Authors

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Climate Advisers is grateful for the support given to this report by the Government of Norway.
Table of Contents

EXECUTIVE SUMMARY........................................................................................................................................4
I. INTRODUCTION ..............................................................................................................................................7
II. NATURAL & TECHNOLOGICAL CDR: KEY FACTORS FOR COMPARISON ....................................................9
   A. PUTTING NATURE TO WORK: NATURAL CDR APPROACHES ................................................................10
      Reforestation and Afforestation ......................................................................................................................10
      Improved Forest Management .........................................................................................................................12
      Soil Organic Carbon Sequestration (SOCS) .....................................................................................................12
   B. ADDING ENGINEERING: TECHNOLOGICAL CDR APPROACHES ..........................................................13
      Biochar .........................................................................................................................................................14
      Bioenergy with Carbon Capture and Storage (BECCS) ..................................................................................15
      Direct Air Capture (DAC) ...............................................................................................................................17
      Enhanced Weathering (EW) ............................................................................................................................18
IV. SEIZING NATURE’S OPPORTUNITY TODAY ..................................................................................................20
V. RECOMMENDATIONS ......................................................................................................................................22
Executive Summary

Natural solutions are abundant, well-understood, and readily-available carbon dioxide removal options that exist today. They should be deployed fully and without delay.

Scientists and other experts increasingly believe that nations will need to proactively deploy planetary-scale solutions to remove carbon dioxide (CO$_2$) and other greenhouse gases (GHGs) from the atmosphere in addition to rapidly decarbonizing the global industrial economy in order to limit the impacts of climate change. The 2015 Paris Agreement recognizes this dual challenge. In addition to limiting temperature rise to well below 2°C (and striving for 1.5°C), its long-term goals commit signatories to balancing emissions from sources and removals in sinks in the second half of the century.

What is Carbon Dioxide Removal (CDR)? CDR includes both natural and technology-based methods to capture and either store or use CO$_2$. Natural approaches use photosynthesis to absorb atmospheric CO$_2$, storing it in above-ground biomass, as well as in roots and soil. Technological approaches use man-made methods to remove CO$_2$ from point sources such as power plants and industrial facilities, as well as from the atmosphere. Table ES-1 provides a summary of the most prevalent CDR approaches.

In this review, we attempt to bring CDR into the mainstream climate conversation by identifying powerful solutions that are ready and cost-effective to deploy today.

Key Findings

- Natural solutions are the most readily-available CDR options. Most are very well-understood and have been deployed on a large scale for decades. Technological solutions are still largely immature, most exist only at the laboratory or demonstration stage.
- Natural solutions are currently a far more cost-effective option to capture carbon dioxide, with a price tag that is an order of magnitude lower per ton of CO$_2$ captured than technological solutions.
- Natural CDR also offers numerous co-benefits, including more resilient ecosystems, increased wildlife habitat and biodiversity, improved water quality and erosion control. With some minor exceptions, technological CDR would be deployed purely for its climate mitigation benefits. This might make it more difficult to obtain buy-in from a diverse group of stakeholders.
- Natural CDR may not be enough to meet the goals of the Paris Agreement. There are significant limiting factors to Natural CDR through both saturation effects—the natural limit of biomass to store carbon—and land constrain will cap the mitigation potential of solutions such as afforestation/reforestation and make them costlier.
- The cost of technological approaches will likely decrease in the decades to come while their mitigation potential will remain largely unchanged.
- Encouraging large-scale deployment of CDR should be a component of all truly visionary international climate action agendas and national long-term emissions strategies, with a strong early emphasis on natural CDR over the next few decades and continued research and development of technological CDR as an insurance policy over the long term.

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1 Although some approaches capture non-CO$_2$ gases, the majority target CO$_2$. This is why CDR is used as a shorthand for all solutions that result in net negative emissions. We use CDR throughout this paper.
2 We include in technological approaches those solutions like enhanced weathering that would involve large-scale human disruption of geological processes using technologies like rock crushing or mining and spreading minerals that capture CO$_2$ from the atmosphere.
Figure ES-1: Summary of CDR Approaches, by Factor

<table>
<thead>
<tr>
<th>Approach</th>
<th>Technical Mitigation Potential (GtCO₂/yr)</th>
<th>Average Cost (US$/tCO₂)</th>
<th>Readiness</th>
<th>Co-benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
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<td>5</td>
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<td>10</td>
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<tr>
<td>20</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reforestation/Afforestation</td>
<td>1.3</td>
<td>17.9</td>
<td>Mature</td>
<td><img src="tree" alt="" /></td>
</tr>
<tr>
<td>The planting of trees where none exist or have not existed for decades.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improved Forest Management</td>
<td>1.1</td>
<td>9.2</td>
<td>Mature</td>
<td><img src="tree" alt="" /></td>
</tr>
<tr>
<td>Management practices that increase the rate of CO₂ capture and the amount stored in forests.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil Organic Carbon Sequestration</td>
<td>6.8</td>
<td>12.6</td>
<td>Mature</td>
<td><img src="tree" alt="" /></td>
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<tr>
<td>Enhancing the storage of carbon in soils.</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Natural + Technological</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biochar</td>
<td>3.7</td>
<td>6.6</td>
<td>Demonstration</td>
<td><img src="tree" alt="" /></td>
</tr>
<tr>
<td>Converting biomass to decomposition-resistant charcoal.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bioenergy plus Carbon Capture and Storage</td>
<td>3.5</td>
<td>20</td>
<td>Demonstration</td>
<td><img src="lightning" alt="" /></td>
</tr>
<tr>
<td>Generating energy from biomass and storing the resulting CO₂, emissions in geological reservoirs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technological</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Air Capture</td>
<td>3</td>
<td>16</td>
<td>Demonstration</td>
<td><img src="lightning" alt="" /></td>
</tr>
<tr>
<td>The use of chemicals to absorb CO₂ from the atmosphere.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enhanced Weathering</td>
<td>1</td>
<td>4</td>
<td>Laboratory</td>
<td><img src="tree" alt="" /></td>
</tr>
<tr>
<td>The grinding of rocks that naturally absorb CO₂, and spreading of the fragments on land or in the ocean.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes: 1. Mitigation potential represented as a range of technical or maximum potential across various literature sources (see text). Technical potential estimates are not additive across approaches, as there may be tradeoffs between them. 2. Cost estimates are represented as ranges of average cost from various literature sources (see text), and are not intended to represent the range of cost estimates at a specific mitigation potential.

![tree] = Ecosystems improvement ![plant] = Land productivity ![house] = Income generation ![lightning] = Energy generation
**Recommendations**

To meet the climate challenge, we must achieve a balance between GHG sources and sinks, through actions to reduce emissions and increase removals. However, attention to the latter half of the equation has not kept pace. Therefore, governments, companies and advocates should:

- Deploy mature natural solutions as early as possible to the greatest extent possible. Natural, biological sinks offer the best combination of benefits for the climate at the lowest cost *today*. Vegetation also takes time to reach its full sequestration potential.

- At the same time, invest in continued research, development, and demonstration of technological CDR options so that they can be deployed by mid-century. New technology takes time to become cost-effective and reach commercial scales.

- Focus on forests and land as a near term solution to galvanize international action and create more climate ambition in the short term.

**Figure ES-2: Timeline for Implementing Natural and Technological CDR Solutions**

<table>
<thead>
<tr>
<th>Short-Term</th>
<th>Medium-Term</th>
<th>Long-Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-2030</td>
<td>Mid-Century</td>
<td>Late-century</td>
</tr>
<tr>
<td><strong>Decarbonization</strong></td>
<td><strong>Natural CDR: Implementation</strong></td>
<td><strong>Tech CDR: Implementation</strong></td>
</tr>
<tr>
<td><strong>Tech CDR: Research &amp; Demonstration</strong></td>
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</tr>
</tbody>
</table>
I. Introduction

In the 2015 Paris Agreement, nations agreed to limit temperature rise to well below 2°C (and strive for 1.5°C) and to balance emissions from sources and removals by sinks in the second half of the century in order to limit the impacts of climate change. Scientists and experts increasingly accept that, to achieve these goals, nations will need to proactively deploy planetary-scale solutions that remove carbon dioxide (CO₂) and other greenhouse gases (GHGs) from the atmosphere. Global climate models largely support this conclusion. In fact, of the emissions pathways that keep global temperature rise below 2°C described in the most authoritative literature on climate action, 90 percent employ some carbon dioxide removal (CDR) technology; no pathways achieve 1.5°C warming without CDR.³

Encouraging large-scale deployment of CDR should therefore be an essential component of truly visionary international climate action agendas and national long-term emissions strategies—in tandem with continued and rapid decarbonization. This report attempts to elevate large-scale CDR into mainstream climate planning by identifying powerful CDR solutions that are ready and cost-effective to deploy today.

What is CDR? CDR—sometimes referred to as negative emissions technologies (NETs)—comprises both natural and technological methods to capture and either store or use CO₂.⁴ Natural approaches use photosynthesis to absorb atmospheric CO₂, storing it in above-ground biomass, as well as in roots and soil. These include planting new forests as well as boosting the ability of existing plants and soils to absorb carbon. The vast majority of natural approaches are well-practiced—humans have been planting trees for thousands for years—and cost-effective in many parts of the world.

Technological approaches, on the other hand, use man-made methods to remove CO₂ from point sources such as power plants and industrial facilities, as well as from the atmosphere. These include already-piloted technologies such as bio-energy with carbon capture and storage (BECCS, defined in Box 1) as well as more nascent approaches such as direct air capture and enhanced weathering. Generally, although technological CDR options have the potential to capture large amounts of CO₂, significant barriers, including prohibitively high costs, continue to hinder their wide scale application at present. The CDR options considered in this report are defined in Table 1, below.

Box 1. What Do We Mean by Bio-Energy with Carbon Capture and Storage (B+E+CCS)?

It is important to understand that BECCS represents a system that combines three activities, natural and technological:

1. B = the storage of carbon in biomass through natural photosynthesis.
2. E = the conversion of that biomass, through combustion, to energy.
3. CCS = carbon capture and storage of emissions from the combustion process.

The CDR is only occurring in the natural part of this system – the growth of the biomass - and the CCS part simply reduces the portion of that stored carbon that would have been otherwise emitted in the conversion to energy.

CCS technology can also be applied in fossil fuel energy systems (thermal generating plants). The benefit of BECCS relies on the bioenergy being used as a substitute for fossil fuel derived energy, not an addition.

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³ IIASA AR5 Scenario Database; all scenarios matching climate category 1.
⁴ Although some approaches capture non-CO₂ gases, the majority target CO₂. This is why CDR is used as a shorthand for all solutions that result in net negative emissions. We use CDR throughout this paper.
Although the international community will likely have to deploy all tools at its disposal to meet the ambitious goals of the Paris Agreement by 2100, policymakers do not enjoy infinite resources and will have to make critical decisions about the climate mitigation options to pursue in the short- to medium-term. These decisions should ensure that already-available and cost-effective CDR options are deployed most immediately to their fullest extent while laboratory-scale and still-theoretical approaches are supported with continued research.

The purpose of this paper is to bring large-scale carbon dioxide removal into the mainstream climate conversation by identifying powerful solutions that are ready and cost-effective to deploy in the short-term. It does this by: 1) providing a framework through which policymakers can begin to compare and time the deployment of varied CDR approaches, including the cost, mitigation potential, resource intensity, and co-benefits of the solution; 2) examining the relative advantages of natural versus technological carbon sequestration options; and 3) offering recommendations for effectively incorporating CDR into national long-term climate planning and international climate diplomacy.

Table 1. Carbon Dioxide Removal Approaches

<table>
<thead>
<tr>
<th><strong>CARBON DIOXIDE REMOVAL (CDR):</strong> Natural and man-made solutions that deliberately remove carbon dioxide from the atmosphere</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NATURAL: Employ photosynthesis to capture CO₂.</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Reforestation / Afforestation</strong></td>
<td>The planting of trees where none exist or have not existed for decades. Trees capture CO₂ and store it in living biomass.</td>
</tr>
<tr>
<td><strong>Improved Forest Management</strong></td>
<td>Management practices that increase the rate of CO₂ capture and the amount stored in forests, including reduced impact logging, increased planting after harvesting, and improved post-fire regeneration.</td>
</tr>
<tr>
<td><strong>Soil Organic Carbon Sequestration</strong></td>
<td>Enhancing the storage of carbon in soils, including through reduced tilling, crop rotation, and better pasture management.</td>
</tr>
<tr>
<td><strong>NATURAL + TECHNOLOGICAL</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Biochar</strong></td>
<td>Converting biomass to decomposition-resistant charcoal. Biochar added to soils can store carbon for thousands of years.</td>
</tr>
<tr>
<td><strong>Bioenergy plus Carbon Capture &amp; Storage (BECCS)</strong></td>
<td>The generation of energy from biomass and subsequent storage of the resulting CO₂ emissions in geological rock formations.</td>
</tr>
<tr>
<td><strong>TECHNOLOGICAL: Employ technologies, chemicals or other processes to capture CO₂.</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Direct Air Capture</strong></td>
<td>The use of chemicals to absorb CO₂ from the atmosphere. The carbon is then stored in reservoirs or mineralized into a solid formation.</td>
</tr>
</tbody>
</table>
| **Enhanced Weathering** | The grinding of rocks that naturally absorb CO₂ and spreading of the fragments on land or in the ocean. Grinding a rock increases its surface area and thus increases the pace of CO₂ absorption. 

*Also called CO₂ mineralization and mineral carbonation.* |
II. Natural & Technological CDR: Key Factors for Comparison

In the coming years, policymakers will have to grapple with the implications of the Paris long-term climate targets for their national emissions trajectories. This will become particularly urgent with the release of the Intergovernmental Panel on Climate Change (IPCC) report on the implications of a 1.5°C world in 2018, as we move toward the first update period of Nationally Determined Contributions (NDCs), or national targets in 2020, and as the international community takes stock of the impact of collective action in 2019. Increasingly, countries will have to evaluate climate change mitigation options that both reduce emissions from a variety of sources as well as increase the removal of CO₂ and other GHGs from the atmosphere.

While emission reduction solutions are discussed frequently, CDR solutions—especially how natural sequestration options compare with technological approaches along several key criteria—have only recently begun to attract widespread attention and remain difficult for policymakers to evaluate cohesively. There are many reasons for why this is the case. First, many observers believe that rapidly reducing global emissions can be done with existing technologies and is enough to put the world on the less than 2°C pathways. In essence, they believe CDR, especially technological CDR, to be unnecessary and a waste of resources. Moreover, although some CDR solutions are cost-effective, policymakers and advocates continue see CDR as an expensive and unproven avenue for climate action—one that will remain largely out of reach or the foreseeable future. Finally, due to the large scale of the needed interventions, many environmentalists worry that undertaking carbon dioxide removal will have untold consequences on the global environment. The latter point often touches on geoengineering, a much broader concept that goes well-beyond carbon removal. We discuss geoengineering in Box 2.

In order to help policymakers begin to think about how different CDR approaches might fit in both their short- and long-term climate mitigation strategies, we undertook a detailed review of the most prevalent CDR options. In this section, we compare both natural and technological CDR along the same set of dimensions. These include:

1. **Readiness**: The current feasibility and availability of the approach, from theoretical, to pilot and demonstration stage, to commercialization at scale.
2. **Mitigation potential**: The annual emissions removal potential, including a differentiation between theoretical/technical and economic potential.
3. **Cost**: The per-metric ton (ton) CO₂-equivalent cost of the approach, including discussion of how this may change in the future.
4. **Resource-Intensity**: The land, water, and energy requirements of implementing the approach.
5. **Co-benefits**: The non-climate benefits of the approach.
6. **Other**: Other issues include timing, storage loss (the risk of reversal or non-permanence of the GHG benefit), and public perception.

The purpose of this review is to bring CDR into the mainstream climate conversation by identifying powerful solutions that are ready and cost-effective to deploy today. Many of these are not theoretical technologies that exist on paper only, like opponents of CDR have believed in the past, but rather real options that we already know how to implement well. Not doing so in the near-term could be a huge missed climate mitigation opportunity.

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5 Because several approaches represent nascent technologies, data on their cost and potential impact are relatively sparse and have high uncertainty. We note data availability and comparability issues where relevant in the discussion of CDR solutions.
Box 2. Geoengineering

Geoengineering is the large-scale alteration of environmental processes that affect the earth’s climate to mitigate the effects of climate change. While geoengineering includes some CDR, it also encompasses broader climate-altering strategies such as solar radiation management which may be used to offset some of the effects of increased GHG emissions. Large-scale geoengineering is highly controversial due to a lack of understanding of the secondary and long-term effects of deliberate human intervention in the atmosphere and ecosystems. Moreover, many approaches (e.g., injecting sulphate aerosols into the lower stratosphere to mimic the effect of volcanic eruptions, placing shields in space to deflect solar energy away from the Earth) remain purely theoretical.

Although we review a number of theoretical and pilot-stage CDR approaches, we have not included those that are often defined as geoengineering. One such strategy is ocean fertilization (also known as iron fertilization or ocean seeding), the process of introducing iron into the ocean’s upper layer in order to encourage the growth of CO$_2$-absorbing phytoplankton. Ocean fertilization typically falls under the popular conception of geoengineering because growing organisms on such a large scale could have as-yet unknown impact on ocean ecosystems.

A. Putting Nature to Work: Natural CDR Approaches

Natural climate solutions are among the most tried-and-tested carbon removal options available. They have enormous combined carbon sequestration potential—approximately 12 GtCO$_2$ at the lower end of the available ranges—and require only modest amounts of land, water and energy inputs compared to their technological counterparts (see Table 2). Several of the most promising natural solutions are discussed in depth below.

Reforestation and Afforestation

Afforestation and reforestation (described in shorthand as Forestation for our purposes) is currently the most popular method to remove CO$_2$ from the atmosphere. Afforestation is the planting of new forests on lands that historically have not contained forests, and reforestation is the planting of forests on lands that have previously contained forests but have been converted to some other use.

Readiness: Forestation is the most well-developed and widely-available CDR approach available today. People have been planting trees for centuries, for shelter, fuel, erosion control and other uses. The Bonn Challenge, a global effort to restore at least 150 million and 350 million hectares (ha) of forest by 2020 and 2030, respectively, demonstrates the current political momentum behind forestation. To date, forty-seven countries have pledged to restore 160.2 million ha as part of the challenge. The mitigation benefit of forestation has been recognized under the Kyoto Protocol (including the Clean Development Mechanism), and the Paris Agreement (including, in Article 5, within the scope of Reducing Emissions from Deforestation and Forest Degradation and enhancing forest carbon stocks - or REDD+).

Mitigation Potential: Forestation is significantly underutilized given its biological potential and wide availability. In fact, over two billion hectares of land around the world are suitable for restoration (including forestation, among other land restoration activities)—an area larger than South America. Estimates of 6

untapped forestation sequestration potential range from 1.3 to 17.9 GtCO₂/yr globally. The wide range of estimates is caused by different assumptions about constraints on land availability by different models and authors, uncertainty in land availability for any given assumption, uncertainty in sequestration rates per hectare, the wide range of different types of potential forestation ranging from agroforestry to natural regeneration and intensively managed plantations, and maximum carbon prices.

**Cost:** The cost of forestation depends on factors such as the size of the area planted, tree species used, and the condition of the site in which trees are planted. Published bottom-up estimates of cost generally range from about $7.5 to $29.4 per ton of CO₂ removed. Forestation typically requires low start-up cost with few significant capital investments. Perhaps more so than other CDR approaches, estimates of mitigation potential and cost of forestation are closely related — at higher and higher carbon prices, it becomes economically efficient to plant trees on more and more marginal land and/or land that would have gone to other uses.

**Resource Demand:** Forestation has relatively low resource demands compared to other CDR strategies. Land is the primary requirement, with the amount used depending on the area’s economic and biophysical potential, and on the objective — e.g. to reforest all degraded land, or to achieve a quantified mitigation goal. Forestation is one option within a complex, interconnected set of land use and climate solutions. It may compete for land with agriculture, urban development and other natural resource uses. Also, large-scale forestation could be complementary to an increased demand for woody biomass energy, while on the other hand it could compete with bioenergy crops (such as hemp, switchgrass or jatropha).

Depending on the type of trees planted, soil quality and the biogeoeclimatic zone, mature forests are capable of storing 165 to 785 tCO₂/ha. To put these numbers into context, removing 1Gt of CO₂ would require planting between 1.3 to 6 million hectares of land—the latter figure is about the size of Costa Rica. Trees need water to grow and large forestation projects can interact in complex ways with local temperatures and water availability. For example, they can either enhance or deplete local water tables, depending on the tree species planted, and at the same time can affect local and regional climate to reduce temperatures and temperature extremes and promote local rainfall, both contributing to water availability.

Energy inputs are minimal and are tied to the seedling nurseries, site preparation, transporting people and material to the planting sites, and fertilizer, if applied.

**Co-benefits:** Forestation has significant environmental and socioeconomic co-benefits. Increasing forested land can increase wildlife habitat and biodiversity, improve water quantity and quality, provide erosion control, and lead to cooler and wetter micro-climates, which are better for farming. In urban areas, the shading and water retention can reduce energy and water management costs. Forestation can also lead to improved health and livelihoods from increased access to timber and non-timber forest products.

**Other issues:** As with almost all climate mitigation solutions, if the activity is not part of a transformational change that establishes a new, climate-friendly, ‘business as usual’ for the sector, then there an inherent risk of non-permanence of mitigation impact. For forestation, this means that there is a risk that the CO₂ captured and stored in woody biomass could be re-emitted to the atmosphere if the new forest is subsequently cleared and converted to another land use. There is also a risk of forestation displacing the prior land use activities to other locations, which could result in clearing of existing forests.

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9 To maintain comparability of the mitigation potential and cost estimates for natural versus technological NETs, Tables ES-1 and 2 use estimates of technical potential for mitigation, and bottom-up cost estimates where available.
10 Calculated from [https://link.springer.com/article/10.1007%2Fs11027-012-9417-z](https://link.springer.com/article/10.1007%2Fs11027-012-9417-z)
**Improved Forest Management**

Improving the way an existing forest is managed, and shifting forest products towards longer-term storage, can increase the ability of managed forests to capture CO$_2$. Enhanced forest management practices include reduced impact logging, increased planting after harvesting and better post-fire regeneration.

**Readiness:** As with forestation, improved forest management is a mature CDR approach. In fact, many of its encompassing activities are being undertaken by forest managers around the world daily using long-available technologies and know-how. Improved forest management can be implemented quickly and with low start-up costs.

**Mitigation Potential:** The mitigation potential of improved forest management is significant compared to other natural CDR options, including forestation. A recent literature synthesis estimated technical mitigation potentials of 1.1 to 9.2 GtCO$_2$ in 2030, about evenly divided between the temperate/boreal and tropical/subtropical zones.\(^{11}\)

**Cost:** Although bottom-up aggregate cost estimates for improved forest management techniques are not available, the carbon prices associated with the above mitigation ranges are instructive. About 60 percent of the technical potential could be realized (up to 5.5-5.8 GtCO$_2$) at a carbon price of up to $100/ton; about half of that (up to about 2.5 Gt) could be achieved at costs of under $10/ton.\(^{12}\)

**Resource Demand:** Resource requirements for improved forest management techniques vary depending on the type of activity. Generally, however, energy and water usage would be similar to conventional logging. There are no additional land requirements for improved forest management because, by definition, it is a set of activities that occur on land already under timber production.

**Co-benefits:** Improved forest management has multiple co-benefits, including ecosystems and biodiversity preservation. Individual activities also contribute to adaptation and sustainable development.\(^{13}\) The residual biomass can contribute 12-74 EJ/yr to energy consumption.\(^{14}\)

**Other:** As with other land-based mitigation activities, the actual mitigation benefits are subject to inter-annual variability in climate and weather – affecting growth rates and natural disturbances and associated risks of non-permanence.

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**Soil Organic Carbon Sequestration (SOCS)**

Soil organic carbon sequestration (SOCS) is the process of improving the ability of soils to store CO$_2$. Carbon is primarily stored in soil organic matter, which is formed from decomposing plant and animal tissue, microbes, and carbon associated with soil minerals. As with forestation, many different activities can boost SOCS. These include conservation tillage, crop rotation, cover cropping and better pasture management.

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\(^{11}\) Griscom et al 2017 Online Supplement, Table S1, including natural forest management and improved plantations, but excluding reduced emissions from fire management and avoided woodfuel harvest.

\(^{12}\) Griscom et al 2017 Online Supplement, Table S4


\(^{14}\) Ibid.
**Readiness:** SOCS is a mature mitigation strategy. A large quantity of scientific evidence supports its mitigation potential and the techniques to bolster SOCS are already developed. Farmers can use these techniques immediately and begin to see results.

**Mitigation Potential:** Because SOCS is feasible anywhere that there is agricultural activity, its mitigation potential is significant. Estimates show that, globally, improving soil carbon storage can remove approximately 6.8-12.6 Gt CO$_2$/yr, depending on the soil type and ecosystem.\(^{15}\)

**Cost:** Because SOCS can be achieved using a wide range of techniques, it is difficult to derive one cost estimate for this approach. One study hypothesized that 1.5 GtCO$_2$ could be removed at a carbon price of $20/ton, sequestering greater quantities would raise the cost to $100/ton or higher.\(^{16}\) Another was more generous, postulating average costs of about $17/ton globally (for about 13GtCO$_2$ sequestered annually) across intervention types.\(^{17}\)

**Resource Demand:** Because SOCS is an additive activity, there is little to no opportunity cost. Land already under agricultural production can be used for additional carbon capture through conservation or regenerative agriculture. The additional water and energy requirements are therefore also negligible.

**Co-benefits:** SOCS has many co-benefits, the largest of which is food security. Because activities that increase SOCS also restore degraded land, they could help increase the land area capable of supporting long-term sustainable agricultural production. Similarly, SOCS-based interventions can also help build resilient livelihoods for farmers.

**Other issues:** Although SOCS interventions are incredibly promising, issues such as permanence (limited duration of the carbon sink), leakage (increasing carbon in soil stocks could lead to decreases elsewhere) and additionality (soil-based mitigation above-and-beyond traditional agriculture) can hamper wide-scale implementation. Some farmers also worry that SOCS activities would not produce as the high yields of current practices for growing annual monoculture crops.

**B. Adding Engineering: Technological CDR Approaches**

Unlike natural CDR approaches, technological CDR approaches are less mature and remain small-scale. Although commercial-scale implementation has the potential to remove large amounts of carbon dioxide—about 10 GtCO$_2$ at the lower end of the available ranges—these nascent technologies will need to overcome significant barriers, including high costs and other resource constraints (see *Figure 3*), in order to achieve their full potential. Carbon capture and storage (CCS) systems that capture GHG emissions from the burning of fossil fuels (for energy production), compress the gas and transfer it to geological reservoirs are currently operating at industrial scale. These systems involve the removal of CO$_2$ from the air in the industrial pipe or smokestack, with the effect of avoiding an amount of CO$_2$ emissions. However, this paper is focused on assessing CDR approaches and systems that result in negative emissions (or net removals). The most promising technological solutions are discussed in depth below.

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\(^{15}\) Lal 2018, Frank et al 2017, Paustian 2016


\(^{17}\) Calculated from Table E3, WRI in Carbon Sequestration In Agricultural Soils: http://documents.worldbank.org/curated/en/751961468396701332/pdf/673950REVISED000CarbonSeq0Web0final.pdf
**Biochar**

Biochar is biomass that has been converted to decomposition-resistant charcoal. It is created when biomass is heated with little or no oxygen in order to drive off volatile gases and leave behind carbon, a process called pyrolysis. Biochar added to soils can sequester carbon for thousands of years.

**Readiness:** Although the basic technique dates back to pre-Columbian Amazonians to enhance soil productivity, scientific research on biochar’s climate mitigation potential is relatively new. Commercial biochar production is currently at the demonstration scale, with pilot projects in the United States, Vietnam, Malaysia, Uganda and Peru.18

**Figure 1: The Process of Creating Biochar**

![Image of the process of creating biochar]

**Source:** www.biochar-international.org/technology, courtesy of Johannes Lehmann

**Mitigation Potential:** The mitigation potential of biochar depends on the type of feedstock, temperature used for pyrolysis, the fertility of the soil amended and type of fuel being offset. For instance, feedstock that is grown explicitly to make biochar (switchgrass) would have a lower mitigation potential than agricultural residues that would have no other uses (e.g. manure, rice straw, and nut shells). The maximum biologic mitigation potential is 6.6 GtCO₂e/yr. However, the economic potential is just over half (3.7 GtCO₂e/q/yr) due to competing demands for non-waste biomass.19

**Cost:** The cost of biochar varies by production inputs (feedstock) and type of pyrolysis used and, as a relatively new technology, are highly uncertain. Estimates found in literature range from $35-$300/tCO₂, including the effects of additional revenue from energy co-generation. Costs for biochar production include feedstock collection, pyrolysis, and transport and handling for soil application.

**Resource Demand:** The resource demand for biochar is variable and not well researched. It is highly dependent on the type of inputs and type of biochar production system used. Both land and water are required to grow the feedstock. However, if biochar production only uses byproducts of other agricultural processes as feedstock, the land requirement becomes negligible. Biochar production facilities can be small and do not require much land.

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18 International Biochar Initiative, Biochar in Developing Countries, 2014: [http://www.biochar-international.org/developingeconomies](http://www.biochar-international.org/developingeconomies)

19 Woolf et al 2010 in IPCC AR5
**Co-benefits:** Biochar can increase crop yields and the process’s byproducts (syngas and bio-oil) can generate energy. Biochar enhances soils by reducing leaching of nitrogen into groundwater, improving soil fertility, moderating soil acidity and increasing water retention and beneficial soil microbes. Because biochar can improve the productivity of low-fertility and degraded soils, it can boost the livelihoods of the world’s poorest farmers.

**Other issues:** While biochar has promising climate mitigation potential, barriers to implementation include the acquisition of sustainable feedstock and competing biomass uses. Additionally, if biochar feedstock replaces higher carbon value lands such as forests, biochar production can actually have a negative climate mitigation impact.

**Bioenergy with Carbon Capture and Storage (BECCS)**

Bioenergy with Carbon Capture and Storage, commonly known as BECCS, is among the most discussed CDR solutions in recent literature. The key aspect of BECCS is that it begins with CO₂ capture and storage in trees, grasses and other biomass. This biomass, which is then combusted to generate energy, can come from either dedicated bioenergy plantations or as a bi-product of harvesting and processing for other uses. The CCS system of a BECCS facility captures the CO₂ emissions that are produced when the biomass is burned. CO₂ is then compressed and injected into geologic or other reservoirs for long-term storage.

The process of capturing and storing emissions that result from energy generation, CCS, can be combined with any CO₂-intensive fuel source to produce net zero emissions. BECCS, however, is unique in that the use of biomass for energy allows new biomass to grow in its place, thus removing even more CO₂ from the atmosphere. In this way, and unlike coal plus CCS or natural gas plus CCS, BECCS is actually a *net negative* technology – removing CO₂ from the atmosphere (in the form of plant matter) and shifting it to long-term storage (through CCS), while in the process generating energy. This rare trifecta – capturing CO₂ from the air, storing it underground, and generating (rather than expending) energy all the while – has made BECCS an attractive “safety valve” for climate modelers who have been asked to generate scenarios that meet 1.5 or 2°C scenarios. But most modelers will admit that BECCS’ appearance in their models is as much a stand-in for unknown or as-yet undeveloped technological solutions as it is a prediction that BECCS itself is a realistic mitigation pathway.

**Readiness:** Although BECCS technology is not yet deployed at scale, it is the most developed technological CDR approach. Currently, six projects are in operation—four in the United States, one in the United Kingdom and one in Japan—and another six are planned.²⁰ If all of the planned projects come online as designed, BECCS facilities around the world will be removing about six million tons of CO₂ from the atmosphere annually. This is just a fraction of the estimated BECCS potential globally and less than 1.5 percent of the CDR achieved through forestation in China alone in 2005.²¹

**Mitigation Potential:** Estimates from a sample of published studies (see Figure 2, below) show technical mitigation potential of up to 10-20 GtCO₂/yr around mid-century, depending on the biomass type and combustion method used. This potential, however, is likely not realistic given both cost constraints as well

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²¹ China’s National Communication to the UNFCCC, 2012: [https://unfccc.int/documents/71515](https://unfccc.int/documents/71515)
as competing demands for resources such as land and water. The economic potential is often much smaller, possibly just up to one-third of the technical potential.\textsuperscript{22}

**Figure 2: Global BECCS Potential**

Note: Many studies do not indicate whether the mitigation range they provide reflects technical or economic potential. The minimum value is explicitly the economic potential in Koornneef (2011) and McLaren (2012).

**Cost:** BECCS cost estimates have wide ranges, between $50-$250/ton of CO\textsubscript{2}. As with many nascent technologies, these costs are expected to decrease with time. BECCS, however, is unique in that the downward price trajectory that is common among newly deployed technologies will directly affect the increase in prices that often characterizes resource-constrained interventions. This means that, at upper levels of BECCS penetration, land and water scarcity will actually cause prices to rise.

**Resource-Intensity:** Because BECCS can use a wide range of biomass, its land requirements are highly dependent on factors such as the proportion of bioenergy that is derived from residues and waste and the extent to which biomass can be grown on land that is not currently productive. Generally, studies show that BECCS’s land intensity is quite high, possibly ranging from 0.03-0.1 hectares per ton of CO\textsubscript{2}-equivalent (ha/tCO\textsubscript{2}e) for energy crops specifically grown for bioenergy to 0.3-0.5 ha/tCO\textsubscript{2}e when using forest residue.\textsuperscript{23} To put this into perspective, removing just 3Gt of CO\textsubscript{2}e annually using the least land-intensive crops could require about 90 million hectares of land – the equivalent of more than a quarter of the Brazilian Amazon. The land use intensity of bioenergy with CCS would likely be less than without CCS due to the need to site the bioenergy plants in close proximity to suitable CCS reservoirs, and where sufficient feedstock is available at within economic limits due to transportation costs. Policies that have increased to the demand for bioenergy have been controversial as it may result in driving deforestation and food price increases through land use competition.

BECCS’s water requirements are similarly variable, yet potentially significant, possibly averaging 60 cubic kilometers per year (km\textsuperscript{3}/yr) for one Gt of CO\textsubscript{2}e removed.\textsuperscript{24} Thus, removing and storing 3GtCO\textsubscript{2}e could require 180 km\textsuperscript{3}/yr of water. For context, humans use about 7,000 km\textsuperscript{3} of freshwater for agriculture each year.\textsuperscript{25} If BECCS systems, collectively, capture 3GtCO\textsubscript{2}e annually, global agricultural water use could increase by 2.6 percent.

\textsuperscript{22} Ibis.

\textsuperscript{23} Smith, Pete et al., “Biophysical and economic limits to negative CO\textsubscript{2} emissions” http://aura.abdn.ac.uk/bitstream/handle/2164/7937/7955_2_merged_1445366890_1_.pdf?sequence=1

\textsuperscript{24} Calculated from data in http://aura.abdn.ac.uk/bitstream/handle/2164/7937/7955_2_merged_1445366890_1_.pdf?sequence=1

\textsuperscript{25} Rogers, Peter, “The Role of Irrigation in Meeting the Global Water Challenge”, Harvard University, http://research.unl.edu/events/futureofwater/ppt/PeterRogers.pdf
Co-benefits: Implementing BECCS as a climate solution has a number of social and environmental co-benefits. In addition to removing CO₂ from the atmosphere and storing it for a long time, BECCS generates energy—an important resource on which modern society depends. Growing biomass for energy production can also contribute to sustainable land management and have secondary effects on the health of regional ecosystems.

Other: Although many studies have highlighted the technology’s potential contribution to climate mitigation, BECCS remains controversial. In public perception, some express cautious optimism while others are vehemently opposed to any large-scale bioenergy system that could convert natural landscapes and exacerbate water deficits. However, unlike many natural approaches, BECCS can theoretically store CO₂ in geological formations for thousands of years. Although possible leakage remains a concern, the release of CO₂ would likely follow seismic or geologic events rather than economic and political decisions.

Direct Air Capture (DAC)

Similar to CCS, Direct Air Capture systems can extract and store (or use) CO₂ in order to limit atmospheric concentrations of GHGs. Unlike CCS, however, DAC plants pull the gas from the open air rather than from a point source such as the flue gas of a power plant. DAC captures CO₂ by using chemicals that attract the gas but not other atmospheric gases such as oxygen and nitrogen. Plants then apply energy to isolate the CO₂ from the other chemicals and either sequester it in geological reservoirs or convert it into other materials. The chemicals are then reused to attract additional CO₂.

Readiness: Unlike CCS, DAC is a much more nascent technology. A handful of demonstration projects are under development in Canada, Europe and the United States, but public results have been limited.

Mitigation: Although DAC systems theoretically have limitless mitigation potential, cost and availability of vital resources such as energy substantially constrain the amount of CO₂ that can realistically be removed from the atmosphere. Because DAC has been far less-studied than CCS or BECCS, only a handful of mitigation estimates exist in published literature. One study estimates that DAC systems may reasonably be able to capture 3-16 GtCO₂ annually.²⁶ Scalability, however, may be an issue. In Switzerland, Climeworks has built a pilot plant that is currently removing 900 tons of CO₂ per year. To boost that number to 1Gt of CO₂—as is the company’s vision for the company’s decades—Climeworks would need to build over 1.1 million similar plants. Carbon Engineering, based in Canada, has claimed that their technology, scaled to commercial size, would be able to capture 1 million tons of CO₂ annually. Even at this scale, the company would need to build one thousand such facilities to remove a gigaton of carbon pollution annually.

Cost: Compared to CCS and other mitigation approaches, DAC systems are currently very costly. Because the concentration of CO₂ in air is about 100 to 300 times lower than, say, that in the flue gas of a power plant, the process to extract equivalent amounts of the gas is much more energy intensive in a DAC system. Studies estimate that DAC could cost $500 to as much as $1,000 per ton of CO₂ captured.²⁸

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²⁷ Jacobson, Rory and Noah Deich, “Giant Machine Sucks CO2 Directly from Air!!”, Center for Carbon Removal, June 2017: http://www.centerforcarbonremoval.org/blog-posts/2017/6/14/6zol0196zn1f3apkn6ms3gk6kyf
These costs are likely to decrease, of course, and DAC technology could become cost-competitive with other mitigation options as the world exhausts cheaper solutions—possibly beginning around mid-century.²⁉  

**Resource-Intensity:** Although DAC requires a negligible amount of land and very small amounts of water—Climeworks’ system actually pulls moisture from the air and therefore generates its own water supply—the technology is very energy-intensive. Extracting CO₂ from the air requires about 0.49 gigajoules of energy per ton of captured CO₂ (GJ/tCO₂).³⁰ This is about three times larger than the energy required to capture CO₂ from flue gas, for example through conventional CCS. Processing, transporting and injecting CO₂ has additional energy requirements, potentially raising the per tCO₂ energy intensity to 12.3 GJ. At this rate, achieving 1 Gt of removals could require 3,417 terawatt-hours of electricity annually—an amount that is nearly equivalent to all electricity generated in the United States in 2017.

**Co-benefits:** Unlike land-based approaches, CDR technologies such as Direct Air Capture do not have significant co-benefits outside of the climate space.

**Other:** As with CCS, DAC can theoretically store carbon dioxide for thousands of years with minimal risk of leakage. The technology, however, remains incredibly controversial, in part because of its cost. Moreover, because DAC’s primary benefit is climate mitigation, it does not have the broad stakeholder support that many natural solutions enjoy.

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**Enhanced Weathering (EW)**

Weathering, the chemical breakdown of rocks, is a natural process that removes large amounts of CO₂ from the atmosphere. Natural weathering, however, is extremely slow, limited by the surface area of rocks such as silicates that can absorb CO₂. Enhanced weathering, sometimes called mineral carbonation, speeds up this process by mechanically breaking down rocks in order to increase their surface area. The resulting powder can then be deposited on land or in the ocean to increase CO₂ uptake.

**Readiness:** EW is among the least developed CDR approaches, with only a handful of research efforts dedicated to studying the process around the world. Private sector initiatives such as the Mineral Carbonation International have struggled to make headway in the absence of federal and philanthropic research funding.

**Mitigation:** The estimated mitigation potential of EW is somewhat smaller than other CDR approaches, generally 1-4 GtCO₂ per year depending on the mineral used and where its fragments are deposited. For example, one study estimates that adding the minerals carbonate and olivine to both oceans and soils could remove an average of 0.7 GtCO₂ per year, or up to a maximum of 3.7 GtCO₂ by 2100.³¹ Another

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³¹ Smith, Pete et al. “Biophysical and economic limits to negative CO₂ emissions”, Nature Climate Change: https://www.nature.com/articles/nclimate2870
study estimated that the land-based potential is upwards of 4 GtCO₂ per year while the ocean potential is smaller at 1 GtCO₂.\textsuperscript{32}

**Cost:** The range of EW cost estimates is extremely wide and has a large amount of uncertainty, anywhere from $23-$578 per ton of CO₂ captured.\textsuperscript{33} Depositing rock fragments on land is estimated to be less costly than doing so in the ocean.

**Resource-Intensity:** The land and water requirements for EW are relatively minimal. Although the process requires distributing crushed rock fragments over vast land areas, at about 0.01 ha/tCO₂,\textsuperscript{34} the land-intensity is still the second smallest after DAC. Moreover, EW does not necessarily have to compete with other land uses. For example, spreading crushed carbonate and olivine on acidic agricultural and forest soil can actually raise its pH levels and actually make the land more productive more productive.

Despite requiring little land and water, EW is very energy-intensive: 0.08-0.2 GJ/tCO₂. As with DACs, processing and transporting massive amounts of rock could increase the per tCO₂ energy intensity to 12.5 GJ—matching the DAC requirement.

**Co-benefits:** As mentioned above, adding certain minerals to acidic agricultural or forest soils has the potential to improve their productivity. Increasing yields on cultivated land could, in turn, avoid additional conversion of forest land to agriculture. Moreover, recycling silicate waste from mining activities could reduce the environmental impacts of mining operations.

**Other:** Similar to the other technological solutions, the weather process has the potential to store carbon for thousands of years with minimal to no leakage. The technology, however, is controversial due to its requirement for large-scale mining and land-use related food security concerns, and many question whether the large-scale pulverization of rock is the best solution to the climate questions, especially given the availability of other approaches.

\textsuperscript{33} Ibid; Renforth, Phil, “The potential of enhanced weathering in the UK”, University of Oxford, 2012: http://orca.cf.ac.uk/60892/
\textsuperscript{34} Smith, Pete et al. “Biophysical and economic limits to negative CO2 emissions”, Nature Climate Change: https://www.nature.com/articles/nclimate2870
IV. Seizing Nature’s Opportunity Today

While both natural and technological CDR solutions can theoretically capture at least 20 Gt of carbon dioxide through the end of the century, not all may be deployed simultaneously—and, in fact, they may compete for some of the same limited resources, most notably land. In order to effectively include CDR in their national climate strategies, policymakers must consider the readiness and cost-effectiveness of specific technologies from the short-term to mid-century and beyond.

Today, natural solutions are the most abundant and readily-available CDR options. Most, including afforestation/reforestation, improved forest management, and some soil organic carbon sequestration methods, are incredibly well-understood and have been deployed on a large scale in the past. Moreover, they are currently a far more cost-effective option to capture carbon dioxide, with a price tag that is an order of magnitude lower per ton of CO$_2$ captured than technological solutions. By not deploying tried-and-tested natural CDR to the greatest extent possible in the near-term, policymakers could lose the opportunity to capture 2.7 to 15.8 Gt (midpoint 6.1 Gt) of carbon dioxide annually by 2030 at less than $100/ton,$^{35}$ and potentially more (Figure 3). Technological solutions, on the other hand, are still largely immature, with most existing at the laboratory or demonstration stage only.

Beyond their climate mitigation potential, natural CDR also offers numerous co-benefits, including more resilient ecosystems, increased wildlife habitat and biodiversity, improved water quality, erosion control, and cooler and wetter micro-temperatures which are better for farming. Cleaner air, water and soils could also improve health outcomes. With some minor exceptions, most technological CDR would be deployed purely for its climate mitigation benefits. This might make it more difficult to obtain support, buy-in and resources from a diverse group of stakeholders.

Over the long-term, policymakers should look at the fuller set of CDR option. As time goes on, both saturation effects as well as land constrains will limit the mitigation potential of solutions such as afforestation/reforestation and make them costlier. Meanwhile, the cost of technological approaches will likely decrease in the decades to come while their mitigation potential will remain largely unchanged. The exception is BECCS, whose costs will drop up to a certain sequestration level only. At high levels of CO$_2$ removal, large land requirements associated with expanding plantations of biofuel crops will have an upward effect of prices.

$^{35}$ Calculated from Griscom et al 2017 Online Supplement, Table S4. The range from Griscom et al 2017 is used to avoid double-counting between categories and to use a common economic constraint for each approach.
Figure 3. Summary of CDR Approaches, by Factor

<table>
<thead>
<tr>
<th>Approach</th>
<th>Technical Mitigation Potential (GtCO₂/yr)</th>
<th>Average Cost (US$/tCO₂)</th>
<th>Readiness</th>
<th>Co-benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scale:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reforestation/ Afforestation</td>
<td>1.3</td>
<td>17.9</td>
<td>7</td>
<td>Mature</td>
</tr>
<tr>
<td>The planting of trees where none exist or have not existed for decades.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Improved Forest Management</td>
<td>1.1</td>
<td>9.2</td>
<td>20</td>
<td>Mature</td>
</tr>
<tr>
<td>Management practices that increase the rate of CO₂ capture and the amount stored in forests.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil Organic Carbon Sequestration</td>
<td>6.8</td>
<td>12.6</td>
<td>10</td>
<td>Mature</td>
</tr>
<tr>
<td>Enhancing the storage of carbon in soils.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural + Technological</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biochar</td>
<td>3.7</td>
<td>6.6</td>
<td>35</td>
<td>Demonstration</td>
</tr>
<tr>
<td>Converting biomass to decomposition-resistant charcoal.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bioenergy plus Carbon Capture and Storage</td>
<td>3.5</td>
<td>20</td>
<td>50</td>
<td>Demonstration</td>
</tr>
<tr>
<td>Generating energy from biomass and storing the resulting CO₂ emissions in geological reservoirs.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technological</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Air Capture</td>
<td>3</td>
<td>16</td>
<td>500</td>
<td>Demonstration</td>
</tr>
<tr>
<td>The use of chemicals to absorb CO₂ from the atmosphere.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enhanced Weathering</td>
<td>1</td>
<td>4</td>
<td>23</td>
<td>Laboratory</td>
</tr>
<tr>
<td>The grinding of rocks that naturally absorb CO₂ and spreading of the fragments on land or in the ocean.</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Notes: 1. Mitigation potential represented as a range of technical or maximum potential across various literature sources (see text). Technical potential estimates are not additive across approaches, as there may be tradeoffs between them. 2. Cost estimates are represented as ranges of average cost from various literature sources (see text), and are not intended to represent the range of cost estimates at a specific mitigation potential.

- = Ecosystems improvement  = Land productivity  = Income generation  = Energy generation
V. Recommendations

- Natural, biological sinks offer the best combination of benefits for the climate at the lowest cost today. They should be deployed to the greatest extent possible.

- Early action or investment is required for both natural and technological solutions:
  - Vegetation takes time to grow → invest in natural solutions today.
  - New technology takes time to scale and become commercialized → invest in R&D and deployment of early-stage technologies.

- Focus on forests & land as a near term solution will galvanize international support toward this sector and create more ambition in the short term.

- Governments (national and subnational) and businesses need to evaluate which CDR systems can be, and should be, the focus of investment as part of their domestic climate change strategies.
  - Forested countries, particularly in tropical regions, will have significant potential for immediate implementation of natural NET systems, particularly forestation of degraded land and improved forest management, and may be included in countries’ REDD+ strategies.
  - A landscape management approach should be followed when designing natural NET and BECCS or biochar systems, to prevent negative environmental or social impacts.
  - Natural solutions should try to maximize co-benefits – from local livelihoods and food security to climate resilience and biodiversity.

- In order to support developing countries in their mitigation and adaptation efforts, donor countries should invest more in forest and climate smart agriculture in developing countries, while also helping them develop long term low carbon development plans to address the full economy.

Figure 4: Timeline for Implementing Natural and Technological CDR Solutions

<table>
<thead>
<tr>
<th>Short-Term</th>
<th>Medium-Term</th>
<th>Long-Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-2030</td>
<td>Mid-Century</td>
<td>Late-century</td>
</tr>
<tr>
<td>Decarbonization</td>
<td>Natural CDR: Implementation</td>
<td>Tech CDR: Research &amp; Demonstration</td>
</tr>
<tr>
<td>= Reforestation and Afforestation</td>
<td>= Improved Forest Management</td>
<td>= SOCS</td>
</tr>
<tr>
<td>= BECCS</td>
<td>= DAC</td>
<td>= EW</td>
</tr>
</tbody>
</table>