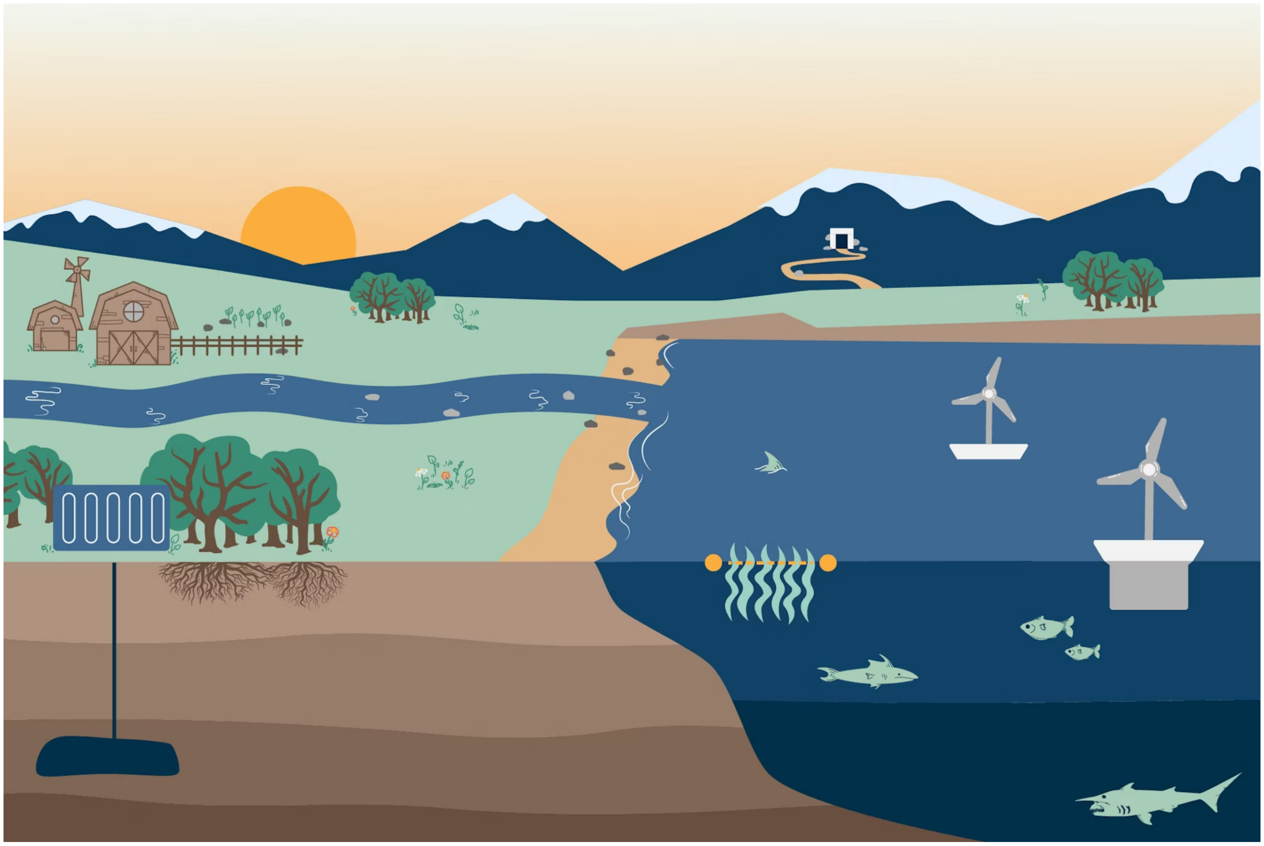
THIRD WAY

MEMO *Published March 5, 2024 • 16 minute read*

An Explainer Guide to Carbon Dioxide Removal



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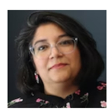

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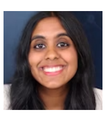

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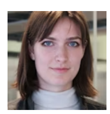

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Executive Summary

In its most recent synthesis report, the Intergovernmental Panel on Climate Change (IPCC) notes that it is highly likely that the planet will surpass 1.5-degrees Celsius of warming before the year 2050. [1]

While the IPCC reports that returning global temperatures to below this 1.5-degree Celsius threshold is possible, it emphasized that such a scenario will be impossible without significant carbon dioxide removal (CDR) efforts to drawdown legacy emissions (i.e., emissions from previous years) from the atmosphere. In fact, the National Academy of Sciences has estimated

that meeting the Paris Agreement's goals will require scaling up to 10 gigatons (Gt) of CDR annually by 2050, with 20 Gt of CDR each year by 2100. [2]

While the US has emerged as a global leader in the CDR space by pushing major federal investments in CDR research, development, and deployment (RD&D) and CDR tax credit policy support, many of these efforts have been focused on a select few methods, namely direct air capture (DAC), i.e., an engineered process for removing CO2 from the ambient air. Achieving the high levels of CO2 removal necessary to reach our climate goals will require large-scale development and deployment of a diverse portfolio of CDR methods in addition to and beyond DAC. However, many of these non-DAC CDR methods are still nascent and not as well understood compared to DAC, with many operating at relatively low technology readiness levels (TRLs) and high costs from their initial installation and operation.

The objective of this explainer guide is to provide readers with detailed visual tools and basic descriptions of the nascent CDR methods currently being developed. The CDR methods outlined in this guide include biomass with carbon removal and storage (BiCRS), biomass burial, enhanced rock weathering, ocean alkalinity enhancement, direct ocean capture (DOC), ocean-based carbon sinking, nutrient alteration, and nature-based removal. Through this guide, readers will develop a fundamental understanding of the processes involved in these CDR methods. Our hope is that members of the energy policy community will be able to use this guide as a reference source when engaging in CDR policy work.

Introduction

The Intergovernmental Panel on Climate Change (IPCC) has made it clear that limiting global warming to 1.5 to 2-degrees Celsius by the year 2100 will be nearly impossible without widespread, commercial-scale carbon dioxide removal (CDR). [3] In fact, a 2023 report led by the University of Oxford suggests that technology-based CDR capacity will have to increase 1,300 to 4,900 times by 2050 to limit warming to 1.5 to 2-degrees Celsius by the end of the century. [4] To give you a sense of the scale-up required, current CDR capacities cap at the kiloton level, with some prominent examples being Climeworks' Orca DAC plant which can remove up to 4,000 metric tons of CO2 per year [5] and Heirloom's recently unveiled California DAC facility which can remove up to 1,000 tons of CO2 per year. [6] **The biggest limitations on CDR scaling differ based on the type of approach: nature-based approaches require large areas of land and ocean surfaces to achieve large-scale CO2, while technological approaches require energy to draw from an already strained grid system.** [7]

What is Carbon Dioxide Removal (CDR)?

Carbon dioxide removal (CDR) is the practice of removing carbon dioxide (CO_2) from the ambient air and oceans. Once removed, the CO_2 can either be stored for a very long time (i.e., sequestration) or transformed and used for other purposes (i.e., utilization). CDR differs from carbon avoidance in that CDR captures carbon emissions already existing in the atmosphere while carbon avoidance prevents future carbon emissions from being released into the atmosphere. [8] CDR encompasses a wide variety of removal methods with varying levels of cost, CO_2 capturing capacity, storage permanence (i.e., how long the CO_2 is securely sequestered), and monitoring requirements (i.e., the resources needed to ensure the CO_2 is securely sequestered). However, **the most important characteristic of a CDR method is that the amount of carbon removed and sequestered should be more than the carbon emitted throughout the method's value chain. [9] If a method does not achieve this, then it is not considered true CDR.**

The State of CDR

Over the last few years, the US has allotted billions of dollars towards increasing its CDR capacity through the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA). Much of this policy support has come in the form of project funding and tax credit policy enhancements primarily focused on building out one method of CDR: Direct Air Capture (DAC), i.e., removing CO_2 from the ambient air. For example, in 2022, IRA enacted the 45Q tax credit enhancement which increased the credit value from $50 to $180 per ton of CO_2 for DAC and CO_2 sequestration in saline geologic formations. [10] Besides DAC, many CDR methods exist at relatively low technology readiness levels (TRLs), meaning these methods are still in the early stages of research, development, and deployment (RD&D). Increasing CDR capacity to the magnitude necessary to achieve our climate goals will require significant policy support towards the RD&D of these more nascent CDR methods and growing a more diverse CDR portfolio.

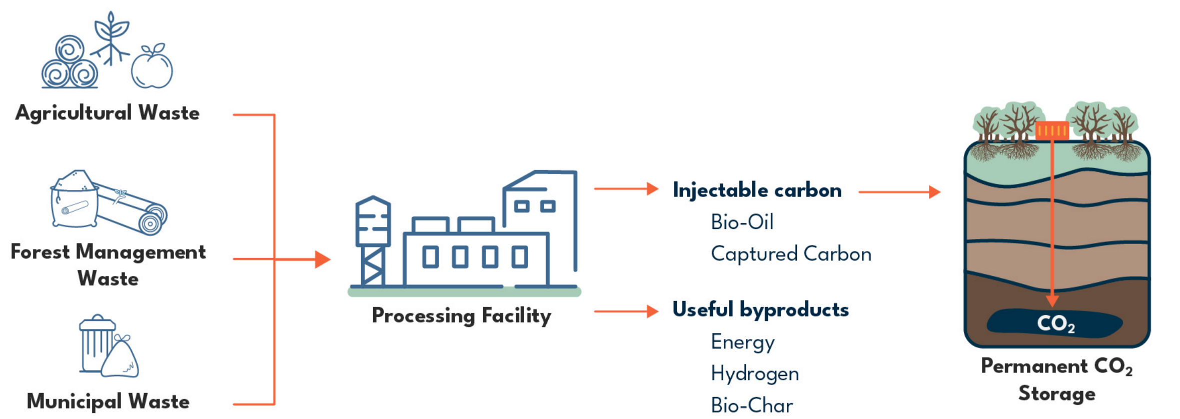
Why a CDR Explainer Guide?

CDR is an umbrella term that covers a broad portfolio of removal methods involving a plethora of nascent technologies and scientific processes, many of which are not well understood by the public nor some members of the energy policy community. **This explainer guide aims to inform the reader on the processes behind these nascent CDR methods using simple diagrams, topline summaries, and jargon-free descriptions.** Further consideration of issues such as permanence, cost, and scalability of these methods can be found in our Scaling to the Skies whitepaper.

Carbon Dioxide Removal (CDR) Methods Explained

Biomass with Carbon Removal and Storage (BiCRS)

Biomass with Carbon Removal and Storage



Note: Depiction of the general process shared by several techniques for biomass with carbon removal and storage. From the left to the right the following are pictured: waste biomass materials that contain carbon, a facility that can process those carbon rich biomass materials, a list of products created from that processing including injectable carbon and other useful products, a depiction of the created injectable carbon being injected into secure permanent underground geological storage.

See also: A Guide to Carbon Dioxide Removal Methods

Sources:

National Academies of Sciences, Engineering, and Medicine 2019. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259.

D. Sandalow, R. Aines, J. Friedmann, C. McCormick, D. Sanchez. 2020. Biomass Carbon Removal and Storage (BiCRS) Roadmap. Innovation for Cool Earth Forum.

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Summary

Biomass with carbon removal and storage (BiCRS) combines photosynthesis with high-heat chemical reactions to transform biomass waste into various carbon-rich materials for permanent underground sequestration and/or utilization.

Description

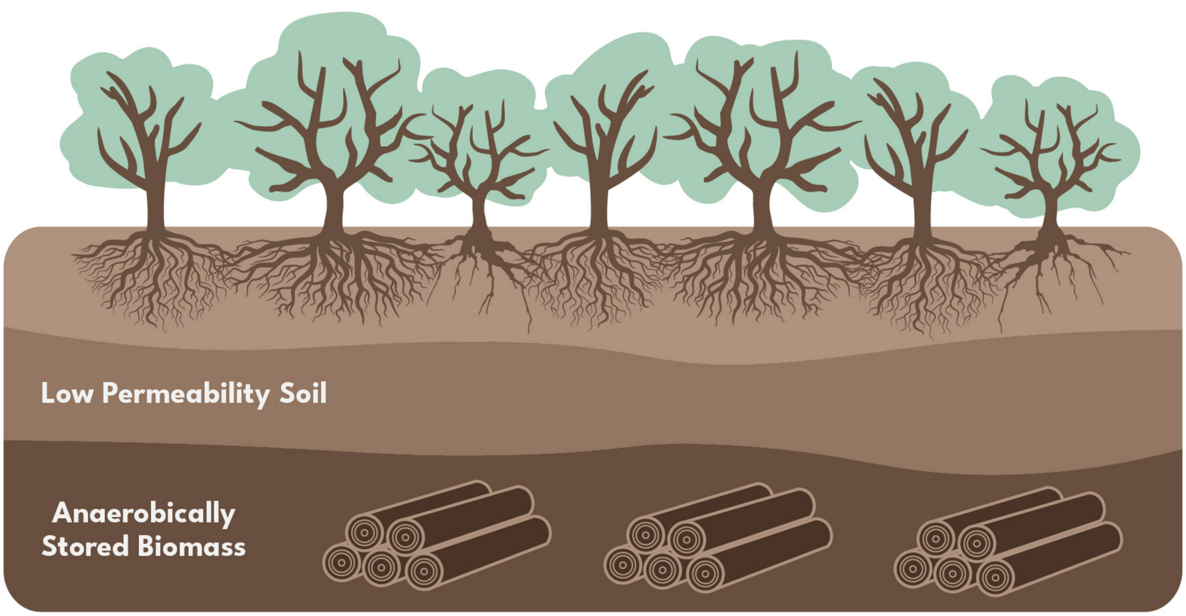
During photosynthesis, plants capture CO2 and convert it to a carbon-rich material called biomass. Photosynthesis is a natural method of carbon removal from the atmosphere; however, the carbon is only stored in the plant during its lifetime. When a plant dies, its biomass decomposes, and CO2 along with other greenhouse gases (e.g., methane and nitrous oxide) are released back into the atmosphere.

The biomass with carbon removal and storage (BiCRS) process begins with collecting biomass in the form of agricultural, forest management, or municipal waste and transporting it to a processing facility. There, the waste is heated to extremely high temperatures in a vessel where it is either exposed to a controlled amount of air and steam (i.e., gasification) or no air at all to produce liquids (via pyrolysis) or solids (via torrefaction). These high-heat and chemical processes transform the biomass waste into other carbon-rich materials. These carbon-rich materials will consist of varying amounts of solids (e.g., biochar), liquids (e.g., bio-oil), and gases (e.g., syngas) depending on whether gasification, pyrolysis, or torrefaction was used in the vessel.

Biochar can be used on agricultural lands as fertilizer and impact the soil's carbon sequestration capacity. Bio-oil can be injected deep underground in porous rock formations beneath an impermeable layer of rock for permanent sequestration or refined into fuel. Syngas can be converted to a mixture of hydrogen and CO2. Once separated, the hydrogen can be used as fuel or for other industrial purposes and the CO2 can be captured and permanently sequestered underground.

Biomass Burial

Biomass Burial



Source: Gooding, James L. "Geologic perspective for carbon sequestration by woody biomass burial." Science and Technology for Energy Transition 78 (2023): 17.

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Summary

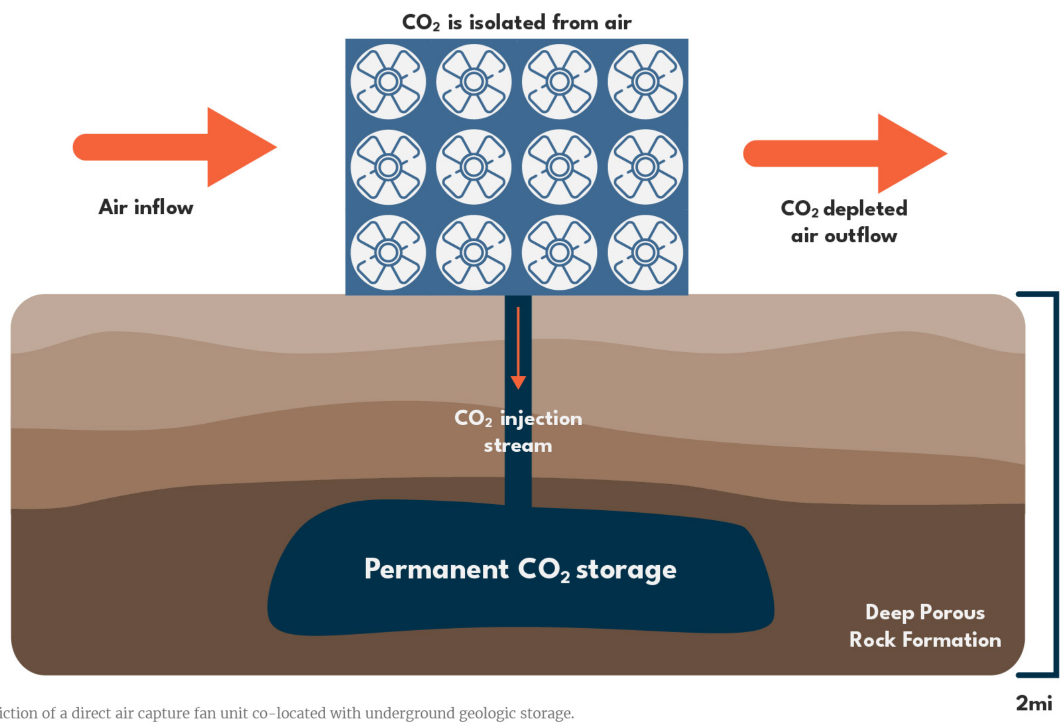
Biomass burial combines photosynthesis with burial practices to securely sequester carbon stored in biomass below nearly impermeable soil.

Description

Another form of biomass-based carbon removal involves its burial, but without undergoing high-heat and chemical treatment in a processing facility (e.g., the processes described in the previous section). Here, the biomass is directly sequestered several yards underground below nearly impermeable soil (e.g., clay). Though not sequestered at the same depths as BiCRS, e.g., approximately 2 miles, the nearly impermeable layer of soil above the buried biomass helps to lock out oxygen and water. This prevents the buried biomass from decomposing and consequently releasing CO2 back into the atmosphere. However, further analysis needs to be done to better understand the storage permanence, as well as monitoring and measuring requirements for this method, as noted in our Scaling to the Skies report.

Direct Air Capture (DAC)

Direct Air Capture



Note: Depiction of a direct air capture fan unit co-located with underground geologic storage.
See also: A Guide to Carbon Dioxide Removal Methods
Sources:
National Academies of Sciences, Engineering, and Medicine 2019. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.
Washington, DC: The National Academies Press. https://doi.org/10.17226/25259.

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Summary

Direct air capture (DAC) uses fans to channel ambient air through CO2-reactive materials that capture CO2 for permanent underground sequestration without capturing other air molecules.

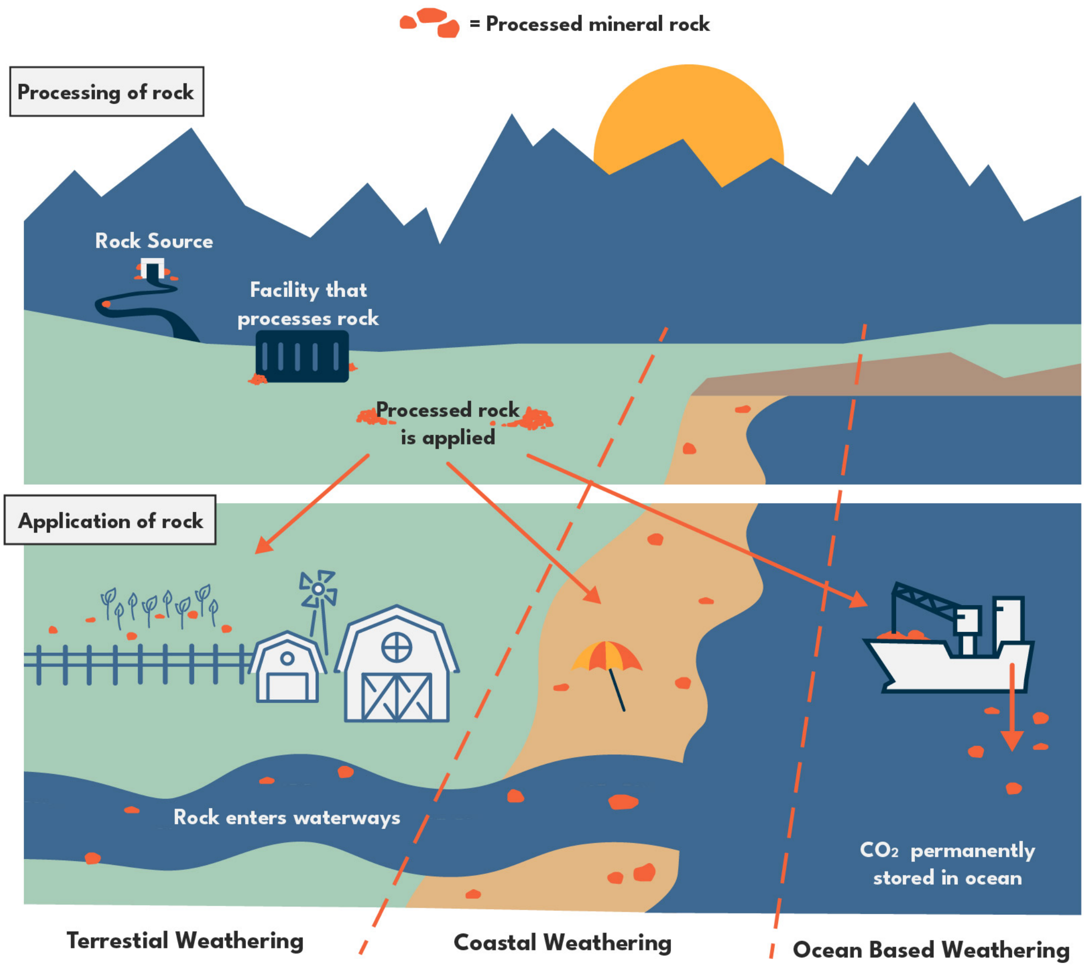
Description

A direct air capture (DAC) module uses fans to push ambient air through stacks of frames embedded with certain solids (i.e., sorbents) or liquids (i.e., solvents) that chemically-bond with CO_2 molecules but allow other air molecules (i.e., nitrogen, oxygen, etc.) to pass through. These frames are then removed from the module and treated with heat, pressure, or chemicals to separate the CO_2 from the sorbents/solvents. The separated CO_2, which is high purity (i.e., air stream with greater than 97% CO_2 concentration), is then compressed, injected, and sequestered deep underground in porous rock formations beneath an impermeable layer of rock. While DAC for carbon removal is relatively new, the other steps (i.e., compression and subsurface injection) have been around for a while. It is also important to note that CO_2 sequestration is not the same as enhanced oil recovery (EOR). While both involve compressing and injecting CO_2 underground, CO_2 sequestration is for the sole purpose of permanently storing the CO_2 underground, while EOR is used to increase oil flow from fossil-fuel reservoirs.

Now depleted of the CO_2, the frames are re-inserted into the DAC module and re-used to capture more ambient CO_2. Capturing CO_2 from the air is pricier and demands more energy compared to capturing it from a specific source. This is because CO_2 in the atmosphere is much more spread out than, for instance, in the emissions of a power station or a cement plant.

Enhanced Rock Weathering (Ex-Situ Mineralization)

Enhanced Rock Weathering (Ex-Situ Mineralization)



Sources:
National Academies of Sciences, Engineering, and Medicine 2019. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.
Washington, DC: The National Academies Press. https://doi.org/10.17226/25259.

THIRD WAY

Summary

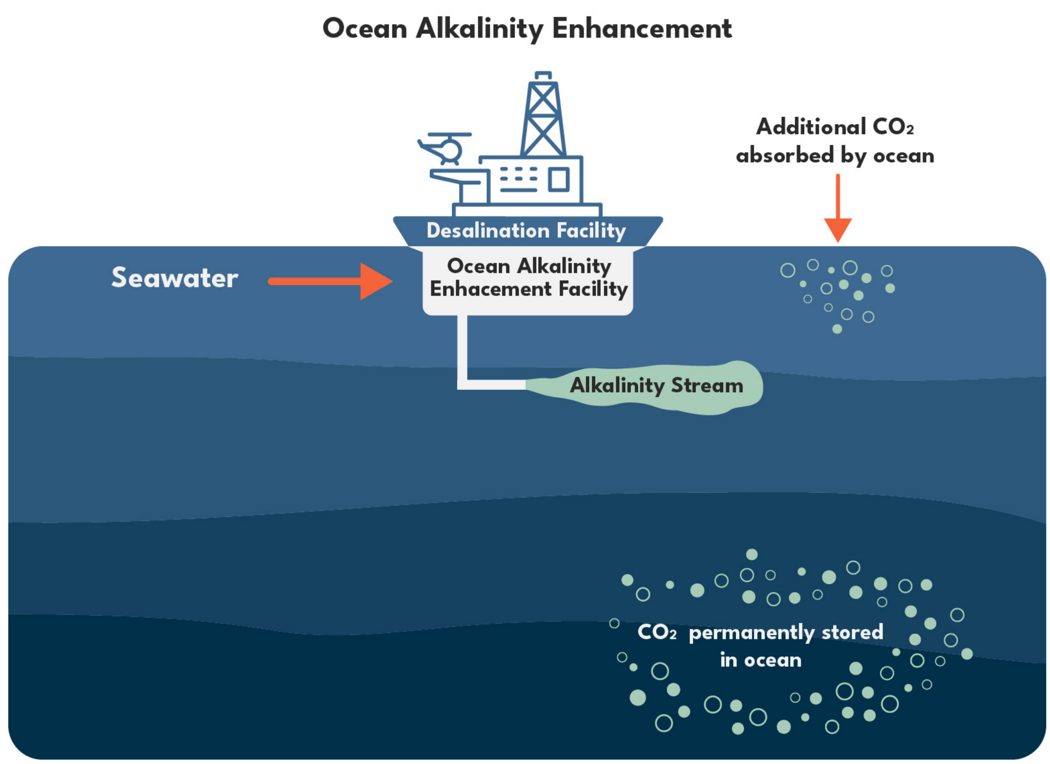
Enhanced rock weathering (ex-situ mineralization) involves grinding CO2-reactive rocks in a processing facility and distributing them across land and ocean surfaces to accelerate carbon removal via CO2 mineralization.

Description

Enhanced rock weathering utilizes a naturally occurring process called CO2 mineralization for carbon removal. CO2 mineralization occurs when atmospheric CO2 dissolves in rainwater, which then bonds with alkaline rocks (i.e., rocks rich in minerals that are highly reactive with CO2) to form solid carbon minerals. This effectively draws CO2 out of the atmosphere and absorbs it into the rock. Ex-situ mineralization refers to CO2 mineralization processes that take place at or above the earth's surface.

Enhanced rock weathering involves collecting and grinding alkaline rocks in a processing facility to increase their surface area for CO2 reactions, thus increasing the rate of carbon removal via CO2 mineralization. The processed rock can be applied to land surfaces (e.g., agriculture plots), coastal surfaces, or ocean surfaces. When exposed to water, this processed rock reacts, captures, and permanently sequesters atmospheric CO2 as carbon minerals.

Ocean Alkalinity Enhancement



Source: Cross, J.N., Sweeney, C., Jewett, E.B., Feely, R.A., McElhany, P., Carter, B., Stein, T., Kitch, G.D., and Gledhill, D.K., 2023. Strategy for NOAA Carbon Dioxide Removal Research: A white paper documenting a potential NOAA CDR Science Strategy as an element of NOAA's Climate Interventions Portfolio. NOAA Special Report. NOAA, Washington DC. DOI: 10.25923/gzke-8730

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Summary

Ocean alkalinity enhancement involves transforming CO2-reactive minerals into an alkaline solution and injecting the solution into the ocean to increase the conversion of CO2 into dissolved carbon compounds for permanent carbon sequestration in the ocean.

Description

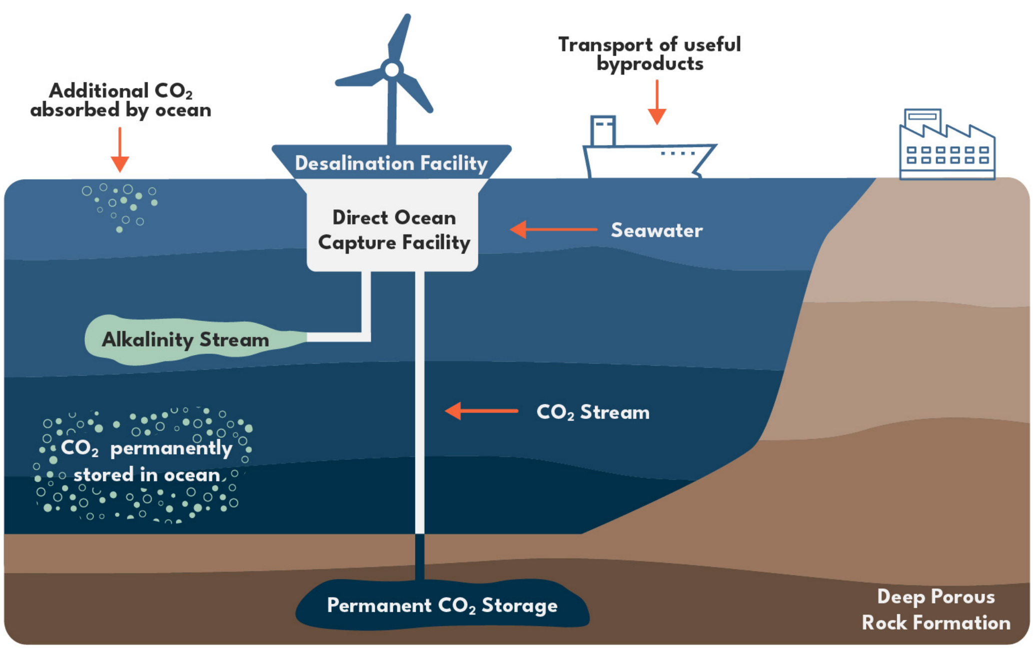
The surface of the ocean reacts with atmospheric CO2, resulting in the CO2 being dissolved into the seawater. Rising levels of atmospheric CO2 have caused the amount of CO2 being absorbed by the ocean to dramatically increase, resulting in harmful ocean acidification.

Oceans contain dissolved CO2 that naturally bonds with dissolved alkaline minerals (i.e., minerals that are highly reactive with CO2 and enter the ocean during natural weathering processes) to form stable, dissolved carbon compounds. Converting dissolved CO2 into dissolved carbon compounds reduces the concentration of CO2 in the upper layer of the ocean, freeing up capacity for surface level seawater to capture atmospheric CO2.

Like the enhanced rock weathering method described in the previous section, ocean alkalinity enhancement accelerates this naturally occurring process by collecting and crushing alkaline rocks at a processing facility. This ground up alkaline rock is then transformed into an alkaline solution that is injected below sea level at sites such as a desalination plant. After capturing the dissolved CO2, the CO2 is transformed into a stable, dissolved carbon compound that then sinks to the deep ocean for permanent sequestration.

Direct Ocean Capture (DOC)

Direct Ocean Capture



Source: Cross, J.N., Sweeney, C., Jewett, E.B., Feely, R.A., McElhany, P., Carter, B., Stein, T., Kitch, G.D., and Gledhill, D.K., 2023. Strategy for NOAA Carbon Dioxide Removal Research: A white paper documenting a potential NOAA CDR Science Strategy as an element of NOAA's Climate Interventions Portfolio. NOAA Special Report. NOAA, Washington DC. DOI: 10.25923/gzke-8730

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Summary

Direct ocean capture (DOC) uses electricity to separate dissolved CO_2 in the ocean into an acid and base which can be used for ocean alkalinity enhancement or direct CO_2 removal from seawater for utilization or underground sequestration.

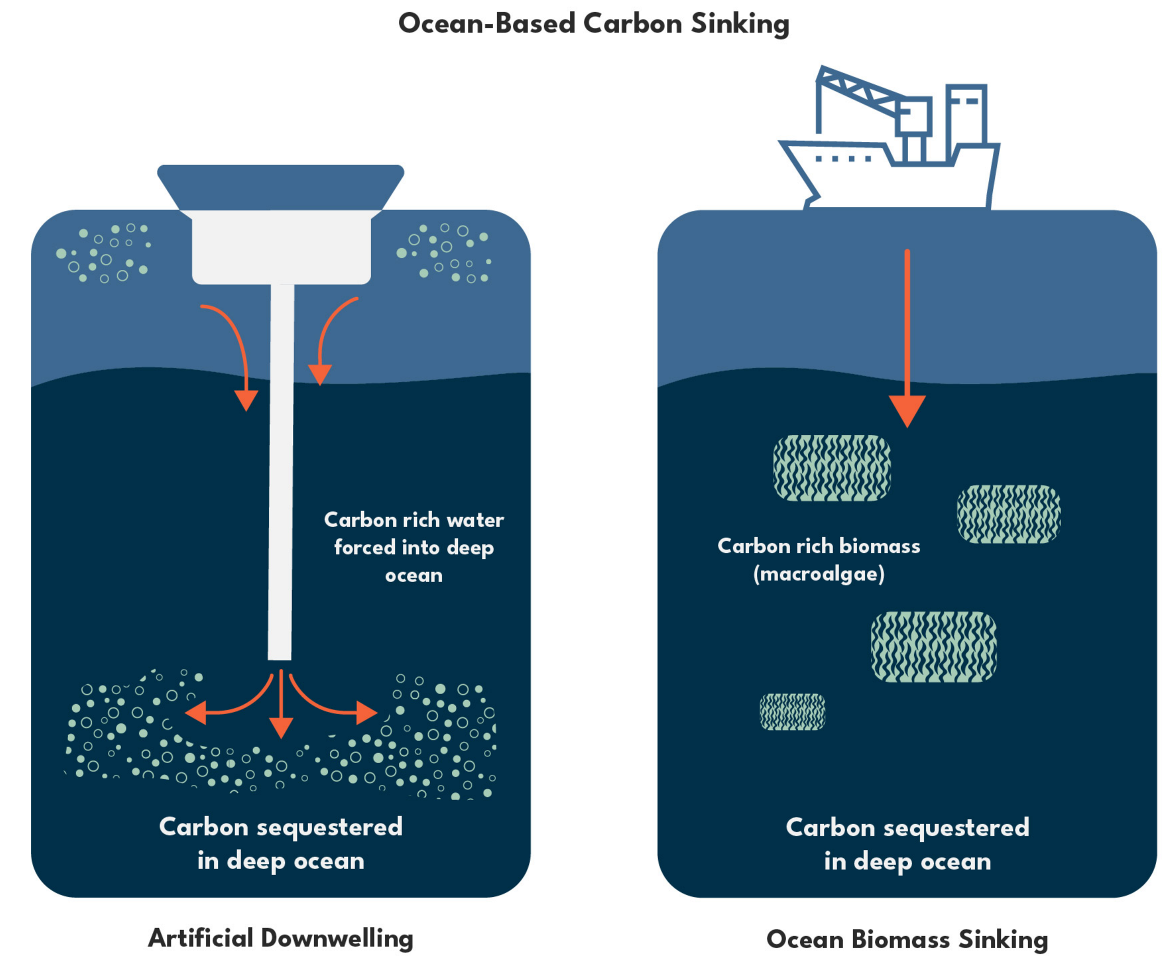
Description

Direct ocean capture (DOC) utilizes onshore and offshore infrastructure, e.g., desalination plants, for seawater collection and carbon removal. The DOC process starts by using electricity to separate collected seawater into an acid and a base in a process known as electrodialysis. There are two ways of using the acid and base produced via electrolysis to capture dissolved CO_2:

- The acid is added to collected seawater to convert dissolved CO_2 into a stream of CO_2 for capture and a stream of CO_2-depleted seawater. The captured CO_2 can either be transported and used for other purposes (e.g., producing transport fuels or manufacturing building materials) or injected below the ocean floor in porous rock formations beneath an impermeable layer of rock for permanent sequestration. The base is then added to the CO_2-depleted seawater to neutralize the previously added acid and prevent any consequent ocean acidification. This carbon-depleted seawater is then diluted with normal seawater and returned to the ocean where it can re-absorb CO_2 from the atmosphere.

- The base is directly injected back into the upper layer of the ocean to increase surface alkalinity and drawdown atmospheric CO_2. At this point, CO_2 removal occurs through ocean alkalinity enhancement, as defined in the previous section. The acid can be transported and used for industrial purposes.

Ocean-Based Carbon Sinking



Source: Cross, J.N., Sweeney, C., Jewett, E.B., Feely, R.A., McElhany, P., Carter, B., Stein, T., Kitch, G.D., and Gledhill, D.K., 2023. Strategy for NOAA Carbon Dioxide Removal Research: A white paper documenting a potential NOAA CDR Science Strategy as an element of NOAA's Climate Interventions Portfolio. NOAA Special Report. NOAA, Washington DC. DOI: 10.25923/gzke-8730

THIRD WAY

Summary

Ocean-based carbon sinking involves moving carbon near the surface of the ocean to the deep ocean for long-term sequestration via engineered downward water pumps or seaweed sinking.

Description

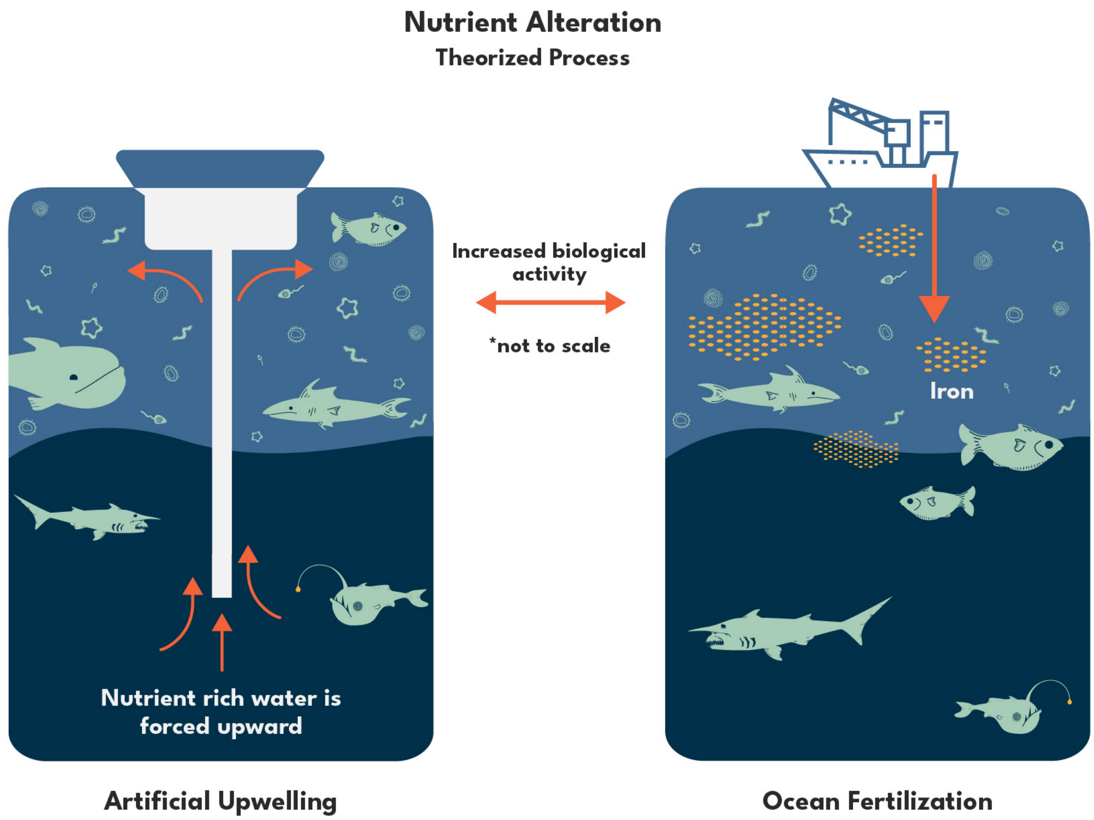
Ocean-based carbon sinking involves moving carbon near the surface of the ocean to the deep ocean, where the carbon can be sequestered for a long time. The low temperature, high pressure, and high salinity of the deep ocean would ensure that the sunk carbon does not return to the surface, convert back into CO_2, and re-enter to the atmosphere. However, further analysis and modeling needs to be done to provide more insight about sequestration permanence and ecosystem impacts.

There are two major methods of ocean-based carbon sinking: artificial downwelling and ocean biomass sinking.

- **Artificial downwelling** involves using engineered-solutions to pump surface level, carbon-rich ocean water to the deep ocean for sequestration, freeing up space at sea level for carbon-depleted ocean water to capture and dissolve atmospheric CO_2.

- **Ocean biomass sinking** involves dumping seaweed (i.e., macroalgae) that has absorbed carbon via photosynthesis to be sunk to the deep ocean for sequestration.

Nutrient Alteration



Source: Cross, J.N., Sweeney, C., Jewett, E.B., Feely, R.A., McElhany, P., Carter, B., Stein, T., Kitch, G.D., and Gledhill, D.K., 2023. Strategy for NOAA Carbon Dioxide Removal Research: A white paper documenting a potential NOAA CDR Science Strategy as an element of NOAA's Climate Interventions Portfolio. NOAA Special Report. NOAA, Washington DC. DOI: 10.25923/gzke-8730

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Summary

Nutrient alteration involves increasing the amount of nutrients near the surface of the ocean, via engineered upward water pumps or adding nutrients to the ocean, to accelerate carbon-capturing marine biological activities and deep ocean sequestration via biomass sinking.

Description

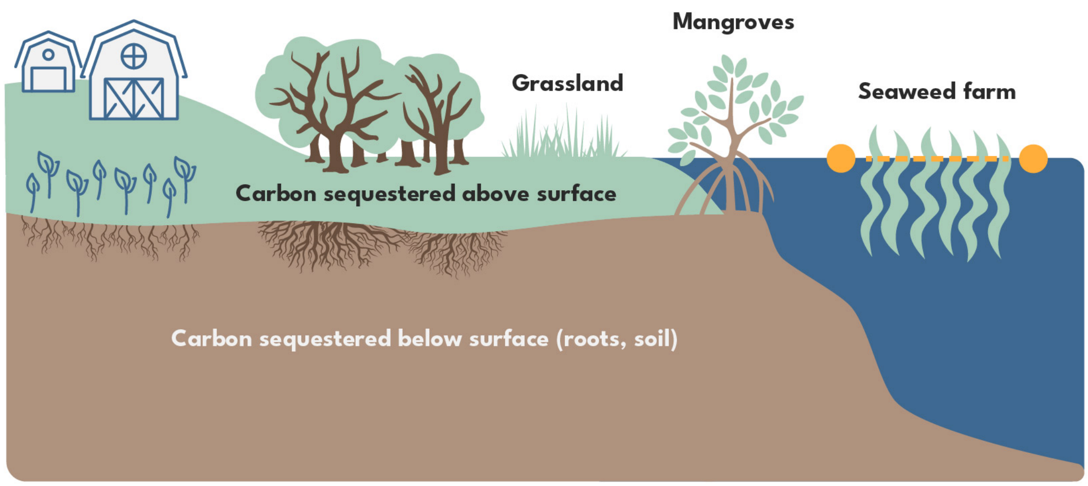
Marine organisms near the ocean's surface (e.g., phytoplankton) naturally intake dissolved CO2 and store it in their bodies during biological activities, such as photosynthesis. Nutrient alteration aims to increase the amount of nutrients near the surface of the ocean to increase biological activities, thus increasing the amount of carbon being stored in marine organisms. Some of the carbon captured and stored by these marine organisms will naturally sink to the deep ocean for long-term sequestration. Like ocean-based carbon sinking, further analysis and modelling is needed to better understand the sequestration permanence and ecosystem impacts of nutrient alteration.

There are two major methods for nutrient alteration: artificial upwelling and ocean fertilization.

- **Artificial upwelling** involves using engineered-solutions to pump nutrient rich water from the deep ocean to the nutrient-depleted upper layer of the ocean. These upwelled nutrients will feed and accelerate the carbon-capturing biological processes of marine organisms.
- **Ocean fertilization** involves adding nutrients, such as iron, to the surface of the ocean to feed and accelerate the carbon-capturing biological processes of marine organisms.

Nature-Based Removal

Nature-Based Removal



Note: Depiction of several nature-based removal methods taking place in the same landscape. Depicted methods include reforestation, soil carbon sequestration, coastal blue carbon, and seaweed cultivation.

See also: A Guide to Carbon Dioxide Removal Methods

Sources:

National Academies of Sciences, Engineering, and Medicine 2019. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. Washington, DC: The National Academies Press. https://doi.org/10.17226/25259.

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Summary

Nature-based removal involves various pathways focused on increasing vegetation to increase photosynthesis for carbon capture and/or implementing land management practices to increase soil carbon storage.

Description

CO2 is naturally removed from the atmosphere and stored in plants through photosynthesis. There are several pathways for enhancing photosynthetic processes to increase natural atmospheric carbon removal that require little to no engineered intervention.

Some of these pathways are depicted in the above diagram: reforestation, soil carbon sequestration, coastal blue carbon, and seaweed cultivation.

- **Reforestation** involves replanting trees in damaged or destroyed forest ecosystems. Trees sequester carbon in their biomass for as long as the trees live.

- **Soil carbon sequestration** involves implementing land management practices that increase the soil carbon content, as well as the sequestration time of carbon in the soil. Some examples of these land management practices include no-till agriculture to reduce soil carbon exposure and planting cover crops to reduce soil erosion and consequent carbon release.

- **Coastal blue carbon** involves implementing land management practices that increase coastal vegetation, thus increasing the amount of carbon stored in coastal ecosystems, such as mangroves and marshes.

- **Seaweed cultivation** involves growing and maintaining seaweed at the ocean's surface where carbon is removed from the atmosphere and stored in the seaweed's biomass via photosynthesis.

Conclusion

There is no silver bullet when it comes to addressing climate change. Achieving net-zero by 2050 and limiting global warming to 1.5 to 2 degree-Celsius by 2100 will require a combination of deep decarbonization to mitigate future emissions and diverse CDR deployment to remove existing emissions from the atmosphere while also meeting the needs of communities where they are deployed.

The goal of this guide is not to sell readers on these technologies, but rather broaden their understanding of what CDR processes look like and how varied they can be. Most of the CDR methods outlined in this guide are still relatively nascent and are not operating at the scale necessary to reach our emissions targets. However, by diversifying its CDR policy support and funding, the US can rapidly accelerate the development and deployment of these technologies. Doing so will enable the US to solidify itself as a global leader in emissions reductions and CDR innovation, as well as make significant progress in the fight to stop climate change.

These nascent technologies are crucial as they offer emissions mitigation solutions that are timely and address climate change, all while utilizing legacy workforces/skillsets and operating within the constraints of our current reality—an economy heavily reliant on fossil fuels, supported by powerful oil companies, and characterized by their availability and low cost.

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- **Lisa Kreibe**, PhD; Bioenergy Science and Technology, National Renewable Energy Laboratory.
- **Anne E. Ware**, PhD; Renewable Resources and Enabling Sciences Center, National Renewable Energy Laboratory.

TOPICS

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