporate new methods as they develop.

Table 1.1. *Summary of Carbon Dioxide Removal (CDR) methods, the route through the carbon cycle that they employ, their Technology Readiness Level (TRL), their cost and global mitigation potential estimated for 2050, their key hazards and co-benefits, and the feasibility of monitoring, reporting and verification (MRV) of net carbon dioxide removal. TRL ranges from 1 for a technology which exists only in terms of basic outlined principles to 9 for operationally proven systems. Costs at scale and mitigation potentials are judgements based on the literature; these are particularly uncertain for methods with a TRL around 7 and below. MRV is assessed for both capture and storage steps, scoring the simplicity/precision of quantifying the amount of carbon removed (low/med/high/v high, based on author judgement) and the existence or not of an MRV methodology in the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories (yes/no). Hazards and co-benefits listed here are not exhaustive and are often context specific. Sources: 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories[14]; IPCC WG3 AR6 Chapter 12, Table 12.6[13], which presents the synthesis of available literature by the IPCC authors at the time of preparation of their report, in 2021.*

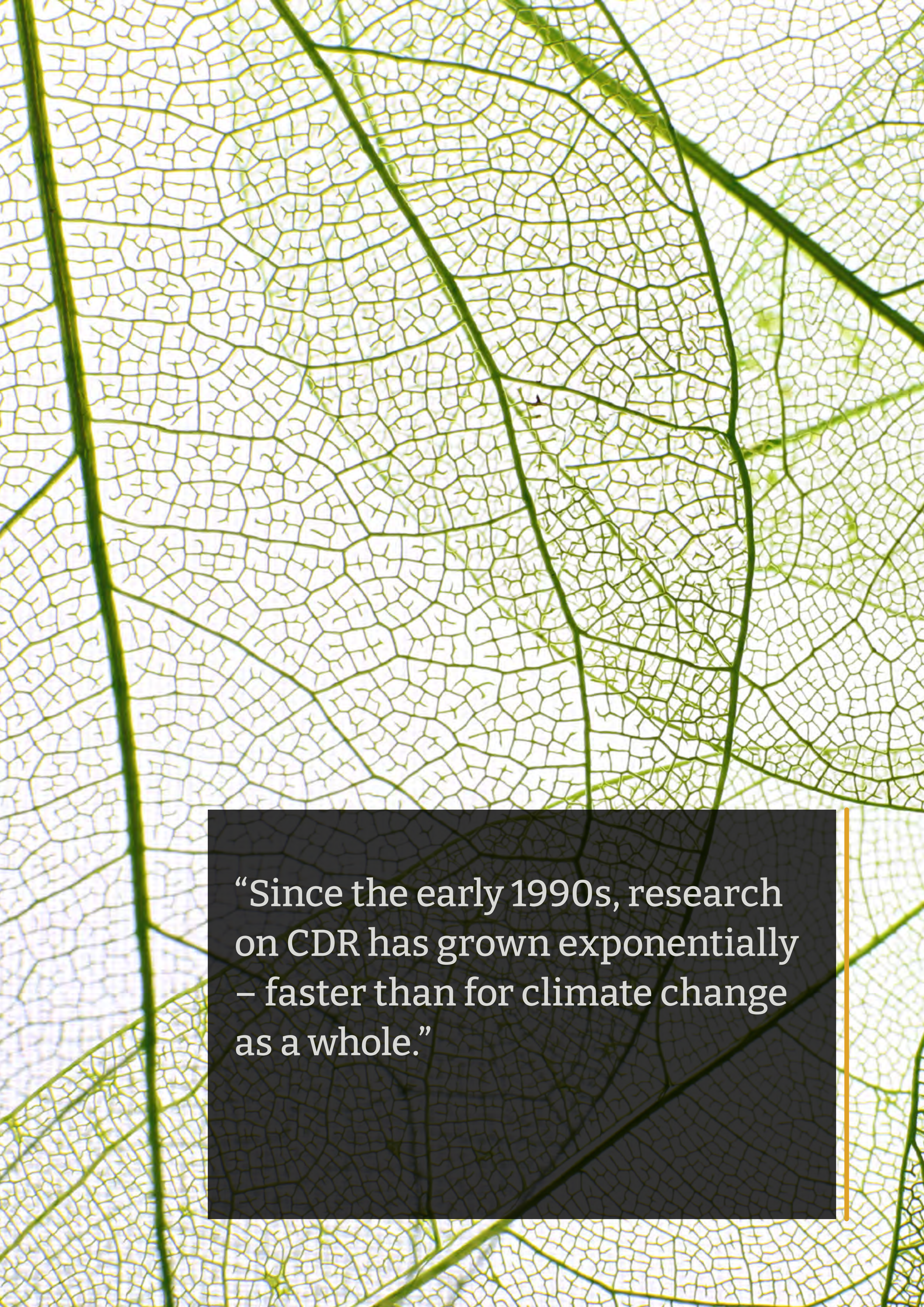
Method	Route of CDR*	TRL	Cost at scale ($/tCO$_2$)	Mitigation potential (GtCO$_2$/yr)	MRV	Example hazards	Example co-benefits
DACCS (Direct Air Carbon Capture and Storage)	(Chemical capture via solid sorbent or liquid solvent) -> (Concentrated CO$_2$ stream) -> (Storage in lithosphere)	6	100 - 300	5-40	Capture: v high, no Storage: high, yes	Increased energy use can lead to greenhouse gas emissions or competition for renewable energy. Increased water use with some options.	Water produced (solid sorbent Direct Air Capture designs only).
Enhanced rock weathering	(Geochemical capture via spreading crushed silicate rocks on land or ocean) -> (Storage in minerals or as bicarbonate)	3-4	50 - 200	2-4	Capture: low, no Storage: low, no	Mining impacts; air quality impacts of rock dust when spreading on land. Heavy metal contamination, especially nickel and chromium, from some rock types.	Reduced soil acidity and increased nutrient supply, which can enhance plant growth and soil carbon sequestration.
Ocean alkalinisation	(Geochemical capture via adding alkaline materials to the ocean such as silicate or carbonate rocks) -> (Storage in minerals or as bicarbonate)	1-2	40 - 260	1-100	Capture: low, no Storage: low, no	Increased seawater pH and saturation states may have local adverse impacts on marine biota. Possible release of nutritive or toxic elements and compounds may perturb marine ecosystems. Mining impacts.	Reduced ocean acidification can benefit biodiversity, especially corals and crustaceans.
Ocean fertilisation	(Biological capture via fertilisation or enhanced upwelling) -> (Storage in marine sediment)	1-2	50 - 500	1-3	Capture: low, no Storage: low, no	Nutrient redistribution, enhanced oxygen consumption and acidification in deeper waters could perturb marine ecosystems. Could encourage toxic algae. The fraction of removed CO$_2$ reaching durable storage is uncertain, due to re-metabolisation.	Enhanced biological productivity, which could increase fish catch.
Coastal wetland (blue carbon) management	(Biological capture via aquatic biomass) -> (Storage in aquatic biomass)	2-3	Insufficient data	<1	Capture: low, no Storage: med, no	Vulnerable to reversal through sea level rise. Difficult to quantify CDR accurately.	Can contribute to ecosystem-based adaptation, coastal protection, increased biodiversity. Can reduce methane emissions. Could benefit human nutrition or be used to produce fertiliser for agriculture, to produce a methane-reducing feed additive, or as an industrial feedstock.

BECCS (Bioenergy with Carbon Capture and Storage)	(Biological capture via plant growth -> cropping and forestry residues, organic wastes, or purpose-grown crops) -> (Concentrated CO_2) -> (Storage in lithosphere)	5-6	15 - 400	0.5-11	Capture: high, yes Storage: high, yes	Competition for land and water resources, if based on purpose-grown biomass feedstock. Loss of biodiversity, carbon stock and soil fertility if from unsustainable biomass harvest. Use of potentially contaminated biomass residues (such as post-consumer wood waste) can pose air pollution risks.	Bioenergy (bio-electricity, biofuel, biogas) displaces fossil fuels and enhances fuel security. Reduction in air pollution when engineered BECCS facilities displace in-field biomass burning. Utilisation of residues provides additional income and can improve crop growth and health. Purpose-grown biomass crops can enhance biodiversity, soil health, water quality and land carbon.
Afforestation/ Reforestation	(Biological capture via trees) -> (Storage in trees)	8-9	0 - 240	0.5-10	Capture: high, yes Storage: high, yes	Reversal of CDR through wildfire, disease, pests. Reduced catchment water yield and lower groundwater level if species and biome are inappropriate. Finite carbon carrying capacity of land; capacity may be reduced under climate change.	Enhanced employment and local livelihoods, improved biodiversity, improved renewable wood products provision, soil carbon and nutrient cycling. Possibly less pressure on primary forest.
Biochar	(Biological capture via cropping and forestry residues, organic wastes, or purpose-grown crops) -> (Storage in biochar)	6-7	10 - 345	0.3-6.6	Capture: high, yes** Storage: med, yes**	Particulate and greenhouse gas emissions from biochar production; biodiversity and carbon stock loss if from unsustainable biomass harvest.	Increased crop yields; reduced non-CO_2 emissions from soil; resilience to drought.
Soil carbon sequestration	(Biological capture via various agricultural practices and pasture management) -> (Storage in soils)	8-9	-45 - 100	0.6-9.3	Capture: med, yes Storage: low, yes	Increased nitrous oxide emissions due to higher levels of organic nitrogen in soil. Finite capacity of soil to protect organic matter; capacity may be reduced under climate change.	Improved soil quality, resilience and agricultural productivity.
Peatland and wetland restoration	(Biological capture via rewetting and revegetation) -> (Storage in soils)	8-9	Insufficient data	0.5-2.1	Capture: low, yes Storage: low, yes	Increased methane emissions.	Increased productivity of fisheries, improved biodiversity, soil carbon and nutrient cycling.
Agroforestry	(Biological capture via trees) -> (Storage in trees)	8-9	Insufficient data	0.3-9.4	Capture: med, yes Storage: med, yes	Trade-offs with agricultural crop production.	Enhanced employment and local livelihoods, variety of products, improved soil quality, more resilient systems.
Durable Harvested Wood Products***	(Biological capture via trees) -> (Storage in wood in construction)	8-9	Insufficient data	0.2-1.3	Capture: high, yes Storage: med, yes	Increased fertiliser use and introduced species could reduce biodiversity and increase eutrophication. Fire risk.	Reduced ecological toxicity, improved human health and wellbeing and reduced duration of construction compared with alternative building materials.
Improved forest management	(Biological capture via trees) -> (Storage in trees)	8-9	Insufficient data	0.1-2.1	Capture: med, yes Storage: med, yes	Increased fertiliser use and introduced species could reduce biodiversity and increase eutrophication.	Improved productivity, enhanced employment and local livelihoods; can enhance biodiversity.

*For each method's route, the ultimate form of carbon storage is colour coded to match the carbon pools in Figure 1.2.

**The Intergovernmental Panel on Climate Change (IPCC) provides a biochar MRV methodology as an option for national inventories.

***Data for wood in construction taken from Himes & Busby. Wood buildings as a climate solution. Developments in the Built Environment 4, 100030 (2020). doi.org/10.1016/j.dibe.2020.100030, and Mishra et al. Land use change and carbon emissions of a transformation to timber cities. Nat Commun 13, 4889 (2022). https://doi.org/10.1038/s41467-022-32244-w



> “Since the early 1990s, research on CDR has grown exponentially – faster than for climate change as a whole.”

Chapter 2 | Research landscape

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Since the early 1990s, research on Carbon Dioxide Removal has grown exponentially – faster than for climate change as a whole. Most of this rapid growth has been driven by biochar research.

Box 2.1 Key findings

- There is a vast and fast-growing scientific literature on Carbon Dioxide Removal (CDR) of about 28,000 studies in Web of Science and Scopus alone – two of the largest English-language bibliographic databases.

- Studies on CDR make up less than 4% of the scientific literature on climate change but are growing exponentially by about 19% per year (1990-2021). Annual publications are currently doubling every three to four years.

- Scientific studies on CDR are dominated by biochar, soil carbon sequestration and afforestation/reforestation. Such methods account for about 80% of the CDR methods covered in the scientific literature.

- Research on biochar is growing faster than that of any other CDR method, accounting for about 40% of the coverage on CDR methods in the scientific literature overall and about 50% of the studies published in 2021.

- Bioenergy with Carbon Capture and Storage as well as Direct Air Capture and Direct Air Carbon Capture and Storage receive comparatively little attention in the CDR literature – despite dominating discussions on, respectively, the role of CDR in climate change mitigation scenarios and private CDR investment.

- Only about a third of the scientific literature on CDR has a geographical focus, highlighting a potential lack of information tailored to specific local or regional contexts, particularly Africa and South America.

- Based on first author affiliation, 32% of scientific studies on CDR are written in China, 9% in the United States and 4% in Australia. This is particularly driven by a strong dominance of biochar research in China.

- The scientific literature on CDR is mainly published in natural science (49%), agricultural science (25%) and engineering and technology journals (23%). Only 3% is published in social science journals, and a handful in the humanities.

2.1 Overall scientific attention

The scientific literature on Carbon Dioxide Removal (CDR) is small compared with climate change as a whole, but growing faster.

A key indicator of the state of CDR is how much scientific research is being carried out. In this chapter, we use a machine-learning approach to identify, track and analyse the scientific literature published on CDR since the early 1990s (Box 2.2). We find a dynamic picture of the level of scientific attention on CDR over time, both as a general topic and at the level of individual CDR methods.

Box 2.2 Our methods for tracking scientific research on CDR

We use a machine learning-based approach to measure attention to CDR in the scientific literature[24–27].

First, we design combinations of search terms ("search strings") for each CDR method based on a comprehensive list of keywords. We then validate the search strings against a set of studies included in the Intergovernmental Panel on Climate Change's Sixth Assessment Report, ensuring that these studies are returned. These search strings retrieve a total of 60,000 records from two large bibliographic databases: the Web of Science and Scopus. We then manually screen the title, abstract and keywords of 400-600 records per search string and label them with their suitability for inclusion (relevant/irrelevant) and the specific CDR method being studied. In total, we labelled 5,600 documents. Finally, we use this labelled data to train a state-of-the-art machine-learning classifier[28] to predict relevance for inclusion and the specific CDR method for the 56,000 remaining records. Our automated approach enables a comprehensive search for scientific literature in bibliographic databases while still ensuring a high level of precision in terms of the identification of relevant studies.

While the machine-learning methodology allows a more comprehensive assessment of the state of scientific research on CDR than has previously been possible, the analysis presented here has important limitations. First, our use of two major bibliographic databases (Web of Science and Scopus) covers most peer-reviewed literature, including social science studies, but excludes large parts of the non-peer-reviewed literature. Second, the search methodology is limited to returning articles with English-language abstracts. Third, we include not only studies on Direct Air Carbon Capture and Storage but also studies on Direct Air Capture without knowing about the fate of the captured CO_2. Hence, some of those Direct Air Capture studies might not count as CDR, as we define it in this report (see Chapter 1 – Introduction).

By the end of 2021, there were about 28,000 English-language scientific studies on CDR in the Web of Science and Scopus – the two largest commercial bibliographic databases. This is a vast number of publications and a much larger figure than previously indicated in the scientific discussion or any ongoing community effort to track CDR research[29,30]. Based on estimates that the Web of Science covers about 43% of the entire scientific literature[31], and assuming that this share is representative also for the literature on CDR, there could be about 50,000 English-language studies on CDR overall.

The total number of studies on CDR makes up less than 4% of the scientific literature on climate change[26,32,33], but growth has been very rapid. Since the early 1990s, the number of studies on CDR has grown exponentially by about 19% per year – faster than the literature on climate change (13% per year). Right now, the number of annual publications doubles every three to four years. This growth started from a very low level, however: in the 1990s, publications per year reached no more than a few dozen, while almost 4,700 papers on CDR were published in 2021 alone.

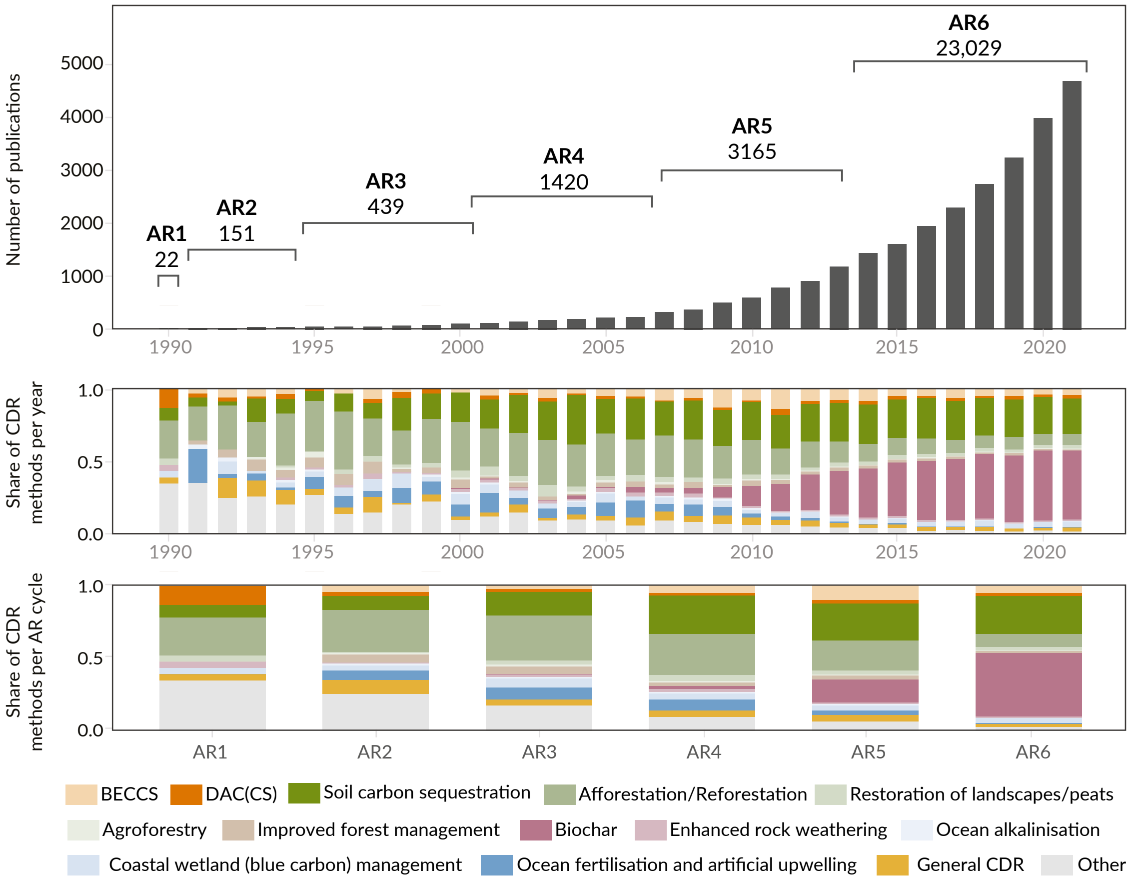

Figure 2.1. *Exponential growth in the scientific literature on Carbon Dioxide Removal (CDR) over time. Total number of scientific publications on CDR per year from 1990 to 2021 in the Web of Science and Scopus (top panel). Share of CDR methods covered in these scientific publications per year (middle panel). Share of CDR methods covered in scientific publications released during each Assessment Report (AR) cycle of the Intergovernmental Panel on Climate Change (bottom panel). Definitions: Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture (DAC) and Direct Air Carbon Capture and Storage (DACCS).*

The analysis presented above does not include scientific publications on Carbon Capture and Storage (CCS) nor on biomass harvested for energy without CCS – as these do not, on their own, count as CDR (see Chapter 1 – Introduction, Box 1.2). The growth rate of the CCS literature, however, provides an interesting contrast with that of CDR (see Box 2.3).

Box 2.3 Tracking scientific literature on Carbon Capture and Storage

While fossil Carbon Capture and Storage (CCS) does not count as CDR (see Chapter 1 – Introduction, Box 1.2), it is still instructive to also track the literature on CCS, as many critical aspects of CCS are not comprehensively discussed in the dedicated CDR literature.

We find approximately 16,000 scientific publications on CCS in the Web of Science and Scopus overall (see Box 2.2), with a notably different growth pattern to that of CDR and the different CDR methods. The literature base on CCS grew steadily during the 2000s, peaking at about 1,500 publications annually in 2017. Annual publications subsequently declined to about 900–1,300 publications in subsequent years. Compared with total publications on CDR, as well as the climate change literature as a whole, there appears to be a recent levelling out of scientific literature dedicated to CCS. This is despite the strong reliance on CCS in climate change mitigation scenarios that are consistent with meeting the Paris temperature goal[34–36] (see Chapter 7 – Scenarios).

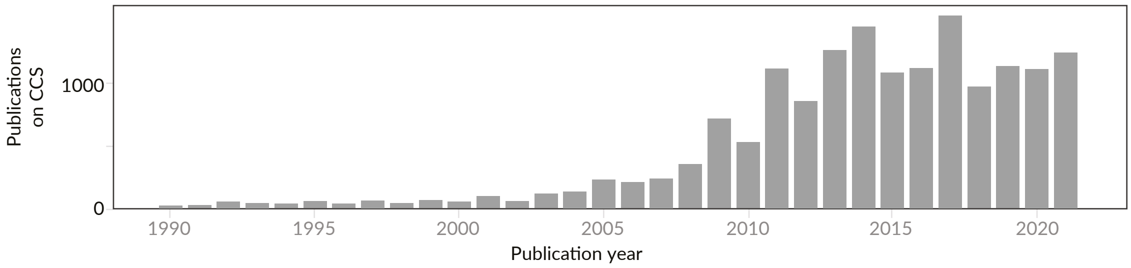

Figure 2.2. *Total number of publications on Carbon Capture and Storage (CCS) per year from 1990 to 2021. Growth in the scientific literature on CCS appeared to peak in 2017 with around 1,500 publications per year.*

2.2 Individual CDR methods, geographical focus and scientific disciplines

Scientific studies on CDR are concentrated on particular methods and regions, with others receiving little attention. Natural science and engineering perspectives heavily dominate over the social sciences.

Individual CDR methods

Biochar accounts for almost 40% of the coverage on CDR methods in the approximately 28,000 scientific publications on CDR (Figure 2.1). Biochar is material made from harvested biomass that has removed CO_2 from the atmosphere during plant growth and has been pyrolysed (heated in an oxygen-limited environment), with a portion of the CO_2 being locked into the char.

There is also a sizeable scientific literature on soil carbon sequestration (accounting for 26% of the coverage on CDR methods) and afforestation/reforestation (12%). Bioenergy with Carbon Capture and Storage (BECCS) represents only about 5% of the CDR methods covered in the scientific literature, despite being the dominant novel CDR method in most scenario pathways for meeting the Paris temperature goal[4,37,38] (see Chapter 7 – Scenarios) and having received considerable space in high-level editorials and commentaries on CDR[39–41]. Three per cent is on coastal wetland (blue carbon) management. Direct Air Capture (DAC) and Direct Air Carbon Capture and Storage (DACCS), which have received a lot of attention in the CDR innovation and investment space, only make up about 2% of the CDR methods covered in the scientific literature. There are several hundred studies on peatland and wetland restoration (2%), ocean fertilisation (1%), enhanced rock weathering (1%) and improved forest management (1%). Scientific literature on ocean alkalinisation and agroforestry in the context of CDR is still in its infancy, with about 100–200 studies each. There are about 1,000 studies (3%) dealing with CDR in a generic sense, without focusing on a specific method.

During most of the 2000s, only 3-5% of the discussion of CDR methods was on biochar. But over the last decade (2011-2021), biochar research grew by about 32% annually – faster than any other CDR method and than the average growth across all methods (19% per year). In 2021, biochar accounted for about 50% of the CDR methods covered in the scientific literature (2,900 studies) – most of these being laboratory studies or field experiments. Growth in the literature on other CDR methods has been more moderate. Research on coastal wetland (blue carbon) management, enhanced rock weathering and soil carbon sequestration has grown by about 25%, 23% and 21% per year, respectively. The remaining CDR methods have developed slower than the average growth in scientific publications on CDR as a whole: research on DAC(CS) by 14% per year and on BECCS by 6% per year.

Geographical focus

Research on CDR that is specific to a geographical location (place-specific) is important as it can consider the local circumstances that determine the efficacy of CDR methods; their potential co-benefits and adverse side effects; and their equitable implementation, operation and governance. However, less than a third of the English-language scientific publications on CDR covered here (8,900 out of 28,000 studies) mention a location in the title or abstract. Of those 8,900 studies, 69% mention national-level locations and about 30% subnational locations. Few studies mention broader regions or continents in their abstracts (Figure 2.3). The distribution of study locations mentioned is very uneven across major world regions (Figure 2.4). More than 40% of all place-specific CDR research refers to locations in Asia (~3,700 studies), 24% in North America (~2,100 studies) and about 18% in Europe (~1,600 studies). Only 5-6% of place-specific CDR research focuses on South America, Oceania and Africa (~500 studies or fewer). This indicates that there is a potential gap in site-specific knowledge with respect to CDR methods in Africa and South America – despite their importance for carbon storage from land-use change and the provision of biomass for various CDR pathways in global integrated assessment models[42,43].

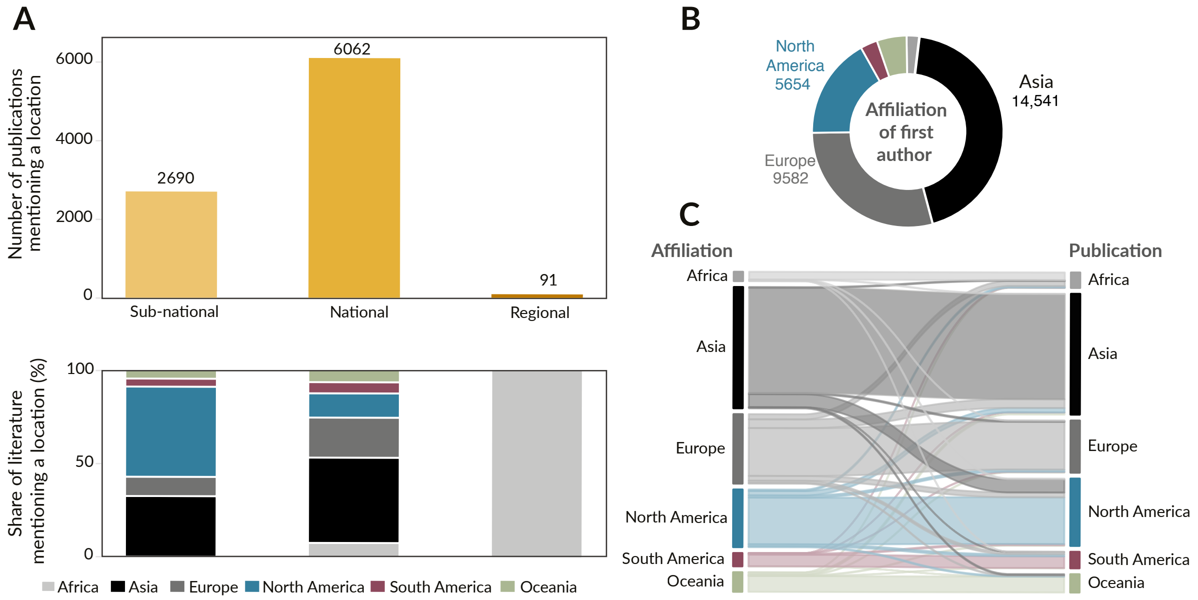

Figure 2.3. *Geographical locations mentioned in the abstract and/or title of Carbon Dioxide Removal (CDR) research publications, shown by level of analysis (subnational, national or regional – for example, Western Africa, North Africa) and by world region (panel A top and bottom, respectively). Continent in which CDR research is produced, derived from the first author's affiliation (panel B). How geographical locations mentioned in the abstract/title of a CDR research publication are related to the first author affiliation (panel C).*

The geographical focus of place-based CDR research also differs strongly for different CDR methods. The vast majority of place-based CDR research is on CDR methods involving biological storage on land or in biochar – soil carbon sequestration (32%), biochar (24%) and afforestation/reforestation (20%) together make up more than three-quarters of place-specific CDR research. Other CDR methods such as DAC(CS) (1%; ~40 studies) feature only marginally, partly because the overall size of the scientific literature on these methods is much smaller.

In general, CDR methods that involve biological storage on land are much more likely to feature place-specific research. For example, about 50% of studies on afforestation/reforestation have an explicit geographical focus. In contrast, only about 6% of scientific studies on DAC(CS) have a specific regional focus. About a quarter of all research on enhanced rock weathering is place-specific, while this is the case for only 8% of studies on ocean alkalinisation. This may be primarily due to institutional challenges involved in setting up experimental research in the ocean.

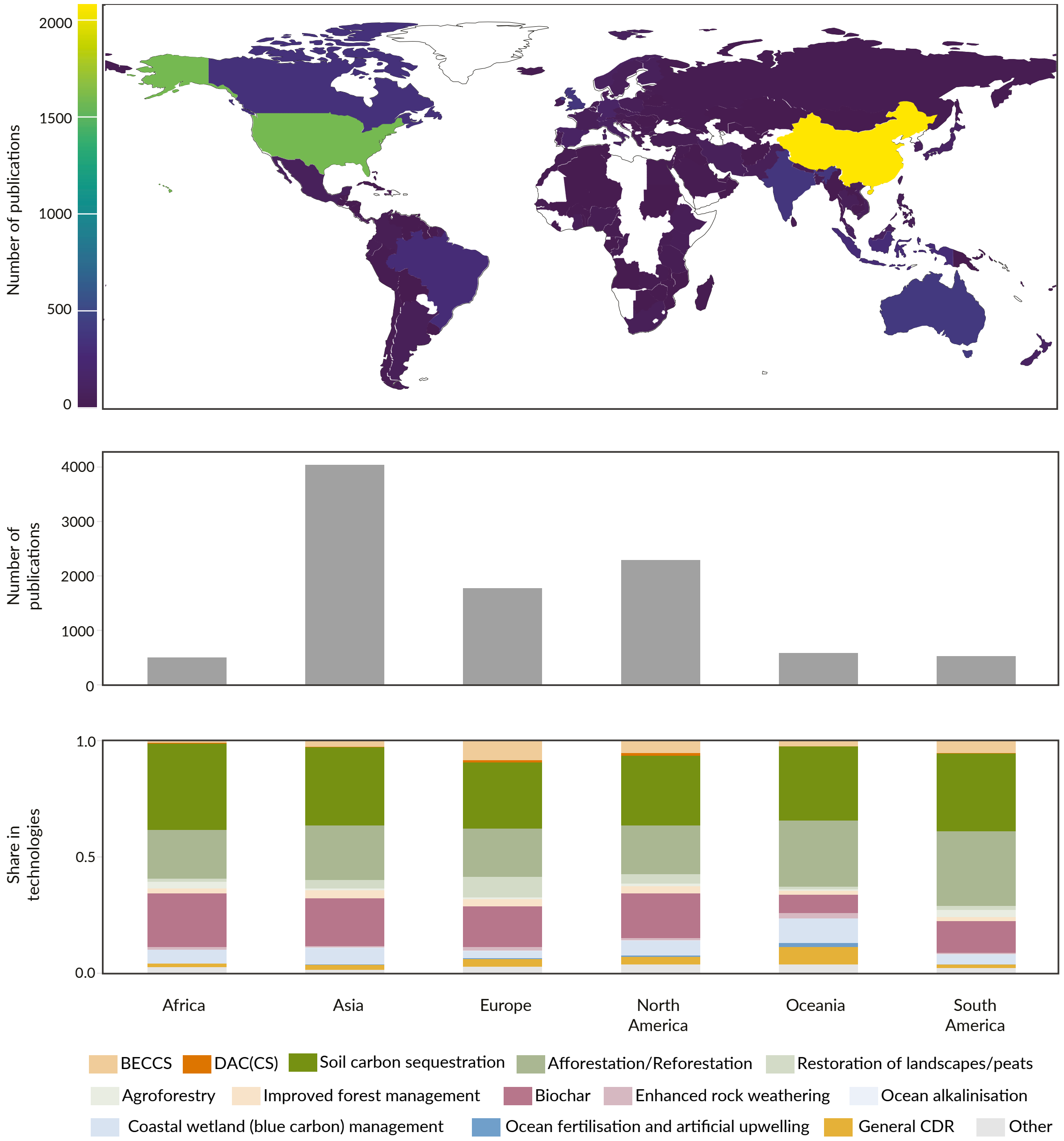

Figure 2.4. *The distribution of place-based Carbon Dioxide Removal (CDR) research is very uneven across major global regions. Total number of CDR research publications that mention a geographic location in abstract or title, shown by country (top) and world region (middle). Share of CDR methods in scientific research publication that refer to a specific geographic location, shown by world region (bottom). Definitions: Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture (DAC) and Direct Air Carbon Capture and Storage (DACCS).*

Analysing the affiliations of the (first) authors of English-language peer-reviewed research on CDR, we find that Asia – and in particular China – is a hotspot in terms of producing CDR research. This is mainly driven by high levels of research activity on conventional CDR methods on land, as well as biochar. Overall, there are about 8,900 publications on CDR for which the first author's affiliation is in China, followed by the United States (2,600) and Australia (1,200). This finding is particularly driven by a strong dominance of biochar research in China. This is also reflected when looking at research organisations. Of the research organisations with the largest numbers of first-authored publications on CDR, nine of the top ten are in China.

In general, place-based CDR research is led by research teams from the country under investigation. Studies led by European research organisations are the most likely to cover regions outside Europe (28% of their total publications), while research organisations based in Asia dedicate a smaller fraction of their CDR research to other regions (13%).

Scientific disciplines

About half the CDR research is taking place in the domain of the natural sciences. About 49% of the scientific discussion around CDR is published in academic outlets that classify themselves as natural science journals. These also include a range of interdisciplinary journals such as *Science* or *Nature*. Two other scientific domains attract substantive CDR research: about 25% of research papers are published in agricultural science journals and 22% in journals on engineering and technology. This highlights the focus of the CDR research community to date on studying the workings of individual CDR methods.

So far, only a very small share (~3%) of CDR studies are published in social science journals, and there are only a handful of studies in humanities journals. The social sciences and humanities are crucial for discussions on implementation, equity and governance of CDR, but scientific discussion in the English-language peer-reviewed literature is not yet fully developed in these areas[29].

2.3 Building understanding

Closing the evidence gap requires research on CDR methods where it is missing or scarce as well as improvement in our understanding of local and regional aspects of deploying and upscaling CDR.

There are very large differences in scientific attention to different CDR methods. While there is a very large amount of evidence on certain CDR methods, such as biochar or soil carbon sequestration, a range of other CDR methods are still the subject of relatively few studies, such as peatland and wetland restoration, ocean alkalinization and DAC(CS). This suggests great differences in the detailed understanding of the various CDR methods, which needs to be addressed for a sound understanding of the entire portfolio of CDR methods.

Critically, place-specific research on CDR is still underdeveloped for almost all novel CDR methods except biochar. Regional and local circumstances will determine the costs, mitigation potentials and side effects of specific CDR methods and also relate to important governance aspects. Place-specific research will be critical for advancing scientific evidence on CDR, notably in regions that are typically projected to provide substantial deployments of specific CDR methods in global mitigation pathways that limit warming to well below 2°C[37]. Finally, only a very small share of research is published in social science journals – and almost none in the humanities. This is an indication that CDR research still mainly focuses on the development and application of CDR methods. There is a need within the scientific community to give more attention to issues around policy, governance and equity.

Our results suggest that the size of the literature on CDR – already vast and fast-growing – may make it difficult to keep an overview of developments in research. This suggests the need for tracking CDR research in quasi real time. Moreover, there is a growing need for this evidence to be continuously synthesised and presented in an accessible format, requiring rigorous systematic review work to ensure that the best-available CDR knowledge can be considered in science and policy.

> “Public funding, patenting and investment in CDR have expanded dramatically in the past two years.”

Chapter 3 | Innovation

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Growing public funding, patenting and investment show that innovation in Carbon Dioxide Removal is active. But the pace is still modest compared with what is needed to meet industry targets and the Paris temperature goal.

Box 3.1 Key findings

- Global public investment in Carbon Dioxide Removal (CDR) Research, Development and Demonstration (RD&D) was approximately $4.1 billion between 2010 and 2022.
- Public RD&D funding is concentrated in a few regions. Proposed Direct Air Capture (DAC) demonstration hubs in the United States account for the vast majority of traceable public funding ($3.5 billion).
- Global CDR patenting activity has increased over the last 15 years, with a large and growing share occurring in China. In 2018 – the last year of complete data – China accounted for 36% of all CDR patents.
- DAC (a component of Direct Air Carbon Capture and Storage, DACCS) is dominant in the share of total CDR patents from 2000 to 2018. Ocean-based methods make up only a small portion of total CDR patents. The technological focus of patents has become more diverse in recent years.
- Investment in new CDR capacity totalled approximately $200 million between 2020 and 2022. The vast majority of announced purchases focus on DACCS, with biochar the next most prominent method.

3.1 Measuring growth in Carbon Dioxide Removal innovation

Innovation in Carbon Dioxide Removal (CDR) has expanded dramatically in the past two years, as measured by publicly funded Research, Development and Demonstration (RD&D), patents and investment in new capacity.

Examining innovation is important because it provides an understanding of how CDR methods are evolving, how fast they might become deployed and how costs are changing. Innovation requires multiple metrics to assess, given that it consists of a sequence of interlinked processes (Figure 3.1)[5]. This chapter assesses the state of CDR innovation using three sets of metrics[44]: public investment in CDR RD&D; patenting; and investment in new capacity. These indicators assess the rates of change in different stages of the innovation process (Figure 3.1). Public investment in RD&D measures supply factors, particularly early-stage inputs in the RD&D stage of innovation.

Patenting is a measure of inventive activity that relates to supply factors (Research and Development, demonstrations, and scale-up) as well as demand factors such as niche markets and demand pull. Investment in new capacity relates to demand factors (demand pull towards increased adoption while establishing public acceptance). Looking ahead, we examine the future rates of growth in CDR innovation (relating to the scale-up stage) implied by the targets set by companies and industry groups. We note that feedbacks from later stages to earlier ones have been crucial for other technologies (e.g. market experience identifies new directions for development). We expect these feedbacks to also be important for CDR.

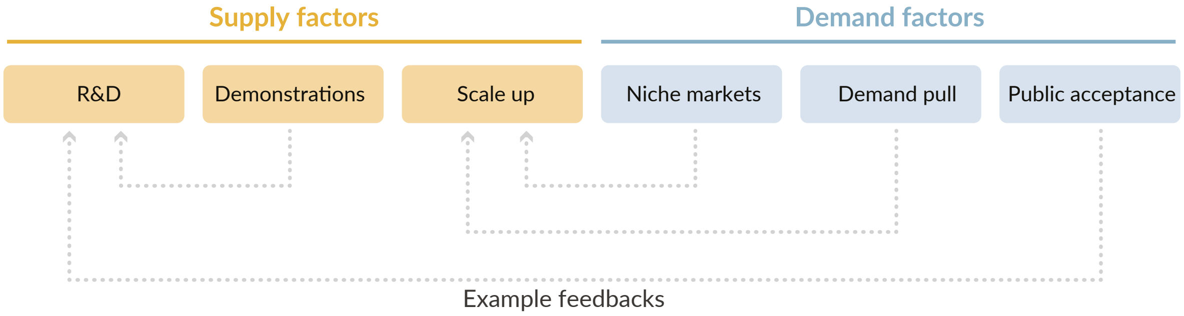

Figure 3.1. *The process of innovation for Carbon Dioxide Removal consists of a sequence of interlinked stages that feed back and build on one another. These stages are broadly split into two categories: supply factors (Research and Development [R&D], demonstrations and scale-up) and demand factors (niche markets, demand pull and public acceptance). Source: Nemet et al.*[5]

Box 3.2 Our methods for assessing growth in Carbon Dioxide Removal innovation

Research, Development and Demonstration (RD&D) – Data on RD&D spending specifically related to Carbon Dioxide Removal (CDR) is patchy, in contrast to other climate change mitigation methods, but it is also similar in that respect to energy RD&D in its early years. We use publicly available data from country plans, policies and announcements that are explicitly labelled as funding research on CDR, greenhouse gas removal or negative emissions methods. We do not include funding for elements that are not CDR methods in themselves but are important components (e.g. Carbon Capture and Storage [CCS] and biomass use). Nor do we include funding which is not labelled as CDR but may still include relevant methods (e.g. tree planting, soil management). Data on public RD&D investment is for 2010-2022. We convert currencies to US dollars for comparison using currency values from the Federal Reserve[45]. For more detail on CDR research directions, refer to Chapter 2 – Research landscape for a summary of the English-language, peer-reviewed scientific literature on CDR.

Patent activity – To measure patent activity for CDR methods and/or components over time and by method we use patent family counts, and to measure country activity we use patent application counts. We use the search methodology from Kang et al. in the Derwent Innovations Index to gather patent data[46]. Patent families avoid double-counting by grouping patents for the same invention that are filed in multiple countries or patent offices. Analysing patent applications, on the other hand, ensures that we account for each of the different countries where patents are filed. We use the patent application date for the time range of 1980-2020, using the search terms from Kang et al. The search terms for Direct Air Capture do not include storage. We do not include patents related to CCS without a CO_2 removal component, even though these patents are related to elements of some CDR methods (such as Direct Air Carbon Capture and Storage and Bioenergy with Carbon Capture and Storage).

Investment in new capacity – We use the Marginal Carbon database, which collects known announced purchases of durable CDR, including the year of purchase and CDR method. The announced purchases are included in the database, and thus in this chapter, if the CO_2 is stored for at least 100 years. For announced purchases without a purchase price, we apply a cost per tonne by method[47]. We assess the cost per tonne from the other announced purchases for each method and year. The database gives an indication of the level and relative share of CDR methods on the market. However, it is not a complete database and includes uncertainties. For example, the database lists “carbon dioxide from concrete” as a CDR method. It is unclear, however, if the CO_2 in this method is from a fossil origin or biogenic origin, which would classify it as fossil CCS rather than CDR (see Chapter 1 – Introduction, Box 1.2). These instances of uncertainty have been included in the total investment calculations to capture the full scope of investments.

Public Research, Development and Demonstration

Research, Development and Demonstration that is funded by the public sector (public RD&D) provides important information on where early-stage development is being directed and where gaps exist[45]. While public RD&D is typically smaller than private RD&D at the economy level, the former can play a much bigger role for nascent technologies and be crucial to entraining the latter[48]. Using publicly available data, we find global public investment in CDR RD&D of approximately $4.1 billion during the period 2010-2022. To put this in perspective, global annual spending on energy RD&D in 2021 alone was $17 billion for Organisation for Economic Co-operation and Development (OECD) countries, which excludes China.

Global public investment in RD&D funding is concentrated in a few regions, and the overwhelming majority of the total is $3.5 billion for Direct Air Capture (DAC) hubs in the US, spread over multiple years. This demonstration programme is open to projects that utilise or store the captured CO_2. While not all the CO_2 captured is therefore likely to be durably stored, we include this programme within our analysis of innovation because demonstration of the DAC components advances the Direct Air Carbon Capture and Storage (DACCS) method as a whole.

Below, we summarise the diverse sets of CDR activities covered by public RD&D funding in eight countries and regions that have accessible information on public CDR RD&D – either data on public RD&D funding or net zero targets that will require CDR. We have not found

RD&D programmes specifically labelled as CDR in the rest of the world. We are aware, however, that there is further public RD&D investment in programmes that incorporate CDR methods but that are not labelled as such, for example European Union (EU) funding for research into CDR from agricultural/forestry management practices[48,49]. Like other areas of science and technology, publicly funded RD&D is overwhelmingly concentrated in high-income economies, although other countries may have unique characteristics that make them well suited for conducting CDR research (such as energy sources and local climate) in the future. Financial flows and technology transfer between countries can aid CDR innovation beyond the countries described below[1].

Australia

In 2021, the Australian government funded an A$4 million (US$2.5 million) DACCS demonstration project[50]. Although the government has funded several Carbon Capture and Utilisation projects, no large-scale funding for CDR has yet been announced.

Canada

Canada has committed to achieving net-zero greenhouse gas (GHG) emissions by 2050 through the Canadian Net-Zero Emissions Accountability Act[51]. While Canada has invested in RD&D for Carbon Capture and Utilisation and low-carbon technologies, the federal government has not yet announced investments explicitly for CDR. The Net Zero Accelerator Initiative and the Climate Action and Awareness Fund may both fund CDR research in the future[52,53].

China

China has established a target of carbon neutrality by 2060 that will require CDR methods[54]. Total investment from the Chinese government in 2018 on forestry and grasslands totalled about ¥140 billion ($21 billion), although only a portion of this funding is specifically focused on carbon storage via biological methods[55]. Data on total RD&D expenditures for CDR in China is not publicly available.

European Union

The European Climate Law includes a target for climate neutrality[56]. In April 2022, the European Commission announced funding for one Bioenergy with Carbon Capture and Storage (BECCS) project worth €180 million ($180 million) via the EU Innovation Fund, which is funded by revenues from the EU's Emissions Trading System[57]. The second mechanism for funding CDR is Horizon Europe, the EU's programme on research, development and innovation[58]. This supports a variety of CDR methods. An analysis from Carbon Gap, an environmental NGO, estimates that funding from Horizon Europe will be €185 million for activities both directly and indirectly related to CDR (funding 34 projects) and €161 million for projects directly related to CDR (funding 28 projects)[59]. The Horizon Europe programme includes funding for projects specifically on RD&D under the Climate, Energy and Mobility cluster: on CDR approaches (€21 million) as of 2021 and on Negative Emissions as of 2020[57,58].

Germany

Since 2021, the German Federal Ministry of Education and Research has funded two major research missions: one on ocean-based CDR methods and marine CO_2 storage methods (*CDRmare*) and the other on land-based CDR methods (*CDRterra*). *CDRmare* began funding six projects in 2021 worth a total of €26 million ($26 million)[60]. *CDRterra* began funding projects on DACCS, biochar, enhanced rock weathering, BECCS, and afforestation/reforestation worth a total of €21 million ($21 million)[61].

Japan
The Moonshot Research and Development Program in Japan was developed by the Council for Science, Technology and Innovation and the Headquarters for Healthcare Policy and includes a goal on sustainable resources[62,63]. The purpose of the programme is to promote "challenging R&D based on revolutionary concepts" and includes CDR in the "Moonshot for beyond Zero-Emission Society"[64]. In 2022, a call for proposals for Moonshot funding was announced with a maximum amount per project of ¥500 million ($3.6 million). Japan's Ministry of the Environment also provided funding for a large-scale BECCS plant in 2020[65].

United Kingdom
The UK has invested in RD&D on a wide range of GHG removal technologies – primarily CDR methods but also some methane removal projects. The first GHG removal RD&D programme ran from 2017 to 2021, funding 11 projects totalling £8.6 million ($9.7 million)[66]. The UK Government's Net Zero Strategy, published in 2021, includes CDR deployment goals and two new RD&D programmes focused on demonstration[67]. The first is a pre-commercial innovation competition funded through the Department for Business, Energy and Industrial Strategy[68]. In the first phase, 23 projects focusing on the design and feasibility of CDR methods each received £250,000 (a total of £5.9 million, or $6.7 million). In Phase Two, an additional £58 million ($65 million) will be awarded to pilot the 15 most promising designs (ending March 2025)[69]. Afforestation and other conventional CDR methods on land are excluded from the competition, though their role in meeting the net zero target is recognised. As the second programme, UK Research and Innovation announced over £30 million ($34 million) to investigate the viability of five GHG removal demonstration projects and a central research hub[70]. The projects vary in method and include peatland restoration, enhanced rock weathering, biochar, afforestation, and biomass crops for use in BECCS[71].

United States
In 2021, the US announced a target to achieve net-zero greenhouse gas emissions economy-wide[72]. The US Department of Energy (DOE) launched the Carbon Negative Shot as an RD&D initiative for CDR focused on storing CO_2 at gigatonne scales for less than $100/net tonne[73]. In 2020, the US Congress appropriated $40 million for CDR Research and Development (R&D), of which $15 million was specifically appropriated for DAC[74]. In 2021, $63 million was appropriated for CDR R&D, with $22 million specifically for DAC[75]. In 2021, RD&D projects worth $18 million were announced through the DOE and the Office of Fossil Energy and Carbon Management to fund DAC[74,76]. Congressional appropriation for CDR R&D increased to $104 million in 2022, with $75 million specifically for DAC[77]. In 2022, the DOE announced $3.5 billion in funding under the Bipartisan Infrastructure Law's programme on CDR to develop the Regional Direct Air Capture Hubs programme to support four DAC hubs[75]. As a part of the Carbon Negative Shot initiative, the DOE announced $30 million to fund RD&D on DAC and ocean-based CDR methods that include "permanent storage or utilization"[78]. Since 2010, the US DOE and the US Department of Agriculture have funded RD&D for land-based CDR totalling about $49 million, through "improved crops for soil carbon sequestration" and biochar research[79]. The National Science Foundation has also funded R&D ocean-based CDR methods, including iron fertilisation[79].

Patenting

Patenting activity can provide a useful measure of innovation by indicating the pace of invention. Inventive activity comes from supply-side RD&D, demonstration and scale-up and can also be supported by demand factors such as niche markets and demand pull. Our examination of CDR patenting activity at the global level suggests an overall increase over the last 15 years, with a large and growing share of patenting occurring in China. The most prominent component in terms of growth in patents is DAC. China is also a hotspot in terms of generating scientific research on CDR – though this is driven particularly by studies on biological CDR methods (see Chapter 2 – Research landscape). Patenting activity is one measure of innovation, and one with accessible data, but innovation can also occur outside of what firms choose to patent. Invention, experimentation and learning can be retained as tacit knowledge and trade secrets. Another alternative is a transparent approach, with inventions published unprotected as research papers (see Chapter 2 – Research landscape) or as freely available data and designs (e.g. OpenAir Collective)[80].

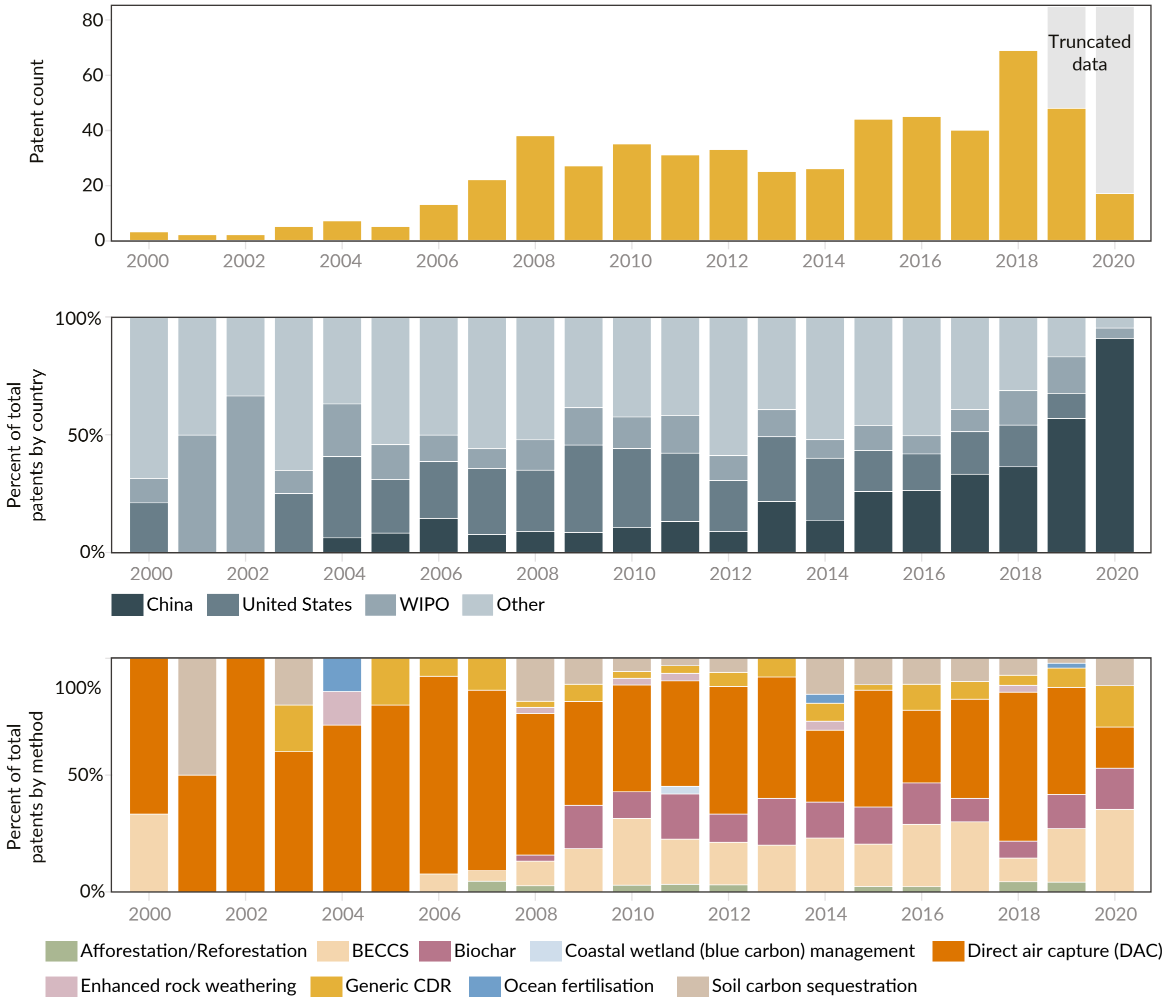

Figure 3.2. *Global increase in Carbon Dioxide Removal (CDR) patenting activity. Total number of patents per year for 2000-2020, grouped by patent families (top). Families refer to the same invention files in multiple countries. In 2019 and 2020, the data is truncated because of the time it takes to process the application before publishing. Percent of individual patent applications per year by the country where the patent was filed (middle). The World Intellectual Property Organization (WIPO) is a centralised patent office. Percent of total patent families per year by method/component (bottom). Definition: Bioenergy with Carbon capture and Storage (BECCS).*

Over the past 20 years, the number of CDR patents has increased (Figure 3.2, top panel). This, in turn, indicates an increase in innovation in CDR. The last year of full data is 2018, whereas 2019 and 2020 data is truncated due to the typical two-year time it takes to review applications.

In terms of distribution of patents between different countries, China has had an increasingly large share of CDR patents since 2004 (Figure 3.2, middle panel). In the last year of complete data (2018), patents filed in China made up 36% of all CDR patents filed. China's share of total patents is very high in the truncated data for 2019 and 2020, which may, at least in part, be a result of a faster time to approval in China's patent offices compared with other countries, such as the US. The US has also had a large share of all CDR patents, accounting for an average of 23% of annual applications from 2000 to 2018. However, from 2015 to 2018, the share of patents filed in the US decreased to 15-20% of annual patent applications, compared to 23-37% from 2003 to 2014. WIPO, the World Intellectual Property Organization, is a centralised patent office where approximately 5-10% of total CDR patents were filed during 2003-2018. In a majority of cases in which a patent was filed with WIPO (88%), the patent was also filed in at least one other country. All other countries are grouped into an "Other" category, which makes up a large portion of total annual patents during 2000-2018 (31-68%, with an average of 48% per year). The patents represented by this category are split between many regions and countries. By 2018, the last year of full data in the analysis, the split is about equal between China (36%), the United States and WIPO (19% and 15%, respectively, for a total of 34%), and all other countries combined (31%).

In terms of CDR method/component technologies, DAC is dominant in the share of total CDR patents during 2000-2018 (Figure 3.2, bottom panel). BECCS made up 33% of CDR patents in 2000, then an average of 18% during 2006-2018. Ocean-based CDR methods make up only a small portion of CDR patents, with 11 patents on ocean-based methods filed sporadically during 2000-2018: coastal wetland (blue carbon) management (one patent), enhanced rock weathering (seven patents) and ocean fertilisation (three patents). Biochar patents began in 2008 and have continued through 2020. We observe a decline in technological concentration in the last few years of the data (i.e. smaller shares for the largest CDR technologies).

Investment in new CDR capacity

The ultimate manifestation of innovation is widespread adoption of a technology. This happens when it is relatively advantageous compared with other technologies, demand pull is sufficient and the technology is publicly accepted. Using the Marginal Carbon database (see Box 3.2 on methods), we find announced purchases totalling approximately $200 million and 510,000 tonnes of CDR for 2020-2022. Some of this is for offtake agreements for future purchases (in which the payment comes at the time of delivery) while some is for pre-purchases, where the tonnes have been paid before the project is complete. This data includes efforts to increase demand for CDR to spur innovation (demand pull) such as the Frontier advance market commitment (a funding mechanism that involves aggregating funding and facilitating purchases of CDR)[81]. Only a small fraction of purchases have actually been delivered to customers, however (see Chapter 6 – Deployment).

The vast majority (75%, worth $150 million) of announced purchases are focused on DACCS. This is largely driven by one announcement from 1PointFive/Carbon Engineering (two companies that work to design and deploy DAC facilities) of 100,000 tonnes per year for four years, with a 2022 average cost per tonne of DACCS of $270. In order of value, following this there are two announced purchases of a combined $6.4 million, which include several CDR methods but do not delineate monetary or tonnage amounts per method. Otherwise, where methods are specified, biochar features as the second most prominent method among announced purchases.

Some method costs per tonne have gone up from 2020 to 2022 (including DACCS: \$780 in 2020 to \$1,200 in 2021; and biochar: \$250 in 2021 to \$430 in 2022). This could be seen as surprising, but the changes are largely driven by single purchases. For example, Shopify purchased 2,500 tonnes of CO_2 removed through biochar for \$570/tonne from one supplier in 2022, driving up the average price. It could also be argued that there are no real market prices for CDR at this early stage. We see that many early backers of novel CDR (by which we mean methods other than the well-established land-based methods already deployed at scale, such as afforestation/reforestation, soil carbon sequestration, etc.; see Chapter 1 – Introduction for our definitions) are paying for the cost of production as a way of supporting early development, rather than buying a commodity at market prices. Diffusion theory and learning rate theories hypothesise that, over time, method costs will decrease as the methods develop and supply increases, but novel CDR methods might not have entered the phase where this starts to happen.

To put this data in perspective, Bloomberg estimates global climate-technology investments (for all mitigation technologies, not just CDR) at \$170 billion in 2021 – of which only \$0.3 billion relates to CDR[82]. That means the size of equity investments in CDR is similar to amounts of pre-purchases and offtake agreements. An additional data source, ClimateTech VC, estimates that the level of CDR equity investments in 2021 was \$170 million, and in 2022 \$830 million, totalling about \$1 billion[83]. Although this data is not directly comparable to announced purchase levels, the data is on the same order of magnitude.

3.2 Future growth targets

The novel CDR industry needs to grow by four to six orders of magnitude by mid-century to meet its own targets and to meet the Paris temperature goal.

We provide an indication of the challenge to scale up CDR by comparing announcements of CDR targets from companies and industry groups with the current size of the industry and with estimates of the CDR potential of different methods by 2050. Mid-century CDR potential is the magnitude of CO_2 that can be removed and durably stored from each CDR method by 2050, while taking into account biophysical limits, economic costs and potential side effects of deployment.

Box 3.3 Our methods for assessing future growth in Carbon Dioxide Removal innovation

Growth rates – We use publicly announced company and industry targets for Carbon Dioxide Removal (CDR) as an indicator for growth in innovation. To calculate company announcements and capacity for Direct Air Capture (DAC) from 2021 to 2035, we combine the announced scale-up targets from Carbon Engineering and Climeworks, two DAC companies[84,85]. Biochar estimates are from the European Biochar Industry Consortium, a biochar industry group[86]. Company announcement targets for Bioenergy with Carbon Capture and Storage (BECCS) scale-up are from Drax Global[87], a UK-based energy company with a BECCS plant, and Stockholm Exergi[88]. These targets are publicly available and, although not comprehensive of all CDR companies or industry groups, illustrate the expectations for direction and scale of the market in the coming decades.

For the mid-century potentials of individual CDR methods (Direct Air Carbon Capture and Storage, BECCS and biochar), we use low and high estimates of sustainable global technology potentials in 2050 from a systematic literature review from Fuss et al[4].

The figure below shows the growth trajectories of three specific CDR methods, incorporating both announced and built capacities from industry and businesses. The shaded areas show how the last year of company capacity announcements compares with the range in the mid-century potential (the low and high data points shown for 2050) for each CDR method[4].

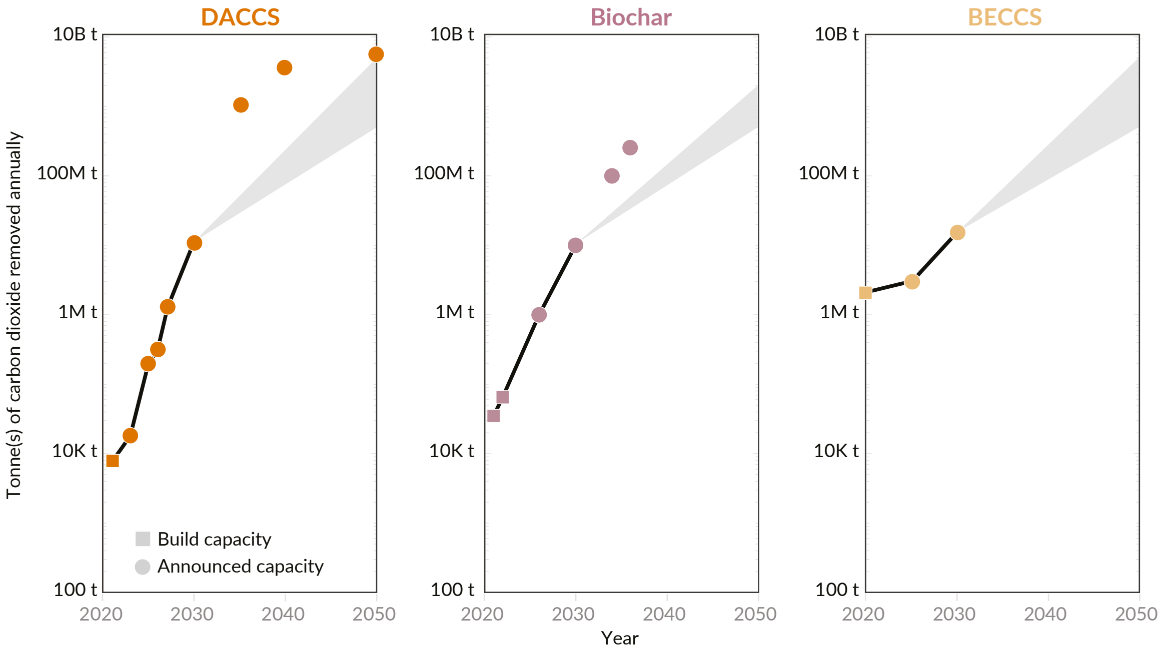

Figure 3.3. *Announced Carbon Dioxide Removal (CDR) targets from industry groups and companies imply faster growth than has been seen historically for most technologies. Squares represent built capacity in three example CDR methods (Direct Air Carbon Capture and Storage [DACCS], biochar and Bioenergy with Carbon Capture and Storage [BECCS]). Circles represent announced plans for capacity additions. The shaded areas for each CDR method show how the last year of company capacity announcements could grow to meet CDR socio-technical potential by mid-century: the low and high data points in 2050 represent the range of maximum potential removal, which is dependent on biophysical limits, economic costs and side effects of deployment.*

The figure suggests that the CDR targets of companies and industry groups are generally aligned with achieving mid-century CDR potentials (see Box 3.3)[4], particularly for DACCS and biochar, because the slopes of the curves for those mid-term targets are steeper than those after. However, the figure also makes clear that the CDR industry is currently five orders of magnitude smaller than those mid-century potentials. In the particular case of DACCS, for example, we assess that in mid-2022 about 8,000 tonnes of annual removal capacity exists[89], compared with a mid-range potential of 2 billion tonnes annually by 2050[4].

Growing from the current level to maximum mid-century potential implies an exponential growth rate of over 50% per year. That exceeds most previous technologies, but not all (such as the production of liberty ships in the United States during World War Two and worldwide computing growth).

3.3 Spurring growth in innovation

There is an urgent need for comprehensive policy support to spur growth in CDR.

To achieve the growth rate in investment in new capacity indicated in our analysis of over 50% per year, there is an urgent need for comprehensive, durable policy support for CDR. Policies can spur growth in the CDR market to achieve mid-century goals for CDR – and these expectations are crucial for private investment in CDR innovation and deployment to reach gigatonne scale. Ensuring that data on CDR RD&D funding, patents and investment in new capacity is comprehensive and publicly available can support the type of policies needed for CDR scale-up.

> “Research shows that people’s initial reactions to CDR are usually tied to their values, beliefs and sense of identity.”

Chapter 4 | Public perceptions

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How Carbon Dioxide Removal (CDR) is perceived will play a critical role in its future prospects. Awareness of CDR is still low in studied countries, but social media attention is growing fast. People are generally supportive of CDR research, but they have more complicated views about deploying it at scale, depending on the specific method.

Box 4.1 Key findings

- A systematic search of the English-language peer-reviewed literature reveals a small but growing evidence base, with 39 papers specifically on public perception of Carbon Dioxide Removal (CDR).
- Only ten of these peer-reviewed publications are from outside of Western Europe and North America, with none covering public views in South America, Eastern Europe or West/Central Asia.
- Among the general public in the countries studied, awareness of CDR (as a general topic and regarding specific CDR methods) is low. Perceptions of this nascent field are still forming.
- Despite low prior awareness, studies find reasonable public support for research into CDR but more concerns about deployment at scale. These involve perceptions of potential adverse side effects and tampering with nature, among many other factors.
- The number of tweets on CDR has grown rapidly over the last decade, increasing from about 15 tweets per day in 2010 to about 350 tweets per day in 2021. This is much less than for climate change in general, at 10,000 tweets per day, but growing faster.
- Of the tweets mentioning specific CDR methods, 70% involve biological storage on land and in oceans, such as soil carbon sequestration, afforestation/reforestation or coastal wetland (blue carbon) management. There are comparatively few mentions of novel CDR methods such as Direct Air Carbon Capture and Storage, but these are growing rapidly.
- Public perception research and analysis of the sentiment of tweets suggest that familiar CDR methods (particularly afforestation/reforestation) are generally preferred, and ocean fertilisation is viewed as most risky.
- Sentiments expressed in tweets on CDR methods have become more positive over time, with the single exception of Bioenergy with Carbon Capture and Storage.

4.1 Understanding public perception

Two different and complementary sources – peer-reviewed scientific literature and Twitter – can offer insights into public perception of Carbon Dioxide Removal (CDR).

If CDR is to scale to several gigatonnes of removals by mid-century, the next two decades will be critical. Alongside progress in developing and deploying the CDR methods themselves, how CDR is perceived will play a vital role. Similarly, attention to CDR in public discourse reflects the salience of the debate in addressing climate change. Studies show that public acceptance of new technologies is crucial to their widespread adoption[5,90–92], meaning that how technology adopters and the wider public perceive different CDR methods will influence the prospects for scaling them up[5,93–95]. Understanding perceptions on and engaging people with CDR, if done well, can support responsible innovation efforts.

There are three broad lines of evidence for gauging people's perceptions: sampling of a large group of people (e.g. surveys or survey experiments); studies that focus on individuals and/or small groups (e.g. interviews or deliberative studies); and big-data analysis of social media (e.g. sentiment analysis or stance detection). In this chapter, we take two complementary approaches to analysing attention to and perceptions of specific CDR methods and of CDR in general: a synthesis of the main insights from the English-language peer-reviewed scientific literature on public perception and an analysis of Twitter activity on the topic over time. While the scientific literature provides very detailed insights into how citizens perceive CDR methods in different contexts, the Twitter analysis indicates how the salience and tone of communication about CDR has changed over time. As such, together these approaches provide complementary lines of evidence on perceptions of CDR.

Box 4.2 Types of evidence for assessing (public) perceptions

Working with multiple types of evidence (such as large sample studies, small group studies, social media analysis) is particularly useful when trying to assess perceptions towards nascent technologies, because each method has specific advantages and limitations and is rooted in its own set of assumptions. Therefore, the context and scope of the results may differ. Survey and participatory methods offer researchers greater control over how and from whom evidence is collected at a particular point in time, while data-driven analyses of social media content allow researchers to track attention to a topic and sentiment towards it continuously over time. Surveys can understand perceptions at the time of the study in relation to a fixed research question, while social media analysis allows continuous adjustment of the scope of the inquiry and re-analysis of historical data accordingly.

Who is "the public"? Different approaches to gauging public perception can define "the public" in different ways, and definitions such as "public" and "stakeholder" are not fixed. People also operate from different positions at different times, for instance acting as "professional" or "civic" actors depending on the context[96]. Survey studies (Section 4.2) often focus on the attitudes or opinions of a representative sample of a general population (for example, using recruitment quotas) but may not capture the diversity of "publics" within that sample. Communication on Twitter (Section 4.3) is dominated by experts, professionals and corporate interests and, as such, may not represent opinions held by the general population.

Elicited versus non-elicited information: The benefit of surveys, experiments or deliberative approaches for eliciting information is that these studies operate within an artificial environment, allowing researchers to control and analyse the context. However, public awareness of many CDR methods is low, which can lead to methodological challenges. For example, participants may need to be presented with a certain amount of information on the topic, on which to base their response. This can lead to responses being influenced by the way the question is presented, known as "framing effects". Nevertheless, a large body of work suggests that, in general, people are competent in their deliberations and are capable of discussing complex and novel topics even with low prior awareness[97]. Analysis of social media is based on non-elicited statements by people who already have an awareness of CDR. People may express their opinion differently online than in more private settings or surveys, however. See Box 4.3 for further discussion of our methodology for social media analysis.

4.2 Scientific evidence on public perceptions

Evidence on how people perceive CDR has large regional disparities, and in studied populations awareness of CDR remains low.

Research on public perceptions of CDR is spread across a wide variety of social science disciplines, each of which carries certain assumptions. For example, there are differences in how researchers understand "the public", which are reflected in the methods used (see Box 4.2). However, most agree that public perceptions of CDR must be understood in relation to broader issues around emerging technologies and the environment. This area of research is partly driven by concerns about potential future public opposition, fuelled by past protests against technologies that CDR sometimes grouped with, such as solar geoengineering methods or Carbon Capture and Storage (CCS)[98].

To understand the existing field of research on public perceptions of CDR, we carried out a systematic search in February 2022 of the English-language academic databases Scopus and Web of Science. A search for papers labelled as "public perceptions", "attitudes" or "opinions" on CDR returned 36 papers[99–114], with a further three new papers added in September 2022[93,115,116]. A large number of studies have been published on perceptions of related techniques, such as CCS, bioenergy, forestry and ecosystem restoration. These were only included in our review if they specifically discussed carbon dioxide *removal*. Thus, for example, CCS of point-source emissions was not included, as it reduces CO_2 rather than removing it. This may exclude a large body of work on carbon sink management, for example forestry programmes such as REDD+ (Reducing emissions from deforestation and forest degradation in developing countries), which may include the perspectives and experiences of "frontline" communities. The literature we reviewed uses a number of methods for understanding public responses to CDR, including large representative surveys, experimental approaches using surveys and questionnaires, and qualitative inquiries such as focus groups, interviews and deliberative workshops. Despite low prior awareness, evidence shows that the general public is very capable of discussing complex and novel topics[97].

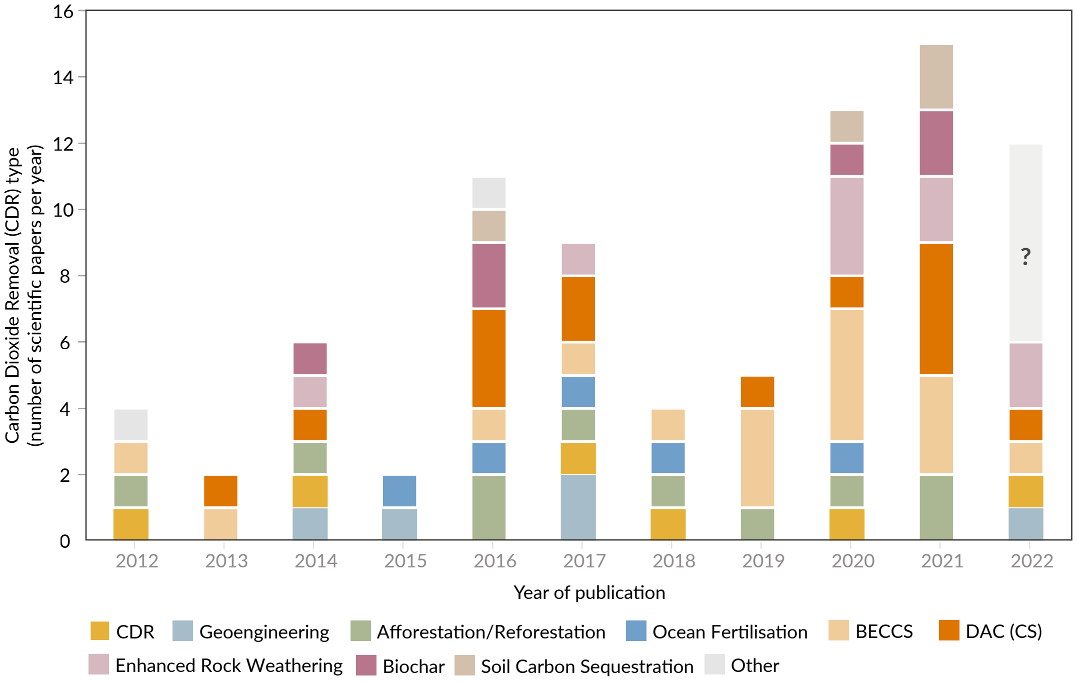

Figure 4.1. *Evidence in the scientific literature on how people perceive Carbon Dioxide Removal (CDR) is growing but still small. The figure shows the number of research papers on public perception of CDR by year and CDR method*[*]*. Total number of publications = 39. Many papers include more than one CDR method, so the total counts of publications across CDR methods in the graph adds up to more than 39. Data for 2022 includes January-September publications only. BECCS = Bioenergy with Carbon Capture and Storage, DACCS = Direct Air Carbon Capture and Storage.*

Our review found large regional disparities in the peer-reviewed research on public perceptions of CDR. Only ten of the papers we reviewed researched public views outside of Western Europe and North America, of which only one was from Africa and two from East Asia; none were from South America, Eastern Europe, or West/Central Asian regions (Figure 4.2). This may be a limitation of our English-language sampling methodology, although some research papers also raise concerns about regional disparities[117,118]. Mitigation pathways that meet the Paris temperature goal, for instance those assessed by the Intergovernmental Panel on Climate Change (IPCC), often include scaling-up of CDR in precisely the regions where scientific literature on public perceptions is absent.

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[*] Studies on “geoengineering” include participant information and/or questions on both CDR and solar radiation management, meaning that CDR is included as a component of “geoengineering”.

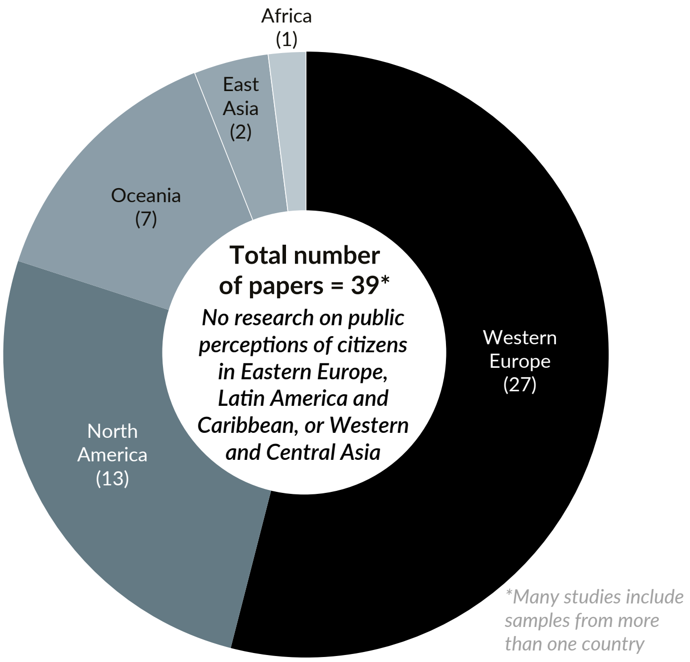

Figure 4.2. *Research on public perceptions of Carbon Dioxide Removal (CDR) shows large regional disparities, with only a small proportion of studies from outside Western Europe and North America.*

Public awareness of CDR

The scientific literature on public perceptions consistently finds low levels of awareness and knowledge of CDR in the populations of the countries studied, primarily Western Europe, the US, Australia and New Zealand. Table 4.1 summarises key results from the small subset of studies which contain quantitative awareness data. It is not possible to discern trends in this data, due to the small number of studies and the fact that awareness is measured and reported in a wide variety of ways.

Table 4.1. *Awareness of Carbon Dioxide Removal (CDR) is low among the general public in Western Europe, the US, Australia and New Zealand. The table shows public awareness of CDR, quantitative findings only, by year of data collection and country. Where multiple statistics are reported, these correspond to the countries listed, in order. Some studies aggregate across countries. Definitions: Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS).*

Year	Country	Method or CDR initiative investigated	Reported statistic	Measure	Reference
2012	Australia + New Zealand	BECCS + DACCS + Enhanced rock weathering	18%	"Aware"	Carlisle et al. (2020)[119]
2013	Australia	Carbon Farming Initiative	39%	"Aware"	Dumbrell et al. (2016)[120]
2013	Germany	Afforestation	60%	"Heard of"	Braun et al. (2018)[121]
2016	United Kingdom	Enhanced rock weathering	6.5%	"Know great deal / fair amount"	Pidgeon & Spence (2017)[122]
2018	United Kingdom	BECCS	21.2%	"Know fair amount"	Bellamy et al. (2019)[95]
2018	Switzerland	Afforestation BECCS Biochar DACCS Enhanced rock weathering Ocean fertilisation Soil carbon sequestration	3.15 (out of 6) 2.22 1.68 2.09 1.84 1.64 2.07	6-point scale 1: "never heard of it" 6: "know a lot"	Jobin & Siegrist (2020)[123]
2018	Australia New Zealand United Kingdom United States	BECCS + DACCS + Enhanced rock weathering	14% 15% 16% 18%	"Aware"	Carlisle et al. (2020)[119]
2018	United Kingdom	BECCS + DACCS + Enhanced rock weathering	19%	"Aware"	Carlisle et al. (2021)[124]
2019	United Kingdom United States	CDR	5.8% 9.6%	"Know great deal / fair amount"	Cox et al. (2020)[93]
2019	Australia United Kingdom United States	Enhanced rock weathering	26% 38% 30%	"Heard of"	Spence et al. (2021)[117]

Risks, benefits and specific CDR methods

Research shows that people's initial reactions to CDR are usually tied to their values, beliefs and sense of identity. Specific factors include trust in the actors involved, beliefs about tampering with the natural world, and perceived trade-offs against alternative approaches for mitigating or adapting to climate change[125]. For novel CDR methods (see Chapter 1 – Introduction for definitions) with low public awareness, perceptions are highly susceptible to how methods are framed by researchers. Deliberative research has shown that people may support CDR methods provided they meet certain conditions regarding elements such as impacts, risks, benefits and costs – for example, that they are feasible, controllable and reversible; that the side effects are minimal; and that scientific uncertainty is low[93,126].

Perceptions of CDR also depend on the policy context. For example, support may require a clear and joined-up approach to policymaking for climate action across sectors. Otherwise, CDR may be perceived as simply a "band-aid" to the problem of continued high emissions[115,121,127]. The policy context will also need to attend to other environmental and social goals, because support for CDR may be lower if it creates the same harms that it tries to avoid, for instance by damaging biodiversity or widening inequalities (see Table 1.1 in Chapter 1 – Introduction for potential hazards associated with different methods). Another concern about CDR is that it could reduce the incentive to tackle emissions[128], and public discourses around CDR are likely to evolve alongside emerging debates and concerns over "net zero" promises – in particular, whether CDR is simply a means of enabling particular sectors or sections of society to continue emitting CO_2. A strong body of evidence from multiple sectors demonstrates that attempting to overcome scepticism through campaigns to increase public awareness, understanding or scientific literacy is likely to be ineffective and potentially even counterproductive[129,130]. As innovation programmes gain pace, efforts to engage the public with CDR are vital but must go beyond notions of securing "acceptance".

Studies find a preference among participants for CDR methods perceived or framed by researchers as more "natural", yet definitions of what constitutes "natural" are vague and differ between studies. Familiar conventional land-based methods (particularly afforestation) tend to be generally preferred over others[94,120,123,131,132], and ocean fertilisation tends to be perceived as most risky[133,134]. Less familiar novel CDR methods, such as enhanced rock weathering and Direct Air Carbon Capture and Storage (DACCS), often encounter uncertainty and a high proportion of "don't know" responses[93,124]. Land-based CDR methods encounter concerns about land use, biodiversity and environmental impacts, although for some CDR methods such as afforestation this greatly depends on how it is carried out. Bioenergy with Carbon Capture and Storage (BECCS) in particular appears to arouse concerns about land competition, food prices, biodiversity and the sustainability of feedstocks[135,136]. Research on methods involving underground CO_2 storage builds on a much larger body of literature on CCS perceptions and finds concerns around safety, monitoring, leakage and earth tremors, and perceptions of the deep underground as unknowable and unpredictable[93,135]. Ocean-based CDR methods may be perceived as most risky because of perceived uncontrollability and irreversibility, although this may also depend on the degree to which the methods are perceived as "natural"[98,123,131].

4.3 Tracking CDR on Twitter

Attention to CDR on Twitter has proliferated in recent years, growing faster than attention to climate change in general. Some methods, such as afforestation/reforestation, are discussed more favourably than others.

The social media platform Twitter is known for driving online political debates. Twitter data shows how communicators who are aware of CDR talk about it in public. The fact that users are dedicated communicators such as experts, policymakers, and media and company representatives means that the results are not representative of general populations[137–140]. Nevertheless, analysing this data allows us to track the development of communication around CDR over time. In this chapter, we search and analyse English-language tweets in the full Twitter archive (2010-2021). Our queries capture general CDR keywords as well as those related to specific CDR methods (see Box 4.3).

Box 4.3 Method for analysing Carbon Dioxide Removal on Twitter

We focus our analysis on ten Carbon Dioxide Removal (CDR) methods – DAC(CS)*, coastal wetland (blue carbon) management, Bioenergy with Carbon Capture and Storage (BECCS), soil carbon sequestration, ecosystem restoration**, afforestation/reforestation, biochar, enhanced rock weathering, ocean fertilisation and ocean alkalinisation – as well as general CDR mentions.

For each of these, we develop and test a set of keywords in an iterative process to retrieve tweets from the Twitter full-archive search application programming interface (API) during the period 2006-2021. We download tweets separately for each set of keywords, excluding non-English tweets and retweets. In addition, we use the Twitter count API to get estimates of the volume of all English-language tweets on Twitter, as well as the number of tweets mentioning “climate change”.

In total, our consolidated dataset contains 471,386 unique tweets on CDR (both general mentions and mentions of specific methods). These tweets were posted by 171,233 distinct users, of which the most active 1% contributed 28% of the tweets. The tweets in our dataset were retweeted 1,004,533 times and received 200,055 replies and 2,776,170 likes – which is on average 2.1 retweets, 0.4 replies and 5.8 likes per tweet. Of the tweets in the dataset, 16,587 (3.5%) were matched by more than one query. Our dataset only contains original tweets containing at least one of the keywords from our search strings. These may be part of a conversation but do not include all other tweets in that conversation.

For each CDR method, as well as the general CDR keywords, we (1) measure attention by counting the number (and proportion) of tweets and (2) apply sentiment analysis to understand the tone of each statement, using the aggregated information as a proxy of perceptions towards CDR methods. We automatically label sentiment in our dataset using a state-of-the-art, transformer-based classification model[141] trained on public gold-standard training data[142].

There are several limitations of such an analysis. First, Twitter data is not representative of the general public, which can lead to differences in our analysis compared with representative surveys. However, we argue that the data is particularly useful for new and emerging technologies that are not yet well known among the broader population, by providing a large archive of statements by a large number of people with a general awareness of these CDR methods[119,134]. Second, our search for tweets is optimised to provide a high share (>80%) of relevant tweets (high precision), at the expense of not retrieving everything said about CDR on Twitter (lower recall). Third, we focus on English-language tweets only. This means that considerable parts of Twitter activity with respect to CDR are not represented here – particularly in non-English-speaking parts of the world. Fourth, reactions on Twitter might be biased by algorithmic prioritisation of tweets that users are presented with, and by bots. Fifth, since Twitter was only founded in 2006, the quantity and quality of tweets are influenced by the Twitter company’s continuous development and growth of its user base. To this end, we exclude the early years from our analysis and focus on the timeframe 2010-2021.

*The keywords used for this allow for mentions of both Direct Air Capture (DAC) – which does not include utilisation and storage - as well as for Direct Air Carbon Capture and Storage. These additional steps are necessary for this to be classified as a CDR method. We therefore refer to DAC(CS) in this section, as distinct from DACCS, and recognise that these mentions may not necessarily refer to the entire CDR method but may only include the capture component without storage.

**The keywords used for this allow for mentions that go beyond the peatland and wetland restoration method outlined in Chapter 1 – Introduction.

Overall attention to CDR on Twitter

The public Twitter debate on CDR is still young. Since the start of Twitter in 2006, about 470,000 English-language tweets on CDR-related topics have been shared on the platform (see Box 4.3). This is comparatively small given that there are tens of millions of tweets on climate change[143].

However, attention to CDR on Twitter has grown rapidly in recent years – faster than the number of tweets on climate change overall. In the observed period from 2010 to 2021, the number of tweets on CDR increased from about 5,500 (~15 tweets per day) to about 130,000 (~350 tweets per day) – an average growth rate of about 33% per year (Figures 4.3 and 4.4). This is faster than the growth in tweets on climate change (~10,000 per day in 2021, with 28% annual growth) and the average increase in the total number of tweets posted on the platform (17% per year).

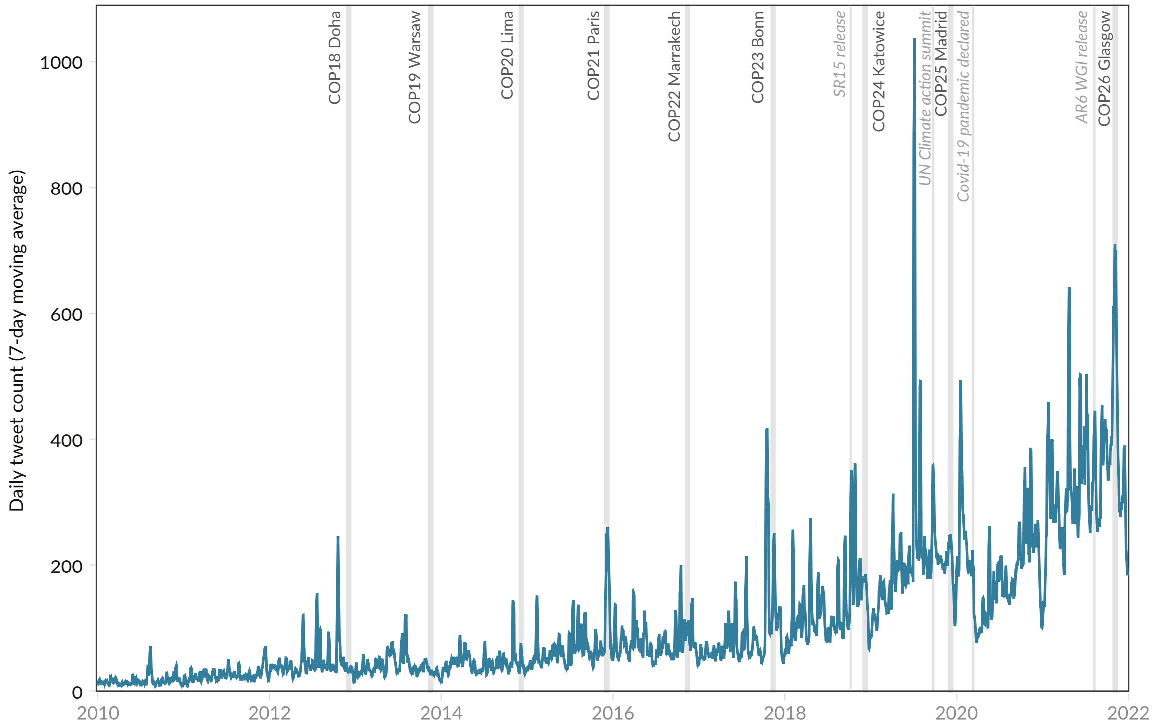

Figure 4.3. *Attention on Twitter is driven by events, particularly the annual United Nations Framework Convention on Climate Change (UNFCCC) Conferences of the Parties (COPs). Number of tweets on Carbon Dioxide Removal (CDR) per day shown as 7-day moving average (2010-2021). Attention spiked during the COPs and the releases of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Global Warming of 1.5°C (SR15) and the Working Group I contribution to the Sixth Assessment Report (AR6 WG1). The peak in 2019 is related to the release of a high-profile scientific paper on global forest restoration*[144].

Due to the outbreak of the Covid-19 pandemic in early 2020, attention shifted away from CDR temporarily. However, attention quickly recovered in 2021, faster than the number of tweets on the general topic of climate change; the number of tweets was about 75% higher than in 2020 and 62% higher than in the years before the pandemic (Figures 4.3 and 4.4).

General versus specific aspects of CDR

About 30% of all CDR-related tweets concern general aspects of CDR, responding to general keywords such as “carbon dioxide removal”, “carbon removal” or “negative emissions”. Over time, this share has increased from 3% in 2010 to 27% in 2021 and has grown faster than all CDR-related tweets together. In 2021, there were about 46,000 general CDR tweets discussing topics such as corporate plans to compensate emissions, the necessity of using CDR, or carbon-neutral products. This now regular and frequent reference to general aspects of CDR highlights the establishment of CDR as a part of the climate policy debate in its own right on Twitter.

Tweets that mention terminology related to specific CDR methods – such as afforestation/reforestation, coastal wetland (blue carbon) management, BECCS and DAC(CS) (see Box 4.3 for the full set) – account for about 70% of tweets in our dataset.

Attention to different CDR methods varies widely. More than 70% of all method-specific tweets are about CDR methods using biological storage: soil carbon sequestration (91,000 tweets; 27%), afforestation/reforestation (81,000 tweets; 24%), and coastal wetland (blue carbon) management (75,000; 22%) are all characterised by sizeable and continuously growing Twitter conversations. The debate on ecosystem restoration (20,000 tweets; 4%) is considerably smaller but is the fastest growing among these methods.

Novel CDR methods such as BECCS and DAC(CS) have received comparatively moderate levels of attention, but the number of tweets on DAC(CS) has seen substantial growth, at an average rate of about 57% per year over the last decade. Twitter activity on DAC(CS) tripled from 2020 to 2021, mirroring rapid dynamics in DAC(CS) investments (see Chapter 3 – Innovation). Similarly to the scientific literature (see Chapter 2 – Research landscape), enhanced rock weathering and ocean alkalinisation still receive little attention.

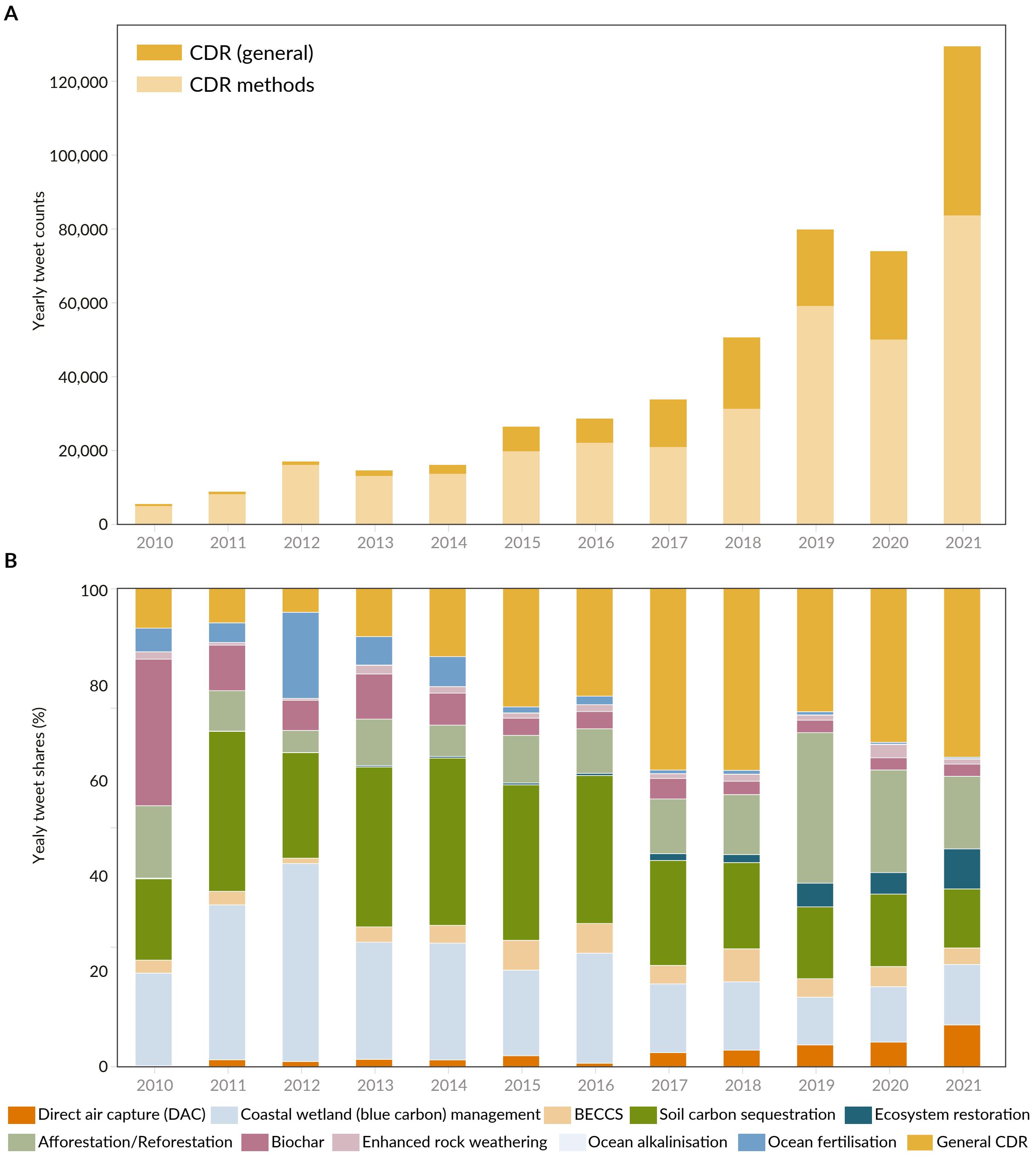

Figure 4.4. *Number of tweets per year on general Carbon Dioxide Removal (CDR) and method-specific CDR (panel A). Relative shares of overall CDR tweets by method (panel B). General CDR discussions that do not feature specific CDR methods are reported under CDR (general). Definition: Bioenergy with Carbon Capture and Storage (BECCS).*

Sentiments in tweets on CDR

The sentiment of tweets refers to whether the tone of the message is positive, negative or neutral. Sentiments do not directly reflect the stance of Twitter users towards a CDR method, for example whether they support or oppose a specific CDR method. However, sentiments reveal whether a CDR method appears more often in a rather positive or negative context.

Compared with tweets on CDR methods, a smaller share of tweets on general aspects of CDR – responding to keywords such as “carbon dioxide removal”, “carbon removal” or “negative emissions” – have a neutral sentiment, and that fraction is shrinking over time. However, the shares of positive and negative sentiments remained mostly balanced until a trend towards more positive sentiments emerged over the last three years (2019-2021), perhaps pointing toward an increasingly favourable framing of CDR on Twitter.

Tweets on individual CDR methods feature higher shares of positive than negative sentiments, except for ocean fertilisation. Ocean iron fertilisation is discussed very negatively following some failed field experiments[145]. This also corresponds to widespread scepticism found both in the scientific community and in public perceptions research with regard to its effectiveness and side effects[3]. The tone of tweets on afforestation/reforestation and biochar is more positive and less negative than for other CDR methods. This is also true for enhanced rock weathering, but the small number of tweets may skew the result. Most CDR methods show trends towards more positive tweeting over time. Only for BECCS do we find negatively trending sentiments. This may reflect growing concerns in the public debate about associated risks, as identified in perceptions studies (see Section 4.2).

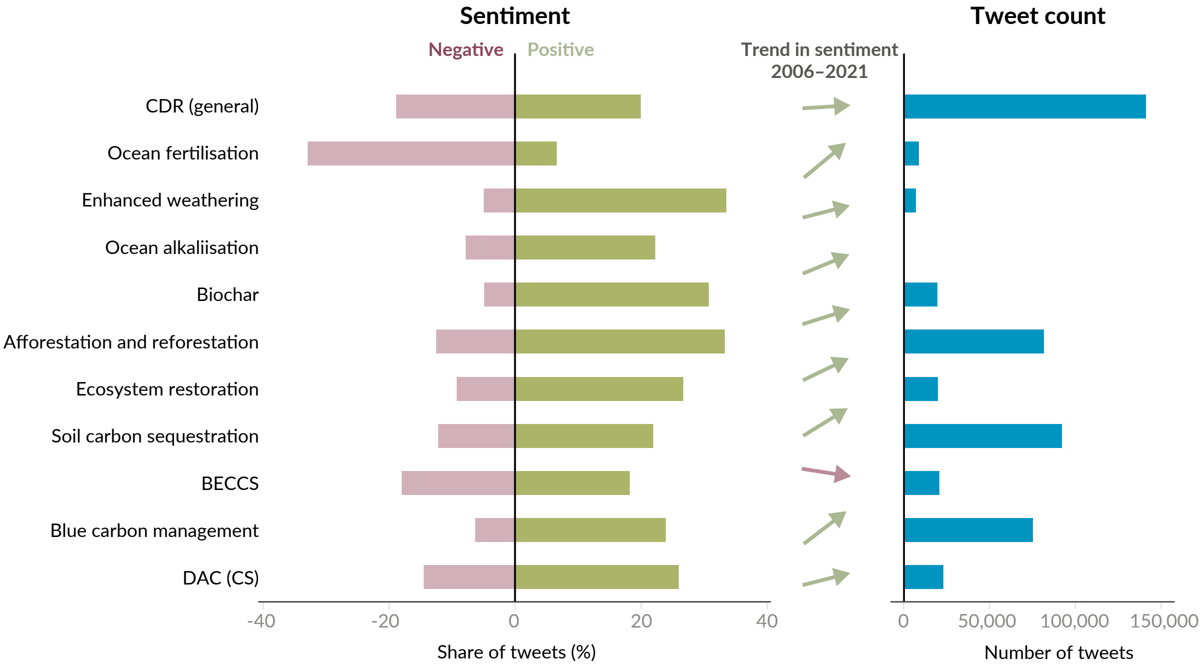

Figure 4.5. *Share of original tweets on Carbon Dioxide Removal (CDR) that express either a positive or negative sentiment (2010-2021); trends in sentiment (positive - green arrow; negative - red arrow) over time; tweet counts for different CDR methods (2010-2021). Definitions: Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture (DAC) and Direct Air Carbon Capture and Storage (DACCS).*

4.4 Future needs

Engaging the public with CDR requires policymakers and investors to understand the nuances of how different methods are perceived, extending beyond English-language scientific literature.

Meeting the Paris temperature goal will require maintaining carbon sinks from conventional CDR on land and most likely also substantial scaling-up of novel CDR. It is well established in the scientific literature that perceptions of CDR by investors as well as the general public can influence the speed and direction of innovation and deployment.

Our analysis here highlights that public awareness of CDR as reflected in English-language social science studies is still fairly low. This may be related to low awareness amongst policymakers, reflected in the lack of concrete plans to scale CDR in many countries and regions of the world (see Chapter 5 – Policymaking). Analysing and understanding the public debate on CDR-related issues, especially method-specific topics, is therefore critical, especially in the coming years as CDR methods are deployed in response to net zero commitments by governments and companies. There is a need to extend the analysis of public perceptions beyond English-language and scientific literature to further specify insights and knowledge gaps in other contexts.

Our Twitter analysis also shows that attention to CDR is growing rapidly and that these discussions feature an increasingly positive tone. Real-time tracking of public perceptions using social media platforms such as Twitter, Facebook, Reddit and other locally relevant networks could provide a sort of "early warning" system for shifts in CDR debates. However, such analysis can only contribute to robust social science alongside mixed methods approaches that generate qualitative insights in situations where participants have low prior knowledge of the investigated CDR methods. In addition, as CDR moves from research into deployment, local issues are likely to come to the fore, for instance around demonstration and scale-up projects, siting proposals, and policy implementation. This will require much more attention to spatial dynamics, perceptions of specific stakeholder groups (notably those directly involved in and affected by CDR deployments, and frontline and "fenceline" communities) and the existence of many diverse "publics".

> “While many countries have committed to net-zero emissions targets, few have robust plans or policies on how to achieve CDR.”

Chapter 5 | Policymaking

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Where examples of dedicated Carbon Dioxide Removal governance exist, they are found primarily at the level of individual countries and the European Union. Guidance and incentives from the United Nations Framework Convention on Climate Change and other multilateral initiatives are limited in comparison.

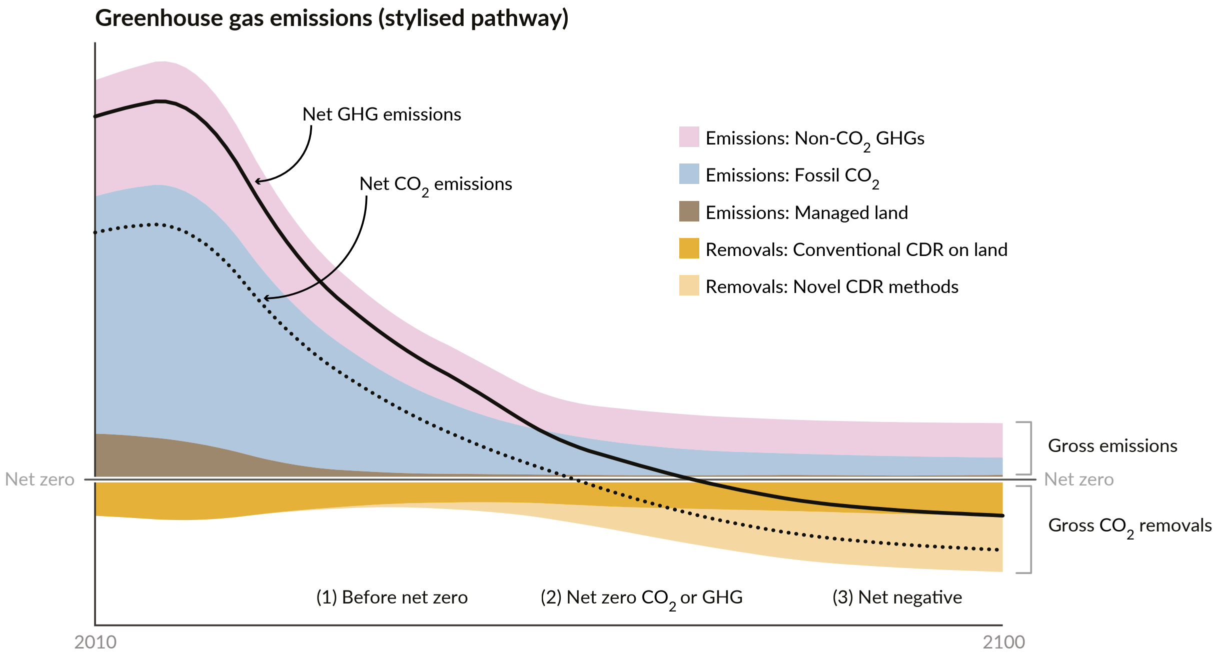
Box 5.1 Key findings

- More than 120 national governments have set a net-zero emissions target, yet only a small minority explicitly integrate Carbon Dioxide Removal (CDR) into their climate policy.
- Four case studies (European Union, United Kingdom, United States and Brazil) show tangible progress and policymaking dedicated to CDR. However, even in these cases no explicit removal targets or robust plans on how to achieve them exist.
- Policymakers' focus to date has been on conventional CDR on land, through forestry and agriculture. Attention on Bioenergy with Carbon Capture and Storage, Direct Air Carbon Capture and Storage and other novel CDR methods is rising in all four cases, especially in the UK and the US.
- The UK and European Union mainly refer to CDR as an option to counterbalance residual emissions in the context of a net zero target. In the US and Brazil, reducing emissions in the short term plays a larger role. None seriously considers reaching net-negative emissions.
- Understanding the conditions that influence upscaling of CDR will continue to require case studies that take into account countries' respective political contexts.

5.1 Growing recognition of Carbon Dioxide Removal in climate policy

More than 120 national governments have a net-zero emissions target, which implies Carbon Dioxide Removal (CDR).

Governments' approval of the recent Intergovernmental Panel on Climate Change (IPCC) Working Group III report shows they recognise that alongside deep, rapid and sustained emissions reductions, CDR can fulfil three complementary roles[1]: further lowering net emissions in the near term; counterbalancing hard-to-abate residual emissions (for example, from agriculture, aviation, shipping and industrial processes) in order to reach net-zero CO_2 or greenhouse gas (GHG) emissions in the medium term; and achieving or sustaining net-negative emissions in the long term if deployed at levels exceeding annual residual emissions (see Chapter 1 – Introduction and Figure 5.1). The global mitigation pathways assessed in the same IPCC report show conventional CDR on land maintained throughout the century, while novel CDR methods scale up over time (see also Chapter 7 – Scenarios and Chapter 1 – Introduction for definitions of "conventional" and "novel").



Greenhouse gas emissions (stylised pathway)

Figure 5.1. *Roles of Carbon Dioxide Removal (CDR) in ambitious mitigation strategies, applicable at national and global level. Basic emission and removal components of mitigation pathways, and the corresponding trajectories for both net carbon dioxide (CO2) and greenhouse gas (GHG) emissions. (Adapted from Cross-Chapter Box 8, Figure 2 in Babiker et al. 2022[13]).*

CDR has climbed up national policy agendas in recent years. While deploying conventional CDR methods on land is already well established (see Chapter 6 – Deployment), governments have now begun to envisage and specify the role of CDR in their domestic climate strategies, either explicitly through CDR-specific policies and strategies, or implicitly through the adoption of national net zero targets. More than 120 governments have set net zero targets to date[2].

5.2 Limited commitment to developing CDR

While few governments have actionable plans for developing CDR, some countries are beginning to integrate CDR into their climate policy, in different ways.

While, in principle, national governments are starting to recognise the strategic role that CDR will have to play in meeting agreed climate targets, governmental action on CDR is falling short. For example, although setting a *net-zero* (rather than a *zero*) emissions target implicitly indicates that governments are counting on CDR in some form, robust plans for CDR implementation are scarce. Reflecting a more general deficiency of net zero announcements[146], governments usually do not express how large the contribution of CDR should be on reaching net zero, and which CDR methods this might entail.

Examples of dedicated CDR policy and governance are found mainly on national and (in the case of the European Union) supranational levels, and only to a very limited extent in global multilateral initiatives and the United Nations Framework Convention on Climate Change (UNFCCC).

Governance at UNFCCC level

The Paris Agreement stipulates in its Article 4.1 that a “balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases” should be achieved “in the second half of this century” (see Chapter 1 – Introduction). Furthermore, all IPCC mitigation scenarios that likely limit warming to 2°C or lower assume the use of CDR (and almost all that limit warming to 1.5°C assume net-negative CO_2 emissions) (see Chapter 7 – Scenarios). Yet this has not so far been mirrored by corresponding UNFCCC decisions on the global need for large-scale CDR[147,148]. While the negotiations of CDR-specific issues are nascent, recent developments in the context of implementing the Paris Agreement’s Article 6 on international cooperation indicate that the UNFCCC could play a more active role in the near term. Additional efforts to develop methodologies for monitoring, reporting and verification (MRV) of carbon flows would be an important step towards operationalising CDR as part of mitigation strategies (see Chapter 1 – Introduction, Table 1.1, for an overview of current MRV guidance).

Governance at the UNFCCC level extends to a request for national governments to submit Long-term Low Emission Development Strategies (LT-LEDS). In contrast to the Nationally Determined Contribution (NDC), submitting an LT-LEDS is not mandatory for parties to the Paris Agreement and no requirements on format or content exist (see Chapter 8 – The CDR gap for further details of the ambiguities of LT-LEDS). By September 2022, there were only 53 LT-LEDS, some of which do contain considerations on preferred CDR methods and modelling data indicating CDR at the intended time of reaching net-zero emissions. But none contains a target for CDR combined with a politically robust plan for how to achieve it[149]. While this might be due to the long-term perspective of these strategies, this also holds true for NDCs, which usually focus on 2030. National legislation is also often more up to date than LT-LEDS, meaning the latter cannot be taken as a primary reference for commitments.

While the NDCs of many countries have been regularly updated since 2015, they usually refer only to CDR through the UNFCCC inventory category *Land Use, Land-Use Change and Forestry* (LULUCF). Detailed reporting on this sector is already mandatory for developed countries and captures emissions and removals on “managed land”[150,151]. However, NDCs referring to conventional CDR on land show a high degree of ambiguity (for example, on the separate contributions of LULUCF emissions and removals) and use widely differing accounting approaches, which is allowed under the Paris Agreement[152,153].

At the level of UN climate negotiations, specific CDR methods such as Bioenergy with Carbon Capture and Storage (BECCS) or net-negative emissions trajectories to deal with temperature overshoot are not yet covered[147,154]. Only a few national long-term mitigation plans or legal acts envision achieving net-negative GHG emissions[149]. For example, Finland, Sweden and Germany include such objectives in national legislation.

National and supranational policymaking

As reporting practices under the UNFCCC currently cover only two facets of CDR governance (target setting via NDCs and LT-LEDS, and accounting for removals via national GHG inventories[151]), exploring paths to scale up CDR requires a closer look at national and supranational policymaking. Unsurprisingly, CDR policymaking is shaped by the dominant ways climate policy works in a given country[155]. Of particular significance are the incentive structures for CDR deployment and the distributive effects of envisaged CDR upscaling (e.g. who bears responsibility for delivering and paying for removals).

Only a small minority of the 120 national governments that have set a national net-zero emissions target have started explicitly integrating CDR into climate policymaking. This exists in various forms, such as setting explicit targets; modelling scale-up of CDR in national mitigation pathways; increasing Research, Development and Demonstration funding for CDR (see Chapter 3 – Innovation); or implementing CDR-specific incentives and policies[156,157]. Comparative case studies have identified different types of CDR policymaking[157]. Here, we provide snapshots of CDR policy in practice via four illustrative case studies. Focusing on the European Union (EU), the United Kingdom, the United States and Brazil, we cover three Organisation for Economic Co-operation and Development (OECD) economies that have started to govern CDR in different ways and one country projected to provide pivotal CDR capacity in modelled global mitigation pathways[158] (see Chapter 3 – Innovation for complementary information on public funding for Research and Development). While all four have recently enhanced dedicated CDR regulation, these case studies reveal important similarities and considerable differences in the way CDR is regulated, which are not apparent in the reporting practices under the UNFCCC.

CDR policy in practice: European Union, United Kingdom, United States and Brazil

European Union

While the EU has been critical of the inclusion of CDR in mitigation strategies in the past, CDR has received new impetus in the context of the European Green Deal. The adoption of a legally binding target of net-zero GHG emissions by 2050 and net-negative GHG emissions thereafter (as yet unquantified) codified the need for CDR[159,160]. In recent years, CDR has become an integral part of the EU's mitigation policymaking. The original economy-wide 2030 goal adopted in 2014 of achieving a GHG emissions reduction of 40% (compared to 1990 levels) had targeted only gross emissions. The European Climate Law passed in 2021 strengthened the 2030 target to at least 55% *net* emissions reductions with a limited contribution of net removals from LULUCF (225 $MtCO_2e$). Furthermore, the European Commission, a few Member State governments and individual Members of the European Parliament have been pushing for the development of CDR incentives and regulation[161,162].

As part of its Sustainable Carbon Cycle initiative, the Commission plans to increase incentives for all LULUCF-based CDR methods (under the term *carbon farming*), expand support for innovation in Carbon Capture and Storage (CCS)-based CDR methods such as BECCS and Direct Air Carbon Capture and Storage (DACCS), and establish a certification framework for a broad range of CDR methods.

The EU Member States and the European Parliament are still in the process of identifying and agreeing on their positions on CDR. Some Member States (for example, Denmark, Netherlands and Sweden, together with closely associated non-EU member Norway) are pushing for the rapid and full integration of CDR into the EU's climate policy architecture, while others have yet to articulate specific preferences. No Member State opposes CDR outright, and all but a few (such as Ireland, Netherlands and Denmark) have achieved net LULUCF removals over the last decade. Since climate policy is a domain where the competence to act lies mainly at the supranational EU level, the development of an overarching CDR governance structure will be based on a common approach. Yet national differences in CDR deployment are expected to persist due to varying geographies, socio-political preferences and expected compositions of "hard-to-abate" residual emissions[163].

The strengthened LULUCF Regulation establishes a new target of achieving 310 MtCo2e net removals by 2030, which will likely lead to new support and incentive structures for the implementation of conventional CDR on land in the coming years. The EU Innovation Fund (fed through revenues from the EU Emissions Trading System) is so far the main tool to support the development of novel CDR methods, complemented by funding through the EU's research and innovation programme Horizon Europe (see also Chapter 3 – Innovation). One CDR demonstration project is already co-financed through the EU Innovation Fund (*Beccs Stockholm*[88]), in addition to projects that fall under the broader category of "carbon management" (i.e. capture, utilisation, transport or storage of fossil CO_2), which will shape the future expansion of CDR. Industry is beginning to advocate for the development of CDR-related infrastructure, such as CO_2 transport. Companies with large amounts of potentially hard-to-abate emissions are starting to call for cross-border collaboration on carbon management, including CDR.

United Kingdom

CDR is a topic of proactive research and policy development in the UK[157], where it is often referred to as Greenhouse Gas Removal (GGR) to include potential removal of other greenhouse gases. The most recent strategy published by the government emphasises the primacy of ambitious decarbonisation across society, while noting that Greenhouse Gas Removal is essential to compensate for residual emissions[67].

UK climate policy is guided by legislation which requires five-year limits on net domestic GHG emissions (known as "carbon budgets") to be set on the path to at least a 100% reduction in net GHG emissions (i.e. net zero) by 2050. Within these targets, CDR's role is not separated from emissions reduction but is accounted for as fully exchangeable with emissions. The legislation requires the government to regularly publish its plans and policies for achieving these targets. The most recent strategy publication contains an ambition to increase tree planting to 30,000 hectares per year from 2025 onwards, restore 280,000 hectares of peat in England by 2050, increase use of wood in construction, and remove at least 5 $MtCO_2$ per year by 2030 with methods like BECCS, DACCS, biochar and enhanced rock weathering[67]. Currently only CDR reported in the land sector is counted towards UK targets. The government's strategy seeks to amend the legislation to account for a wider range of CDR methods, and explore new regulatory oversight for MRV.

The UK has generally adopted carbon pricing and market-based approaches to support climate change mitigation. Tree planting is incentivised through a government-created system of MRV and credit generation for woodland carbon[164]. Consultations have been launched by the national government in 2022 on business models for CDR methods like BECCS and DACCS[165,166] as well as discussion in the context of developing the UK Emissions Trading System (ETS)[167]. These consultations indicate that the government currently intends to incentivise such methods through contracts guaranteeing a fixed price per tonne of CO_2 removed.

CDR Research and Development is supported in the UK primarily through two programmes. These total £100 million ($113 million) over four years and include a range of demonstration projects and a research hub (see Chapter 3 – Innovation for further details). A wide variety of methods is supported in these programmes (for example, CO_2 capture from seawater and capture of methane from cattle sheds), in addition to those included for deployment in the national net zero strategy.

Despite this relatively high level of policy ambition in the UK, progress is lagging. The government's official advisory body reports that tree planting and peat restoration are significantly behind targets, while the delays to CCS development in the UK are a particular risk to BECCS and DACCS deployment[168].

United States

The US' NDC aims to cut GHG emissions by at least 50% in 2030 compared to 2005 levels, including LULUCF[169] (annual net removals via LULUCF were roughly 10-15% of total US GHG emissions in the past decade[169,170]). The Biden administration has also announced additional targets, including achieving net-zero GHG emissions economy-wide by 2050. There is no federal legislation with emissions reduction targets consistent with the US NDC, nor to achieve net-zero GHG emissions by 2050. As such, the envisaged contribution of CDR in US climate policy is unclear. Modelling analyses indicate that achieving net-zero GHG emissions in the US will involve a significant role for CDR, on the order of 1 $GtCO_2$ per year by 2050[171].

CDR has received bipartisan support despite the lack of consensus on climate change in US politics[157]. Partly, this is because methods like DACCS and BECCS are seen as technological innovation with broader economic benefits. Methods such as soil carbon sequestration have also received bipartisan support as they may benefit more rural states, which have disproportionately high political representation. Several recent federal bills have CDR components. For instance, the bipartisan Energy Act of 2020, signed into law by the Trump administration, allocated funding for an interagency CDR research programme and set up a technology prize competition for Direct Air Capture (DAC) (see Chapter 3 – Innovation). In 2021, the bipartisan Infrastructure Investment and Jobs Act assigned $3.5 billion to four DAC hubs, including connecting infrastructure such as pipelines and storage. The goal is to achieve 1 $MtCO_2$ capture per year per hub. While these hubs are expected to catalyse investment in subsequent DAC plants, it is unclear to what extent the initially captured CO_2 will be utilised for short-lived products like synthetic fuels, rather than being durably stored.

The Inflation Reduction Act (IRA) of 2022 includes major changes to an uncapped tax credit – 45Q – which supports CCS projects of all kinds. The credit was originally enacted in 2008 for fossil CCS. It has undergone multiple revisions in the past decade. The value of this directly paid credit for DAC combined with geological storage has been increased to $180 per tonne of CO_2. IRA also lowers the threshold to claim this credit from 100,000 tCO_2 captured annually to just 1,000 tCO_2 per year, making the credit much more attainable for current and future DAC facilities. While IRA's investments in fossil CCS do not count as CDR, the associated build-up of infrastructure such as pipelines and geological storage can benefit CDR methods such as DACCS and BECCS. There is also roughly $20 billion in the IRA allocated to methods such as afforestation/reforestation and soil carbon sequestration.

Finally, the US Department of Energy launched the Carbon Negative Shot programme in 2021, which targets innovation across multiple CDR approaches to enable capture and storage at gigatonne scale for less than $100 per tonne of CO_2[73]. Given that MRV with robust standards does not currently exist for many methods – either globally or nationally – the Carbon Negative Shot also targets the development of MRV methods to "ensure effective and permanent CO_2 removal"[73].

Brazil

The deployment of CDR in Brazil is pursued through public and private sector initiatives, particularly in agriculture and nature conservation. In April 2022, the Bolsonaro government updated its NDC, committing to net-zero GHG emissions by 2050 without details on the balance between emissions reductions and removals, and without an explicit CDR strategy. Under the government of President Lula de Silva, the addition of Climate Change to the name of the Ministry of Environment and the proposed creation of a National Climate Security Authority (*Autoridade Nacional de Segurança Climática*) signal a new impetus to climate policy.

In May 2022, the Brazilian government issued a decree to establish sectoral mitigation plans and a national registry that differentiate GHG removals and emissions reductions[172]. Under the current policy trajectory, CDR actions will be subsidiary to sectoral strategies – rather than considering CDR as a new independent sector. In the energy industry, for instance, the revised domestic fuel standard (*RenovaBio*) and tradable certificate system is expected to incentivise the addition of point-source carbon sequestration into biorefineries, with at least one project already announced[173,174].

Companies and NGOs have already developed reforestation and restoration programmes as part of international voluntary emissions compensation schemes. According to the latest inventory data, in 2020 net LULUCF emissions were 637 $MtCO_2e$, amounting to 38% of the national balance[175]. After a decade of progress, the decline of deforestation halted in 2012, followed by a sharp rise after 2018[176]. Unless the deforestation trend is reversed in line with the existing legal framework[177], achieving net-zero emissions is not plausible. However, restoration and reforestation activities are scaling up in biomes affected by centuries-old deforestation[178], as in the Atlantic Forest. These are driven by priorities such as ecosystem conservation, biodiversity protection and water management, rather than CDR. Such activities are enabled by partnerships including environmental NGOs and federal and local governments, with financing from private sources. In these initiatives, CDR is an additional co-benefit.

The most relevant developments have occurred in agriculture, which represents 28.5% of national GHG emissions[175]. Today, business groups participating in global commodity markets are interested in compensating for emissions occurring within the same sector. This was preceded by a decade-old programme called the Low Carbon Agriculture Plan or Plan ABC, to finance the recovery of degraded pastures, the use of crop-livestock-forestry integrated systems, no-till systems and biological nitrogen fixation[179]. In fact, restoration of grazing land, integrated crop-livestock systems and no-till farming were already considered within Brazil's Copenhagen Accord submission and later as part of the country's Nationally Appropriate Mitigation Actions (NAMAs)[180,181]. The convergence of the pre-existing Plan ABC and new business initiatives is best captured by the recent development of a standard for GHG-neutral agricultural commodities. The state-owned Brazilian Agricultural Research Corporation (Embrapa) has developed the protocol which, for example, allows companies to label meat as GHG neutral (Carne Carbono Neutro) when having deployed soil carbon sequestration[182,183]. The results of an ongoing soil census as part of the National Soils Program will provide a benchmark and additional information to accelerate this initiative[184].

Summary of case studies

Specific policy approaches to CDR vary from country to country and are shaped by respective climate policy paradigms and institutional architectures, by political interests, by the relevance of different actors and by the relative importance of different economic sectors, among other factors.

To establish new funding and revenue streams, the US has expanded tax credits as one of the most prominent tools to support CDR deployment, whereas the UK and the EU are investing in innovation funds. In Brazil, there is no major funding for CCS-based CDR methods, but the government has established large programmes to promote CDR in the LULUCF sector. While none of the four cases has adopted an explicit target for novel CDR yet, all are pursuing a deeper integration of CDR into climate policy, including through advancing MRV and standards for removal accounting to further operationalise CDR as an important element of the mitigation toolbox.

Additionally, the different roles that CDR can play in mitigation strategies are not considered equally in the cases presented here:

- In the EU and UK, where much attention is being paid to reaching net-zero GHG emissions, scaling up CDR is mostly seen as a means to counterbalance hard-to-abate residual emissions. The UK has always applied the principle of full and unlimited fungibility to its climate targets (i.e. emissions reductions and removals are treated as interchangeable and mutual substitutes in accounting practices). The EU, on the other hand, has only recently moved to a net emissions logic for its domestic climate targets.

- In the US, where no federal law targeting net-zero emissions has yet been enacted, recent reforms suggest that CDR's near-term role in reducing net emissions is already a key consideration.

- Brazil illustrates a development that is relevant in all four cases but is particularly visible here: CDR policy is shaped by aspects that go beyond climate policy, and a multiplicity of possible justifications for CDR policy exist (e.g. managing interests of important economic sectors like agriculture through promising additional revenue streams).

- None of the case study countries gives any indication of planning for achieving net-negative emissions. The EU is the only case where a formal net-negative GHG target has been adopted, but it does not appear to drive current CDR policy development.

- Policy approaches and integration patterns also vary from method to method in the case studies. While novel methods like BECCS and DACCS tend to be part of new industrial policy initiatives, previous policy designs and governance structures for biological CDR methods that do not involve CCS are shaped by different interests. Conventional CDR on land mainly tends to be addressed by agriculture and forestry governance[185,186].

5.3 Future action

In the near term, innovations in CDR governance and policymaking are mainly expected at national and supranational levels. Tailoring to specific country contexts will be key.

At the UNFCCC level, the main task in terms of CDR policy and governance lies in developing robust accounting rules for CDR and establishing trusted MRV frameworks[151,187], strengthening rules for reporting on land-based biological removals and creating additional guidance for methods like DACCS or enhanced rock weathering[13]. This will be relevant not only for national inventory reporting but also in the context of establishing international carbon trading under the Paris Agreement's Article 6.4 mechanism. Yet UNFCCC inventory rules – currently based on IPCC guidelines from 2006 and 2019 – are unlikely to change without the explicit request of national governments, primarily those that want to have the outcomes of DACCS or enhanced rock weathering recognised in their official national inventories, thereby helping reduce net emissions and fulfilling pledges made in NDCs.

Beyond the UNFCCC process, action at a multilateral level can be expected primarily in fora like the CDR Mission under *Mission Innovation*, established at COP26 in 2021 with an official goal of enabling "CDR technologies to achieve a net reduction of 100 million tons of CO_2 per year by 2030"[188]. While limited institutional capacity may hamper achievement of this goal, this platform co-led by the US, Saudi Arabia and Canada may contribute to enhanced governance and policymaking through facilitating exchange of best practices and mutual learning on technology development and MRV frameworks for novel CDR methods.

Looking closer into case studies and identifying commonalities and differences in governance and policymaking practices will continue to be crucial to understanding the various enabling and constraining conditions that influence upscaling of CDR, including shared physical infrastructure (e.g. for CO_2 transport and storage). This is because even in the hypothetical case that all governments submit LT-LEDS, provide regular updates and use more standardised formats – including more explicit information on intended volumes and types of CDR – there is usually a significant degree of inconsistency between climate policy decisions and actions[189]. This leads to substantial implementation gaps[190]. Capturing real-world dynamics will therefore continue to require case studies that take into account the respective political contexts in which the enhancement of CDR emerges as a sub-domain of climate policy.

“CDR from novel methods contributes 0.1% of current deployment. Conventional CDR on land accounts for over 99%.”

Chapter 6 | Deployment

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The amount of Carbon Dioxide Removal (CDR) currently occurring around the world is roughly 2,000 $MtCO_2$ per year, of which almost all comes from conventional methods on land. However, accurately estimating CDR deployment is challenging.

Box 6.1 Key findings

- We estimate the amount of conventional Carbon Dioxide Removal (CDR) currently occurring on land (for example, through afforestation and reforestation) is 2,000 $MtCO_2$ per year.
- Adopting the methods used by countries to report their emissions and removals on land increases this estimate to 6,400 $MtCO_2$ per year. This is because national greenhouse gas inventories use a less strict interpretation of removals from human activity, including indirect effects.
- We estimate an additional 2.3 $MtCO_2$ per year of CDR from novel CDR methods, including Bioenergy with Carbon Capture and Storage, Direct Air Carbon Capture and Storage, biochar, enhanced rock weathering and coastal wetland (blue carbon) management.
- If all novel CDR projects currently under development are completed, the gross amount of novel CDR projects will increase to 11.75 $MtCO_2$ per year by 2025.
- Currently available data for novel CDR focuses on gross removals from projects in Europe and North America, with limited coverage of lifecycle emissions and other geographies. This means our estimate of deployment is likely incomplete.

6.1 Our approach to estimating global Carbon Dioxide Removal deployment

Estimating global Carbon Dioxide Removal (CDR) deployment is challenging, given uncertainty around defining what counts as CDR, data availability and issues with reporting approaches.

Generating an estimate of the amount of CDR currently occurring requires solving three main challenges. The first is defining which activities should be considered as CDR. The second is gathering sufficient data on those activities. The third is developing a reporting approach that addresses the risk of overestimating total deployment in cases where the CDR process takes many years to complete.

Challenge 1: Defining CDR

In this assessment, we adopt the definition of CDR used by the Intergovernmental Panel on Climate Change (IPCC)[38] (see Chapter 1 – Introduction, Section 1.3). We define CDR in this chapter, therefore, as:

> *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.*

Not only does this definition rule out activities which capture fossil carbon, or which do not store atmospheric carbon durably, it also has important implications for the measurement of CDR generated through conventional CDR on land (see Chapter 1 – Introduction, Section 1.5 for definition) and other land management activities. Specifically, carbon removed and stored in the land reservoir can be a result of biomass growth on managed land, of direct human intervention that enhances or creates new biomass (such as forest management or planting trees), or of indirect climate effects (e.g. plant growth stimulation caused by elevated atmospheric CO_2, known as the CO_2 fertilisation effect).[*] According to the IPCC definition, CO_2 uptake not caused directly by human activities does not count as CDR, so an accurate CDR deployment estimate should remove indirect climate effects from land data. For example, the carbon impact of planting new trees should be counted, but the extra carbon stored in those trees due to the CO_2 fertilisation effect should not be.

Challenge 2: Finding sufficient data

Our estimate of current deployment of conventional CDR on land is based on an aggregated and standardised National Greenhouse Gas Inventory (NGHGI) database developed by Grassi et al. (2022)[191]. NGHGIs are reports submitted by countries to the United Nations Framework Convention on Climate Change on an annual basis. They contain country-level estimates of greenhouse gas fluxes to and from the atmosphere from activities that occur in that country. While globally comprehensive, these NGHGI estimates come with two complications that must be addressed. Firstly, NGHGI estimates of fluxes from managed land include emissions as well as removals, meaning the gross volume of CDR is obscured. As an approximate correction for this we removed all non-forest-management fluxes, for example the impacts of deforestation or peat fires. Secondly, NGHGI-managed land estimates include both direct effects of human intervention and indirect effects of increased atmospheric CO_2 (see above). We estimate current CDR deployment with indirect effects removed by applying a correction generated by the OSCAR model[192]. Because land-use storage fluctuates from year to year, we have used the average managed land storage estimate for 2000-2020. For more information on measuring land sink size, see Box 8.2 in Chapter 8 – The CDR gap.

Data availability regarding the deployment of novel CDR projects is currently very limited - including for Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), biochar, enhanced rock weathering and coastal wetland (blue carbon) management. With no centralised repository of projects, information on deployment must be drawn from fragmented data sources, including CDR sale records and contracts, carbon offset registries, and NGO or corporate databases and reports. Here, we have systematically combined and cleaned 20 publicly available CDR databases and registries to develop a comprehensive view of present-day deployment of these CDR projects[8,23,47,86,193–207].

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[*] Following the approach of National Inventory reporting, for the purposes of this analysis, we consider (1) biomass growth on managed land and (2) direct human intervention on managed land to be one and the same – in other words, we assume all biomass on managed land is managed.

Challenge 3: Developing an effective measurement approach

Developing an estimate of the net removal achieved through current deployment of CDR is challenging from a reporting perspective. Firstly, most CDR projects do not report total lifecycle emissions. Secondly, some CDR methods provide removal of CO_2 over multiple years, and approaches for reporting the carbon removed and stored by such methods can overestimate their total impact (see Box 6.2). While the first issue is critical, it is not one that is possible to solve here. We resolve the second by following a “stock-and-flow” based accounting approach[193]. This measures CDR where and when it actually occurs by differentiating between two types of CDR activity: carbon sinks (carbon that is removed from the atmosphere and stored in a non-atmospheric reservoir in a given year) and carbon transfers (carbon that is moved between one non-atmospheric reservoir and another in a given year).

Box 6.2 Avoiding overestimation in Carbon Dioxide Removal deployment estimates

The climate impact of Carbon Dioxide Removal (CDR) activity is determined by removals out of – and any emissions into – the atmosphere over the whole lifecycle of the CDR method. This considers not only the carbon captured but also other factors, such as emissions associated with the construction of facilities, energy use and other inputs, and the fate of the stored carbon over time. Removals and emissions take place over different time periods for different CDR methods, as they involve different sequences of transfers through carbon pools (sometimes extended over multiple years), different inputs during the process (in terms of fuels and materials) and different final storage pools with differing durability of storage.

For this reason, there are two problems when estimating removals resulting from present-day CDR deployment. Firstly, the quantity of CDR reported by most projects is the gross quantity transferred from the atmosphere to the final carbon pool, excluding production emissions and any re-release of previously stored carbon. As such, any estimate of climate impact using reported data will be an overestimate of the actual net volume of CO_2 being removed from the atmosphere on an annual basis.

Secondly, when a CDR method involves conversion of atmospheric carbon into other forms, there may be a separation between when the CDR activity is recorded as occurring, and the actual timing of removal from the atmosphere. For example, in cases such as Bioenergy with Carbon Capture and Storage (BECCS) or the production of durable harvested wood products (HWP), the CDR activity tends to be reported in the year of biomass conversion to an energy product or wood product, rather than the time the carbon was transferred from atmosphere to plant (Figure 6.1). These will be one and the same for BECCS when using annual crops, but not forest biomass and other perennial crops. As such, these volumes run the risk of being double-counted if CDR methods make use of biomass that has also been recorded as a sink in prior years.

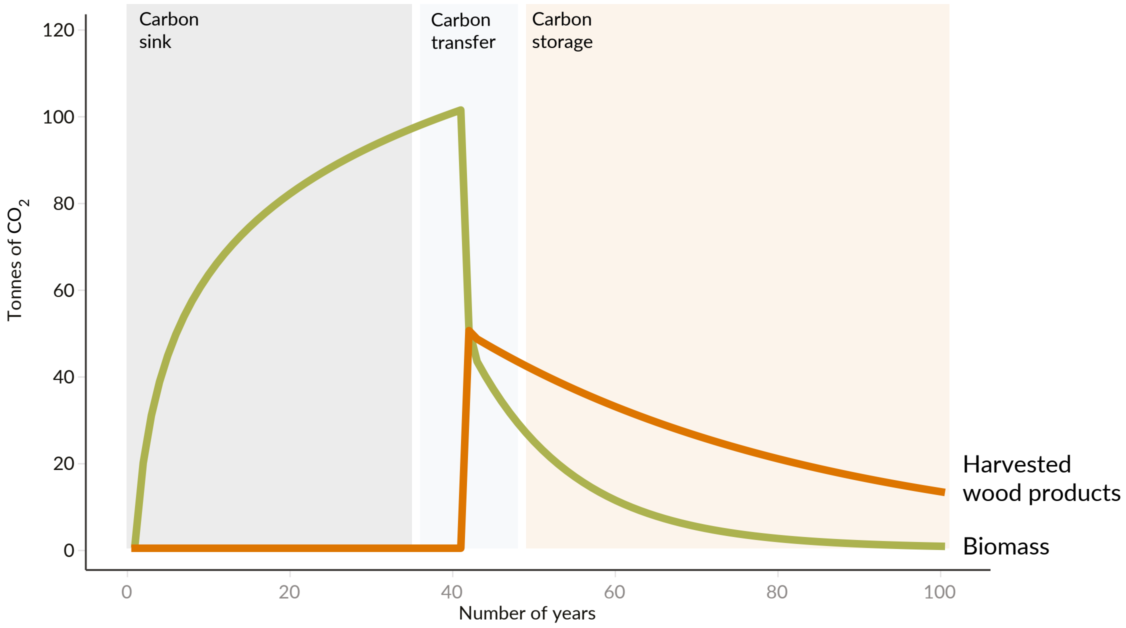

Figure 6.1. *An illustrative carbon dioxide (CO_2) removal and storage pathway for the production of harvested wood products (HWPs). During the carbon sink phase, carbon is removed and stored incrementally by biomass growth in forests[208]. During the carbon transfer phase, a portion of stored carbon is transferred from forest biomass to HWPs, with the remainder deposited as deadwood[209]. During the storage phase, both the deadwood and HWP decay to the atmosphere, though at different rates[210].*

While it is not currently possible to resolve the lifetime emissions reporting issue here, it is possible to resolve the issue of double-counting by multi-year CDR processes. We do this by adopting a stock-and-flow reporting system193, which splits CDR into two complementary but separate activities mapped onto the various pools of the global carbon cycle:

- The first activity is termed “carbon sinks” and is defined as activities which remove carbon from the atmosphere and durably store it in a non-atmospheric pool in the same year.

- The second activity is termed “carbon transfers” and is defined as activities which transfer carbon from one non-atmospheric pool to another in the same year.

In so doing, carbon removed from the atmosphere is always recorded as a carbon sink in the year in which it actually occurs, and activities such as the production of durable HWPs are recorded separately as carbon transfers in the year they are produced, a sum which is useful for tracking changes in carbon storage but which is reported separately from carbon sinks to avoid double-counting.

According to our estimates of current CDR deployment, all identified BECCS and biochar projects use annual crops or forest residues as inputs. For both of these carbon sources, the carbon sink and transfer are considered to occur in the same year. While forest residues have, technically, grown over many years before deposition, they are commonly assumed to behave the same way as annual crops because, like annual crops, the amount of deposition and decay in a given year is about equal, so they are neither a net source nor a sink of carbon. Hence, the only current CDR method with carbon removal and carbon transfers occurring in separate years is the production of durable HWPs.

6.2 Current CDR deployment

Virtually all current CDR comes from conventional methods on managed land. Only a tiny fraction results from novel CDR methods including BECCS, biochar, DACCS, enhanced rock weathering and coastal wetland (blue carbon) management.

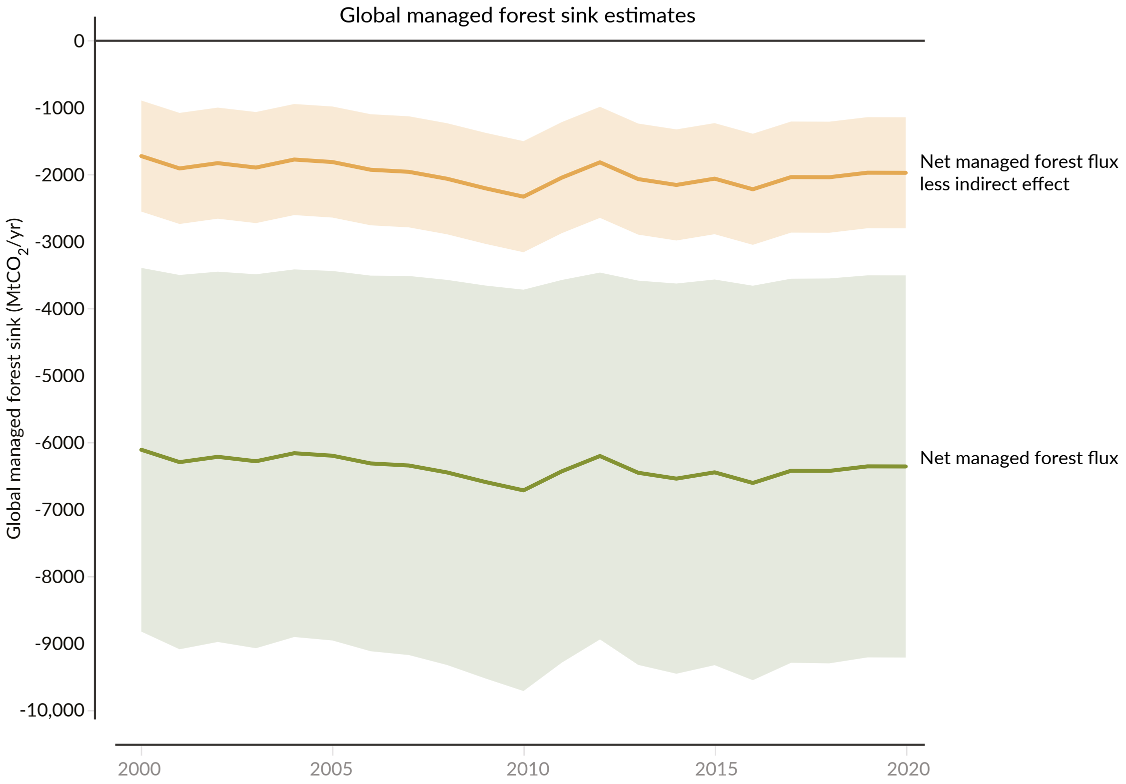

Figure 6.2. *Estimates of Carbon Dioxide Removal (CDR) from managed land during 2000-2020. Storage from net managed forest flux, including indirect climate effects, based on National Greenhouse Gas Inventory data (green). Storage from net managed forest flux, minus indirect climate effects (orange). Shaded regions indicate the range of measurement uncertainty.*

We estimate society is currently generating roughly 2,000 MtCO$_2$ per year of gross CDR (carbon that is removed from the atmosphere and stored in a durable non-atmospheric pool). Of this total, almost all comes from managed land.

NGHGI data indicates total global removals from managed forest land of around 6,400 ± 2,800 MtCO$_2$ per year, averaged over 2000-2020. Removing indirect climate effects, we arrive at an estimate of 2,000 ± 900 MtCO$_2$ per year for conventional CDR on land (Figure 6.2). This is smaller than a comparable estimate derived from bookkeeping models, which puts direct forest removals at 3,300 ± 1,100 MtCO$_2$ per year. The difference is likely due to inclusion of shifting cultivation (cutting forest for agriculture, then abandoning), which leads to large emissions and removals within each year. We exclude this activity from our estimate. The remaining 2.3 MtCO$_2$ of gross carbon sinks comes from novel CDR methods. The breakdown for different CDR methods is as follows: 1.82 MtCO$_2$ from BECCS, 0.5 MtCO$_2$ from biochar production and 0.01 MtCO$_2$ the combined result of all other methods, including DACCS, enhanced rock weathering, coastal wetland (blue carbon) management and others (Figure 6.3).

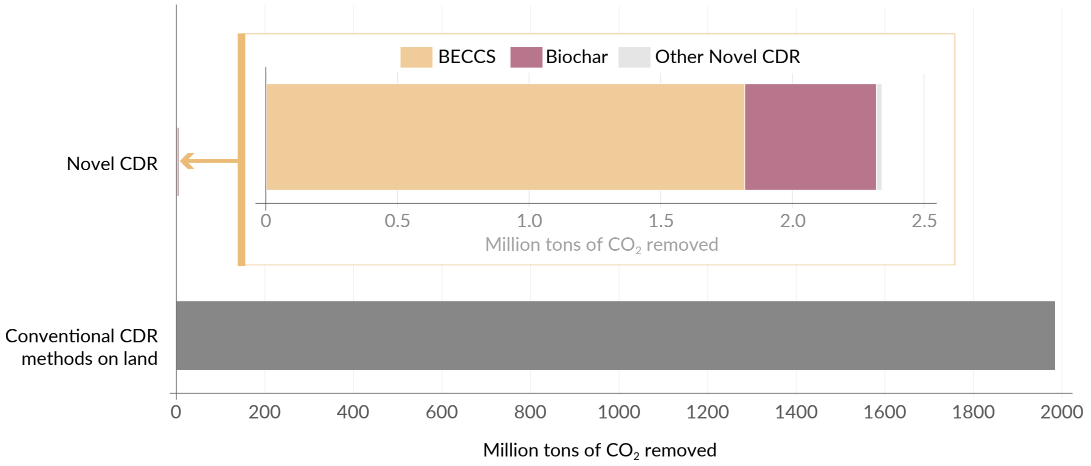

Figure 6.3. *Estimate of current Carbon Dioxide Removal (CDR) deployment. Definition: Bioenergy with Carbon Capture and Storage (BECCS).*

Furthermore, we estimate the volume of carbon transfers currently generated each year is about 223 $MtCO_2$. All 223 Mt are generated through the production of durable harvested wood products (HWPs), specifically sawnwood and wood panels, which transfer carbon from forest stock into durable wood products (Figure 6.4).

6.3 Future CDR deployment

There are a number of CDR projects in development that will become operational over the course of this decade, the pace of which can be used to estimate future growth.

It is possible to forecast CDR deployment, assuming no new projects are started and all in-development projects are completed. Under this assumption, atmospheric removals generated using non-land-management CDR projects will grow from 2.3 $MtCO_2$ per year in 2022 to 11.75 $MtCO_2$ per year by 2025, driven almost entirely by the completion of the Summit Carbon Solutions BECCS project, which involves bringing online 30 coupled ethanol-production BECCS plants and associated geological storage. By 2025, the annual volume of atmospheric removals using methods other than BECCS, DACCS and biochar will remain well below 1 $MtCO_2$ per year in volume.

Another way to project future CDR deployment is to extrapolate current deployment data. This approach is informative as it is unrealistic to assume there will be no additional CDR project development beyond 2025. To provide an approximate range of what might be expected, we fit both linear and exponential trends to the 2020-2025 deployment data for each CDR method as plausible upper and lower bounds. Under these assumptions, by 2030 we could see 30.5-208.5 $MtCO_2$ per year of BECCS deployment, 7-297.5 $MtCO_2$ per year of DACCS deployment, 1.8-65 $MtCO_2$ per year of biochar deployment and 0.036-0.061 $MtCO_2$ per year from all other methods (see Figure 6.4). Based on a longer available historical dataset and knowledge of the demand dynamics behind HWPs, we expect HWPs will at most continue to exhibit linear growth moving forward. While the exponential extrapolations used for novel CDR projects may seem large, it is important to note that despite persistently linear forecasts, solar and wind energy deployment have exhibited exponential trends over the past decade[211], and similar dynamics for CDR methods cannot be ruled out. For this to occur, however, substantial acceleration in innovation pace and scope would need to take place (see Chapter 3 – Innovation).

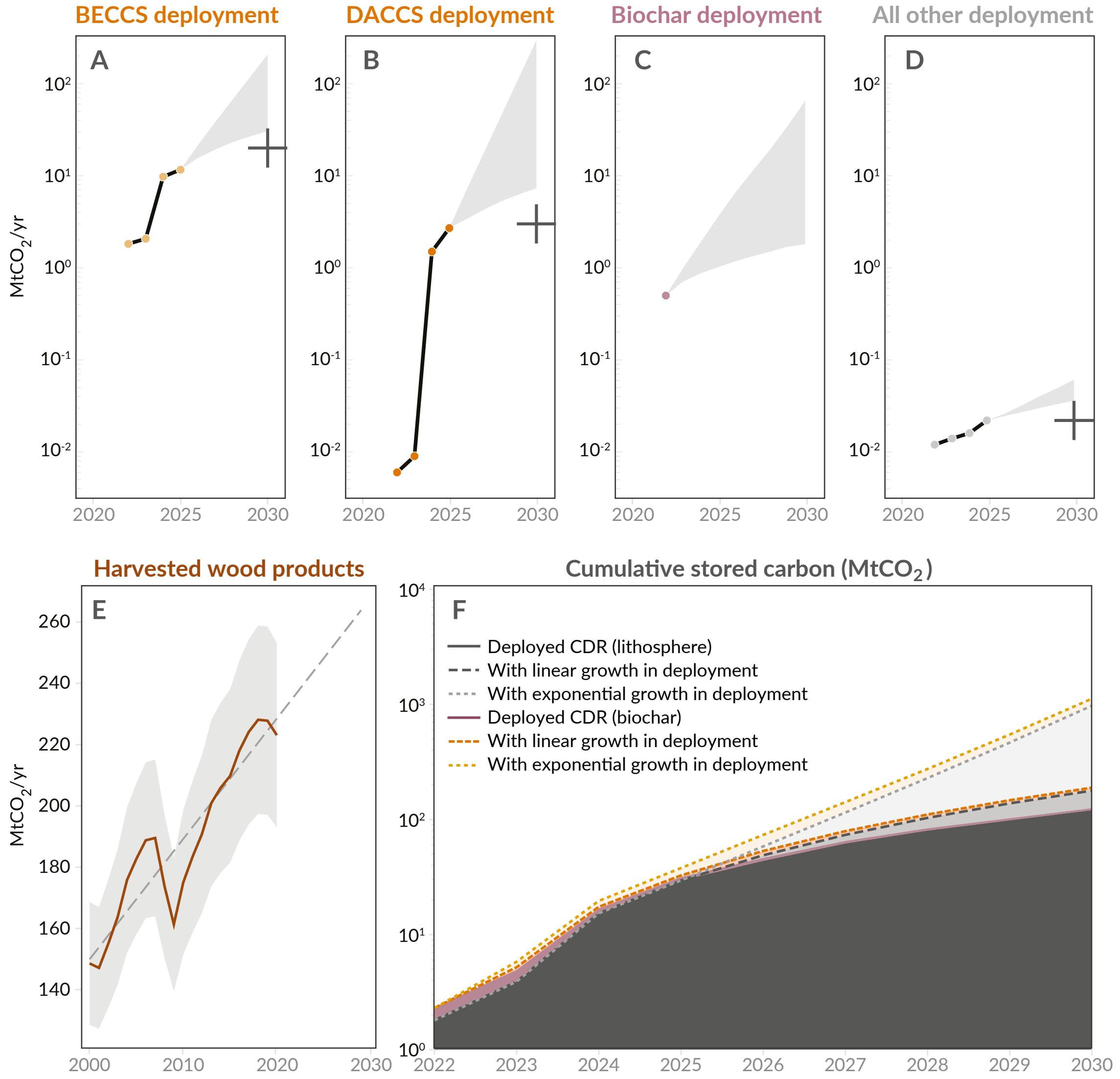

Figure 6.4. *(A-D) Deployment of various methods for generating carbon sinks, measured in $MtCO_2$ per year. Grey projections indicate a lower (linear) and upper (exponential) extrapolation of 2020-2025 deployment data. The grey crosses indicate 2030 deployment if only currently in-development projects are completed. (E) Harvested wood product production, measured in $MtCO_2$ per year, with a linear projection to 2030, with 9-95% uncertainty in grey. (F) Cumulative stored carbon by storage reservoir/pool, given observed deployment, continued linear deployment and continued exponential deployment, measured in $MtCO_2$. Definitions: Bioenergy with Carbon Capture and Storage (BECCS); Carbon Dioxide Removal (CDR); Direct Air Carbon Capture and Storage (DACCS).*

6.4 Looking ahead

Improving estimates of CDR deployment requires issues around measurement, data and reporting to be resolved.

Developing an accurate estimate of CDR deployment is necessary if we want to achieve the goals of the Paris Agreement, as without an accurate deployment baseline it is challenging to determine if we are generating sufficient volumes of CDR (see Chapter 8 – The CDR gap). There are three main barriers that need to be overcome to ensure we can maintain an accurate CDR deployment estimate going forward. Firstly, agreement will need to be reached on how to accurately measure CDR from conventional CDR methods on land and CDR achieved through other managed land based activities. Second, a central repository for CDR project data will need to be built. Thirdly, CDR project reporting will need to be standardised (see Chapter 9 – Future assessments).

“Every year of delaying rapid and sustained emission reductions increases the requirements for CDR deployment in the long term.”

Chapter 7 | Scenarios

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Carbon Dioxide Removal (CDR) increases in all pathways that limit global temperature to 1.5°C and 2°C. How much we rely on CDR in the second half of the century depends critically on how quickly we reduce emissions in the first half.

Box 7.1 Key findings

- The cumulative amount of Carbon Dioxide Removal (CDR) deployed between 2020 and 2100 varies substantially across pathways that likely limit global temperature rise to 2°C or lower, ranging from 450 to 1,100 $GtCO_2$.

- All scenarios that likely limit warming to 2°C or lower involve substantial emission reductions prior to any significant scale-up of CDR. During the second half of the 21st century, CDR becomes increasingly important. However, near-term scale-up of CDR is critical to achieve required deployment in the long term.

- CDR is scaled up more quickly in scenarios that limit warming to 1.5°C with no or limited overshoot than in scenarios that likely limit warming to 2°C, but the latter often involve higher long-term annual CDR. Over the course of the century, both sets of scenarios see similar total CDR deployment.

- Scenarios that limit warming to 1.5°C with no or limited overshoot reduce annual net CO_2 emissions by 19 (14-27) $GtCO_2$ in 2030 relative to 2020. Annual CDR increases by 2.6 (0.8-5.4) $GtCO_2$ over the same time period and by 9.5 (5.5-16.0) $GtCO_2$ per year at the point of net-zero CO_2 emissions.

- Conventional CDR on land is responsible for 99% (78-100%) of CDR in 2030 in both 1.5°C and 2°C pathways. Conventional CDR levels continue to grow thereafter – peaking around 2050, approximately doubling in 1.5°C pathways and increasing by around 50% in 2°C pathways compared to 2020 levels. Novel CDR methods typically increase throughout the century.

- Almost all scenarios that limit warming to 1.5°C by 2100 involve some level of temporary temperature overshoot. On average, in "high overshoot" pathways that exceed 1.5°C by more than ~0.1°C before returning to it by the end of the century, about 14% more CDR is used cumulatively than in scenarios with no or limited overshoot.

- Net-negative CO_2 emissions occur when annual levels of CDR exceed annual levels of gross positive CO_2 emissions and are a feature of almost all scenarios likely to limit warming to 2°C or lower.

- Almost all assessed scenarios (502 of 507) contain Bioenergy with Carbon Capture and Storage. A majority of scenarios also include conventional CDR on land (407 of 507).

- Limiting our dependence on CDR in the long term requires faster emissions reductions in the near term by increasing shares of renewable energy, enhancing energy efficiency, reducing energy demand and limiting or eliminating fossil fuel-based processes.

7.1 Mapping alternative future pathways

Integrated assessment models provide possible pathways to achieve the Paris temperature goal.

To understand the role of Carbon Dioxide Removal (CDR) in meeting the Paris temperature goal, it is critical to take a long-term perspective. Given that the future could unfold in very different ways, we evaluate alternative mitigation scenarios[†] that limit global temperature rise to "well below 2°C" (see Chapter 1 – Introduction, Box 1.1). Integrated assessment models are a widely used tool to systematically map out these alternative pathways and the technological, economic and political choices that need to be made in the coming decades to keep the Paris temperature goal within reach (see Box 7.2).

The Paris Agreement contains a long-term temperature goal and a mitigation goal, which it defines in Articles 2 and 4, respectively, as:

> *"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" (Article 2) by "achiev[ing] a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (Article 4)*[212].

Aligning scenario temperature outcomes with global climate goals combines inherently scientific and political processes. It has become increasingly common in the scientific community to distinguish three classes of scenario relevant to the recent history of climate policy – categorised as C1, C2 and C3 by the Intergovernmental Panel on Climate Change (IPCC) (see Table 7.1). There are different opinions regarding the extent to which scenarios in different categories assessed in the recent IPCC Working Group III report reflect the increased long-term ambition of the Paris Agreement to limit warming to "well below" 2°C[213,214] relative to previous climate agreements to keep warming "below" 2°C[215]. In this report, we include in our analysis all three groups – scenarios that are "as likely as not" to keep warming below 1.5°C throughout the century (C1), scenarios that have a "high overshoot" of 1.5°C (C2), and scenarios likely to keep warming below 2°C (C3) – as relevant to, but not necessarily all consistent with, the Paris Agreement. Throughout this report, we refer to C1 scenarios as 1.5°C scenarios and C3 scenarios as 2°C scenarios.

[†] In this report, we use the terms 'scenarios' and 'pathways' interchangeably. In both cases, we refer to outcomes from scenarios as assessed by the IPCC.

Table 7.1. *Scenario definitions likely to keep global temperature increase to 2°C or lower*

Warming limit	IPCC category label	Description	Quantification	Peak warming level (°C, 50% probability)	Warming level in 2100 (°C, 50% probability)	No. of scenarios
1.5°C	C1	Below 1.5°C with no or limited overshoot	<1.5°C peak warming with ≥33% chance and <1.5°C end-of-century warming with >50% chance. Temperature overshoot limited to <0.1°C.	1.6 (1.4-1.6)	1.3 (1.1-1.5)	97
	C2	Below 1.5°C with high overshoot	<1.5°C peak warming with ≥33% chance and <1.5°C end-of-century warming with >50% chance. No limit on temperature overshoot.	1.7 (1.5-1.8)	1.4 (1.2-1.5)	133
2°C	C3	Likely below 2°C	<2°C peak warming with >67% chance.	1.7 (1.6-1.8)	1.6 (1.5-1.8)	311

Box 7.2 Methods: Climate policy scenarios from integrated assessment models

Integrated assessment models (IAMs) are complex models which connect representations of the global economy, energy and land-use systems. These interconnected systems are represented as a mix of different technologies, processes and practices that are deployed to meet the demand for energy and other services within a given set of policy targets or constraints. Such technologies include fossil fuel installations, renewable energy technologies, agricultural production practices and CDR methods, as well as end-use technologies such as road vehicles and appliances.

IAM scenarios depend on a set of key assumptions[216] – such as population growth, level of urbanisation and potential for technological progress – to evaluate the evolution of technologies and consumption patterns in alternative futures. Modelling teams combine these widely used assumptions with their own estimations and quantifications of the potential for technological change, as well as future availability and cost improvements of technologies, and then apply key policy constraints (such as a global temperature limit) to arrive at a pathway or scenario.

Many IAMs use a "cost-effective" approach[217] to estimate economic and energy transitions, in that they try to reach a given climate goal at minimal costs for the global economy. How future costs are valued relative to today (i.e. the assumed discount rate) is a normative assumption required for this approach that can affect key outcomes such as total CO_2 emissions until net zero[218]. Most scenarios assume idealised conditions where currently nascent mitigation technologies become available in the next decade or so, while stringent global climate action starts immediately. However, IAMs are also used to study scenarios in which climate policy and the low-carbon transition are delayed or in which not all technologies are (fully) available[219]. As such, IAMs are a key resource to explore the constraints or possibilities that shape how we meet climate goals, including the key roles of CDR methods in doing so.

We use the collection of scenarios compiled for the Intergovernmental Panel on Climate Change's Sixth Assessment Report (IPCC AR6) as a starting point here[220]. The database features 1,202 scenarios with climate assessments from 14 modelling teams[221]. While scenarios provide standard data on novel CDR (mainly BECCS), conventional CDR on land was only partially assessed in AR6 because different models used different data reporting methodologies and approaches. Using the reduced-complexity climate model OSCAR[222], we develop reanalysed estimations of conventional carbon removal on land – such as via afforestation/reforestation – following definitions of national emissions inventory submissions to the United Nations Framework Convention on Climate Change[192]. We exclude "indirect" carbon removals from environmental changes on managed land (such as CO_2 fertilisation) from these estimates, in line with the definition of anthropogenic CDR utilised by the IPCC, as well as in Chapter 1, and the estimates of current CDR deployment in Chapter 6.

7.2 Scenarios that limit warming to 1.5°C and 2°C

All scenarios that limit global temperature rise to 1.5°C or 2°C feature substantial increases in CDR in addition to sustained and deep emission reductions. Failing to deliver these emission reductions in the short term increases scale and dependence on CDR in the long term.

All emissions pathways that limit global warming to 2°C or lower feature multiple gigatonnes of CDR annually (see Figure 7.2), making CDR a critical component of any mitigation strategy relevant to the Paris Agreement. In assessed scenarios, CDR does not play this role in the near term, however, as absolute emission reductions dominate mitigation activities during the first half of the 21st century. For example, by 2030 net CO_2 annual emissions decline by 19 (14-27) $GtCO_2$ and 8 (0-17) $GtCO_2$ relative to 2020 levels in 1.5°C and 2°C pathways, respectively. During that same timeframe, annual deployment of conventional CDR on land – such as via afforestation/reforestation – increases by 0.8 (-0.1 to 3.0) $GtCO_2$, while novel CDR – such as via Bioenergy with Carbon Capture and Storage (BECCS) or Direct Air Carbon Capture and Storage (DACCS) – increases by 0.01 (0-0.83) $GtCO_2$. CDR levels expand faster in 1.5°C pathways than 2°C pathways, growing by 2.6 (0.8-5.4) $GtCO_2$ removals annually by 2030 compared with 2020 levels. Both CDR types reach their maximum deployment only after mid-century (see Chapter 1 – Introduction for our definitions of "conventional" and "novel"). Conventional CDR on land is responsible for 99% (78-100%) of 2030 CDR in both 1.5°C and 2°C pathways. Conventional CDR on land continues to grow thereafter until its peak around 2050, approximately doubling in 1.5°C pathways and increasing by around 50%

in 2°C pathways compared with 2020 levels. Novel CDR methods such as BECCS or DACCS are typically scaled up throughout the century.

1.5°C scenarios achieve net-zero CO$_2$ emissions by around mid-century, and the vast majority (93%) of 2°C scenarios do so on average about two decades later. CDR grows steadily in these deep mitigation pathways. At the time of net-zero CO$_2$, CDR levels range between 5.5 and 16 GtCO$_2$ per year in 1.5°C pathways and between 6.8 and 16 GtCO$_2$ per year in 2°C pathways. During the second half of the century, after the point of net-zero CO$_2$ emissions, CDR becomes an increasingly dominant feature of climate change mitigation efforts. All 1.5°C and most 2°C pathways feature a sustained period of net-negative CO$_2$ emissions from enhanced levels of CDR that reduces atmospheric carbon concentrations and (often) leads to a drawdown in global mean temperatures. Almost all pathways achieve net-zero or net-negative CO$_2$ emissions through utilisation of CDR, and many achieve net-zero greenhouse gases (GHGs) in the long term. However, as Chapter 3 (Innovation) illustrates, new technologies can take decades to mature and reach large-scale adoption. Steady near-term progress in deploying novel CDR – such as BECCS and DACCS – is critical to achieving the required scale-up in the long term.

The level and composition of CDR deployed in scenarios varies widely and depends on a number of factors within a given scenario, as discussed in Section 7.3. Table 7.2 shows cumulative CDR deployment across the 21st century, where values for 2°C pathways range between 440 GtCO$_2$ and 1,100 GtCO$_2$, with a median value of 630 GtCO$_2$. More ambitious scenarios that limit warming to 1.5°C with no or limited overshoot show very similar levels of CDR deployment, reaching a median value of 740 GtCO$_2$ with a range of 420-1,100 GtCO$_2$. To still limit warming to 1.5°C in 2100 but with a high temporary overshoot of temperatures (>0.1°C), the range of required cumulative CDR increases by about 110 GtCO$_2$ on average. This is about 14% higher than in limited-overshoot 1.5°C scenarios. The additional CDR is needed to draw down temperature levels after peaking[223]. As a result, every year of delaying rapid and sustained emission reductions increases the requirements for CDR deployment in the long term[4,37,224].

Scenarios to date have focused on a narrow set of CDR methods, principally afforestation/reforestation and BECCS. This requires great care in the interpretation of the scale of CDR methods in climate change mitigation as well as the role of individual CDR methods. In this report, we interpret BECCS deployments as being representative of a broader set of novel CDR methods and afforestation/reforestation as being representative of conventional CDR on land. Modelling teams have recently begun to incorporate other novel CDR methods, such as DACCS or enhanced rock weathering, into their modelling frameworks[225]. As teams expand their representation of CDR methods, trade-offs across the CDR portfolio have become more apparent.

Table 7.2 highlights the variability in the composition of CDR portfolios in existing scenarios.BECCS is present in almost all scenarios considered (502 of 507), and deployment levels vary widely, spanning 170-760 GtCO$_2$ cumulatively throughout the century. Conventional CDR on land is also included in a majority of scenarios (407 of 507) and has a slightly smaller span of cumulative removals (130-560 Gt CO2).

In contrast, fewer than 1% of considered pathways include active contributions from enhanced rock weathering. A range of studies have reported that including other CDR methods in addition to BECCS might reduce not only the range of mitigation costs but also the impact of CDR on energy use, emissions, land and water. However, contributions of these methods to CDR are sensitive to the rate at which they can be scaled up, which remains highly uncertain (Box 7.3).

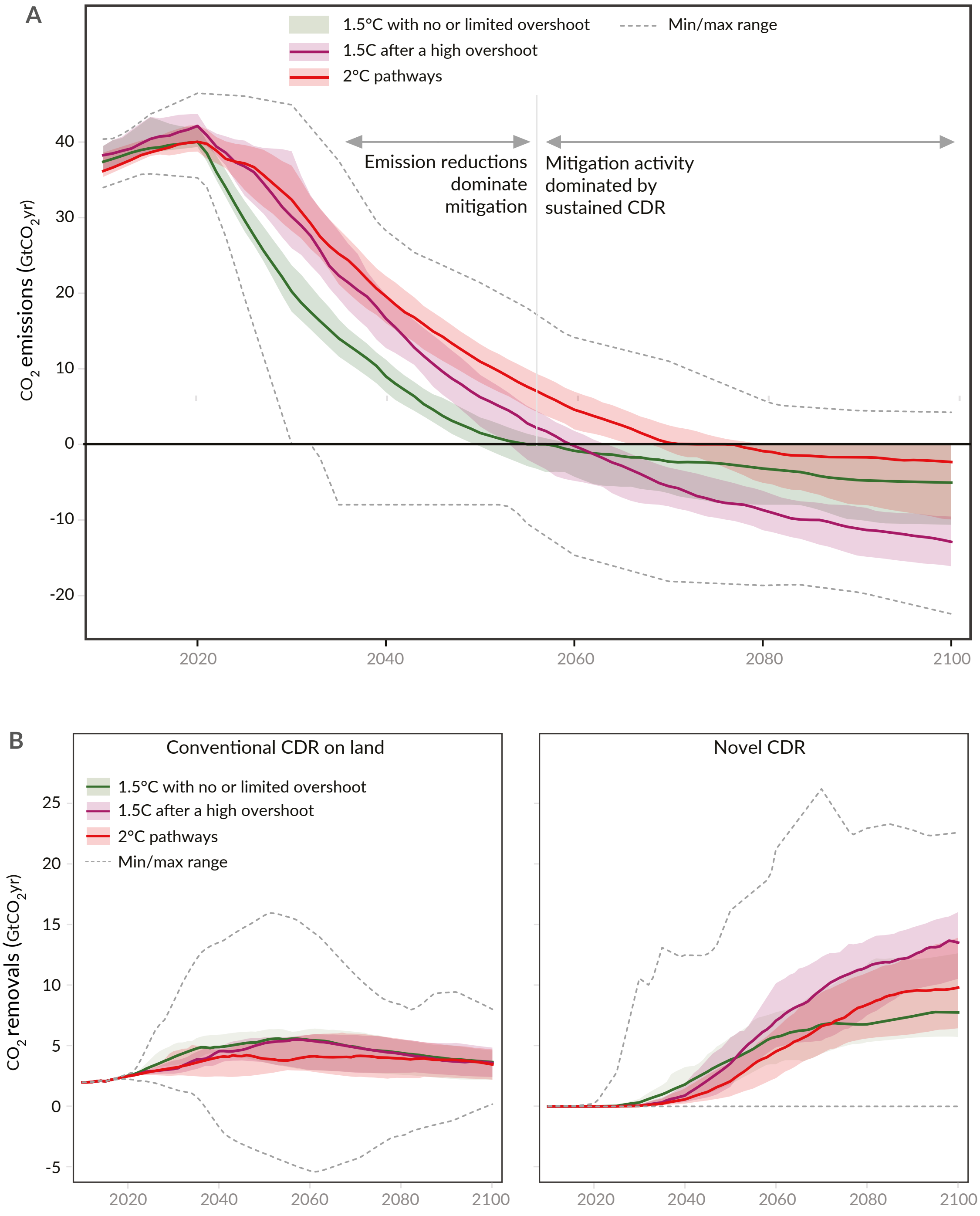


Figure 7.1. *(A) Global net carbon dioxide (CO_2) emissions in scenarios assessed in the Intergovernmental Panel on Climate Change Sixth Assessment Report and (B) upscaling of Carbon Dioxide Removal (CDR) methods under different pathway categories, as described in Table 7.1. Shaded regions show the 5-95th percentile ranges.*

Table 7.2. *Cumulative Carbon Dioxide Removal (CDR) from 2020 to 2100 in GtCO*$_2$ *in assessed pathways, highlighting the median and 5-95% range of values. "Number of scenarios" indicates the total number of scenarios evaluated by a range of models that include the CDR method as a variable. Statistical total CDR values presented here do not equal the sum of their components, as values are calculated on a per-scenario basis. Definitions: Bioenergy with Carbon Capture and Storage (BECCS); Direct Air Carbon Capture and Storage (DACCS).*

CDR method	Below 1.5°C with no or limited overshoot (C1)		Below 1.5°C with high overshoot (C2)		Likely below 2°C (C3)		Total (all pathways)	
	Total CDR	Number of scenarios	Total CDR	Number of scenarios	Total CDR	Number of scenarios	Total CDR	Number of scenarios
Total (all CDR options)*	740 (420-1100)	70	850 (590-1,300)	106	630 (440-1,100)	231	700 (450-1,100)	407
Conventional CDR on land*	370 (170-560)	70	360 (160-520)	106	310 (110-560)	231	360 (130-560)	407
Novel CDR	400 (24-860)	91	500 (130-860)	122	390 (160-660)	294	400 (110-790)	507
BECCS	330 (32-780)	91	460 (230-840)	122	290 (170-650)	289	330 (170-760)	502
DACCS	30 (0-310)	31	110 (0-540)	24	19 (0-250)	91	29 (0-340)	146
Enhanced rock weathering	0 (0-47)	2	0 (0-0)	1	0 (0-0)	1	0 (0-0)	4
* Total number of scenarios is lower than for novel CDR because data required for the estimation of conventional CDR on land is not available for all scenarios.								

Box 7.3 Carbon Dioxide Removal methods in mitigation scenarios

Historically, mitigation scenarios have focused on a limited set of Carbon Dioxide Removal (CDR) methods, mostly implementing representations of Bioenergy with Carbon Capture and Storage and afforestation/reforestation. However, a portfolio of CDR methods will most likely be deployed to achieve global and national climate targets. The composition of the portfolio will depend on available resources, technologies and preferences, and will change over time. Inclusion of additional CDR methods in models tends to increase the total CDR deployment in scenarios[43]. As more CDR methods are added to the portfolio, however, a given amount of CDR can be reached with reduced deployment of individual CDR methods, thus also limiting negative side-effects[43].

As some methods show a strong regional concentration – for example, the potential for afforestation/reforestation and for enhanced rock weathering is highest in the tropics – the availability of a CDR portfolio also changes the regional distribution of CDR. This becomes more balanced with the introduction of more CDR options.

The development of a CDR portfolio therefore hedges not only against technological risks but also against institutional risks (by balancing regional deployment) and against ecological risks (by limiting the deployment of single methods).

7.3 The role of CDR in scenarios that limit warming to 1.5°C and 2°C

The amount of CDR differs widely across scenarios that limit warming to 1.5°C and 2°C, depending on when and how we choose to transform the global economy towards net-zero CO_2 and GHG emissions.

The previous section highlighted that 1.5°C scenarios differ considerably from 2°C scenarios, featuring much faster emissions reductions to net-zero CO_2 emissions and a more rapid CDR scale-up. At the same time, total cumulative CDR across the 21st century is very similar, but within each class of scenarios there is a wide range in deployments – from a few hundred gigatonnes to over a thousand – through the course of the century. This range is a reflection of the different mitigation choices available and their direct implications for the level and timing of CDR deployments.

The scale of CDR deployments in 1.5°C and 2°C pathways depends crucially on political responses to climate change, alongside social and economic developments in the coming decades. Key factors that shape CDR deployment in scenarios are (1) the stringency of the temperature limit achieved; (2) the magnitude and duration of any temperature overshoot and eventual drawdown; (3) the speed and depth of near-term emission reductions; (4) the availability of measures to reduce energy demand; (5) the breadth of the portfolio of available CDR methods as well as other mitigation options.

Individually, these key factors shape the level of CDR deployments in scenarios by shaping the risk of carbon budget exceedance (e.g. stringency, delay, demand reduction), as well as the size of the residual emissions that need to be compensated at net-zero CO_2 and net-zero GHGs (e.g. fossil fuel dependence, demand reduction, technological availability). Delay of GHG emission reductions tends to increase CDR requirements in scenarios that achieve a given temperature outcome, while energy demand reductions decreases it. More technological flexibility (for example, increased usage of CCS in industrial processes like cement production) limits CDR requirements by lowering residual emissions, while availability of more CDR options can lead to increased overall deployment by providing potentially cheaper alternatives to some of the more expensive emission reduction options. Scenario evidence indicates that more CDR is utilised after having initially exceeded a specific warming level in order to draw net emissions and temperatures down at a faster pace later in the century, such as in 1.5°C high overshoot scenarios compared with 1.5°C scenarios with no or low overshoot.

Three focus scenarios

To show how different approaches to climate change mitigation are related to different levels and types of CDR, we analyse three “Focus Pathways” (Figure 7.2). These three pathways highlight strategies that focus on emission reductions mainly through demand reduction, renewable energy or carbon removal while limiting warming to 1.5°C.

The *Focus on Demand Reduction* scenario displays how rapid near-term emission reductions facilitated by radical energy efficiency improvements and lower energy demand levels can limit dependence on CDR substantially, with a maximum yearly removal rate of 4.8 $GtCO_2$ in 2050. Cumulative removals across the 21st century (2020-2100) of 330 $GtCO_2$ are provided exclusively from conventional CDR on land, showcasing that novel CDR is not strictly necessary to meet the Paris temperature goal. However, this is one of the few assessed scenarios that limits the cumulative CDR deployments necessary through aggressive near-term mitigation. The *Focus on Demand Reduction* scenario results in an end-of-century net emissions level of around 0.8 $GtCO_2e$, with residual non-CO_2 emissions mostly balanced by net-negative emissions from land use, land-use change and forestry.

The *Focus on Renewables* scenario involves fast and deep emission reductions facilitated by a rapid expansion of renewables. In this case, cumulative carbon removals are 500 $GtCO_2$ between 2020 and 2100, with a maximum annual rate of 8.2 $GtCO_2$ in 2055. CDR in *Focus on Renewables* is provided through a combination of conventional CDR on land and novel CDR, notably BECCS. If CCS facilities can be scaled in time, the geological storage of CO_2 this affords is more durable and less reversible than storage in trees and soils via conventional CDR on land. The *Focus on Renewables* scenario achieves net-zero GHG emissions by around 2090, and net-negative GHG emissions persist thereafter.

Finally, in the *Focus on Carbon Removal* scenario, GHG emissions reductions occur rapidly in the first half of the century and eventually reach net-zero levels by around 2070. Emissions remain to a large extent in the transportation, residential and commercial, and industry sectors, and are balanced at net zero by larger levels of novel CDR methods as well as net-negative CO_2 emissions from land use, land-use change and forestry. Significantly more CDR is deployed throughout the century due in strong part to balancing remaining residual non-CO_2 emissions in, for example, the agricultural sector. Cumulative removals from 2020 to 2100 arrive at 690 $GtCO_2$ and reach a maximum level of 10 $GtCO_2$ per year in 2050. This level is maintained thereafter, of which 75% is from conventional CDR on land at the end of the century.

While there are many scenarios – particularly those with high temperature overshoot– that involve CDR deployments far beyond what is represented in these three Focal Pathways, it is highly questionable whether such levels of CDR can be developed in a sustainable manner, which introduces strong trade-offs with other Sustainable Development Goals.

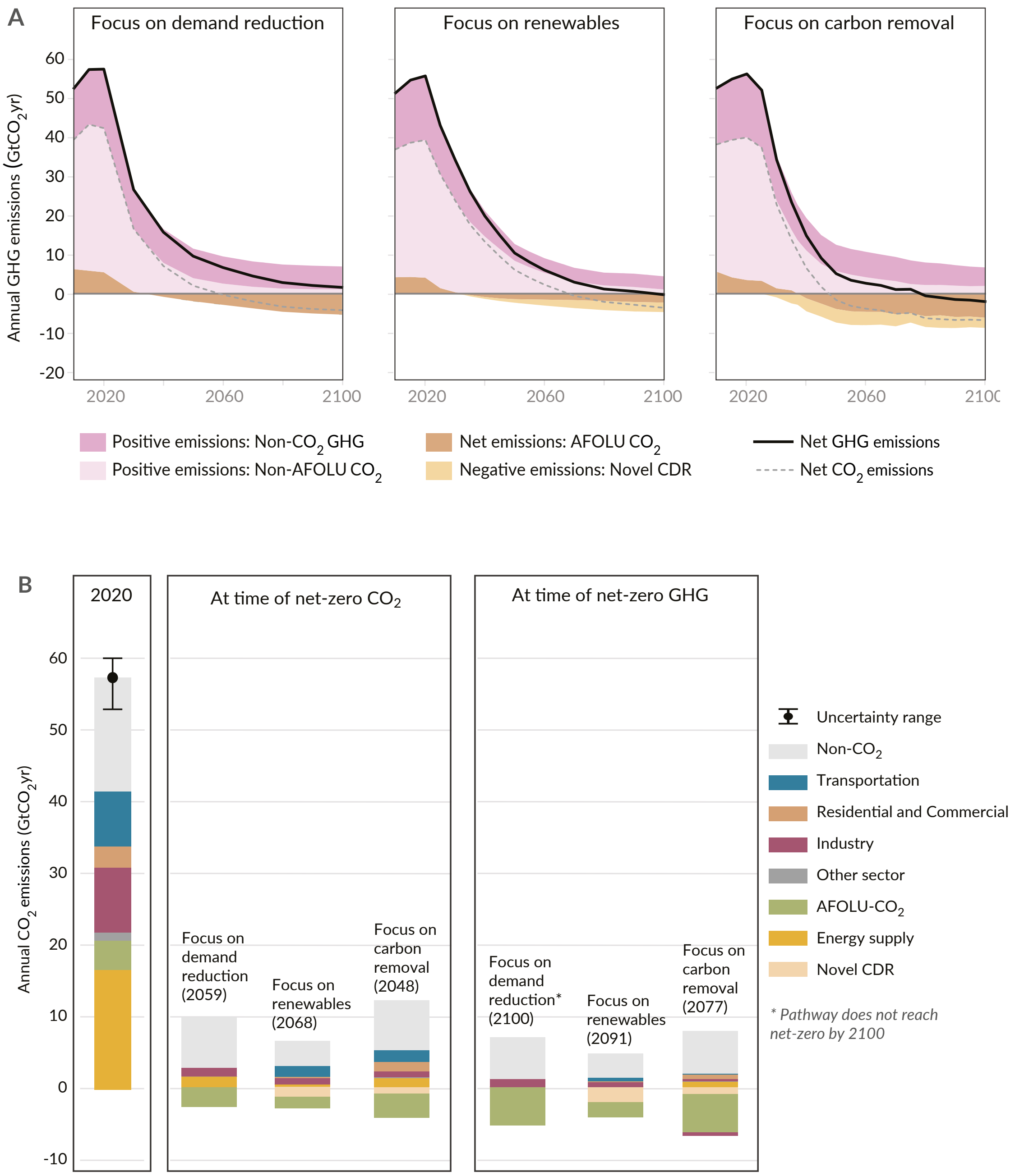


Figure 7.2. *(A) Emissions trajectories across Focus Pathways and (B) sectoral contributions to carbon dioxide (CO_2) emissions and removals at the time of net zero CO_2 and net zero greenhouse gases. Definitions: agriculture, forestry and other land use (AFOLU); Carbon Dioxide Removal (CDR); greenhouse gas (GHG).*

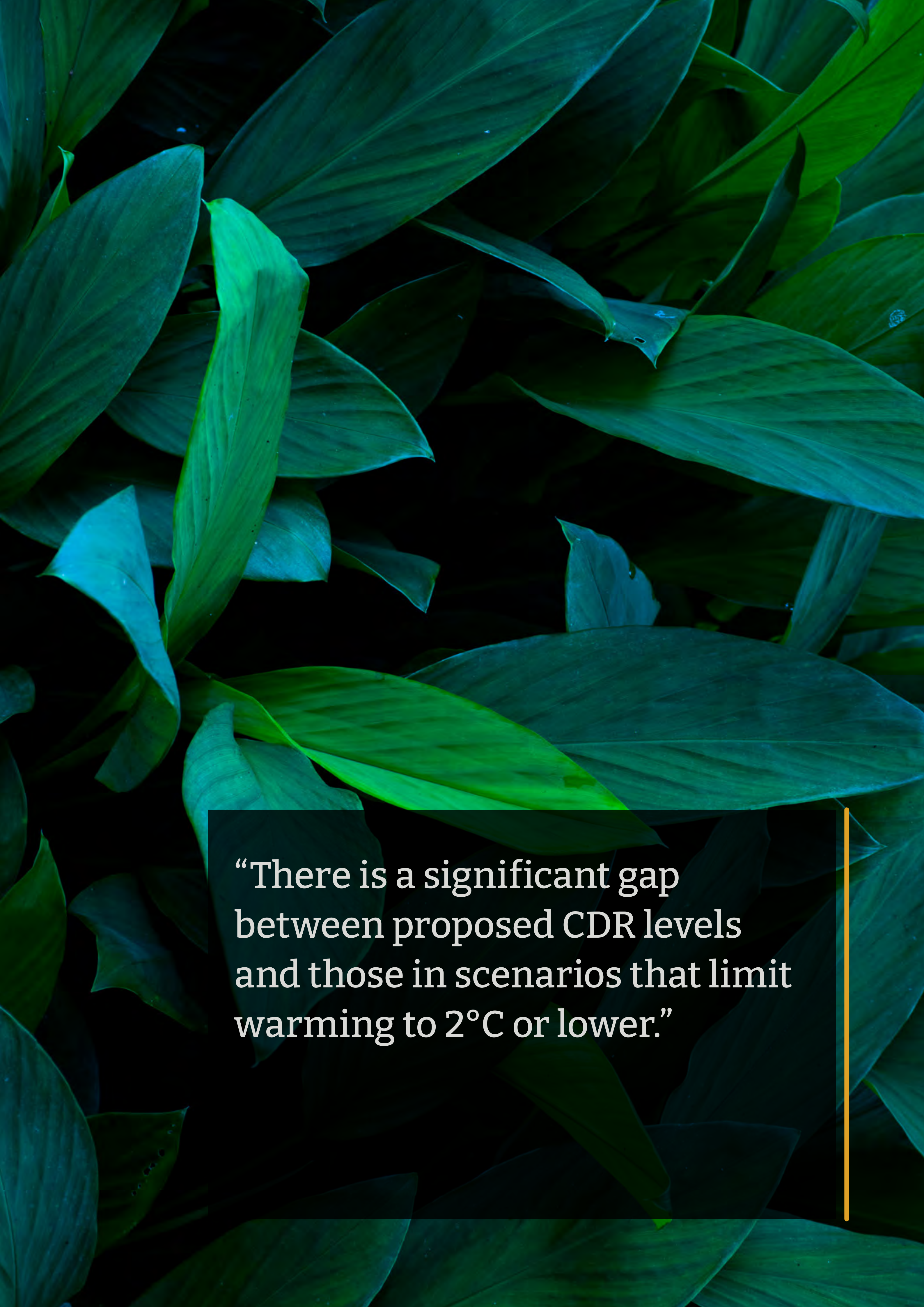
7.4 Limiting future reliance on CDR

Given uncertainties about scaling up CDR, our dependence on it can be limited by reducing emissions fast and using energy more efficiently.

Scenarios produced by the scientific community provide a wide set of possible pathways to meet global climate targets. As such, they provide general guidance on different approaches that can be used to limit global temperature rise, including near eliminating dependence on fossil fuels, electrifying most sectors of the economy, halting deforestation, as well as actively developing and deploying conventional CDR on land and novel CDR. Whether new technologies represented in models will become available at the scale assumed by different scenarios is highly uncertain, however.

The processes and technologies necessary to enable limiting warming to 1.5°C are already presently available – namely, shifting towards higher shares of renewable electricity and electrifying energy processes more broadly while beginning to use energy more efficiently. Current estimates of emissions from existing fossil-based extraction and infrastructure already risk exceeding the Paris Agreement long-term temperature goal, highlighting the importance of transitioning away from these energy sources[2[illegible],2[illegible],2[illegible]]. Simultaneously, novel CDR methods represented in pathways are either nascent, not currently deployed at scale, or still conceptual in nature. Thus, while most scenarios show that a non-trivial amount of novel CDR will be needed eventually, the degree to which different CDR methods will be able to sustainably achieve scale-up is highly uncertain. The most prudent approach is therefore to limit future reliance on novel CDR by actively reducing emissions with current technologies and enhancing regional cooperation to support countries outside of the Organisation for Economic Co-operation and Development to avoid carbon lock-in.

Caution should be taken when trying to use scenarios to directly measure CDR needs against emissions inventories reported by countries to the United Nations Framework Convention on Climate Change. Modelled scenarios consider human-induced (or "direct") emissions and reductions; countries, in their National Greenhouse Gas Inventories (NGHGIs) also consider natural areas when accounting for their total present-day emissions (see Chapter 8 – The CDR gap, Section 8.2). When accounting for the additional forested area considered by countries in the NGHGIs, present-day global CO_2 emissions are around 5.5 Gt lower than calculated by scientific studies such as the Global Carbon Budget. Further, the efficacy of this additional forested area in continuing to remove carbon will change over time depending on the future evolution of global mitigation. Better aligning these values and definitions between scientists and the policymaking community is an area of active development.



> “There is a significant gap between proposed CDR levels and those in scenarios that limit warming to 2°C or lower.”

Chapter 8 | The CDR gap

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We are not on track to meet the Paris temperature goal, in terms of either current or proposed Carbon Dioxide Removal (CDR). Closing the gap means expanding conventional CDR on land and rapidly scaling up novel CDR at the same time as urgently cutting emissions.

Box 8.1 Key findings

- In 2030, global scenarios that limit warming to 2°C or lower indicate additional Carbon Dioxide Removal (CDR) of 0.96 (0 to 3.4) $GtCO_2$ per year, compared with 2020. By contrast, countries have pledged an additional 0.1 to 0.65 $GtCO_2$ by 2030 in their Nationally Determined Contributions (NDCs) – a range that corresponds to unconditional and conditional NDCs. This suggests there is already an emerging CDR gap by 2030.

- In 2050, global scenarios that limit warming to 2°C or lower indicate additional CDR of 4.8 (0.58 to 13) $GtCO_2$ per year, compared with 2020. However, countries have only proposed an additional 1.5 to 2.3 $GtCO_2$ of CDR per year by 2050 in their long-term mitigation strategies. Only a minority of countries have provided transparent, quantifiable scenarios for CDR in long-term mitigation strategies so far. This implies a far more substantive CDR gap in 2050.

- This report distinguishes conventional CDR on land from novel CDR. The former includes afforestation, reforestation and forest management; the latter includes Bioenergy with Carbon Capture and Storage, Direct Air Carbon Capture and Storage, biochar, enhanced rock weathering and coastal wetland (blue carbon) management. Considering these separately is important to highlight the scale-up challenge.

- Global scenarios that limit warming to 2°C or lower scale up conventional CDR on land by a factor of 1.3 (0.95 to 2.2) by 2030 and factor of 2 (0.19 to 3.5) by 2050, compared with 2020.

- Countries plan to maintain or slightly increase current conventional CDR on land until 2030 according to their NDCs. This implies an increase by a factor of 1.1 to 1.3, compared with 2020 (for unconditional and conditional pledges, respectively). Few countries have submitted plans for scaling up conventional CDR on land by 2050, but those that have imply an increase by a factor of 2.7 to 4.2, compared with 2020.

- Global scenarios that limit warming to 2°C or lower involve scaling up novel CDR by a factor of 30 (0 to 540) by 2030 and a factor of 1,300 (260 to 4,900) by 2050, compared with 2020.

- So far, no countries have pledged to scale novel CDR by 2030 in their NDCs. Long-term mitigation strategies suggest some novel CDR deployment by 2050, increasing by a factor of about 300 compared with 2020.
- The next decade is crucial for novel CDR. Failure to create momentum in this formative phase will contribute to a widening gap by 2050 and beyond.
- Achieving the Paris temperature goal with only a small expansion of CDR is possible, but moves further out of reach every year in which greenhouse gas emissions do not fall substantially.

8.1 Components of the CDR gap

For the first time, we can compare current and proposed Carbon Dioxide Removal (CDR) with what would be required in different scenarios that meet the Paris temperature goal.

CDR is required, alongside ambitious emissions reductions, to meet the Paris temperature goal (see Chapter 1 – Introduction and Chapter 7 – Scenarios). But there are few dedicated efforts to track the development of CDR policy and deployments[226, 244], and none that estimate the size of the "CDR gap". It remains unclear to date, therefore, whether current efforts are on course to deliver enough CDR.

There are different components of the CDR gap. Here, we present a systematic comparison of *current*, *proposed* and *scenario-based* CDR to assess how on track we are to meet the Paris temperature goal. "Current CDR" refers to current levels of CDR deployment (see Box 8.2 and Chapter 6 – Deployment). "Proposed CDR" refers to future CDR levels inferred from country submissions to the United Nations Framework Convention on Climate Change (UNFCCC). These are the Nationally Determined Contribution (NDC) 2030 pledges, and scenarios in the long-term strategies through to 2050 (see Chapter 5 – Policymaking). Finally, "scenario-based CDR" refers to benchmarks of future CDR in scenarios that limit warming to 2°C or lower, drawn from the scientific literature (see Chapter 7 – Scenarios).

The aim of this chapter is to analyse the existence and size of a potential CDR gap, drawing on strands of information from across the report and building on efforts elsewhere that assess the ambitions and actions of countries in meeting the temperature goal of the Paris Agreement[227,228].

Current CDR

The assessment of current, proposed and Paris-consistent CDR requires a careful alignment of different data sources (Box 8.2) and definitions. In this assessment, we have developed a new analysis of current CDR (see Chapter 6 – Deployment). We begin with the net annual forest land sink as reported by countries in their national inventories, including harvest, regrowth and afforestation/reforestation, but excluding deforestation (taking the 2000-2020 average)[191]. Across the report, we refer to this as "conventional CDR on land", and it mainly consists of CO_2 capture and storage in forests and wood products (see Chapter 1 – Introduction for definitions of "conventional" and "novel" CDR).

An important implication of using the forest sink from national inventories is that it differs from estimates derived from global bookkeeping models developed in the scientific literature[150,229,230]. This is due to differences in how “anthropogenic” emissions and removals are defined and accounted for. National inventories for land use, land-use change and forestry (LULUCF), following the Intergovernmental Panel on Climate Change (IPCC) Guidelines[231], use an area-based approach that includes all or most of the emissions and removals occurring on land that countries consider managed. The concept of managed land used by countries may be broad, for example including parks and protected areas. Furthermore, national inventories, which are largely based on direct observations, typically include the combined impacts of both direct and indirect effects on managed land. In contrast, the bookkeeping model approach separates (1) direct emissions and removals from anthropogenic drivers (e.g. land-use change, harvest, regrowth) and (2) indirect emissions and removals due to changes in environmental conditions (e.g. fertilisation from rising atmospheric CO_2, climate change, nitrogen deposition).

In this chapter – as well as in Chapter 6 (Deployment) and Chapter 7 (Scenarios) – we remove indirect effects, aligning our measurement of conventional CDR on land with the bookkeeping model approach and the definition of CDR established in Chapter 1 (Introduction). To remove indirect effects, we use the OSCAR Earth system model, following conventions established in the land-use emissions literature[150,222,230]. This conversion reduces the estimate of conventional CDR on land to 2.0 ± 0.9 $GtCO_2$ per year, down from the original estimate (including indirect effects) of 6.4 ± 2.8 $GtCO_2$ per year, as reported in national inventories (Chapter 6 – Deployment). This is smaller than the comparable average estimate derived from bookkeeping models of 3.1 ± 0.9 $GtCO_2$[232], likely owing to those models’ inclusion of more detailed processes (notably of shifting cultivation) that simulate larger overall gross emissions and removals. The removal of indirect effects has implications for the other sources of data in the analysis, which we discuss in subsequent sections. Conventional CDR on land is uncertain to a high degree (approximately ±50%), although five-year averages have been relatively stable since 2000.

Anthropogenic activity on land drives emissions from deforestation, as well as removals. In this analysis, we isolate only the removals. Eliminating global deforestation is a critical condition for achieving the Paris temperature goal, but it is not discussed here[233].
To the estimate of conventional CDR on land we add the gross annual storage from “novel CDR” projects. These include Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), biochar, enhanced rock weathering and coastal wetland (blue carbon) management. Only a small component of total current CDR is from such novel CDR methods (0.002 $GtCO_2$ per year).

The resulting estimate of total current CDR is 2.0 $GtCO_2$ per year, of which 99% is conventional CDR on land. For comparison, total net greenhouse gas (GHG) emissions as a result of human activity – including removals as well as emissions from deforestation in the land sector – were 59 $GtCO_2e$ in 2019[1].

Proposed CDR

Based on the available information, national policymaking on CDR is in its infancy, and few countries have proposed a significant scaling of CDR in documents submitted to the UNFCCC. This finding is based on a qualitative analysis of policy activity in leading countries (see Chapter 5 – Policymaking) and a quantitative assessment of NDCs and long-term mitigation strategies (see Box 8.2).

The NDCs indicate that countries plan to slightly increase current levels of conventional CDR on land up to 2030. Unconditional pledges in the NDCs amount to approximately 2.1 $GtCO_2$ per year in 2030, while conditional pledges amount to 2.6 $GtCO_2$ per year (see Box 8.2 for the differences between conditional and unconditional pledges). Many countries pledge to reduce deforestation emissions, but only a few pledge to increase forest sinks. Together with a few countries that project a decline in their sinks, an overall small net increased in conventional CDR on land is implied by the NDCs. No countries pledge a significant upscaling of novel CDR methods in their NDCs.

Nonetheless, a lack of transparency hinders assessment: many countries indicate that the LULUCF sector is a component of their pledge, but few provide sufficient information to fully quantify this contribution, particularly in terms of the forest sink, potentially leading to an underestimate[153, 234]. To date, no countries have included novel CDR in their NDCs, even if some mention – but do not quantify – methods such as coastal wetland management or components of CDR such as Carbon Capture and Storage in their qualitative description of planned mitigation efforts. The relative lack of attention given by policymakers to novel CDR is further evidenced by the limited number of BECCS, DACCS and biochar projects in the pipeline. Currently announced projects will amount to just a small addition of 0.009 $GtCO_2$ per year in 2025, on top of existing capacity (see Chapter 6 – Deployment).

Out to 2050, the long-term mitigation strategies indicate that governments are starting to consider a wider portfolio of methods beyond conventional CDR on land. Unfortunately, only a limited number of countries have published long-term mitigation strategies (unlike NDCs, countries are not obligated to publish such strategies under the Paris Agreement; see Box 8.2). Further, the strategies and scenarios in these documents are not formal policy commitments by countries but, rather, illustrate how governments may choose to mitigate emissions in the longer term and, in particular, how net-zero emissions could be reached. Many of those submitted contain ambiguities and lack transparency. As a result, the long-term mitigation strategies are a pragmatic, but very imperfect, starting point for an assessment of proposed removals up to 2050.

Of the 53 long-term mitigation strategies submitted by the end of September 2022, only 22 outline mitigation scenarios with quantifiable CDR levels in 2050. Taking the highest combined estimate of CDR from these scenarios, removals total about 2.9 $GtCO_2$ per year in 2050, of which the majority (78%) is conventional CDR on land. The lowest estimate is 2.1 $GtCO_2$ per year, of which 70% is conventional CDR on land. The range reflects the differing scenarios outlined by governments, which have different balances of emission reductions versus CDR deployments.

Box 8.2 Sources used to estimate the CDR gap and their uncertainties

Current Carbon Dioxide Removal (CDR) in this assessment is based on the forest land sink in national greenhouse gas inventories, taking the 2000-2020 average of ~2.0 $GtCO_2$ per year compiled in Grassi et al.[191]. This is combined with a database of existing Bioenergy with Carbon Capture and Storage, Direct Air Carbon Capture and Storage, biochar, enhanced rock weathering and coastal wetland (blue carbon) management projects (see Chapter 6 – Deployment for further details). There are large uncertainties in land-based removals due to data limitations in inventories and complex impacts of both human and natural drivers. Further, there are uncertainties in the number of known novel CDR projects (limited data is available for projects in China, for instance) and their verified levels of storage.

Proposed CDR levels are based on countries' Nationally Determined Contributions (NDCs) and long-term mitigation strategies, both of which are submitted by countries to the United Nations Framework Convention on Climate Change under the Paris Agreement. Private sector announcements are not included here, although early indications suggest they may be substantial (see Chapter 3 – Innovation).

A large amount of literature is dedicated to analysing the NDCs and their implications for the land use, land-use change and forestry flux in 2030, which requires a number of assumptions to be made[152,153,234,235]. Since this chapter focuses on the forest land sink only, we take the 2011-2020 average forest sink from Grassi et al. (2022)[191] as the baseline for removals in the NDCs. We then document where countries commit to additional specific removals or changes to the forest sink in their NDCs, using all documents available by June 2022 following the method of Grassi et al. (2017)[153]. "Conditional" pledges are the sum of pledges that would be fulfilled on the condition that stated actions are taken by other countries (e.g. some countries base their pledges on the condition that they are provided with climate finance or assistance). "Unconditional" pledges refer to those that would be taken regardless of action in other countries.

Proposed CDR in 2050 is quantified using the scenarios in the long-term mitigation strategies (also known as the Long-term Low Emissions Development Strategies, or LT-LEDS). We build on recent efforts to summarise the 2050 CDR levels described in these documents[149,236], finding that as of September 2022 such information exists for most European Union countries, the Russian Federation and the United States, but few others. We extract levels of CDR by 2050 from the underlying scenarios in the long-term mitigation strategies, where available, excluding all "business as usual" or "no policy" scenarios in order to have a comparable set that incorporates climate action. Some large emitters such as China, India and Indonesia have submitted a long-term mitigation strategy but do not provide sufficient information to quantify CDR efforts, while many others have yet to submit one.

In their scenarios, most countries describe the net flux of emissions and removals, rather than removals only. For simplicity, we assume that no deforestation occurs in 2050 under these scenarios and therefore count these net fluxes as removals. This is supported by the fact that countries with high current levels of deforestation, such as Brazil, the Democratic Republic of the Congo, and Indonesia, do not have a quantified long-term mitigation strategy, while other countries with lower current levels of deforestation that do have a quantified scenario, such as Cambodia and Colombia, aim to achieve zero deforestation in their long-term strategies. Of course, this likely underestimates total removals from these countries in 2050, as a certain baseline of emissions on land will always occur, but here we opt for a transparent and simple approach to render the long-term mitigation strategy data comparable with proposed and scenario-based CDR.

The NDCs and long-term strategies are oriented around national inventories and hence include indirect anthropogenic effects, such as CO_2 fertilisation. We therefore remove indirect effects in the NDCs and long-term strategies to render them comparable with the estimates of current and scenario-based CDR. We do this by distinguishing (1) maintained current sinks and (2) newly proposed sinks in the NDC pledge or long-term strategy scenario. These can be distinguished from the document texts or by cross-referencing them with current national inventories. For (1), we apply the ratio of direct to direct and indirect removals (2.0/6.4), as identified in Chapter 6 (Deployment). For (2), we preserve the original value, as newly proposed afforestation or regeneration implies largely direct removals. For example, the Russian Federation's long-term strategy proposes to expand the current flux of ~650 $MtCO_2$ per year to 1,200 $MtCO_2$ per year; we assume a direct current sink of ~200 $MtCO_2$ per year (650 × (2.0/6.4)), plus an additional 550 $MtCO_2$ per year of direct removals, for a total of 750 $MtCO_2$ per year. We apply a global ratio of direct to direct and indirect removals, which may obscure differing contributions of indirect effects by region or biome (an important issue for future research).

Scenario-based CDR levels are based on scenarios drawn from the integrated assessment model (IAM) literature. These scenarios depict alternative future pathways of how the global energy and land-use system can evolve to limit global temperature rise to 1.5°C and 2°C. We use the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC AR6) IAM scenario database, scenario categories C1-C31. These categories have varying probabilities of limiting temperature rise, as well as different levels of peak warming (see Table 7.1 in Chapter 7 – Scenarios). Not all the scenarios are necessarily consistent with the goal of the Paris Agreement. Collectively, we refer to all C1-C3 scenarios as "2°C or lower" scenarios.

Scenarios that limit warming to 1.5°C or 2°C

The amounts of CDR required to limit warming to 2°C or lower are represented here using integrated assessment model scenarios (see Box 8.2 and Chapter 7 – Scenarios). A consistent characteristic of these scenarios is that they all feature multiple gigatonnes of carbon removals annually. However, the amount of CDR in scenarios varies considerably, shaped by a number of factors (see Chapter 7 – Scenarios, Section 7.3).

Table 8.1 depicts the additional CDR by 2030 and 2050 projected across all the scenarios considered. In the second half of the century, conventional CDR on land tends to saturate or even decline, while most of the growth then occurs through novel CDR methods such as BECCS and DACCS (see Figure 7.1 and Table 7.2 in Chapter 7 – Scenarios).

Table 8.1. *Additional Carbon Dioxide Removal (CDR) in scenarios from 2020 to 2030 and 2050. 2°C or lower scenarios are reported as the median and 5-95th percentiles. In the lower range of some of these scenarios, conventional CDR on land actually decreases compared with 2020, explaining the negative numbers. The additional conventional CDR on land in the long-term mitigation strategies(*) is based on the difference between the land use, land-use change and forestry flux in country scenarios versus their latest national inventories in 2020, converted to remove indirect effects.*

Scenarios	Additional conventional CDR on land from 2020 (GtCO2 per year)		Additional novel CDR from 2020 (GtCO2 per year)		Additional CDR (total) from 2020 (GtCO2 per year)	
	2030	2050	2030	2050	2030	2050
2°C or lower scenarios	0.8 [-0.11 - 3]	2.5 [-1.8 - 6.2]	0.059 [0 - 1.1]	2.7 [0.52 - 9.7]	0.96 [0 - 3.4]	4.8 [-0.58 - 13]
Focus on Demand Reduction	1	2.3	0	0	1	2.3
Focus on Renewables	2.7	4.1	0.14	0.91	2.9	5.1
Focus on Carbon Removal	0.66	4.0	0.95	3.5	1.6	7.4
Nationally Determined Contributions (NDCs)	[0.1 - 0.65]	NA	0	NA	[0.1 - 0.65]	NA
Long-term mitigation strategies	NA	[0.9 - 1.7]*	NA	-0.6	NA	[1.5 - 2.3]*

In addition to the full set of scenarios, we highlight **three illustrative scenarios**, which depict different ways to meet the Paris temperature goal (see Chapter 7 – Scenarios). These scenarios do not cover the whole range of possible scenario futures, but they illustrate that key mitigation choices deeply influence how much CDR will be required by mid-century.

- *Focus on Demand Reduction* – Global energy demand is rapidly reduced through improvements in the efficiency of end-use devices and service delivery. This scenario limits warming to 1.5°C with a large contribution from conventional CDR on land (4.8 $GtCO_2$ in 2050) but no additional CDR deployments from novel CDR.

- *Focus on Renewables* – This scenario limits warming to 1.5°C by implementing a rapid supply-side transformation, based on the deployment of increasingly cost-competitive renewable energy technologies. It also envisions a large contribution from conventional CDR on land (6.7 $GtCO_2$ in 2050), but this is complemented by removals from BECCS (0.91 $GtCO_2$ in 2050).

- *Focus on Carbon Removal* – This scenario holds warming to 1.5°C but envisions a slower transformation of the energy supply system with an incomplete phase out of fossil fuels. This scenario also has a large contribution from conventional CDR on land (6.3 $GtCO_2$ in 2050), but significantly more CDR from BECCS and DACCS than in the other illustrative scenarios (3.5 $GtCO_2$ in 2050). This scenario does not feature extreme scaling behaviour for novel CDR but is close to the median of C1 scenarios

All three illustrative scenarios involve immediate, rapid and sustained emission reductions, reaching a peak in global net GHG emissions in 2020 or shortly after, placing them on a path to net-zero CO_2 emissions between 2050 and 2065 (see Figure 7.2 in Chapter 7 – Scenarios). *Focus on Demand Reduction* reduces gross GHG emissions by 48% between 2020 and 2030, whereas *Focus on Renewables* and *Focus on Carbon Removal* reduce them by 31% and 33%, respectively.

8.2 The CDR gap: Conventional CDR on land

Almost all scenarios that limit warming to 2°C or lower expand conventional CDR on land. Yet even maintaining current conventional CDR on land requires dedicated policies and management.

Figure 8.1 brings together estimates of current and proposed levels of CDR and compares these with 2°C or lower scenarios. In this comparison, we observe that current levels of CDR (2.0 $GtCO_2$ per year) need to be at least maintained in the coming decades: all scenarios that reach the Paris Agreement goal require a baseline level of removals to counterbalance expected residual emissions. Maintaining current levels of CDR – which, as it stands, are almost entirely attributable to conventional CDR on land – is a precondition for limiting warming to 2°C or lower. Yet the majority of scenarios do not just maintain current conventional CDR on land but expand it in the coming decades (Table 8.1).

Insofar as we can infer from the NDCs, countries indeed plan to slightly increase current conventional CDR on land. However, these increases fall short of those projected in the scenarios. Proposed CDR from conditional NDCs reaches 2.6 $GtCO_2$ per year in 2030, with 0.65 $GtCO_2$ of additional CDR entirely from conventional CDR on land (the NDCs do not include any novel CDR). In comparison, the further expansions in conventional CDR on land in our three focus scenarios by 2030 are quantified at an additional 0.66 $GtCO_2$ per year (*Focus on Carbon Removal*), 1.0 $GtCO_2$ per year (*Focus on Demand Reduction*) and 2.7 $GtCO_2$ per year (*Focus on Renewables*). These all give rise to a potential near-term ambition gap. Our focus scenarios characterise the range that most scenarios in the IPCC WG3 database span, but we note the existence of scenarios with even higher deployments of conventional CDR on land by 2030.

Further, there is a clear signal in the long-term strategies that forest sinks are a key component of net zero targets. Among those countries with quantifiable scenarios, most plan to at least maintain current forest sinks, while there are several prominent examples of ambition to expand these removals, such as scenarios from the United States (an increase from 0.8 $GtCO_2$ per year in 2020 to 1.3 $GtCO_2$ per year in 2050) and the Russian Federation (an increase from 0.7 $GtCO_2$ per year in 2020 to 1.2 $GtCO_2$ per year in 2050). However, these country estimates include indirect effects; when indirect effects are removed and country scenarios are aggregated, newly proposed conventional CDR on land is much smaller, at 0.9-1.7 $GtCO_2$ per year. This compares to expansion in our three focus scenarios quantified at 3.9 $GtCO_2$ per year (*Focus on Carbon Removal*), 2.3 $GtCO_2$ per year (*Focus on Demand Reduction*) and 4.1 $GtCO_2$ per year (*Focus on Renewables*). Nonetheless, a number of countries with large land areas and potentially significant ambitions regarding other CDR methods are absent from this 2050 data, including Brazil, China and India, whose inclusion would very likely significantly increase proposed CDR levels for 2050.

Countries will need to implement land-use policies and forest management practices just to maintain current conventional CDR on land. These removals are sustained in managed forests by balancing growth and harvest, shifting carbon stocks to long-lasting wood products, and promoting afforestation and reforestation. Forest fires, pests and other disturbances will increasingly threaten conventional CDR on land owing to global warming, requiring further interventions (e.g. thinning, prescribed fires) to preserve these removals[237]. Very high uncertainties in current (and hence future) levels of conventional CDR on land mean that it may not be precisely known if these removals are on track to match requirements in the scenarios.

Further, countries may have to deal with a weakening of indirect effects, such as CO_2 fertilisation, as atmospheric CO_2 levels stabilise. In Paris-relevant scenarios, indirect effects could be halved by 2050[150]. It is unclear whether such a weakening is accounted for in national long-term strategies. If not, countries may find that they cannot reach net zero under their current plans for scaling conventional CDR on land. On the other hand, if countries do not reduce emissions in line with the Paris temperature goal, indirect effects would be preserved to some extent, but forest sinks would instead be threatened by climate impacts. The future robustness of forest sinks is therefore far from guaranteed.

8.3 The CDR gap: Novel CDR

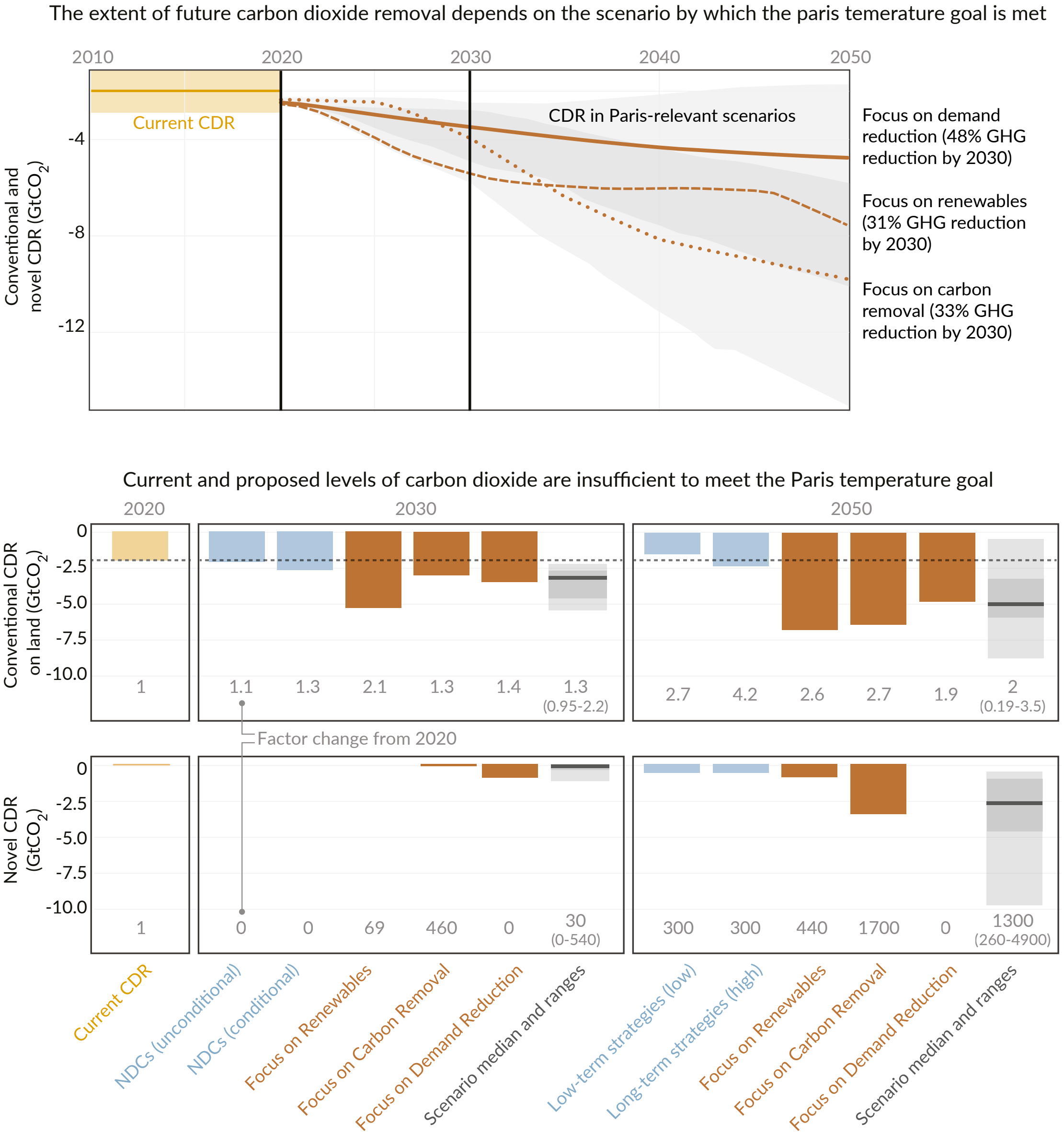
Almost all scenarios that limit warming to below 2°C require novel CDR to be scaled up, but countries currently have few firm plans to do this.

Almost all scenarios that limit warming to below 2°C do not just increase conventional CDR on land but also scale up novel CDR rapidly in the coming decades. In the case of *Focus on Renewables* and *Focus on Carbon Removal*, novel CDR is already implemented by 2030, amounting to 0.14 and 0.95 $GtCO_2$ per year, respectively. Across all below 2°C scenarios, there is a median of 0.059 (0 to 1.1) $GtCO_2$ per year of novel CDR by 2030. While these numbers may appear small, they mean growing novel CDR deployment by a factor of 30 (0 to 540), within seven years.

Although many pathways that limit warming to below 2°C highlight stark demands for novel CDR even in the short- to mid-term, countries so far only have limited plans to scale it up (Chapter 5 – Policymaking), and the NDCs do not include any such plans. However, the innovation literature highlights that the early years of technology development (the “formative phase”) are consequential in determining how fast and to what level novel CDR can be scaled in the longer term[238]. The extent of early deployment of novel CDR over the next decade is therefore crucial, as a failure to create momentum in this formative phase will contribute to a widening gap by 2050 and beyond.

Looking to 2050, the most ambitious scenarios in the long-term mitigation strategies describe total novel CDR removals of 0.6 $GtCO_2$ per year, mainly driven by the United States (0.5 $GtCO_2$ per year). Again, this falls short of scale-up rates in the scenarios, which range from novel CDR levels of 0.91 (*Focus on Renewables*) to 3.5 $GtCO_2$ per year (*Focus on Carbon Removal*), or 450 to 1,750 times larger than current levels. Across the entire sample of below 2°C scenarios, many scale up CDR even more by 2050 – with a median of 1,300 times (260 to 4,900) greater than today’s level.

Only 22 countries have so far submitted quantifiable long-term strategies. While it is possible that the shortfall of novel CDR could be made up by new countries submitting long-term mitigation strategies with underlying scenarios, so far most country scenarios have a far greater focus on conventional CDR on land than on novel CDR. If we include indirect effects (as is standard practice in reporting by countries), then just 16-21% of removals in the long-term strategies come from novel CDR. This suggests that a serious "CDR ambition gap" is emerging: few countries have developed transparent plans to scale novel CDR, leaving a significant shortfall between proposed and scenario-based CDR by 2050.


The extent of future carbon dioxide removal depends on the scenario by which the paris temerature goal is met

Current and proposed levels of carbon dioxide are insufficient to meet the Paris temperature goal

Figure 8.1. *The CDR gap. Carbon Dioxide Removal (CDR) includes conventional CDR on land (the managed forest land sink) plus novel CDR (gross removals from Bioenergy with Carbon Capture and Storage, Direct Air Carbon Capture and Storage, biochar, enhanced rock weathering and coastal wetland (blue carbon) management). Conventional CDR on land estimates exclude sinks that are treated as "natural" or "indirectly human induced" in the global carbon budgeting literature. In the upper panel, the blue line depicts total current CDR and the shaded blue area indicates the uncertainty. The orange shaded area depicts the 5th to 95th and 25th to 75th percentile of Intergovernmental Panel on Climate Change C1-C3 scenarios that limit warming to below 2°C. The orange lines depict three Focus Pathways that limit warming to 1.5°C, based on varying assumptions of action and technology diffusion. The emission reductions described for each scenario in the top panel refer to gross greenhouse gas (GHG) emissions. The lower panels show the contributions of conventional CDR on land and novel CDR in the Focus scenarios, as well as the overall scenario median and ranges (as in the top panel), versus estimates of current and proposed CDR from Nationally Determined Contributions (NDCs) and long-term mitigation strategies. It also depicts the relative scale-up of each category compared with levels in 2020. In the case of conventional CDR on land in the*

long-term strategies, this refers to the difference between the land use, land-use change and forestry flux in country scenarios versus those countries' latest national inventories in 2020. In the case of the scenario ranges, the median and 5th to 95th factor change is shown.

8.4 A low-CDR world

A few scenarios meet the Paris temperature goal with only a small expansion of CDR, but they require aggressive reductions in GHG emissions, which we are not on track to achieve.

There are some scenarios that project comparatively modest increases in current conventional CDR on land, while avoiding novel CDR altogether. These scenarios lie at the lowest end of total CDR requirements across the 21st century and include the *Focus on Demand Reduction* illustrative scenario, which slightly more than doubles current conventional CDR on land to 4.8 $GtCO_2$ per year by 2050. A comparison of current and proposed CDR with these scenarios would suggest that the overall CDR gap is manageable, so long as efforts to expand current conventional CDR on land to meet these levels are successful. However, a key feature of these low-CDR scenarios is that they involve highly ambitious and rapid emission reductions. *Focus on Demand Reduction* requires an immediate implementation of climate policies leading to a global emissions peak in 2020, followed by a rapid pathway to net-zero CO_2 emissions by 2059[239]. Total gross GHG emissions between 2020 and 2030 are reduced by 48% (30$GtCO_2$eq) in this scenario.

To what extent is such a pathway still within reach? According to the latest assessment of the "emissions gap", current policy scenarios project emissions of 58 $GtCO_2$ in 2030, while unconditional and conditional NDC scenarios project emissions of 55 and 52 $GtCO_2$, respectively[240]. In other words, global GHG emissions are set to remain approximately stable between now and 2030 if the unconditional NDCs are implemented or to slightly decrease if conditional NDCs are implemented. Furthermore, as of 2021, global GHG emissions have begun to grow again[240,241]. This suggests that key milestones for planning ambitious mitigation pathways, implementing policies and reducing emissions are not being met, pushing a low-CDR worldfurther out of reach.

8.5 Closing the CDR gap

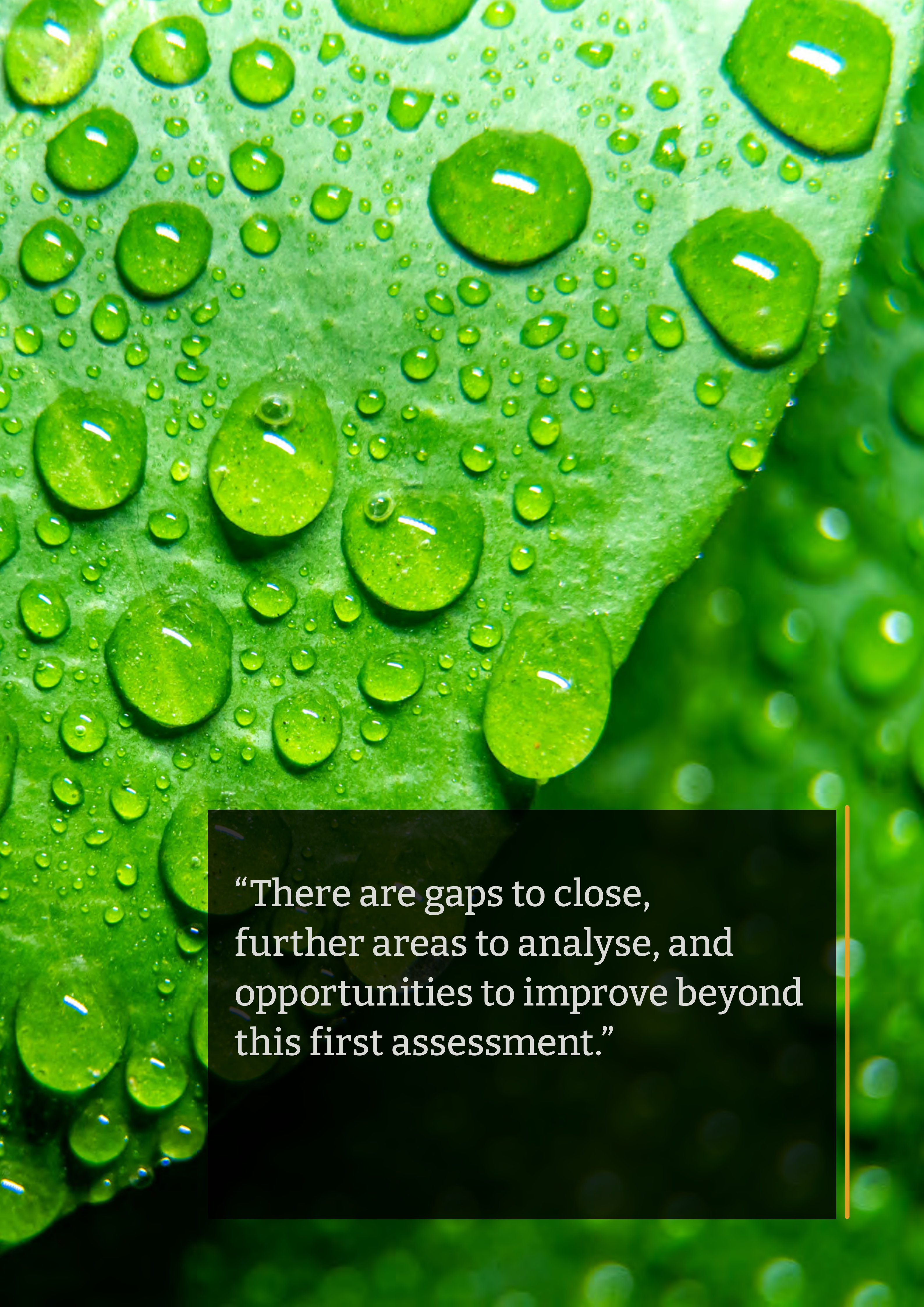
Closing the CDR gap requires us to rapidly reduce emissions, expand conventional CDR on land rapidly scale up novel CDR. If novel CDR is not supported now, during the formative phase of technology development, countries risk a widening CDR gap by 2050. For every year that GHG emissions do not fall substantially, our dependence on CDR increases.

The scenario literature unequivocally highlights that reducing GHG emissions to a small fraction of today's levels is the foundation for limiting global temperature rise to 2°C or below. The faster this happens, the better the chance we have of scaling up CDR sustainably: lower cumulative and residual emissions will ultimately reduce the amount of CDR we require to reach net-zero GHG emissions and to achieve the Paris temperature goal (Chapter 7 – Scenarios).

For every year in which GHG emissions do not fall substantially, our dependence on

CDR increases and a low-CDR world is pushed further out of reach. Key milestones for implementing policies, peaking emissions and ultimately achieving the required emission reduction rates are being missed. As such, it is critical to redouble mitigation efforts but also to explore opportunities for integrated, cross-sector policies that can support both emission reductions and CDR upscaling. For instance, a food system transition to lower meat diets would lower "hard-to-abate" emissions in the agriculture sector that otherwise must be compensated for by CDR, while potentially freeing up space for forest sink removals[242,243]. Developing novel CDR is an important climate measure, given our increasing dependence on such technologies. The lack of comprehensive information, plans and priorities on novel CDR from countries is especially problematic given the long time horizon needed to safely scale up these methods (see Chapter 3 – Innovation). Scenarios already implement substantial novel CDR levels by 2050, reflecting matured BECCS, DACCS, biochar and enhanced rock weathering industries with technologies ready for widespread adoption. Achieving short- to medium-term milestones along the long road to these levels is therefore key, highlighting the need for increased research, investment and policy support for novel CDR.

Pathways that limit warming to 1.5°C or 2°C start scaling novel CDR before 2030. While levels of novel CDR may appear small, they imply substantial increases in deployments. Just 0.1 $GtCO_2$ removed by novel CDR in 2030 implies an increase in current levels by a factor of 50 by the end of the decade. Furthermore, the literature on technology upscaling has shown that the early, formative phases of technology development will strongly determine what contribution novel CDR can make to climate mitigation by mid-century[238]. If novel CDR does not receive support during this formative phase, ensuring that these technologies are ready to deliver significant removals in a few decades, countries risk a widening CDR gap by 2050. Ultimately, this report highlights three key criteria for closing the CDR gap. First, current conventional CDR on land needs to be expanded, likely requiring additional policies and the active management of forest sinks to protect removals from future climate impacts. Second, novel CDR needs to be developed and scaled to meet future possible needs, which will require active support and investment from countries. Third, and above all, our dependence on CDR needs to be limited by implementing stringent emission reductions as soon as possible.



“There are gaps to close, further areas to analyse, and opportunities to improve beyond this first assessment.”

Chapter 9 | Future assessments

This report represents a first step towards a comprehensive scientific assessment of the state of Carbon Dioxide Removal (CDR). It builds on and complements a growing number of initiatives to improve the information landscape around CDR. We, the scientific convenors of this report, believe that such an assessment has an important role to play, informing and aiding the efforts of those who seek to develop CDR as part of successful climate action. There are, however, gaps to close, further areas to analyse, and opportunities to improve beyond this first step. The sections below synthesise the priority areas we have identified, on which assessments in subsequent years can build.

9.1 Expanding the community

Nearly 30 experts have contributed to this report, across three continents and a range of disciplines. And yet our author team is concentrated in Europe and North America, representing only a subset of relevant contexts and perspectives for understanding and tracking CDR developments. We are keen to grow the community to make CDR information more complete, reliable, accessible and inclusive. Specific opportunities for expanding the community include:

- Providing updated assessments of the state of individual CDR methods with regard to costs, potentials, hazards, co-benefits, technology readiness, potential and other factors.

- Incorporating scientific literature in other languages, grey literature, and local and indigenous knowledge.

- Locating and reviewing research on public perceptions from specific stakeholder groups (e.g. local communities affected by deployment, indigenous groups facing land conflicts).

- Assembling a more complete picture of research and innovation across countries and methods, similar to the process followed by the International Energy Agency for energy Research, Development and Demonstration (RD&D) and by the International Renewable Energy Agency for tracking renewable projects and their pipelines.

- Broadening the analysis of CDR policies and governance. This includes quantifying CDR plans beyond those in United Nations Framework Convention on Climate Change (UNFCCC) documents. It may also include case studies of other countries, for instance high-income economies with different emissions profiles (such as Australia, Finland, Iceland, New Zealand, Sweden and Switzerland), emerging economies with growing emissions (such as China, India, and Indonesia) and low-income countries with low emissions levels but high CDR potential. More attention to policy instrument design and evaluation would be valuable, including in areas such as monitoring, reporting and verification.

- Developing local-level and up-to-date information on CDR projects. Currently, our data on novel CDR deployment has limited geographic coverage, with most recorded CDR projects in Europe and North America. The data also generally provides limited coverage of CDR methods such as biochar, which often produce CDR via a large number of small, independently owned plants instead of large commercial plants, as is the case for Bioenergy with Carbon Capture and Storage and Direct Air Carbon Capture and Storage.

9.2 Improving the data

Throughout this report, we highlight a number of areas in which data is hard to assess, is incomplete or is missing. A better picture of the state of CDR is possible, particularly with the following additions:

- The scientific literature on CDR is vast and growing. Manual tracking and synthesising is now intensive and inefficient. Different scientific communities are adopting "living evidence" as a new paradigm for informing research, policy and practice. Using the machine-learning pipeline we have developed for tracking CDR research, we want to create a "living map" of CDR evidence – an interactive, open access and publicly available tool. Such a map can support other elements of evidence synthesis in this assessment, such as on technology readiness, cost, mitigation potential, hazards and co-benefits.

- Our assessment of innovation could include data from RD&D programmes that include CDR methods but that are not labelled as such (particularly land-based methods). Innovation investments by the private sector are typically harder to measure but are likely to be increasingly important as the industry matures.

- Governments could provide greater consistency, transparency and detail on how countries intend to balance sources and sinks of greenhouse gases. The Nationally Determined Contributions provide sparse information regarding conventional CDR on land and none on novel CDR. Long-term mitigation strategies do so in part, but only for a limited number of countries.

- As noted in Section 9.1, data for current novel CDR deployment is limited. No single repository exists to track all projects. Where available, information is not standardised and is often limited. In particular, our estimates are for gross amounts of CO_2 captured and do not account for the greenhouse gas balance over the full project lifecycles. Ideally, project data should include the CDR pathway used (i.e. the carbon pools between which carbon is moved), the location of activity, the time series of greenhouse gas sources and sinks during the full project lifecycle (including any re-release of carbon back into the atmosphere), and the time series of any subsequent transfers of carbon between non-atmospheric pools (including any fossil carbon captured during the process).

- Long-term scenarios from modelling groups should be collected and vetted more regularly and should include more detail on CDR. Specific outputs are needed for conventional CDR on land, and estimates of the gross land sink should be harmonised across different land-use models, as this is a key uncertainty in assessing and comparing the CDR levels within these scenarios. There is also scope for new scenarios that include broader portfolios of novel CDR.

9.3 Honing the analysis

There is further scope to clarify key concepts around CDR, develop consistent analytical approaches and improve analytical tools. This includes:

- Resolving definitional issues for CDR. In particular, durability is a key concept, but one that is not clearly defined for practical applications. It will be important to improve definitions and categorisation of CDR methods in ways that are widely agreed, scientifically justified and relevant for decision-making[2][illegible].

- Tracking emergent new CDR methods. The pace of innovation means that new methods are being proposed and tested rapidly, through either new processes for capture, conversion and storage or new combinations of existing processes. Such tracking will require analysis not only of scientific publications but also of patents, projects and companies.

- Adopting a more consistent approach to CDR methods across the analyses of innovation, public perception, policy, deployment and scenarios. Currently, the analyses we draw from adopt sets of varying detail and completeness. Some focus only on components of CDR methods (e.g. Direct Air Capture without considering storage) or exclude some methods (e.g. converting biomass to bio-oil injected into geological storage).

- Tracking policy developments more thoroughly in several ways, such as through case studies of states and cities developing CDR policies, analysis of interactions between government action and the private sector (including voluntary markets and advance purchase agreements), analysis of developments in the UNFCCC, evaluation of multilateral agreements and cooperation platforms (such as the Bonn Challenge, the 4p1000 Initiative and Mission Innovation on CDR), and analysis of developments to monitor, report and verify CDR activities.

- Encouraging inclusion and analysis of a broader set of CDR methods in integrated assessment models. This would enable a better understanding of how different CDR methods interact and how deployment risks can be hedged via more methods, each deployed at more moderate scales.

- Further improving methods for calculating conventional CDR on land. Generating comparable estimates for current, planned and Paris-consistent levels has required us to make assumptions about land emissions (from deforestation in particular) and indirect effects. These are a step forward but remain an approximation. Countries could improve this by separately reporting sources and sinks as well as direct and indirect fluxes from managed land. In addition, our initial methods for estimating indirect effects, both now and in the future as the climate changes, can be improved.

References

1. IPCC. Summary for Policymakers. in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Shukla, P. R. et al.) (Cambridge University Press, 2022).
2. Hans, F., Kuramochi, T., Black, R., Hale, T. & Lang, J. Net Zero Stocktake 2022. https://zerotracker.net/analysis/net-zero-stock-take-2022.
3. Minx, J. C. et al. Negative emissions—Part 1: Research landscape and synthesis. Environ. Res. Lett. 13, 063001 (2018).
4. Fuss, S. et al. Negative emissions—Part 2: Costs, potentials and side effects. Environ. Res. Lett. 13, 063002 (2018).
5. Nemet, G. F. et al. Negative emissions—Part 3: Innovation and upscaling. Environ. Res. Lett. 13, 063003 (2018).
6. Bui, M. & Mac Dowell, N. Greenhouse Gas Removal Technologies. (Royal Society of Chemistry, 2022).
7. Wilcox, J., Kolosz, B. & Freeman, J. CDR Primer. (2021).
8. CDR Database. Carbon Plan https://carbonplan.org/research/cdr-database.
9. Energy Transitions Commission. Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive. https://www.energy-transitions.org/publications/mind-the-gap-cdr/ (2022).
10. Greenpeace UK. Net expectations: assessing the role of carbon dioxide removal in companies' climate plans. https://www.greenpeace.org.uk/resources/net-expectations-cdr-briefing/ (2021).
11. van Diemen, R. et al. IPCC, 2022: Annex I: Glossary. in IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Shukla, P. R. et al.) (Cambridge University Press, 2022).
12. Zero Emissions Platform. Europe needs a definition of Carbon Dioxide Removal. https://zeroemissionsplatform.eu/europe-needs-a-definition-of-carbon-dioxide-removal/ (2020).
13. Babiker, M. et al. Cross-sectoral perspectives. in IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Shukla, P. R. et al.) (Cambridge University Press, 2022).
14. Buendia, E. et al. Refinement To the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. (2019).
15. Lyngfelt, A., Johansson, D. J. A. & Lindeberg, E. Negative CO2 emissions - An analysis of the retention times required with respect to possible carbon leakage. Int. J. Greenhouse Gas Control 87, 27–33 (2019).
16. Fankhauser, S. et al. The meaning of net zero and how to get it right. Nat. Clim. Chang. 12, 15–21 (2022).
17. Australian Government Clean Energy Regulator. The Emissions Reduction Fund and permanence on the land. https://www.cleanenergyregulator.gov.au/DocumentAssets/Pages/The-Emissions-Reduction-Fund-and-permanence-on-the-land.aspx (2018).
18. California Air Resources Board. Carbon Capture and Sequestration Protocol under the Low Carbon Fuel Standard. https://ww2.arb.ca.gov/sites/default/files/2020-03/CCS_Protocol_Under_LCFS_8-13-18_ada.pdf (2018).
19. Nabuurs, G-J., R. Mrabet, A. Abu Hatab, M. Bustamante, H. Clark, P. Havlík, J. House, C. Mbow, K.N. Ninan, A. Popp, S. Roe, B. Sohngen, S. Towprayoon. Agriculture, Forestry and Other Land Uses (AFOLU). in IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Shukla, P. R. et al.) (Cambridge University Press, 2022).
20. United Nations Environment Programme. Emissions Gap Report 2017. http://www.unep.org/resources/emissions-gap-report-2017 (2017).
21. Bellamy, R. & Osaka, S. Unnatural climate solutions? Nat. Clim. Chang. 10, 98–99 (2020).
22. Seddon, N. et al. Getting the message right on nature-based solutions to climate change. Glob. Chang. Biol. 27, 1518–1546 (2021).
23. Sandalow, D., Aines, R., Friedmann, S. J., McCormick, C. & Sanchez, D. L. Biomass Carbon Removal and Storage (BiCRS) Roadmap. https://www.icef.go.jp/pdf/summary/roadmap/icef2020_roadmap.pdf (2021).
24. Berrang-Ford, L. et al. Systematic mapping of global research on climate and health: a machine learning review. The Lancet Planetary Health 5, e514–e525 (2021).
25. Haddaway, N. R. et al. On the use of computer-assistance to facilitate systematic mapping. Campbell Systematic Reviews 16, (2020).
26. Callaghan, M. W., Minx, J. C. & Forster, P. M. A topography of climate change research. Nat. Clim. Chang. 10, 118–123 (2020).
27. Callaghan, M. et al. Machine-learning-based evidence and attribution mapping of 100,000 climate impact studies. Nat. Clim. Chang. 11, 966–972 (2021).
28. Devlin, J., Chang, M. W., Lee, K. & Toutanova, K. BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding. NAACL HLT 2019 - 2019 Conference of the North American Chapter of the Association for Computational Linguistics: Human Language Technologies - Proceedings of the Conference 1, 4171–4186 (2018).
29. Minx, J. C., Lamb, W. F., Callaghan, M. W., Bornmann, L. & Fuss, S. Fast growing research on negative emissions. Environ. Res. Lett. 12, (2017).
30. Bibliography: Greenhouse Gas Removal / Negative Emissions Technologies – Climate Protection and Restoration Initiative. https://cprclimate.org/bibliography-carbon-dioxide-removal-negative-emissions-technologies/.
31. Khabsa, M. & Giles, C. L. The number of scholarly documents on the public web. PLoS One 9, (2014).
32. Minx, J. C., Callaghan, M., Lamb, W. F., Garard, J. & Edenhofer, O. Learning about climate change solutions in the IPCC and beyond. Environ. Sci. Policy 77, (2017).
33. Haunschild, R., Bornmann, L. & Marx, W. Climate Change Research in View of Bibliometrics. PLoS One (2016) doi:10.1371/journal.pone.0160393.
34. Millar, R. J. & Allen, M. R. Chapter 2 Understanding the Role of CCS Deployment in Meeting Ambitious Climate Goals. in Carbon Capture and Storage 8–35 (The Royal Society of Chemistry, 2020). doi:10.1039/9781788012744-00008.
35. Clarke, L. et al. Energy Systems. in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Shukla, P. R. et al.) (Cambridge University Press, 2022).
36. Bui, M. et al. Carbon capture and storage (CCS): The way forward. Energy Environ. Sci. (2018) doi:10.1039/c7ee02342a.
37. Hilaire, J. et al. Negative emissions and international climate goals—learning from and about mitigation scenarios. Clim. Change (2019) doi:10.1007/s10584-019-02516-4.
38. Riahi, K. et al. Mitigation pathways compatible with long-term goals. in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Shukla, P. R.

et al.) (Cambridge University Press, 2022).

39. Fuss, S. et al. Betting on negative emissions. Nat. Clim. Chang. 4, 850–853 (2014).
40. Anderson, K. & Peters, G. The trouble with negative emissions. Science 354, 182–183 (2016).
41. Galik, C. S. A continuing need to revisit BECCS and its potential. Nat. Clim. Chang. 10, 2–3 (2020).
42. Popp, A. et al. Land-use futures in the shared socio-economic pathways. Glob. Environ. Change 42, 331–345 (2017).
43. Strefler, J. et al. Carbon dioxide removal technologies are not born equal. Environ. Res. Lett. 16, 74021–74021 (2021).
44. Gallagher, K. S., Grübler, A., Kuhl, L., Nemet, G. & Wilson, C. The Energy Technology Innovation System. Annu. Rev. Environ. Resour. 37, 137–162 (2012).
45. The Federal Reserve Bank. Foreign Exchange Rate - H.10. https://www.federalreserve.gov/releases/h10/current/.
46. Kang, J.-N., Zhang, Y.-L. & Chen, W. Delivering negative emissions innovation on the right track: A patent analysis. Renewable Sustainable Energy Rev. 158, 112169 (2022).
47. Höglund, R. List of known CDR purchases. https://docs.google.com/spreadsheets/d/1BH_B_Df_7e2l6AH8_8a0aK70nlAJXfCTwfy-CgxkL5C8/edit#gid=0 (2022).
48. International Energy Agency (IEA). Energy Technology RD&D Budgets: Overview - Analysis. https://www.iea.org/reports/energy-technology-rdd-budgets-overview (2022).
49. European Commission. Soils: Why does research and innovation on soils matter? https://research-and-innovation.ec.europa.eu/research-area/agriculture-forestry-and-rural-areas/soils_en.
50. Australian Department of Industry, Science and Resources. Carbon capture projects receive funding to accelerate technology and reduce emissions. https://www.industry.gov.au/news/carbon-capture-projects-receive-funding-to-accelerate-technology-and-reduce-emissions (2021).
51. Government of Canada. Net-Zero Emissions by 2050. https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html (2022).
52. Government of Canada. Net Zero Accelerator Initiative. https://www.ic.gc.ca/eic/site/125.nsf/eng/00039.html (2022).
53. Government of Canada. Climate Action and Awareness Fund. https://www.canada.ca/en/services/environment/weather/climatechange/funding-programs/climate-action-awareness-fund.html (2022).
54. International Energy Agency (IEA). An Energy Sector Roadmap to Carbon Neutrality in China. (2022).
55. China’s Voluntary National Contribution to Achieving the Targets of Global Forest Goals for the United Nations Strategic Plan for Forests (2017 - 2030). https://www.un.org/esa/forests/wp-content/uploads/2019/05/VNC-China-May2019.pdf (2019).
56. Regulation of the European Parliament of the Council Establishing the Framework for Achieving Climate Neutrality and Amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (‘European Climate Law’). vol. L 243/1 (2021).
57. European Commission. Commission awards over €1 billion to innovative projects for the EU climate transition. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_2163 (2022).
58. European Commission. Horizon Europe: Funding Programmes and Open Calls. https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en.
59. Carbon Gap. Feedback for Horizon Europe Interim Evaluation. https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13460-Orizzont-Ewropa-evalwazzjoni-interim/F3331927_mt (2022).
60. Bundesministerium für Bildung und Forschung (BMBF). Research mission ‘Marine carbon storage as a way to decarbonization’ of the German Marine Research Alliance. https://www.fona.de/de/massnahmen/foerdermassnahmen/210909_Dekarbonisierung.php.
61. Bundesministerium für Bildung und Forschung (BMBF). Is removing carbon dioxide from the atmosphere feasible, effective and socially desirable? The new BMBF funding measure CDRterra is researching terrestrial CO2 extraction methods. https://www.fona.de/de/massnahmen/foerdermassnahmen/co2-entnahmemethoden-cdr.php.
62. Council for Science, Technology & and Innovation (CSTI) and Headquarters for Healthcare Policy. The basic approach for the Moonshot Research and Development Program. https://www.jst.go.jp/moonshot/en/application/202002/pdf/f-policy_en20200227.pdf (2020).
63. Japan Cabinet Office. Moonshot Goal #4. https://www8.cao.go.jp/cstp/english/moonshot/sub4_en.html.
64. MOZES Research. Moonshot for beyond Zero-Emission Society. https://mozes.jp/en/research/.
65. Sosuke Kudo. Toshiba, ‘carbon negative’ in biomass power generation, CO2 separation and recovery. Bikkei Business Publications, Inc. (2020).
66. United Kingdom Research and Innovation. The UK Greenhouse Gas Removal from the Atmosphere Research Programme. https://www.ggrprogramme.org.uk/.
67. HM Government. Net Zero Strategy: Build Back Greener. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf (2021).
68. UK Department for Business, Energy & Industrial Strategy. Projects selected for Phase 2 of the Direct air capture and greenhouse gas removal programme. https://www.gov.uk/government/publications/direct-air-capture-and-other-greenhouse-gas-removal-technologies-competition/projects-selected-for-phase-2-of-the-direct-air-capture-and-greenhouse-gas-removal-programme (2022).
69. UK Department for Business, Energy & Industrial Strategy. Direct Air Capture and other Greenhouse Gas Removal technologies competition. https://www.gov.uk/government/publications/direct-air-capture-and-other-greenhouse-gas-removal-technologies-competition (2020).
70. UK Research and Innovation. UK invests over £30m in large-scale greenhouse gas removal. https://www.ukri.org/news/uk-invests-over-30m-in-large-scale-greenhouse-gas-removal/ (2021).
71. UK Research and Innovation. Greenhouse Gas Removal Demonstrator (GGR-D) projects. https://www.ukri.org/wp-content/uploads/2021/05/NERC-240521-GreenhouseGasRemovalDemonstratorProjects.pdf.
72. The White House. FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies. https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/ (2021).
73. U.S. Department of Energy. U.S. Department of Energy’s Carbon Negative Shot - An Introduction. https://www.energy.gov/sites/default/files/2022-03/3.25.22%20Carbon%20Negative%20Shot_0.pdf (2021).
74. Government of the United States. Division C: Energy and Water Development and Related Agencies Appropriations Act, 2020. (2020).
75. Office of Fossil Energy and Carbon Management. U.S. Department of Energy Announces an Additional $6 Million in Funding for Four Direct Air Capture Projects. https://www.energy.gov/fecm/articles/us-department-energy-announces-additional-6-mil-

lion-funding-four-direct-air-capture (2021).

76. Government of the United States. Division D - Energy and Water Development and Related Agencies Appropriations Act, 2021. (2021).
77. Government of the United States. Division D - Energy and Water Development and Related Agencies Appropriations Act, 2022. (2022).
78. US Office of Fossil Energy and Carbon Management. U.S. Department of Energy Announces $30 Million to Remove Carbon Dioxide from the Air and Oceans and Convert it to Valuable Products. https://www.energy.gov/fecm/articles/us-department-energy-announces-30-million-remove-carbon-dioxide-air-and-oceans-and (2022).
79. Sanchez, D. L., Amador, G., Funk, J. & Mach, K. J. Federal research, development, and demonstration priorities for carbon dioxide removal in the United States. Environ. Res. Lett. 13, 015005 (2018).
80. A Carbon Removal Collective. OpenAir Collective https://openaircollective.cc/ (2021).
81. Frontier. An advance market commitment to accelerate carbon removal. https://frontierclimate.com/ (2022).
82. BloombergNEF. Energy Transition Investment Trends 2022. https://assets.bbhub.io/professional/sites/24/Energy-Transition-Investment-Trends-Exec-Summary-2022.pdf (2022).
83. Climate Tech VC. Climate funding abides in $19B 2022 midyear update. https://www.ctvc.co/19b-2022-midyear-update/ (2022).
84. Carbon Engineering. 1PointFive & Carbon Engineering Announce Direct Air Capture Deployment Approach to Enable Global Build-Out of Plants. https://carbonengineering.com/news-updates/deployment-approach/ (2022).
85. Climeworks. Climeworks' DAC Summit Highlights. https://climeworkscom.cdn.prismic.io/climeworkscom/f0b37e8e-00aa-42cb-a06e-d6697a533af8_Climeworks+DAC+Summit+Highlights+2022.pdf (2022).
86. European Biochar Industry Consortium. European Biochar Market Report 2021-2022. https://www.biochar-industry.com/wp-content/uploads/2022/03/EU-Biochar-Market-Report_2022-03-09.pdf (2022).
87. Gardiner W & Skelton. Drax Full Year Results - 2021. https://www.drax.com/wp-content/uploads/2022/02/Drax-2021-FYR-Analyst-Presentation.pdf (2022).
88. BECCS Stockholm. Carbon Dioxide Removal. https://beccs.se/cdr/.
89. Pernot, E. & Jaruzel, M. Direct air capture is growing around the world, but more policy support is needed. https://www.catf.us/2022/07/direct-air-capture-growing-around-world-more-policy-support-needed/ (2022).
90. Bidwell, D. Thinking through participation in renewable energy decisions. Nature Energy 1, (2016).
91. Krause, R. M., Carley, S. R., Warren, D. C., Rupp, J. A. & Graham, J. D. 'Not in (or Under) My Backyard': Geographic Proximity and Public Acceptance of Carbon Capture and Storage Facilities. Risk Anal. 34, 529–540 (2013).
92. Batel, S., Devine-Wright, P. & Tangeland, T. Social acceptance of low carbon energy and associated infrastructures: A critical discussion. Energy Policy 58, 1–5 (2013).
93. Cox, E., Spence, E. & Pidgeon, N. Public perceptions of carbon dioxide removal in the United States and the United Kingdom. Nat. Clim. Chang. 10, 744–749 (2020).
94. Wolske, K. S., Raimi, K. T., Campbell-Arvai, V. & Hart, P. S. Public support for carbon dioxide removal strategies: the role of tampering with nature perceptions. Clim. Change 152, 345–361 (2019).
95. Bellamy, R., Lezaun, J. & Palmer, J. Perceptions of bioenergy with carbon capture and storage in different policy scenarios. Nat. Commun. 10, 743–743 (2019).
96. Cox, E., Spence, E. & Pidgeon, N. Deliberating enhanced weathering: Public frames, iconic ecosystems and the governance of carbon removal at scale. Public Underst. Sci. 31, 960–977 (2022).
97. Pidgeon, N. Engaging publics about environmental and technology risks: frames, values and deliberation. J. Risk Res. 24, 28–46 (2021).
98. Bertram, C. & Merk, C. Public Perceptions of Ocean-Based Carbon Dioxide Removal: The Nature-Engineering Divide? Frontiers in Climate 2, (2020).
99. Bellamy, R. & Lezaun, J. Crafting a public for geoengineering. Public Underst. Sci. 26, 402–417 (2017).
100. Bolsen, T., Palm, R. & Kingsland, J. T. Effects of Conspiracy Rhetoric on Views About the Consequences of Climate Change and Support for Direct Carbon Capture. Environ.Commun. 16, 209–224 (2022).
101. Campbell-Arvai, V., Hart, P. S., Raimi, K. T. & Wolske, K. S. The influence of learning about carbon dioxide removal (CDR) on support for mitigation policies. Clim. Change 143, 321–336 (2017).
102. Carr, W. A. & Yung, L. Perceptions of climate engineering in the South Pacific, Sub-Saharan Africa, and North American Arctic. Clim. Change 147, 119–132 (2018).
103. Corner, A., Parkhill, K., Pidgeon, N. & Vaughan, N. E. Messing with nature? Exploring public perceptions of geoengineering in the UK. Glob. Environ. Change 23, 938–947 (2013).
104. Corner, A. & Pidgeon, N. Like artificial trees? The effect of framing by natural analogy on public perceptions of geoengineering. Clim. Change 130, 425–438 (2015).
105. Corner, A. & Pidgeon, N. Geoengineering, climate change scepticism and the 'moral hazard' argument: an experimental study of UK public perceptions. Philos. Trans. R. Soc. London, Ser. A 372, 20140063–20140063 (2014).
106. Cox, E., Pidgeon, N. & Spence, E. But they told us it was safe! Carbon dioxide removal, fracking, and ripple effects in risk perceptions. Risk Anal. 42, 1472–1487 (2021).
107. Gannon, K. E. & Hulme, M. Geoengineering at the 'Edge of the World': Exploring perceptions of ocean fertilisation through the Haida Salmon Restoration Corporation. Geogr. Environ 5, e00054 (2018).
108. Schirmer, J. & Bull, L. Assessing the likelihood of widespread landholder adoption of afforestation and reforestation projects. Glob. Environ. Change 24, 306–320 (2014).
109. Lin, J.-C., Wu, C.-S., Liu, W.-Y. & Lee, C.-C. Behavioral intentions toward afforestation and carbon reduction by the Taiwanese public. For. Policy Econ. 14, 119–126 (2012).
110. Wibeck, V. et al. Making sense of climate engineering: a focus group study of lay publics in four countries. Clim. Change (2017) doi:10.1007/s10584-017-2067-0.
111. Wright, M. J., Teagle, D. A. H. & Feetham, P. M. A quantitative evaluation of the public response to climate engineering. Nat. Clim. Chang. 4, 106–110 (2014).
112. Klaus, G., Ernst, A. & Oswald, L. Psychological factors influencing laypersons' acceptance of climate engineering, climate change mitigation and business as usual scenarios. Technol. Soc. 60, 101222 (2020).
113. Wallquist, L., Seigo, S. L., Visschers, V. H. M. & Siegrist, M. Public acceptance of CCS system elements: A conjoint measurement. Int. J. Greenhouse Gas Control 6, 77–83 (2012).
114. Sweet, S. K., Schuldt, J. P., Lehmann, J., Bossio, D. A. & Woolf, D. Perceptions of naturalness predict US public support for Soil

Carbon Storage as a climate solution. Clim. Change 166, 22 (2021).
115. Carvalho, A. & Riquito, M. 'It's just a Band-Aid!': Public engagement with geoengineering and the politics of the climate crisis. Public Underst. Sci. 31, 903–920 (2022).
116. Hart, P. S., Campbell-Arvai, V., Wolske, K. S. & Raimi, K. T. Moral hazard or not? The effects of learning about carbon dioxide removal on perceptions of climate mitigation in the United States. Energy Res. Social Sci 89, 102656 (2022).
117. Spence, E., Cox, E. & Pidgeon, N. Exploring cross-national public support for the use of enhanced weathering as a land-based carbon dioxide removal strategy. Clim. Change 165, 23 (2021).
118. Buck, H. J. & Palumbo-Compton, A. Soil carbon sequestration as a climate strategy: what do farmers think? Biogeochemistry 161, 59–70 (2022).
119. Carlisle, D. P., Feetham, P. M., Wright, M. J. & Teagle, D. A. H. The public remain uninformed and wary of climate engineering. Clim. Change 160, 303–322 (2020).
120. Dumbrell, N. P., Kragt, M. E. & Gibson, F. L. What carbon farming activities are farmers likely to adopt? A best–worst scaling survey. Land use policy 54, 29–37 (2016).
121. .Braun, C., Merk, C., Pönitzsch, G., Rehdanz, K. & Schmidt, U. Public perception of climate engineering and carbon capture and storage in Germany: survey evidence. Clim. Policy 18, 471–484 (2018).
122. Pidgeon, N. F. & Spence, E. Perceptions of enhanced weathering as a biological negative emissions option. Biol. Lett. 13, 20170024 (2017).
123. Jobin, M. & Siegrist, M. Support for the Deployment of Climate Engineering: A Comparison of Ten Different Technologies. Risk Anal. 40, 1058–1078 (2020).
124. Carlisle, D. P., Feetham, P. M., Wright, M. J. & Teagle, D. A. H. Public engagement with emerging technologies: Does reflective thinking affect survey responses? Public Underst. Sci. 31, 660–670 (2021).
125. Raimi, K. T. Public perceptions of geoengineering. Curr. Opin. Psychol. 42, 66–70 (2021).
126. Bellamy, R., Lezaun, J. & Palmer, J. Public perceptions of geoengineering research governance: An experimental deliberative approach. Glob. Environ. Change 45, 194–202 (2017).
127. McLaren, D., Parkhill, K. A., Corner, A., Vaughan, N. E. & Pidgeon, N. F. Public conceptions of justice in climate engineering: Evidence from secondary analysis of public deliberation. Glob. Environ. Change 41, 64–73 (2016).
128. McLaren, D., Willis, R., Szerszynski, B., Tyfield, D. & Markusson, N. Attractions of delay: Using deliberative engagement to investigate the political and strategic impacts of greenhouse gas removal technologies. Environment and Planning E: Nature and Space (2021).
129. Simis, M. J., Madden, H., Cacciatore, M. A. & Yeo, S. K. The lure of rationality: Why does the deficit model persist in science communication? Public Underst. Sci. 25, 400–414 (2016).
130. Pidgeon, N. & Rogers-Hayden, T. Opening up nanotechnology dialogue with the publics: Risk communication or 'upstream engagement'? Health Risk Soc. 9, 191–210 (2007).
131. Gregory, R., Satterfield, T. & Hasell, A. Using decision pathway surveys to inform climate engineering policy choices. PNAS 113, 560–565 (2016).
132. Wenger, A., Stauffacher, M. & Dallo, I. Public perception and acceptance of negative emission technologies – framing effects in Switzerland. Clim. Change 167, (2021).
133. Bellamy, R., Chilvers, J. & Vaughan, N. E. Deliberative Mapping of options for tackling climate change: Citizens and specialists 'open up' appraisal of geoengineering. Public Underst. Sci. 25, 269–286 (2016).
134. Amelung, D. & Funke, J. Laypeople's Risky Decisions in the Climate Change Context: Climate Engineering as a Risk-Defusing Strategy? Human and Ecological Risk Assessment 21, 533–559 (2014).
135. Thomas, G., Pidgeon, N. & Roberts, E. Ambivalence, naturalness and normality in public perceptions of carbon capture and storage in biomass, fossil energy, and industrial applications in the United Kingdom. Energy Res. Social Sci. 46, 1–9 (2018).
136. Merk, C. et al. Public perceptions of climate engineering: Laypersons' acceptance at different levels of knowledge and intensities of deliberation. GAIA - Ecological Perspectives for Science and Society 28, 348–355 (2019).
137. Cody, E. M., Reagan, A. J., Mitchell, L., Dodds, P. S. & Danforth, C. M. Climate Change Sentiment on Twitter: An Unsolicited Public Opinion Poll. PLoS One 10, e0136092–e0136092 (2015).
138. Mellon, J. & Prosser, C. Twitter and Facebook are Not Representative of the General Population: Political Attitudes and Demographics of Social Media Users. SSRN Electronic Journal (2016) doi:10.2139/ssrn.2791625.
139. Klašnja, M., Barberá, P., Beauchamp, N., Nagler, J. & Tucker, J. A. Measuring Public Opinion with Social Media Data. Oxford Handbooks Online (2017) doi:10.1093/oxfordhb/9780190213299.013.3.
140. Barberá, P. & Rivero, G. Understanding the Political Representativeness of Twitter Users. Soc. Sci. Comput. Rev. 33, 712–729 (2014).
141. Twitter-roBERTa-base for Sentiment Analysis. Hugging Face https://huggingface.co/cardiffnlp/twitter-roberta-base-sentiment.
142. Rosenthal, S., Farra, N. & Nakov, P. SemEval-2017 Task 4: Sentiment Analysis in Twitter. (Association for Computational Linguistics, 2017). doi:10.18653/v1/s17-2088.
143. Effrosynidis, D., Karasakalidis, A. I., Sylaios, G. & Arampatzis, A. The climate change Twitter dataset. Expert Syst. Appl. 204, 117541 (2022).
144. Bastin, J.-F. et al. The global tree restoration potential. Science 365, 76–79 (2019).
145. Low, S., Baum, C. M. & Sovacool, B. K. Taking it outside: Exploring social opposition to 21 early-stage experiments in radical climate interventions. Energy Research & Social Science 90, 102594 (2022).
146. Rogelj, J., Geden, O., Cowie, A. & Reisinger, A. Net-zero emissions targets are vague: three ways to fix. Nature 591, 365–368 (2021).
147. Fridahl, M. Socio-political prioritization of bioenergy with carbon capture and storage. Energy Policy 104, 89–99 (2017).
148. Honegger, M., Burns, W. & Morrow, D. R. Is carbon dioxide removal 'mitigation of climate change'? Review of European, Comparative & International Environmental Law 30, 327–335 (2021).
149. Buylova, A., Fridahl, M., Nasiritousi, N. & Reischl, G. Cancel (Out) Emissions? The Envisaged Role of Carbon Dioxide Removal Technologies in Long-Term National Climate Strategies. Frontiers in Climate 3, 675499 (2021).
150. Grassi, G. et al. Critical adjustment of land mitigation pathways for assessing countries' climate progress. Nat. Clim. Chang. 11, 14 (2021).
151. Mace, M. j., Fyson, C. L., Schaeffer, M. & Hare, W. L. Large-Scale Carbon Dioxide Removal to Meet the 1.5°C Limit: Key Governance Gaps, Challenges and Priority Responses. Global Policy 12, 67–81 (2021).
152. Forsell, N. et al. Assessing the INDCs' land use, land use change, and forest emission projections. Carbon Balance Manag. 11, 26

(2016).
153. Fyson, C. L. & Jeffery, M. L. Ambiguity in the Land Use Component of Mitigation Contributions Toward the Paris Agreement Goals. Earth's Future 7, 873–891 (2019).
154. Mohan, A., Geden, O., Fridahl, M., Buck, H. J. & Peters, G. P. UNFCCC must confront the political economy of net-negative emissions. One Earth 4, 1348–1351 (2021).
155. Dubash, N. K. Varieties of climate governance: the emergence and functioning of climate institutions. Env. Polit. 30, 1–25 (2021).
156. Honegger, M., Poralla, M., Michaelowa, A. & Ahonen, H.-M. Who Is Paying for Carbon Dioxide Removal? Designing Policy Instruments for Mobilizing Negative Emissions Technologies. Frontiers in Climate 3, 672996 (2021).
157. Schenuit, F. et al. Carbon Dioxide Removal Policy in the Making: Assessing Developments in 9 OECD Cases. Frontiers in Climate 3, 638805 (2021).
158. Köberle, A. C. et al. Can global models provide insights into regional mitigation strategies? A diagnostic model comparison study of bioenergy in Brazil. Clim. Change 170, 2 (2022).
159. Geden, O. & Schenuit, F. Unconventional Mitigation Carbon Dioxide Removal as a New Approach in EU Climate Policy. https://www.swp-berlin.org/publications/products/research_papers/2020RP08_ClimateMitigation.pdf (2020).
160. Geden, O., Scott, V. & Palmer, J. Integrating carbon dioxide removal into EU climate policy: Prospects for a paradigm shift. Wiley Interdiscip. Rev. Clim. Change 9, e521 (2018).
161. Meyer-Ohlendorf, N. & Spasova, D. Carbon Dioxide Removals in EU Member States. https://www.ecologic.eu/sites/default/files/publication/2022/50084-ECF-CDR-report-web.pdf (2022).
162. Meyer-Ohlendorf, N. EU Framework for CO2 Removals – Targets and Commitments. https://www.ecologic.eu/sites/default/files/publication/2020/60003-removal_ecf_021020_final.pdf (2020).
163. Schenuit, F. & Geden, O. Carbon Dioxide Removal: Climbing up the EU Climate Policy Agenda. https://www.swp-berlin.org/10.18449/2022WP02/ (2022).
164. UK Woodland Carbon Code: Requirements for voluntary carbon sequestration projects. https://woodlandcarboncode.org.uk/ (2022).
165. UK Department for Business, Energy & Industrial Strategy. Greenhouse gas removals (GGR) business models. https://www.gov.uk/government/consultations/greenhouse-gas-removals-ggr-business-models (2022).
166. UK Department for Business, Energy & Industrial Strategy. Business model for power bioenergy with carbon capture and storage (Power BECCS). https://www.gov.uk/government/consultations/business-model-for-power-bioenergy-with-carbon-capture-and-storage-power-beccs (2022).
167. UK ETS Authority. Developing the UK Emissions Trading Scheme. https://www.gov.uk/government/consultations/developing-the-uk-emissions-trading-scheme-uk-ets (2022).
168. Climate Change Committee. 2022 Progress Report to Parliament. https://www.theccc.org.uk/publication/2022-progress-report-to-parliament/ (2022).
169. Government of the United States. Nationally Determined Contribution. https://unfccc.int/sites/default/files/NDC/2022-06/United%20States%20NDC%20April%2021%202021%20Final.pdf (2021).
170. United Nations Framework Convention on Climate Change (UNFCCC). Greenhouse Gas Inventory Data - Time Series. (2022).
171. Larson, E. et al. Net-zero America: potential pathways, infrastructure, and impacts. https://netzeroamerica.princeton.edu/img/Princeton%20NZA%20FINAL%20REPORT%20SUMMARY%20(29Oct2021).pdf (2021).
172. Government of Brazil. Decreto n. 11.075. https://www.irib.org.br/noticias/detalhes/decreto-n-11-075-de-19-de-maio-de-2022 (2022).
173. Silveira, B. H. M., Costa, H. K. de M. & Dos Santos, E. M. The benefit of the RenovaBio Programme for the BECCS market in Brazil. Rio Oil and Gas Expo and Conference (2022) doi:10.48072/2525-7579.rog.2022.440.
174. Global CCS Institute, and CO2RE. Facilities Database - Global CCS Institute. https://co2re.co/FacilityData. (2022).
175. Ministério da Ciência, T. e. I. Estimativas Anuais de Emissões de Gases de Efeito Estufa no Brasil. https://www.gov.br/mcti/pt-br/acompanhe-o-mcti/sirene/publicacoes/estimativas-anuais-de-emissoes-gee/arquivos/6a-ed-estimativas-anuais.pdf (2022).
176. Silva Junior, C. H. L. et al. The Brazilian Amazon deforestation rate in 2020 is the greatest of the decade. Nat. Ecol. Evol. 5, 144–145 (2021).
177. Soterroni, A. C. et al. Future environmental and agricultural impacts of Brazil's Forest Code. Environ. Res. Lett. 13, 074021 (2018).
178. Dockendorff, C. et al. Committed to restoring tropical forests: an overview of Brazil's and Indonesia's restoration targets and policies. Environ. Res. Lett. 17, 093002 (2022).
179. de Mello Brandão Vinholis, M., Macchione Saes, M. S., Carrer, M. J. & Meirelles de Souza Filho, H. The effect of meso-institutions on adoption of sustainable agricultural technology: A case study of the Brazilian Low Carbon Agriculture Plan. J. Clean. Prod. 280, 124334 (2021).
180. Embassy of Brazil. Communication from Government of Brazil to UNFCCC. (2010).
181. Government of Brazil. Brazil's Third Biennial Update Report to the UNFCCC. https://unfccc.int/sites/default/files/resource/2018-02-28_BRA-BUR3_ENG_FINAL.pdf (2019).
182. Embrapa. Carne Carbono Neutro: Um Novo Conceito Para Carne Sustentável Produzida Nos Trópicos. https://ainfo.cnptia.embrapa.br/digital/bitstream/item/203141/1/Carne-carbono-neutro-1.pdf (2015).
183. Macedo, M. C. M., Almeida, R. G. de & Alves, F. V. Low Carbon Brazilian Beef Platform. https://ainfo.cnptia.embrapa.br/digital/bitstream/item/226499/1/LOW-CARBON-BRAZILIAN-BEEF-PLATFORM.pdf (2021).
184. Serviços e Informações do Brasil. PronaSolos Platform allow access to all who produce soil data in Brazil. https://www.gov.br/en/government-of-brazil/latest-news/2022/pronasolos-platform-allow-access-to-all-who-produce-soil-data-in-brazil (2022).
185. Carton, W., Asiyanbi, A., Beck, S., Buck, H. J. & Lund, J. F. Negative emissions and the long history of carbon removal. Wiley Interdiscip. Rev. Clim. Change 11, (2020).
186. vonHedemann, N., Wurtzebach, Z., Timberlake, T. J., Sinkular, E. & Schultz, C. A. Forest policy and management approaches for carbon dioxide removal. Interface Focus 10, 20200001 (2020).
187. Brander, M., Ascui, F., Scott, V. & Tett, S. Carbon accounting for negative emissions technologies. Clim. Policy 21, 699–717 (2021).
188. Mission Innovation. Carbon Dioxide Removal Mission Action Plan 2022-26. http://mission-innovation.net/wp-content/uploads/2022/09/Attachment-2-Public-Facing-CDR-Mission-Action-Plan-Sept-2022.pdf (2022).
189. Geden, O. The Paris Agreement and the inherent inconsistency of climate policymaking. Wiley Interdiscip. Rev. Clim. Change 7, 790–797 (2016).
190. Lecocq, F. H. et al. Mitigation and development pathways in the near- to mid-term. in IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate

Change (eds. Shukla, P. R. et al.) (Cambridge University Press, 2022).

191. Grassi, G. et al. Carbon fluxes from land 2000–2020: bringing clarity to countries' reporting. Earth System Science Data 14, 4643–4666 (2022).
192. Gidden, M. et al. Policy guidance and pitfalls aligning IPCC scenarios to national land emissions inventories. Earth and Space Science Open Archive (2022) doi:10.1002/essoar.10512676.2.
193. Powis R.C.M., Smith S., Minx J., Gasser, T. Quantifying global carbon dioxide removal deployment. In preparation.
194. Berkeley Carbon Trading Project. Voluntary Registry Offsets Database. https://gspp.berkeley.edu/faculty-and-impact/centers/cepp/projects/berkeley-carbon-trading-project/offsets-database.
195. Verra. Verra Registry. Verra (2020) https://verra.org/registry-system/.
196. Gold Standard. Impact Registry. (2022) https://www.goldstandard.org/resources/impact-registry.
197. American Carbon Registry. Public Registry. Public Registry (2022) https://americancarbonregistry.org/how-it-works/registry-reports.
198. Climate Action Reserve. Public Registry. (2022) https://thereserve2.apx.com/mymodule/mypage.asp.
199. Stripe Climate. Carbon Removal Portfolio. https://stripe.com/en-ca/climate.
200. Microsoft Sustainability. Microsoft Carbon Dioxide Removal Program. https://www.microsoft.com/en-us/corporate-responsibility/sustainability/carbon-removal-program.
201. Thirdway. Carbon Capture Projects Map. (2022) https://www.thirdway.org/graphic/carbon-capture-projects-map.
202. Global CCS Institute. CCS Facilities Database. (2018) https://www.globalccsinstitute.com/co2re/.
203. Massachusets Institute for Technology. Carbon Capture and Sequestration Technologies. (2017).
204. Center for International Forestry Research (CIFOR). International Database on REDD+ projects and programmes. (2022).
205. Center for International Forestry Research (CIFOR). Global database of REDD+ and other forest carbon projects. (2022).
206. Forest Trends. Mapping Ecosystem Markets Database. (2018).
207. United Nations Framework Convention on Climate Change. Clean Development Mechanism Project Activities Database. (2022).
208. Doelman, J. C. et al. Afforestation for climate change mitigation: Potentials, risks and trade-offs. Glob. Chang. Biol. 26, 1576–1591 (2020).
209. Butarbutar, T., Köhl, M. & Neupane, P. R. Harvested wood products and REDD+: looking beyond the forest border. Carbon Balance Manag. 11, 4 (2016).
210. Harmon, M. E. et al. Release of coarse woody detritus-related carbon: a synthesis across forest biomes. Carbon Balance Manag. 15, 1 (2020).
211. Way, R., Ives, M., Mealy, P. & Doyne Farmer, J. Empirically grounded technology forecasts and the energy transition. Joule 6, 2057–2082 (2022).
212. United Nations. Paris Agreement. https://unfccc.int/sites/default/files/english_paris_agreement.pdf (2015).
213. Schleussner, C.-F. et al. Science and policy characteristics of the Paris Agreement temperature goal. Nat. Clim. Chang. 6, 827–835 (2016).
214. Rajamani, L. & Werksman, J. The legal character and operational relevance of the Paris Agreement's temperature goal. Philos. Trans. A Math. Phys. Eng. Sci. 376, (2018).
215. United Nations Framework Convention on Climate Change (UNFCCC). Report of the Conference of the Parties on its sixteenth session, held in Cancun from 29 November to 10 December 2010. Addendum. Part two: Action taken by the Conference of the Parties at its sixteenth session. https://unfccc.int/documents/6527 (2011).
216. O'Neill, B. C. et al. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Change 42, 169–180 (2017).
217. IAM Consortium. The common Integrated Assessment Model (IAM) documentation. https://www.iamcdocumentation.eu/index.php/IAMC_wiki.
218. Emmerling, J. et al. The role of the discount rate for emission pathways and negative emissions. Environ. Res. Lett. 14, 104008 (2019).
219. van Soest, H. L. et al. Global roll-out of comprehensive policy measures may aid in bridging emissions gap. Nat. Commun. 12, 6419 (2021).
220. Byers, E. et al. AR6 Scenarios Database. (2022) doi:10.5281/zenodo.5886912.
221. Guivarch, C., Kriegler, E. & Portugal Pereira, J. Annex III: Scenarios and modelling methods. in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Shukla, P. R. et al.) (Cambridge University Press, 2021).
222. Gasser, T. et al. Historical CO2 emissions from land use and land cover change and their uncertainty. Biogeosciences 17, 4075–4101 (2020).
223. Schleussner, C.-F., Ganti, G., Rogelj, J. & Gidden, M. J. An emission pathway classification reflecting the Paris Agreement climate objectives. Communications Earth & Environment 3, 1–11 (2022).
224. Luderer, G. et al. Residual fossil CO2 emissions in 1.5–2 °C pathways. Nat. Clim. Chang. 8, 626–633 (2018).
225. Realmonte, G. et al. An inter-model assessment of the role of direct air capture in deep mitigation pathways. Nat. Commun. 10, 3277 (2019).
226. International Energy Agency (IEA). Tracking Clean Energy Progress. https://www.iea.org/topics/tracking-clean-energy-progress (2022).
227. United Nations Environment Programme (UNEP). Trends in global emissions, new pledges for 2030 and G20 status and outlook. in Emissions Gap Report 2021: The Heat Is On – A World of Climate Promises Not Yet Delivered 15 (UNEP, 2021).
228. United Nations Environment Programme (UNEP). Global emissions trends and G20 status and outlook. in Emissions Gap Report 2020 (UNEP, 2020).
229. Friedlingstein, P. et al. Global Carbon Budget 2021. Earth System Science Data 14, 1917–2005 (2022).
230. Grassi, G. et al. Mapping land-use fluxes for 2001–2020 from global models to national inventories. (2022).
231. Intergovernmental Panel on Climate Change (IPCC). 2006 IPCC Guidelines for National Greenhouse Gas Inventories. https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html (2006).
232. Friedlingstein, P. et al. Global carbon budget 2022. Earth Syst. Sci. Data 14, 4811–4900 (2022).
233. Gasser, T., Ciais, P. & Lewis, S. L. How the Glasgow Declaration on Forests can help keep alive the 1.5 °C target. Proc. Natl. Acad. Sci. U. S. A. 119, e2200519119 (2022).
234. Günther, A., Gütschow, J. & Jeffery, M. L. NDCmitiQ v1.0.0: a tool to quantify and analyse greenhouse gas mitigation targets. Geosci. Model Dev. 14, 5695–5730 (2021).

235. Grassi, G. et al. The key role of forests in meeting climate targets requires science for credible mitigation. Nat. Clim. Chang. 7, 220–226 (2017).
236. Smith, H. B., Vaughan, N. E. & Forster, J. Long-term national climate strategies bet on forests and soils to reach net-zero. Commun Earth Environ 3, 305 (2022).
237. International Boreal Forest Research Association (IBFRA). 2021-11 Sustainable boreal forest management – challenges and opportunities for climate change mitigation. https://www.skogsstyrelsen.se/globalassets/om-oss/rapporter/rapporter-2021202020192018/rapport-2021-11-sustainable-boreal-forest-management-challenges-and-opportunities-for-climate-change-mitigation-002.pdf (2021).
238. Bento, N., Wilson, C. & Anadon, L. D. Time to get ready: Conceptualizing the temporal and spatial dynamics of formative phases for energy technologies. Energy Policy 119, 282–293 (2018).
239. Grubler, A. et al. A low energy demand scenario for meeting the 1.5oC target and sustainable development goals without negative emissions technologies. Nature Energy 3, 515–527 (2018).
240. Jackson, R. B. et al. Global fossil carbon emissions rebound near pre-COVID-19 levels. Environ. Res. Lett. 17, 031001 (2022).
241. Davis, S. J. et al. Emissions rebound from the COVID-19 pandemic. Nat. Clim. Chang. 12, 412–414 (2022).
242. van Vuuren, D. P. et al. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. Nat. Clim. Chang. 8, 391–397 (2018).
243. Roe, S. et al. Contribution of the land sector to a 1.5 °C world. Nat. Clim. Chang. 9, 817–828 (2019).
244. Dooley K. et al. The Land Gap Report 2022. https://www.landgap.org/ (2022).
245. Tong, D., Zhang, Q., Zheng, Y. et al. Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. Nature 572, 373–377 (2019). https://doi.org/10.1038/s41586-019-1364-3
246. Dhakal, S., et al. Emissions Trends and Drivers. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Shukla, P. R. et al.) (Cambridge University Press, 2022).
247. Trout, K. et al. Existing fossil fuel extraction would warm the world beyond 1.5°C. Environ. Res. Lett. 17, 064010 (2022)
248. Hepburn, C. et al. The technological and economic prospects for CO2 utilization and removal. Nature 575, 87–97 (2019).

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Dioxide
Removal