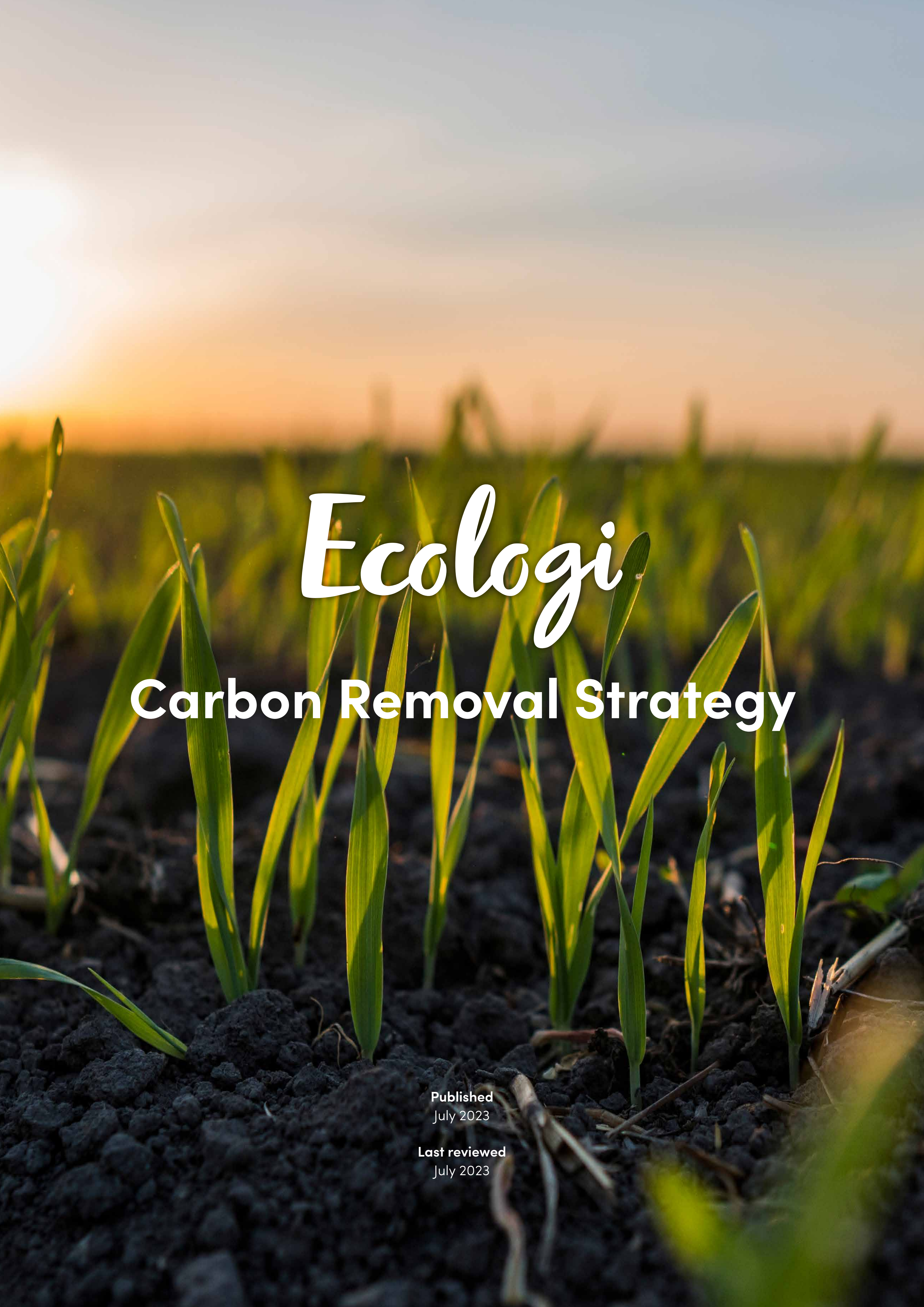

Ecologi

Carbon Removal Strategy

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1. Introduction

1.1 Context

Since the Industrial Revolution, the base level of atmospheric carbon dioxide (CO_2) has been increasing - from around 280 parts per million (ppm) in 1750, to over 420 parts per million in 2022, leading to an increase in global average temperature (NOAA, 2022). This increase in anthropogenic CO_2 emissions is the driving factor behind this change, which is causing dramatic and devastating impacts around the world. Although reducing the amount of CO_2 and other greenhouse gases (GHGs) is the key to address global climate change, the use of carbon dioxide removal (CDR) solutions is also critical to achieve net-zero according to the IPCC (IPCC, 2022a).

Carbon sequestration is one of the solutions, under international cooperation initiatives, to address climate change. Back in 1997, the Kyoto Protocol already considered carbon sequestration as one of the responses to global warming. More recently, the 2015 Conference of the Parties ('COP 21') once again outlined carbon sequestration as a way to address the imbalance of increasing CO_2 concentration in the atmosphere. The Paris Agreement recognises the importance of "achieving a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of the century, on the basis of equity, and in the context of sustainable development and poverty reduction" (United Nations, 2015).

On the scientific end, even the most optimistic IPCC scenario depends on the hypothetical deployment of large-scale CDR technologies. CDR refers to "anthropogenic activities that remove CO_2 from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, or in products" (IPPC, 2022a). Simply, carbon removal is the process in which carbon is removed from our atmosphere and stored away for a long period of time. The IPCC shows that at the point when scenarios for global net-zero CO_2 emissions reach this target, between 5 and 16 $GtCO_2e$ should be compensated by removals (IPCC, 2022a). In addition, 360 $GtCO_2e$ would need to be removed from the atmosphere between the year of net-zero and 2100 on average in the high overshoot scenario (i.e. temporarily exceeding 1.5°C global warming by 0.1°C - 0.3°C for up to several decades before bringing it back down) (IPCC, 2022a).

1.2 CDR and permanent storage

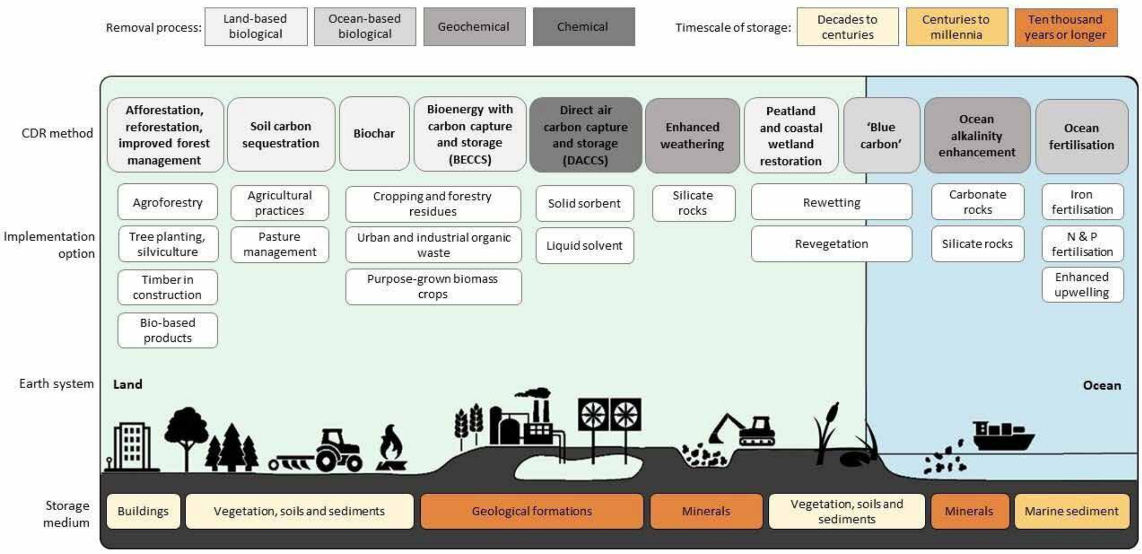


Figure 1. Carbon dioxide removal approaches, split by process and method (Source: IPCC, 2022b).

The removal type depends on the practice and/or the technology being used. Removal types are categorised as biological carbon removal (which stores carbon for shorter lengths of time) or technological carbon removal (which can store carbon for longer periods of time).

Within biological carbon removal, we can distinguish land-based biological removal (e.g. afforestation, reforestation, soil carbon sequestration, biochar, BECCS, etc.) and ocean-based biological removal (e.g. blue carbon management, ocean fertilisation). We can further split land-based removals into conventional land-based and hybrid land-based (e.g. biochar, BECCS). We can split technological carbon removal processes into two sub-categories: geochemical (e.g. enhanced weathering or ocean alkalinity enhancement) and chemical (e.g. direct air capture and storage) (Figure 1). Practices or technologies that remove CO_2 are generally described as enabling the achievement of 'negative emissions'.

Both hybrid land-based and technological CDR are also called 'novel CDR'.

Practically, the two types of mechanisms and locations for storing carbon from atmospheric CO_2 absorption are:

- Natural biological mechanisms (e.g. plant growth, soil, etc.), with the plant itself standing as the storage site (its leaves, fruit, stems, branches, trunk or roots). When these plant parts are cut or die back naturally, they also participate in the storage of carbon either by transfer to the soil or in materials (timber, insulation materials, etc.);

- Technological processes, with large geological cavities or engineered methods as storage sites, which also require transport.

When CO_2 is stored underground, there are two preferred storage sites: deep saline aquifers (water tables unfit for human consumption, at a depth of more than 1,000 m), into which the CO_2 is injected, which dissolves and could subsequently be mineralised; and old oil or gas fields that are no longer being exploited, or are in the process of being exploited, and in which the injection of CO_2 makes it possible to extract more gas or oil in a process called enhanced oil recovery (EOR).

In the storage phase, the carbon no longer participates in the absorption mechanism of atmospheric CO_2, but it does not contribute to the emission of CO_2 into the atmosphere either. This emission may take place later (for example during the final combustion of a wood product) or not (if it is furniture or a long-lasting frame). This is a critical aspect of CDR as the forms of carbon storage constitute a lever for action and for controlling CO_2 emissions in the future, since it is possible to delay them for as long as it is chosen to maintain the stock. The notion of storage introduces a time dimension. Although there's currently no consensus that specifies this time scale, permanent storage usually refers to several decades or more (ETC, 2022).

1.3 CDR, carbon neutrality and net-zero

The scientific consensus argues that these solutions cannot absorb and permanently remove atmospheric CO_2 on a scale large enough to offset a substantial part of global emissions (Stein and Merchant, 2022). This is why achieving global carbon neutrality or global net-zero emissions means first reducing global emissions very significantly, so that only a small residual balance is emitted and removed. The definition of carbon neutrality in the corporate sector is different from the global level. In the former, it is based on a three-step process that consists of measuring emissions, reducing them as much as possible, and offsetting the so-called "unabatable" portion by purchasing carbon credits.

However, each of these three steps involves significant challenges and none of them is rigorously defined. The corporate net-zero approach brings more rigour and transparency to climate strategies, by proposing that companies organise their quantified objectives, and monitor their progress, along three main aspects (Fankhauser et al., 2022):

1. Actual emissions reductions (direct and indirect)

2. Efforts undertaken to help others reduce their emissions and promote sustainable development objectives (e.g. beyond value chain mitigation)

3. Carbon dioxide removal or negative emissions (via the purchase of credits)

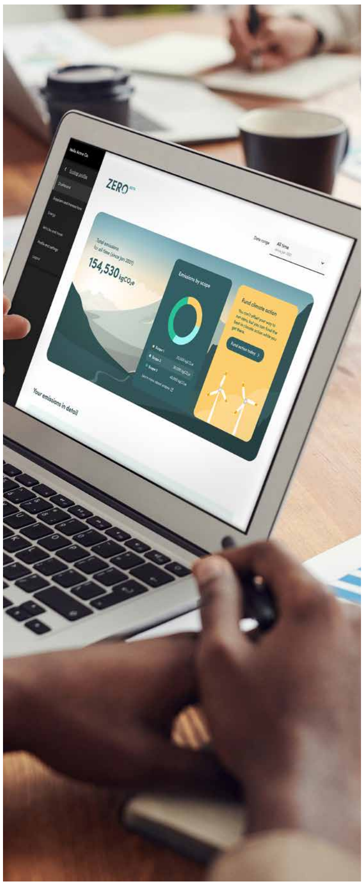
It should be noted that these three axes are independent from each other so that "transfers" from one to the other are not allowed. For example, carbon removal credits purchased in the second aspect cannot count as real emission reductions under the first aspect. CDR solutions are part of the third axis and are discussed in this document.

According to the IPCC, "carbon neutrality" and "net-zero" are synonyms at the global scale.
It refers to a global equilibrium in which an organisation cannot be net-zero alone due to arbitrary boundary setting in non-global scales, but rather contribute to it. Business climate strategies are therefore contribution to global neutrality or net-zero emissions. A company no longer aims to achieve a static state of neutrality, but manages its emissions dynamically in order to contribute to the objective of global neutrality (or to national emission reduction targets). Neutrality is no longer a state, but a process.

1.4 Aims and objectives

In order to maximise our chances of limiting global warming to under 2ºC (or as close to 1.5ºC as possible), we must halve global emissions by 2030 (2019 baseline), and reach global net-zero emissions (or global 'carbon neutrality') by 2050 (IPCC, 2022a). There is no substitute for direct and comprehensive reductions in emissions. For all parties (including businesses), making direct emissions reductions must always be the number one priority. However, businesses and public authorities should also commit to gradually increasing funding in carbon removal.

The aim of this document is to provide guidance for the selection of CDR approaches. The study focuses on carbon dioxide removal only to address one of Ecologi's core business activities: helping businesses contribute to global net-zero emissions. Further details on Ecologi's strategy for climate change mitigation strategy are provided in the Climate Impact Regionalisation Strategy. To gain insights into where CDR solutions are most likely to be needed, this study first provides an overview of CDR approaches potential and side effects on human and natural systems to better capture vulnerabilities, hence the need for targeted interventions. The study will then deep-dive into the future paths for CDR deployment and touch on CDR markets to determine their suitability for Ecologi's engagement.



2. Potential of carbon dioxide removal and side effects

2.1 Biological CDR

Natural carbon sequestration is the 'absorption' or 'storage' of carbon in a long-term carbon sink or reservoir.

There are four main reservoirs of carbon: the atmosphere, the biosphere, the ocean or hydrosphere, and the subsoil or lithosphere. In the atmosphere, carbon is present in gaseous form in the carbon dioxide (CO_2) molecule. In the biosphere, carbon is stored in the form of organic matter, notably in wood and soils. The hydrosphere contains inorganic carbon in the form of limestone as well as in the form of dissolved CO_2. The lithosphere also contains carbon in the form of rocks, sediments and fossil fuels.

2.1.1 Terrestrial ecosystem restoration

Natural carbon sinks, such as forests, peatlands and oceans are ecosystems that naturally absorb CO_2 and store it in a very efficient and more-or-less permanent way. Many companies, including fossil fuel producers, rely heavily on tree planting and forest protection to "offset" their emissions. However, the land surface area needed to significantly reduce CO_2 levels through tree planting - up to twice the size of India - competes with other land uses, such as agriculture. Biodiversity could also suffer if the right criteria for restoring natural ecosystems are not met. The permanence of storage may also be questioned. For example, new forests may also fall victim to fires, which are likely to increase with global warming, releasing all the stored CO_2.

The so-called "natural" techniques include the restoration of ecosystems (e.g. reforestation) or the improvement of agricultural practices and forest management. For example, a grassland can store 80 tC/ha, while a large-scale crop only captures 50 tC/ha (INRAE, 2019). On a global scale and by 2050, restoration and better management of ecosystems could make it possible to capture 58 and 60 $GtCO_2$ respectively in the next 30 years (ETC, 2022). But to reach such volumes, reforestation projects would have to cover 300 million hectares, i.e. six times the area of a country like France, in the next 10 years. Moreover, the improvement of agricultural and forestry practices will have to cover all the land. In reality, the experts denounce numerous cases of rights violations, land grabbing and undermining the food sovereignty of local populations (IPCC, 2021) (Figure 2).

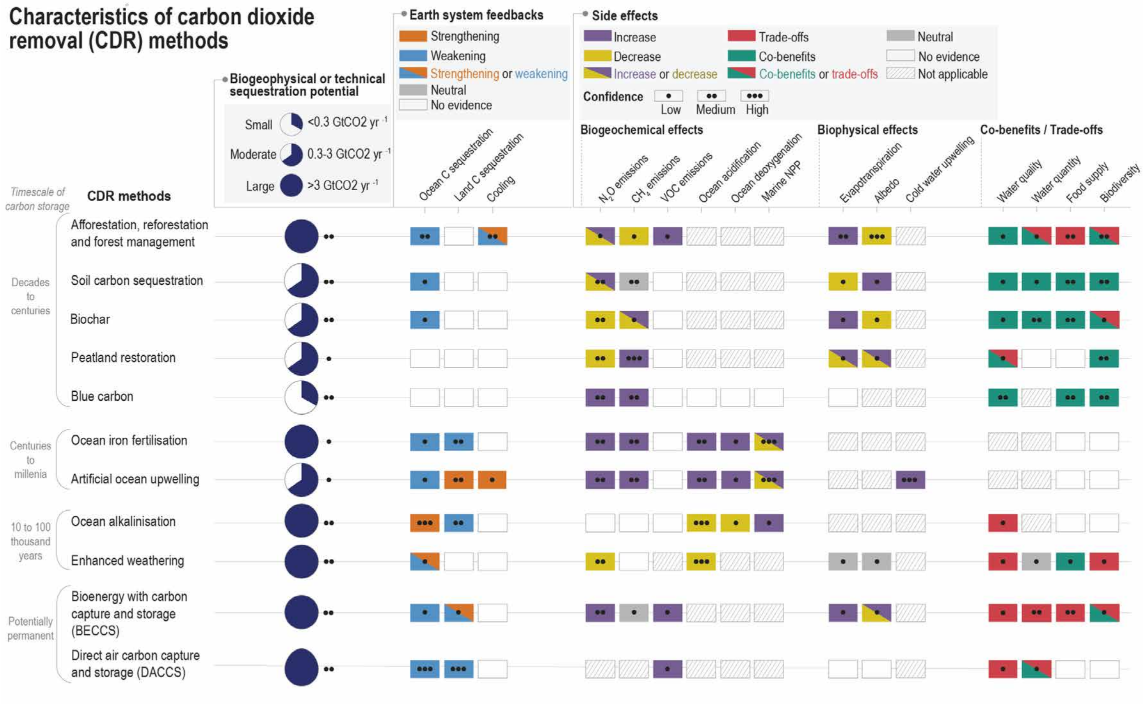


Figure 2. General potential and side effects of CDR approaches (Source: IPCC, 2021)

2.1.2 Biochar

Soils contain two main types of carbon. The first is organic carbon in the form of stable carbon (humus) and labile carbon, i.e. carbon that is available to microorganisms and plants, made up of easily degradable compounds from microbial and plant biomass.

The second is inorganic carbon, which consists of carbonate ions such as calcium carbonate and minerals in the form of rocks and sand. This form of carbon does not provide microorganisms and plants with the energy they need to feed themselves. Intensive agriculture, based on synthetic inputs, drastically depletes the amount of carbon in soils, mainly the organic fraction. Nitrogen fertilisers, combined with tillage, accelerate microbial respiration, using the soil's carbon faster than it is replaced. Some soil scientists now estimate that conversion of natural systems to agroecosystems causes 60% to 75% soil organic carbon depletion (Ivezíc et al., 2022).

As trees grow, they store carbon from the atmosphere in their biomass, through photosynthesis. When biomass decomposes naturally, carbon dioxide and methane are emitted into the atmosphere. However, when this biomass is burned in the absence of oxygen (a process called pyrolysis), it leads to the production of three components: a gas mixture, an oily liquid fraction (bio-oil) and a solid residue with a high carbon content, biochar. Biochar is a highly stable, carbon-rich residue. It has several environmental and climate benefits. For example, it has the capacity to enhance soil water retention due to its porous structure, to increase the cation exchange capacity (i.e. influences the soil's ability to hold onto essential nutrients), to improve microbiological activity, and finally to store carbon in a stable form (Figure 2). It is already widely used in Northern Europe and Canada, and could improve the physical structure of the soil in the long term and improve the biological activity of deficient soils and improve fertility. It retains most of the carbon and if buried, that carbon can be held for centuries in the soil. Applying biochar to soils can reduce other soil greenhouse gas emissions. In infertile soils, biochar can reduce the loss of nutrients through leaching (Tisserant and Cherubini, 2019).

The production of biochar using waste biomass – such as waste timber from commercial forests – is a more permanent method of removing CO_2 from the atmosphere, and storing the carbon on long-term timescales, than allowing the biomass to decompose naturally. Mixing the produced biochar into soil can therefore act to permanently lock away its stored carbon, and studies have also found that it can support the fertility and productivity of the soil (Hepburn et al., 2019). However, its use must be subject to precautions because its retention and absorption qualities can block certain nutrients: it is imperative to "load" the biochar before incorporation, by inoculating it with a solution rich in nutrients and micro-organisms such as fermented forest litter.

2.1.3 Soil carbon sequestration

Soils contain three times more carbon than the atmosphere or vegetation on land. There are three compartments for carbon in organic matter in soils, depending on the rate of degradation: a labile one with degradation of organic matter in days to years, an intermediate or "slow" one that decomposes in years to decades, and a stable or "resistant" one that is renewed in decades to centuries. The challenge is therefore to increase the size of the intermediate and stable reservoirs to maximise permanent carbon storage.

Solution for soil carbon sequestration (SCS) is possible both in the top layer using various techniques such as organic fertilisation, crop residues, intercropping, improved crop rotation, cultivation of perennial fodder crops, reduced tillage, conversion of cultivated land to grassland, and in the subsoil through the cultivation of deep-rooted plants or mechanical input through deep ploughing. These techniques capture CO_2 from the atmosphere through photosynthesis and trap it in the soil through litter and root exudates. Unlike forests, which allow the use of timber, the soil is not a carbon reservoir that can be depleted without having a negative climate impact so that the carbon sink effect has to be maintained for a longer period of time. In theory, large amounts of carbon could be stored into nutrient-poor and often degraded soils in (sub)tropical regions. A 2018 study estimated that a realistic technical potential for SCS is 3.8 (2.3-5.3) $GtCO_2$ per year (Fuss et al., 2018), while a more recent report estimates the potential between 0.9 - 1.5 $GtCO_2$ yr^{-1} (ETC, 2022).

However, there are a few limitations to SCS as it is unclear how much storage can be increased in soils that are already close to saturation, particularly in forests or grasslands. Moreover, field observations show that the rate of storage decreases rapidly over time. Beyond the effects of global warming, soils could sequester 40% less carbon by 2100 (He et al., 2016). Studies show that the effects of annual inputs of organic matter and nitrogen fertilisation, as well as the conversions of cropland to pasture or forest lead to a significant drop in annual carbon storage beyond 60-80 years (Poulton et al., 2018). Overall, empirical studies tend to agree that the achievable potential of SCS as a long-term CDR solution are much lower than the theoretical estimates because the implementation and effect of techniques to foster SCS are strongly conditioned on the long-term by the geographical location and management pattern. A global estimate of SCS is therefore not very meaningful, especially due to great uncertainties from the lack of detailed information on soils in many regions.

2.1.4 Blue carbon

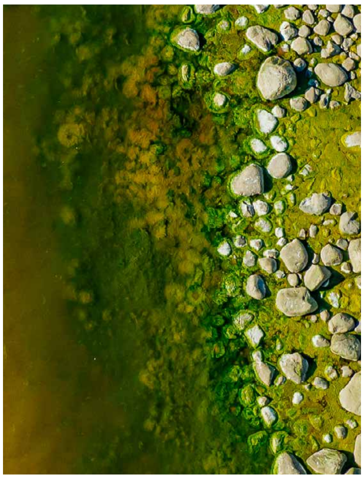
On short time scales, the continental biosphere and the ocean exchange carbon with the atmosphere. Photosynthetic marine organisms, such as algae or phytoplankton, photosynthesise and breathe, as do marine animals. Physical exchanges are also important, continuous, and rapid at the atmosphere-ocean interface. Atmospheric CO_2 will dissolve in the surface waters, and depending on its concentration, atmospheric pressure, temperature and water agitation, some of this gas will return to the atmosphere and some will remain in the oceans.

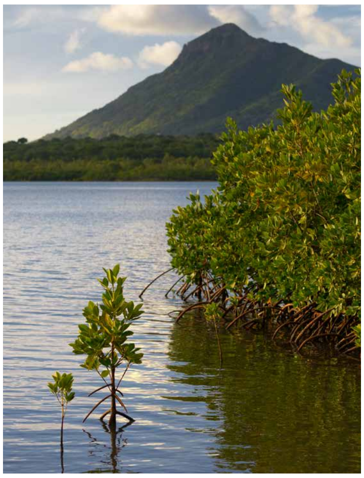
In 2009, the UNEP, FAO and UNESCO defined blue carbon as the "carbon captured by marine organisms". More specifically, this term is most often used to describe coastal ecosystems: mangroves, tidal salt marshes, meadows, and macroalgae such as kelp. It is clear that the ocean is the largest natural carbon sink on Earth and, in particular, coastal ecosystems. Recent estimates showed that the ocean is currently storing around 3,117 GtC in the top 1 m of sediment. However, since most of this carbon is located in Exclusive Economic Zones (EEZs), they are subject to high exploitation leading to a 1-3% loss each year due to climate-related and anthropogenic factors, such as harvesting, eutrophication, and pollution.

Under a plausible scenario of "ambitious but realistic pace of adoption", marine restoration activities as a CDR solution could cover areas of 6.1 Mha for coastal wetland restoration, 16.3 Mha for macroalgae restoration, and 13.4 Mha for seaweed farming. In terms of climate impact, this would equate to 6.5 ± 0.05 $GtCO_2e$ until 2060 (Jankowska et al. 2022).

It is important to note that while coastal wetland restoration and protection have been studied in-depth, more uncertainty lies around macroalgae forests and seaweed farming due to the rate of long-term sequestration that is much more uncertain than the rate of long-term sequestration in coastal wetlands. Estimating blue carbon removal is challenging because coastal ecosystems store most carbon below ground so estimates of carbon burial rates are used to estimate how much carbon is sequestered. However, there is a lot of mixing between older (i.e. deeper, carbon-rich layers) and younger layers on top. Thus, it can be unclear if the carbon measured comes from the restoration itself. In addition, rivers usually feed into coastal ecosystems and export a lot of carbon - up 90% of the carbon found in coastal sediments can come from rivers (hence inland) - making it challenging to estimate how much the coastal restoration is actually sequestering. An illustration is the abyssal difference in carbon burial estimates: 600-fold between the highest and lowest estimates in salt marshes, 76-fold for seagrasses and 19-fold difference for mangroves (Willamson and Gattuso, 2022).

As for other nature-based solutions, ocean-based solutions can provide multiple community benefits, positive environmental and biodiversity impacts, like more extensive habitat for juvenile fish and protection from storm waves, tidal surges or erosion caused by sea level rise (Vanderklift et al., 2019).





2.1.5 BECCS (Bioenergy carbon capture)

There are several solutions for capturing carbon: some are based on nature, others on technology, and some are hybrid such as bioenergy with carbon dioxide capture and storage (BECCS). In BECCS technology, the CO_2 released during biomass combustion is not released into the atmosphere but is captured and stored underground in geological reservoirs. It involves growing trees that absorb CO_2 as they grow, then burning them to produce energy and storing the resulting CO_2 underground. The transition from neutral to negative emission is achieved through capture and storage. The CO_2 emitted during biomass combustion is recovered and purified by either of three separate processes (García-Freites et al., 2021):

- Post-combustion: this extracts the CO_2 produced during combustion using amine solvents;

- Oxycombustion: combustion is carried out under pure oxygen instead of air. This results in a more complete combustion and an easier isolation of the CO_2;

- Pre-combustion: carbon is extracted before combustion. A synthesis gas ($CO + H_2$) is produced by heating the fuel to 700°C in a low-oxygen atmosphere and then converted into CO_2 and H_2 by water.

The purified CO_2 is then compressed and heated, before being transported to the storage area where it is injected at a deep depth generally greater than 800 metres below ground (Fuss et al., 2018). Storage areas are usually depleted gas reservoirs or deep saline aquifers. CO_2 can also be stored for EOR. The top layers of these storage areas must be stable and impermeable to prevent leakage. The technique works in theory, but has yet to materialise on a large scale. One of the few commercial-scale projects in the world, in the UK, has been delisted from the S&P Clean Energy Index after failing sustainability criteria (Ambrose, 2021). At the moment, EOR is the most economically attractive way to use captured CO_2 and can reduce net emissions from conventional oil production (Mulligan and Lashof, 2019). However, it means locking the world further into fossil fuels. EOR could only be viable if it actually displaces conventional oil and is used as the world fully transitions to clean energy.

Realistically, Harper et al. (2018) argued for using BECCS "in regions where bioenergy crops replace ecosystems with high carbon contents could easily result in negative carbon balance". The contribution of BECCS to overall land-based mitigation, if optimised, could be the greatest in North America and Russia (and to a minor extent India) but would lead to a decrease in the carbon uptake from natural ecosystems due to the loss of forests to BECCS (see Impact Regionalisation Strategy) (Figure 2 for side effects). In other regions, Brazil, the rest of South America, or East Africa, for example, both bioenergy crops and forest expand at the expense of agricultural land. Indeed, Hayman et al. (2021) argues that "growing bioenergy crops for BECCS is only preferable where it replaces existing agricultural land", and where it does not put strain on other natural resources such as water, which means BECCS ends up being only preferable in specific regions like Southeast Asia and Western Europe.

2.2 Technological CDR

Technological carbon removal processes are typically split into two sub-categories: geochemical (e.g. enhanced weathering or ocean alkalinity enhancement) and chemical (e.g. direct air capture and storage). They require geological or engineered storage sites for the carbon dioxide captured using chemical processes.

2.2.1 Direct air capture and storage

Direct capture of CO_2 from the air and storage is a recent and still developing technology. The principle is simple: chemical processes extract carbon and convert it into solid form or bury it. CO_2 is filtered directly from the ambient air with chemical processes for geological storage. The air must first be passed through an absorbent with the help of fans. This sorbent fixes the CO_2 until its capacity to absorb the gas is reached. The second stage, called desorption, is when the CO_2 is removed from the sorbent. Depending on the sorbent, this process takes place either at low temperatures of around 100°C or at relatively high temperatures of up to 900°C (Terlouw et al., 2021).

As for BECCS, the storage potential of DACCS is naturally limited by the available geological capacity, which remains largely unknown due to a lack of field studies. Unlike carbon capture and storage (CCS) processes that capture CO_2 at a point source with a high concentration of CO_2, DACCS technology captures CO_2 directly from the ambient air.
For CCS, the CO_2 released by industries is often very low in concentration. It generally represents less than 20% of the volume of the flue gases, which are composed of oxygen, water vapour and nitrogen. As the objective is not to store all the flue gases but only the CO_2, separation methods are necessary, which makes the overall process of capture, transport and storage energy intensive and costly. On the other hand, DACCS has to extract CO_2 concentration in ambient air at concentrations 500 times lower (around 0.042%). As a result, it consumes much more energy, particularly in the form of heat.
To ensure that a DACCS installation makes a positive climate impact, a comprehensive life-cycle analysis must be conducted. The energy must come from a renewable source and it must be possible to recover the heat produced during the process.

In addition, some parts of the process may consume a lot of water. Typically, the risks associated with storage are the same as for BECCS technology.

Besides underground storage, recycled materials provide interesting alternatives for storing the captured CO_2. Mineral carbonation is a process in which the rock naturally fixes CO_2. This phenomenon is also observed in concrete used for construction. Accelerating this process by enriching concrete with concentrated, liquefied CO_2 partially neutralises the chemical reaction that releases CO_2 during cement production. Particularly useful in recycled concrete, accelerated carbonation has the capacity to reduce the CO_2 emissions linked to the manufacture of cement by 10 to 15% (Maia Pederneiras et al., 2022). As the chemical bonding of CO_2 in recycled concrete is very stable, accelerated carbonation processes promise permanent storage of CO_2, possibly for centuries.
The recarbonation of concrete does not seem to pose any significant risk to the environment or to humans (Hanifa et al., 2023). The real limitation is the amount of CO_2 that can be captured from DAC or carbon capture processes.

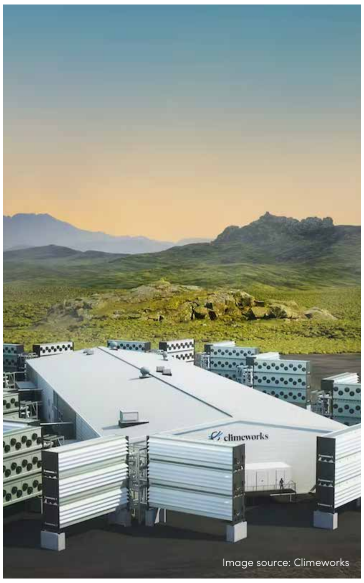
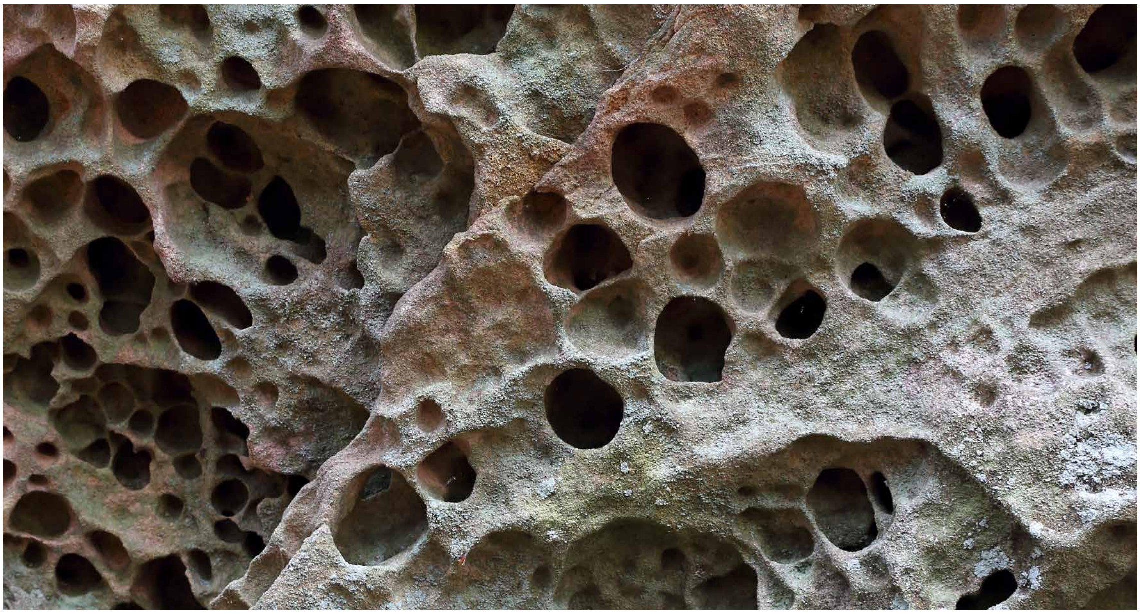


Image source: Climeworks

2.2.2 Enhanced weathering

Weathering is a set of processes that causes rocks to 'weather' - decompose or disintegrate. This natural process, which normally takes place over very long periods of time (a hundred thousand years), can be accelerated to remove CO_2 from the atmosphere on time scales of a decade. This process is called enhanced weathering (EW) (Andrews and Taylor, 2019). It involves crushing mineral-rich rocks that naturally absorb CO_2, and then spreading this dust over the land or ocean surface. EW is generally split into two sub-categories: enhanced carbonate weathering and enhanced silicate weathering. Recently, enhanced silicate weathering (ESW), also defined as the dissolution of the silicate-containing mineral olivine, has received most attention as carbonate weathering tends to provide small or close to zero net removal of atmospheric CO_2 on geological time scale and is half as effective at removing CO_2 than silicate weathering.

Silicate minerals are dissolved in a reaction with atmospheric CO_2 and water, and the products of this reaction, which include calcium (Ca2+), magnesium (Mg2+), and bicarbonate (HCO3−), are transported on land or to the ocean by rivers. Typically the powdered silicate rocks are applied to soils, particularly agricultural and forested lands, or directly into the ocean. In general, croplands are the most promising outlets for ESW due the interactions between the rock with plant roots and the soil, and the operational capacity to apply it on large spatial scales, compared to the open-ocean (Eufrasio et al., 2022). Thus it would be possible to take large quantities of rocks such as basalt, grind them finely to make them much more reactive with atmospheric CO_2 and then spread them over large areas or agricultural surfaces where the carbon would be fixed in the soil in the form of carbonate. The other advantage of this process would be to increase soil fertility. However, this technology is energy-intensive and could have adverse effects on natural ecosystems (Andrews and Taylor, 2019). ESW is also considered a viable solution to ocean acidification. Open ocean dissolution of olivine is known as ocean fertilisation which, when co-deployed with CCS, could double this effect so that by the end of the century, means ocean pH returns close to 2020 levels (Vakilifard et al., 2021). There are a lot of uncertainties around the removal potential of ESW in real-life conditions, as well as feedbacks between hydrological and biogeochemical processes over multiple spatial scales which could reduce the carbon sequestration potential and lead to adverse consequences for biodiversity, the water and soil geochemical cycles (Andrews and Taylor, 2019; Calabrese et al., 2022). Issues of cost and scale up are also important aspects of EW as a CDR solution.



3. Prospects and CDR markets

3.1 State of maturity and cost

While the absorption capacity of biological sinks (i.e. vegetation, soil) can be limited in some regions, the low readiness of technological solutions emphasises the importance of careful planning and selection of future project development. The capacity of biological sinks is very limited in urbanised regions due to the lack of open areas, such as Switzerland or coastal Europe, or in regions where the density of settlement in forested areas is already high along with high levels of carbon reserves in the soil. Using conventional land-based CDR solutions (i.e terrestrial restoration) as the first entry point to CO_2 removal seems logical considering the technological readiness, scalability and funding challenges faced by technological solutions. However, it would be appropriate not to saturate biological sinks to offset avoidable emissions until it is certain that technical approaches such as BECCS or DACCS can produce negative emissions in the necessary amount. Once full, these sinks will no longer be available to offset emissions that are difficult to avoid in the future, such as agricultural emissions. The permanence risk associated with biological solutions is also important to consider.

From a climate perspective, a period of several decades is a minimum to be considered as permanent, especially since temperature targets are set for the end of the century (ETC, 2022). A key advantage of conventional land-based or ocean-based CDR is their co-benefits.

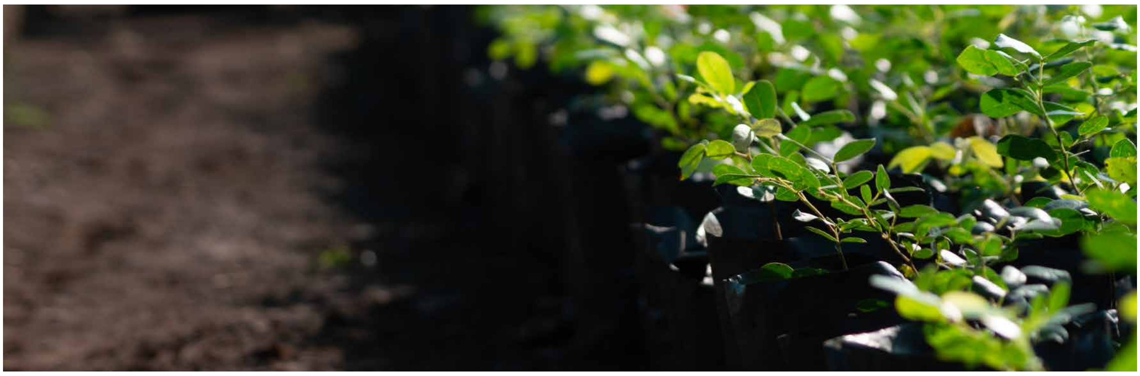
Within the limits of a manageable risk, those bring synergy effects, for example with regard to soil productivity or biodiversity, as well as for human well-being.

The deployment potentials of CDR solutions vary considerably in the literature. Biological mitigation options including afforestation/reforestation, biochar, enhanced weathering as well as soil carbon sequestration each have a potential in the range of 1–5 $GtCO_2$ per year in 2050, considering that the likely achievable removal is in the lower/average end. Achieving the higher end of the ranges gets increasingly resource demanding and will require higher carbon prices (see below). Looking ahead, it is difficult to accurately predict future CDR deployment without an appropriate baseline, and this is not only due to the technological readiness of some solutions. Smith et al. (2023) argue that three conditions should be fulfilled to improve the accuracy of CDR deployment predictions: 1) an agreement on how to accurately measure CDR from current conventional CDR methods on land (i.e. afforestation, reforestation and forest management) and CDR achieved through other managed land-based activities; 2) a central repository for CDR project data, and 3) standardised CDR project reporting.

The scale and timing of deployment depends on several factors: emission trajectories in each sector, maturity of technology, removal process, storage potential, storage medium, technical capacity, financial capacity, governance, etc. Typically, maturity ranges from lower maturity (e.g. ocean alkalinisation) to higher maturity (e.g. reforestation). Removal and storage potential ranges from lower potential (<1 $GtCO_2e$ yr^{-1} such as blue carbon management) to higher potential (>3 $GtCO_2e$ yr^{-1} such as agroforestry). Costs range from lower cost (e.g. USD 10-100/tCO_2e such as reforestation or soil carbon sequestration) to higher cost (e.g., 300-1,000 USD/tCO_2e such as for DACCS). Today, most CO_2 removal technologies are, at best, still at the pilot project stage. In 2022, around 2.3 million tonnes of CO_2 were removed from the atmosphere by new technologies, compared to the 40 Gt emitted per year (54 Gt CO_2e including other gases but excluding CO_2 from land-use) (Naddaf et al., 2023). Assuming no new projects are started and all in-development projects are completed, CO_2 removals generated using non conventional CDR solutions will grow from 2.3 $MtCO_2$ per year in 2022 to 11.75 $MtCO_2$ per year by 2025, most of the growth being absorbed by the completion of the Summit Carbon Solutions BECCS project (Smith et al., 2023). DACCS and biochar should remain well below 1 $MtCO_2$ per year in volume by 2025. However, there is real traction about these solutions in the financial sector. Tech giants Alphabet, Meta, Stripe and Shopify, together with McKinsey, have launched the Frontier Initiative to accelerate the development of these technologies. They are committing to buy US$ 925 million in CO_2 removal by 2030 from companies in the sector (Bloomberg, 2022.

Conventional CDR on land will likely be responsible for 99% (78-100%) of CDR in 2030 in both 1.5°C and 2°C pathways (Smith et al., 2023). It needs to double or increase by 50% until 2050 compared to 2020 levels in the 1.5°C and 2°C pathways, respectively, to peak around 2050. Novel CDR will grow progressively throughout the century with a heavy reliance on BECCS. Since 2005, models have picked up the solution as part of generating least cost pathways for climate change mitigation. However, it is really in the 5th IPCC assessment report in 2014 that it gained momentum. For example, across the 116 scenarios reviewed that were consistent with limiting global warming to 2°C, 101 involved carbon removal either through BECCS or afforestation and reforestation (Brack and King, 2020).

The level of reliance on novel CDR depends on five key factors:
1) how strict is the temperature limit to be achieved; 2) the magnitude and duration of any temperature overshoot and eventual drawdown; 3) the speed and depth of emission reductions; 4) the speed and depth of energy demand reduction;
5) the breadth of the portfolio of available CDR methods as well as other mitigation options (Smith et al., 2013). For example, in a scenario to limit warming to 1.5°C focused on the energy demand reduction and radical energy efficiency improvement, novel CDR would no longer be necessary (only 330 $GtCO_2$ cumulative removals until 2100 from conventional terrestrial solutions). In other scenarios focused on renewable energy and the deployment of CDR, 500 $GtCO_2$ and 690 $GtCO_2$ split between all CDR types would be required. On the other hand, other global scenarios that limit warming to 2°C or lower involve scaling up novel CDR by a factor of 30, but up to 540, by 2030 and a factor of 1,300 on average (range is 260 to 4,900) by 2050, compared with 2020 (Smith et al., 2023).



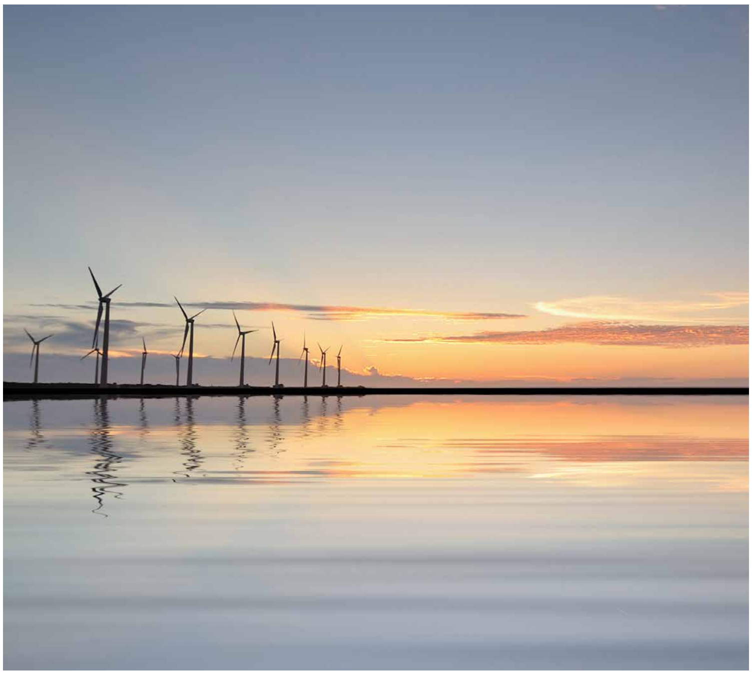
3.2 Opportunities and future challenges

Despite the crucial need to ramp up the deployment of CDR solutions, no countries have pledged to scale novel CDR by 2030 in their Nationally Determined Contributions (NDCs), countries are not obligated to publish such strategies under the Paris Agreement), and a small number of BECCS, DACCS and biochar projects are being developed. Not only will it create a supply bottleneck for businesses in their net-zero journeys it also means that temperature targets are likely to be breached sooner with global warming reaching larger magnitudes.

As mentioned earlier, almost all scenarios that limit warming to 2°C or lower rely almost entirely on conventional CDR on land by 2030. Yet, evidence suggests that dedicated policies and management practices are lacking to even maintain the current conventional removal solutions (about 2 $GtCO_2$ per year). Despite being included in some NDC pledges, there will also be a gap in conventional removal of up to 2 $GtCO_2$ per year in 2030 (Smith et al., 2023).

Since the few scenarios with a low-CDR world are very unlikely to take place since they require drastic cuts in emissions, we need to close the CDR gap - because every year that emissions do not drop substantially, the dependence on CDR in the future increases (ETC, 2022). Ultimately, only stringent emission reductions can limit this dependence. In parallel, current conventional CDR on land needs to be maintained and expanded. It will require additional policies and the active management of land sinks, considering specifically the adaptation to future climate impacts. In addition, novel CDR - hybrid and technological solutions - needs to be developed and scaled, requiring additional investment including from voluntary carbon markets.

In general, large-scale deployment of CDR solutions, as implied by both 1.5°C and 2°C scenarios, appears unrealistic given the biophysical and economic limits that recent research has shown. Until they are demonstrably feasible and available at the global scale there should be no delay in a global peak and decline of emissions. The scientific consensus is becoming clearer: CDR solutions are not a viable option to limit warming to 1.5°C and 2°C. The largest share of our efforts should be put on reducing our emissions and transforming our energy and production systems. At this stage, private funding can be useful to continue research efforts into CDR but large-scale systemic transformations, which require long-term planning and funding, should remain the priority.



4. Conclusion

Carbon sequestration is one of the solutions to address climate change. Even the most optimistic IPCC scenario depends on the hypothetical deployment of large-scale CDR technologies which refers to anthropogenic activities that remove from the atmosphere and store it permanently. Removal types are broadly categorised as biological or technological. The forms of carbon storage constitute a lever for action and for controlling CO_2 emissions in the future. Storage should at least last for several decades. Storage time is one of the key criteria to select the appropriate solution, although others such as natural resources consumption, social and environmental co-benefits, technological readiness, and scalability are other equally important aspects.

On a global scale, restoration and better management of terrestrial ecosystems could sequester 58 and 60 $GtCO_2$ respectively in the next 30 years. However, the size of land required to reach this scale would need to cover 300 million hectares, in the next 10 years, possibly creating issues of land management, trade-offs with food production, etc. Overall, the success of large scale conventional land-based CDR will greatly depend on global land governance. The production of biochar using waste biomass is also an attractive alternative to both ensure permanent CO_2 removal as well as supporting the fertility and productivity of the soil to grow crops and vegetation. The other so-called "hybrid" CDR, BECCS, is promoted in the latest IPCC assessment report as the main solution to reach the required scale of removal. However, once the trade-offs are accounted for, BECCS ends up being only preferable in specific regions.

The deployment potential of CDR varies considerably. Biological solutions whether on land or in the ocean such as afforestation/ reforestation, biochar, enhanced weathering as well as soil carbon sequestration each have a potential in the range of 1–5 $GtCO_2$ per year in 2050, while the removal potential of technological CDR is not really limited by natural saturation, rather by their costs, energy and material requirements and maturity. Therefore, conventional CDR or so called terrestrial nature-based solutions on land will likely be responsible for 99% (78-100%) of all removals by 2030 in both 1.5°C and 2°C global warming pathways. It is critical to bear in mind that the deployment scales of individual technologies cannot be simply added up, as they often compete with each other for the same resources. In addition, the deployment scale of a portfolio of CDR solutions decreases with the amount of solutions deployed simultaneously, suggesting that there could be a natural order for phasing in CDR solutions.

The deployment scale required for technological or novel CDR is of three orders of magnitude by 2050, depending on the technology. While novel technologies may not encounter the saturation issue faced by conventional solutions, the unit cost of removal above US$ 100 / tonnes (up US$ 1,000 / tonnes today) means that higher carbon prices are required globally if larger deployment is to be reached. Besides the low likelihood that novel CDR will be developed and deployed at scale according to the IPCC scenarios, no countries have pledged to scale novel CDR by 2030 in their NDCs which will further delay the political agenda. The private sector has a big role to play for finance to flow in CDR deployment, either through compliance markets or voluntary carbon markets, especially when it comes to offsetting the unabated portion of their emissions towards net-zero targets. Due to the risk averse nature of the private sector, total funding flows towards removals are likely to be limited at least in the near term, creating a funding gap. Whilst governments should focus on emissions reductions as a priority (e.g. ending deforestation and phasing-out coal), their role will be crucial to bridge the initial finance gap and incentivise the take up of removals through carbon markets.

Based on the above, Ecologi follows the precautionary principle when it comes to removals.

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5. Summary table

	BIOLOGICAL / NATURAL CDR					TECHNOLOGICAL CDR		
	Conventional land-based / Ocean CDR			Novel CDR				
				Hybrid CDR		Geochemical CDR		Chemical CDR
	Terrestrial ecosystem restoration	Blue carbon	Soil carbon sequestration	Biochar	BECCS	Enhanced weathering	Ocean alkality enhancement	DACCS
Summary description	Store carbon in vegetation and soils by planting, restoring or managing forest and peatland	Manage coastal ecosystems (e.g. mangroves, wetlands) to increase net primary production and store carbon in vegetation and sediments	Use agricultural management practices to improve soil carbon storage	Burn biomass at high temperature without oxygen to form a highly stable soil amendment	Production of energy from plant biomass combined with carbon capture and storage	Crushed rock speading on land to chemically remove atmospheric CO2 in reactions that form solid minerals (carbonates and silicates) that are stored in soils or in the ocean	Deposition of alkanine minerals (e.g. olivine) in the form of crushed rocks to increased CO2 uptake via increased alkalinity	Direct removal of CO2 from air through chemical reactions, and long-term storage underground, in deep ocean or in long-lasting usable materials
Removal potential in 2050 (GtCO2/year)	0.5 - 5	0.1 - 1	0.9 - 1.5	0.3 - 3	0.5 - 5	2 - 4	0.1 - 10	0.2 - 4.5
Cost (USD/tonnes removed)	10 - 100	10 - 100	0 - 50	30 - 400	100 - 300	50 - 200	15 - 500	300 - 1000
Time scale of storage	Decades to centuries	Decades to centuries	Decades to centuries	Decades to centuries	Potentially permanent	10,000 to 1,000,000 years	10,000 to 100,000 years	Potentially permanent
Technological readiness*	High	Medium - High	High	Medium	Medium (storage) to High (energy from biomass)	Medium	Medium	Medium
Main co-benefits	Biodiversity recovery Local area freshwater supply Economic support to forest-based communities	Biodiversity recovery Local area freshwater supply Economic support to local communities Increased climate resilience, including storm protection	Increased crop yields and water holding capacity No impact on albedo Help biodiversity recovery	Improved soil health, including better water and nutrient retention, resulting in better crop yields	Energy generation (electricity or hydrogen, + heat)	Sustainable and cheap alternative to chemical fertilisers Less energy than direct air capture and less water than some terrestrial biological removals Possibility to use waste material	Reduced acidification	Limited
Main side effects	Slow removal Secure land tenure Economic impact to local communities Albedo effect reduction	Complex carbon fluxes to monitor Economic impact to local communities Prone to climate events and sea-level change	Potential increase in other GHGs (nitrogen) Potential reduction in albedo	Albedo reduction Introduction of harmful contaminants into the soil environment Land requirement Reduced nutrient availability	Compete with food production Compete with conservation and restoration Limited supply of biomass from waste Long lead time for development of geological site	Energy to grind rocks Increase water pH Full impact of on biogeochemical cycles, biomass and carbon stock to be studied, as well as possible toxicitiy to ecosystems	Energy to grind rocks Uncertain impact on biogeochemical cycles Possible toxicitiy to ecosystems Inorganic turbidity and sedimentation Unknown impact on biodiversity	CAPEX cost High demand for low carbon power Long lead time for development of geological site Efficiency of absorption methods
Priority regions	Tropical regions - South America, Africa, South East Asia	N/A	Warmer regions typically have faster saturation time	Global - mostly regions with depleted soils	Southeast Asia, Western Europe, East Africa, USA	Regions with nutrient poor soil. Some tropical regions (e.g. Brazilian Cerrado)	Uncertain	High income regions with low carbon power mix
Funding priority until 2030**	High	Medium	High	High	Medium	Medium	Low	Low
***Low**	Process in development		**** Low**	Solutions with uncertain large-scale potential and that could not be implemented globally				
Medium	Established method but not demonstrated at scale		**Medium**	Solutions with large-scale potential but that could not be implemented globally				
High	Well-designed projects can be executed at scale today.		**High**	Solutions with large-scale potential that could be implemented globally				

For more guidance on the terms used in this report and others please visit our glossary.

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