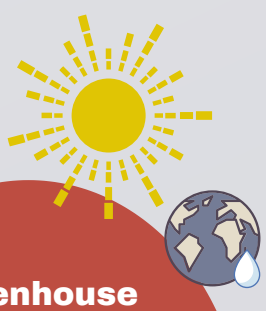
# Carbon Dioxide Removal

## Saving Our Atmosphere Before it's Too Late

## The Problem

**For the past 50 years, U.S. temperatures have been rising faster than ever before. 2016 was the warmest year on record, and 2020 was the second warmest.** [18]



**Greenhouse gases trap heat in the Earth's atmosphere, increasing global temperatures and disrupting natural ecosystems.**[17]

**Carbon dioxide ($CO_2$) is the most common greenhouse gas released into the atmosphere. $CO_2$ is released primarily from the burning of fossil fuels by industrial, energy, and agricultural companies.** [19]

### Carbon Dioxide Removal (CDR)

CDR seeks to extract $CO_2$ from the atmosphere in order to reverse negative environmental effects from emissions. Combatting the effects of greenhouse gases requires a diverse portfolio of management methods. Still, CDR must be used in combination with mitigation to achieve the U.S. goal of Net Zero Emissions by 2050. [13]

## Current Removal Methods

Capture

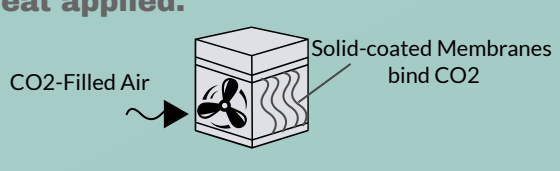
Storage

### Direct Air Capture (DAC) and Storage

**Fans pull air into $CO_2$ capture units → $CO_2$-deficient air flows out**

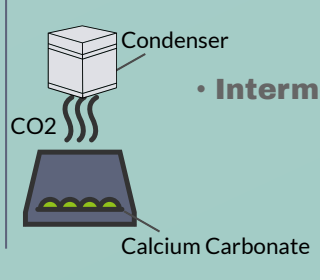
#### Solid DAC[7,9]

- **$CO_2$ in flowing air binds to membranes.**
- **Membranes capture & release $CO_2$ based on heat applied.**




#### Liquid DAC[3,7,12]

- **$CO_2$ in flowing air binds to liquid on membranes.**
- **Intermediate reactions allow for release of $CO_2$.**




### Underground Injection

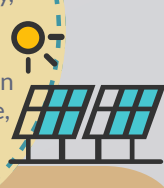
- **$CO_2$ injected deep underground for long-term storage.** [5]

### Fuel Synthesis

- **$CO_2$ can be recycled into vehicle fuel.**
- **Adds a step to the carbon cycle.** [5, 11]

#### Keep it Clean!

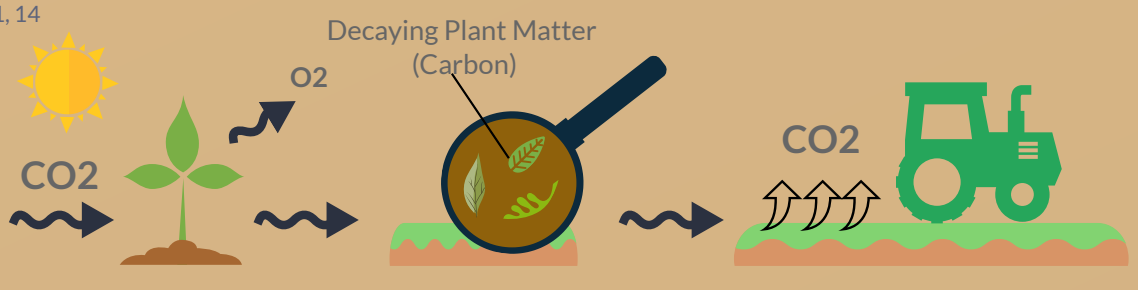
Desorption is the most expensive and energy-intensive step in the process. Fortunately, DAC can be performed anywhere there is air flow, meaning facilities can be built in locations not fit for agriculture, and powered by renewable energy sources.[5]



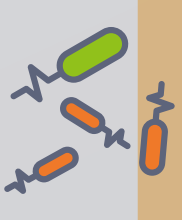
### Soil Carbon Sequestration

**Plants convert $CO_2$ to plant matter by photosynthesis.**

**Soil is a powerful carbon sink - tilling releases stored $CO_2$.** [1, 14]




- **Returning organic plant matter such as roots to the soil after plant harvesting.** [2]



- **Reintroducing microorganisms that have been killed by pesticides into our soil.** [14]

- **Protecting and nourishing wetlands and ponds.** [16]

Methods

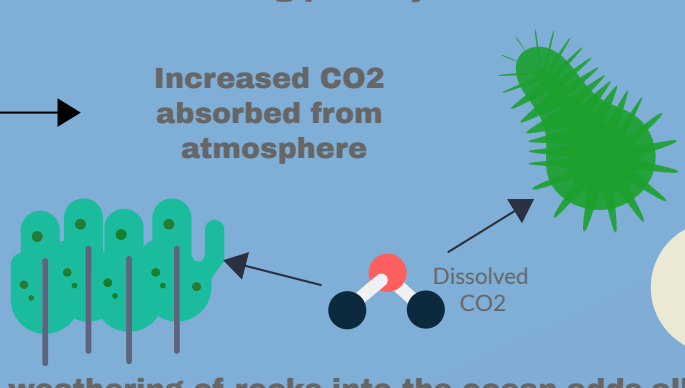
### Ocean-Based Methods

Ocean-based methods are not influenced as strongly by warming temperatures as other plant-based CDR approaches! [4]

#### Biotic Approach
*Support Primary Producers*

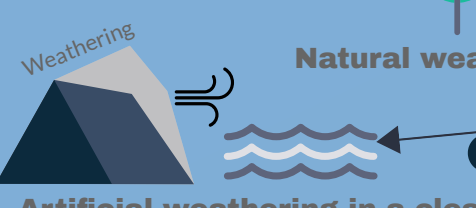
**Primary producers including phytoplankton, mangroves, and seaweed absorb dissolved $CO_2$ in the ocean during photosynthesis.**[4]

**Artificial plankton fertilization and seaweed farming** → **Increased $CO_2$ absorbed from atmosphere**




#### Abiotic Approach
*Increase Ocean Alkalinity*

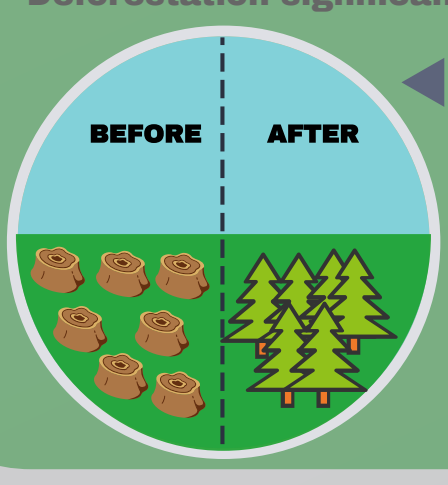
**Natural weathering of rocks into the ocean adds alkaline minerals that convert $CO_2$ to long-lasting carbonates.**[6]




**Artificial weathering in a clean-energy powered facility can produce more minerals to increase $CO_2$ uptake by the ocean.**

### Afforestation & Reforestation

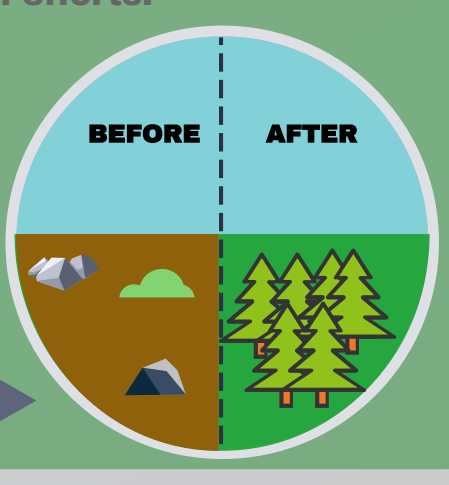
**Forests are a carbon sink: high density of $CO_2$-absorbing plants. Deforestation significantly hinders carbon removal efforts.**




**Reforestation: restores forests that previously existed.** [15]

**These methods are very costly and influenced by rising temperatures.**

**Afforestation: planting forests in formerly non-forested areas.** [8]




## New Developments

### Electro Swing DAC

**Efficient $CO_2$ absorption while minimizing energy loss (>90% efficiency)** [20]

### Rapid Passive DAC

**$CO_2$ capture without the use of fans, using carbon mineralization with abundant natural minerals.** [10]

### Cover Crop Selection

**Efficient soil sequestration using legumes as cover crops to increase mineralized carbon content.** [21]

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Carbon Dioxide Removal
Saving Our Atmosphere Before it's Too Late
Supplemental Information Sheet
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**Current methods of Carbon Dioxide Removal (CDR)**

- Direct Air Capture and Storage
    - As opposed to point-source capture of $CO_2$ at the location of a factory, DAC refers to removing carbon dioxide that is already in the atmosphere. $CO_2$ is much more dilute in the atmosphere, meaning the amount of carbon dioxide captured at any one time is less than that of point-source methods. However, DAC facilities can function anywhere there is air flow, giving this approach much more flexibility than other methods.[7]
    - Currently, DAC is energy intensive. This means that all heat and electricity needed for the process must be sourced from renewable energy sources in order to avoid offsetting the removal done by the process itself. Fortunately, DAC's versatile nature means facilities can be constructed even in barren areas not fit for agriculture, adjacent to solar or wind energy farms.[7]
    - Solid DAC
        - Air flows through membranes coated in solid functional groups that bind to $CO_2$.[7,9]
        - The membranes are heated to release $CO_2$, and cooled before next use while pure $CO_2$ is collected. $CO_2$ must be compressed, transported, and stored, all of which have their own energy costs associated with them.
    - Liquid DAC
        - Membranes which are coated with a liquid solvent, often KOH, bind $CO_2$ in the air. This forms a solution of $K_2CO_3$.
        - $K_2CO_3$ solution is reacted with calcium hydroxide to form calcium carbonate.
        - Calcium carbonate is heated to release $CO_2$.[3, 7, 12]
    - Underground Injection is a proposed storage method.
        - Captured $CO_2$ can be injected into former reservoirs of oil and natural gas. Here, $CO_2$ slowly converts to calcium carbonate and is trapped for millions of years.[5]
    - Fuel Synthesis
        - Using hydrogen obtained from renewably-powered electrolysis of water, $CO_2$ removed from the atmosphere can also be converted to hydrocarbon fuel for vehicles, reducing the need for new fuel.[5, 11]
        - This effectively adds a step in the carbon cycle and would allow for no net increase in carbon emissions even if vehicles continue to emit $CO_2$.

- Soil Carbon Sequestration
    - Plants take in CO2 and convert it to physical carbon in the form of plant material through photosynthesis. Agricultural practices such as tilling as well as natural soil erosion have depleted soil of much of its carbon supply and soil organic content (SOC). Pesticides, fertilizers, and herbicides have also stripped soil of its natural ecosystems which fix gaseous carbon in the topsoil into organic carbon.[1, 14] Methods of soil carbon sequestration include:
        - **Returning organic plant matter such as roots to the soil after plant harvesting.**[2] In addition to sustainable practices including composting, this will raise soil organic content and therefore carbon content.
        - **Reintroducing microorganisms that have been killed by pesticides into our soil.**[14] This can help restore a healthy ecosystem and facilitate the conversion of carbon in decaying plant matter to longer-stored carbonates and other carbon compounds.
        - **Protecting and nourishing wetlands and ponds.**[16] Water in soil hinders $CO_2$ escape because plant decomposition is slowed in the absence of oxygen.

- Ocean-based CDR
    - Ocean-based methods are not as susceptible to warming climates as plant-based methods.[4] As global temperatures rise, wildfires and droughts, both of which negatively affect plants, are more common.
    - Biotic approach
        - Primary producers including plankton, mangroves, and seaweed convert sunlight and dissolved $CO_2$ into plant material through photosynthesis.
        - Seaweed farming and artificial plankton fertilization are two similar methods that exploit the carbon-fixing nature of these organisms. As they absorb more dissolved $CO_2$, more atmospheric $CO_2$ is able to dissolve into the ocean. While farming likely should be done in shallower water, eventual deposit of the organic matter in the deep ocean is necessary for carbon storage.[4]
    - Abiotic approach
        - Increasing alkalinity of the ocean is a method of increasing the $CO_2$ that dissolves into the ocean. Natural weathering of alkaline minerals into the ocean is common, and allows for dissolved $CO_2$ to be converted into long-lasting carbonates. Just as in the biotic approach, this allows more atmospheric $CO_2$ to enter the ocean.

        - Creating artificial weathering facilities is an option to obtain a large supply of alkaline minerals.[6] Electrochemical treatment plants can also be used to produce alkaline solids that can be added to the ocean.
    - Ocean-based CDR also has the advantage of being available as a storage location.This makes transportation less expensive and more convenient for $CO_2$ removal facilities.[4]

- Afforestation/Reforestation
    - Deforestation by humans is acknowledged as a detriment to the CDR effort. Large forests are powerful carbon sinks that absorb large amounts of $CO_2$ through photosynthesis. It is important to preserve nature that is on our side in the atmospheric cleanup effort.[15]
    - Reforestation is a method which involves planting trees in a place where a forest once stood, but no longer does due to human activity or wildfire.[15]
    - Afforestation involves introducing forests in areas that were not previously forested. This is often more difficult as the land may be unsuitable for a forest and requires input of nutrients and water.[8]
    - This method is particularly susceptible to warming temperatures.[4] In addition, its high manpower and energy requirements make it less appealing than others.

**New Research**

- Electro Swing DAC
    - As opposed to controlling the binding and release of $CO_2$ in DAC using heat or chemical methods, electro swing DAC uses electrodes coated in quinones.[20] When a charge is applied, the quinones bind $CO_2$, and release it when the charge is removed. This method has shown to be promising as it is able to efficiently capture and release $CO_2$ with low energy loss. Energy loss is an important factor to consider, as other DAC methods which utilize heat suffer from high energy costs.
- Rapid Passive DAC
    - Heirloom is a DAC company that has created a proprietary method to greatly increase the rate of carbon mineralization, or binding of atmospheric $CO_2$ to $CaOH_2$.[10] The company utilizes passive DAC, which involves allowing air to flow freely over trays of exposed calcium hydroxide. This differs from other methods which require electric fans to pull in air and move it through the system. Furthermore, Heirloom's use of naturally-occurring and abundant calcium hydroxide, as opposed to a synthetic sorbent, further lowers energy costs.

- Cover Crop Selection
    - Cover crops are a commonly-discussed strategy for soil carbon sequestration. They are planted with other agricultural crops, but are not meant to be harvested. Rather, cover crops are able to increase the soil organic content, as well as add to the ecosystem of microorganisms that can fix $CO_2$ into organic carbon. Different cover crops have been tested, including legumes, grasses, and brassicas. A 2022 study[21] showed that a mix of all three of these cover crops was able to increase the soil organic content, in both plant matter and mineralized forms, to a greater extent than any of them alone. This has implications for more efficient cover crop usage.

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