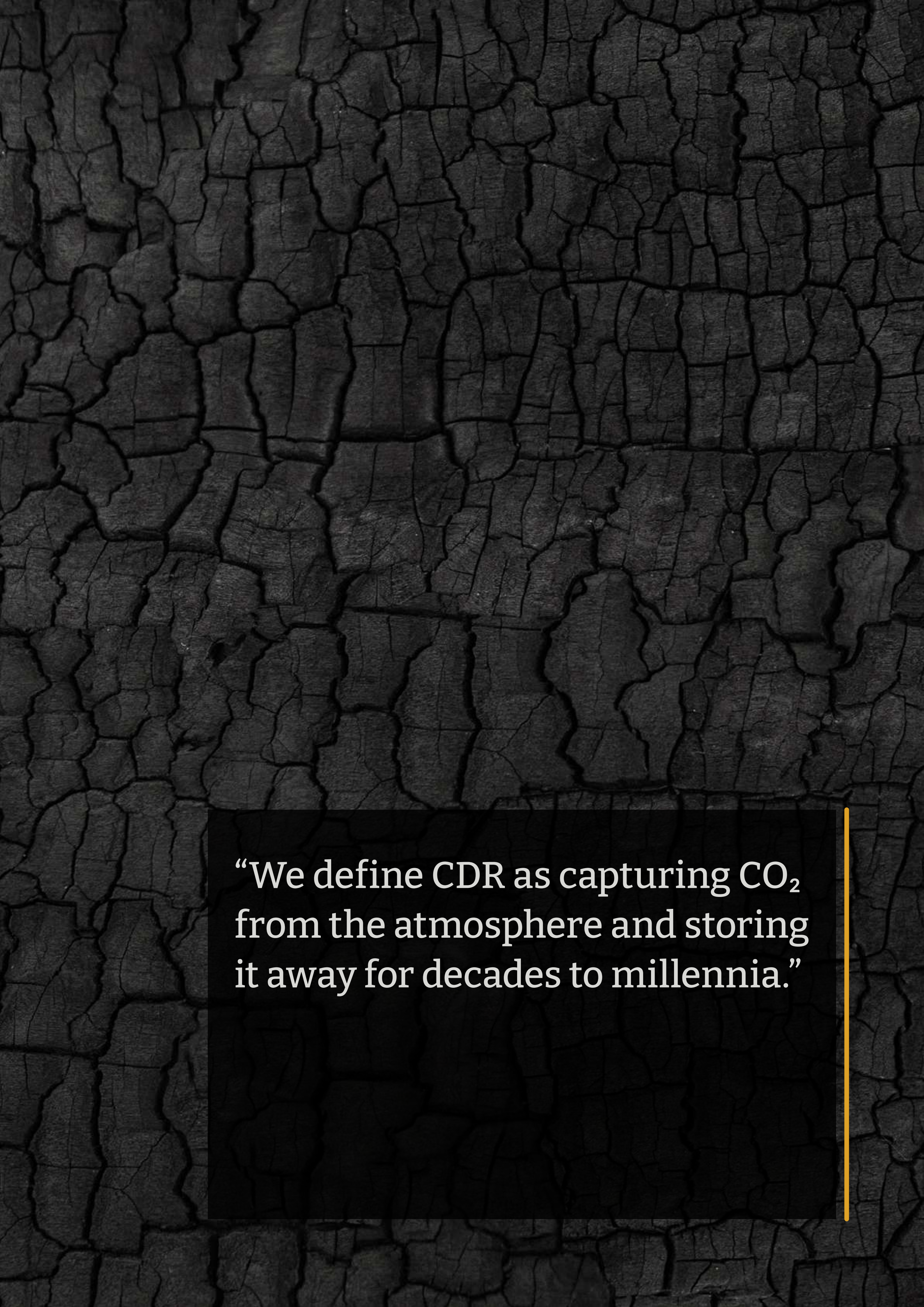

> “We define CDR as capturing CO_2 from the atmosphere and storing it away for decades to millennia.”

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.

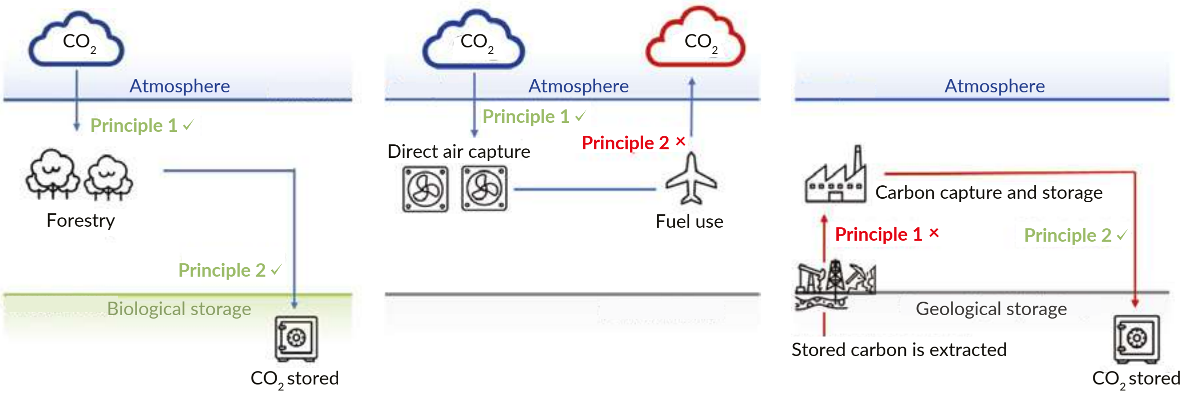

Figure 1.1. *To be defined as Carbon Dioxide Removal (CDR), a method must capture* CO_2 *from the atmosphere (Principle 1) and durably store it (Principle 2). An example of a method which satisfies both principles, and hence qualifies as CDR, is afforestation/reforestation (left). There are several approaches 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.

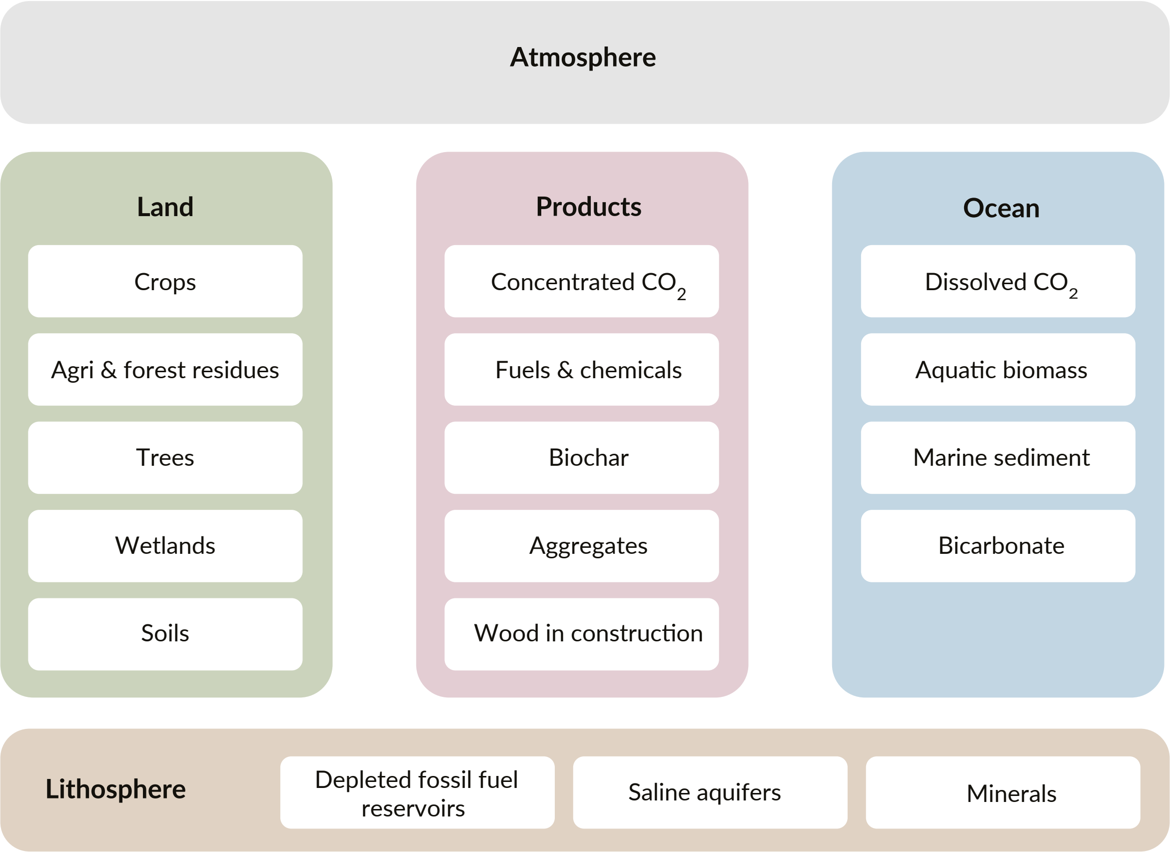

Figure 1.2. *The global carbon cycle consists of five main carbon reservoirs: the atmosphere, land, products, ocean and lithosphere (geological formations). Within each reservoir there are various carbon pools (indicated in each reservoir) whose characteristics vary in terms of storage capacity and durability. 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.

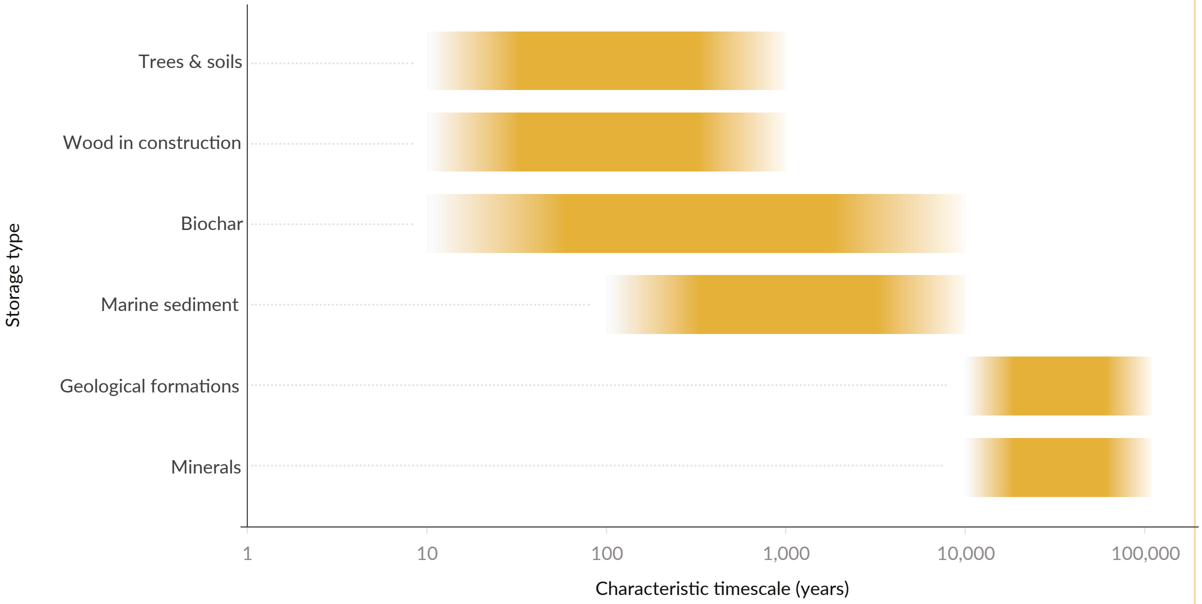

Figure 1.3. *The durability of different carbon storage pools ranges from decades to tens of millennia. Note that these timescales are indicative, assuming no premature disturbance. Source: IPCC WG3 AR6 Chapters 7 & 12*[13,19].

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