Ocean – based carbon dioxide removal

A primer for philanthropy

Antonius Gagern and Lydia Kapsenberg

climateworks FOUNDATION

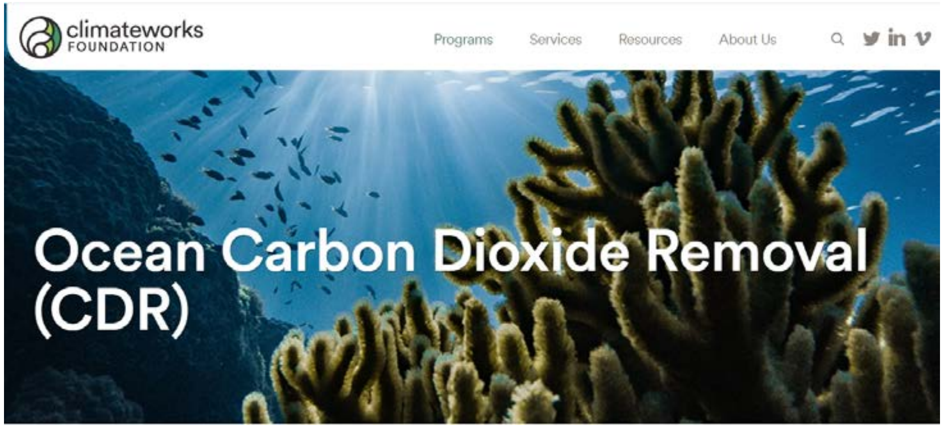
Ocean Carbon Dioxide Removal Pre-read

Sections

Background: ClimateWorks Ocean Carbon Dioxide Removal Program

ClimateWorks Ocean Carbon Dioxide Removal Program aims to support the development of an ocean CDR portfolio by supporting the scientific rigor that is required to vet each promising approach; build a community of actors to accelerate the solution-oriented discourse across scientists, entrepreneurs and policy-makers; and steer the attention of decision makers to the ocean as a potential contributor to carbon dioxide removal. Learn more.

Ocean CDR is part of the larger **ClimateWorks CDR Program** which aims to grow natural, technical, and ocean-based methods to directly remove carbon dioxide from the atmosphere by supporting research, policies, and communications. Since 2018, it has disbursed USD $14.5 million in philanthropic support to advance carbon dioxide removal.



Partners:

About ClimateWorks Foundation: ClimateWorks is a global platform for philanthropy to innovate and accelerate climate solutions that scale. We deliver global programs and services that equip philanthropy with the knowledge, networks and solutions to drive climate progress. Since 2008, ClimateWorks has granted over $1 billion to more than 500 grantees in over 40 countries. More information can be found at www.climateworks.org.

Section 1

The Need for Carbon Dioxide Removal (CDR)

- We are on a trajectory that will increase average global temperatures by 3-4 degrees Celsius compared to pre-industrial levels within the next 80 years alone.
- A 1.5 degrees Celsius future has become impossible to achieve without large-scale carbon dioxide removal (CDR) from the atmosphere.

We are on track to increase average global temperatures by 3-4 degrees Celsius compared to pre-industrial levels

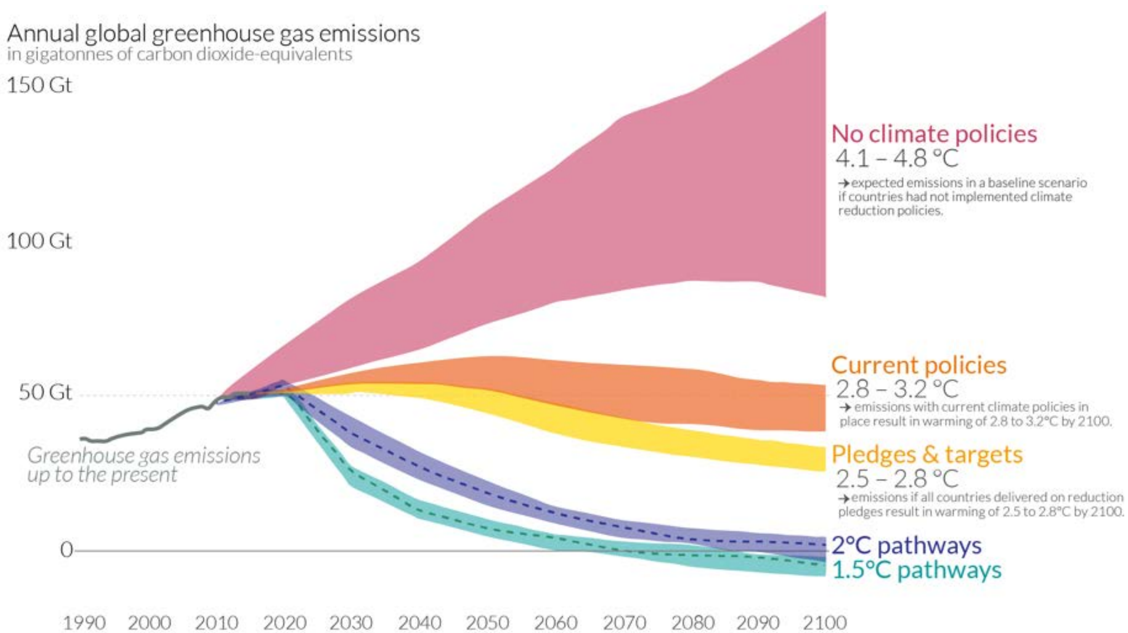


Figure 1: Global GHG emissions and warming scenarios

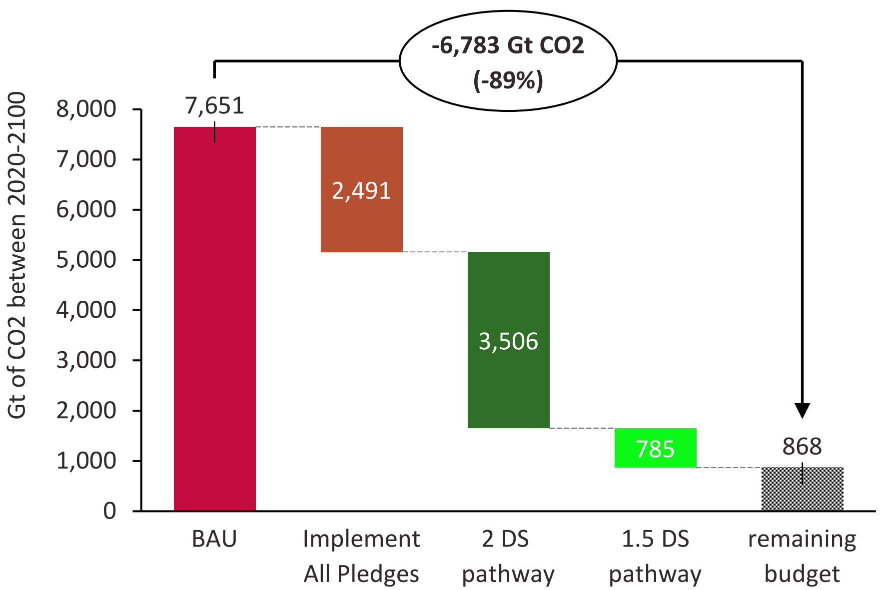
Source: https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Since the 1850s, we have emitted 1.6 trillion tons of planet-warming carbon dioxide CO2 into the atmosphere, an almost unimaginable amount. Unfortunately, the resulting rapidly increasing atmospheric CO2 concentrations are making the planet warmer and the oceans more acidic, disrupting the global climate system. The international response to these threats has largely been slow and insufficient, both in terms of verifiable private sector commitments and nationally binding targets for emission reductions.

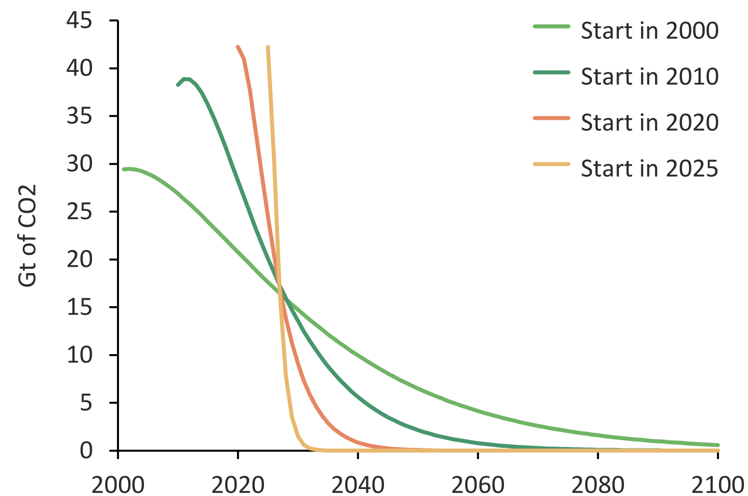
A 1.5 °C pathway is virtually impossible to reach with mitigation efforts alone

The Business as usual (BAU) pathway is based on the observable global trends of energy demand, industry projections, population growth projections, dietary shifts, and so on. If we continue down a BAU pathway, we will emit approximately 7.6 trillion tons of CO_2 in the until 2100. This is unlikely given global climate pledges and policies that are being implemented. However, these would, fully implemented, only cut cumulative emissions by 30 percent. A 1.5°C and 2°C pathway would require extremely ambitious and quick emission cuts in addition to ambitious mitigation efforts.

Carbon budget for 1.5°C and 2°C pathways compared to BAU (2020-2100)



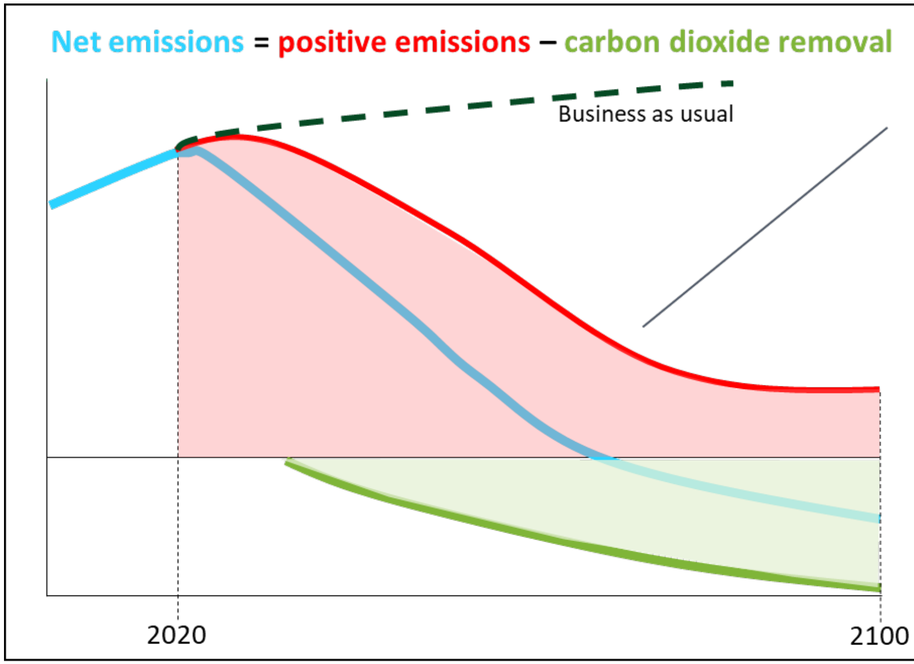
CO2 reductions needed to keep temperature rise below 1.5°C by 2100



Source: ClimateScoreboard.org (Figure 1), https://ourworldindata.org/grapher/co2-mitigation-15c (Figure 2)

IPCC models show that all pathways to minimize temp change to 1.5 °C will require atmospheric CO_2 removal of 100-1000 Gigatons before the end of the century

Even the most aggressive projections of emission reductions do not get anywhere close to staying within the 1.5-degree carbon budget. The Intergovernmental Panel on Climate Change (IPCC) suggests that even aggressive mitigation scenarios, that is, preventing the release of CO2 into the atmosphere--will have to be complemented with carbon dioxide removal (CDR) on the order of 100-1000 billion tons before the end of the 21st century.

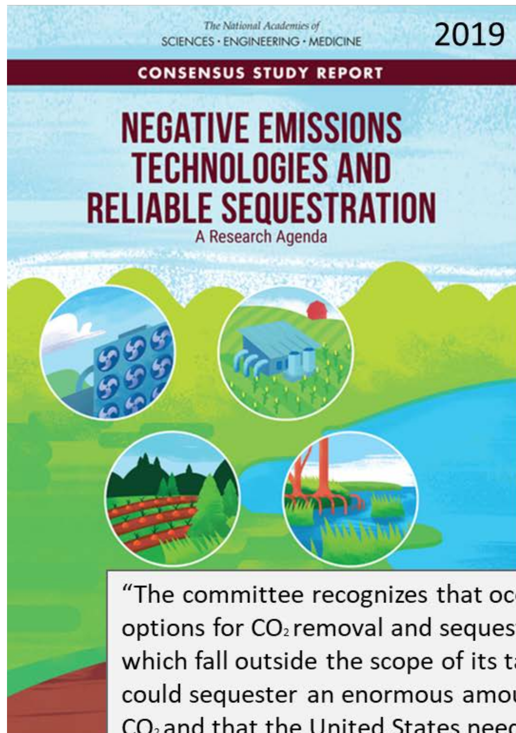


- **Reducing positive emissions is difficult**
- **We have to start with CDR as soon as possible**
- **We will have to ramp up quickly**
- **Every failure to reduce positive emissions increases the need for CDR**

Source: CEA Consulting based on https://www.globalccsinstitute.com/wp-content/uploads/2020/09/Netzero-and-Geospheric-Return-2.pdf)

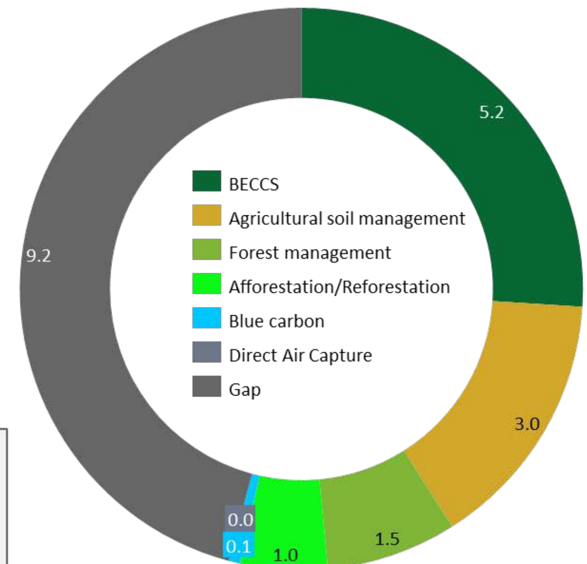
There is no single silver bullet CDR method and land-based methods may be infeasible at the scale needed.

Removing hundreds of billions of tons of CO2 from the atmosphere is an enormous challenge. Some of the most discussed CDR approaches include direct air capture, bioenergy with carbon capture and storage (BECCS), reforestation or afforestation, and agricultural practices that increase the burial rate of organic carbon. While these approaches hold significant promise, there are important impediments to their quick scale-up, including cost, energy requirements, and land use implications. Additionally, some climate-caused “feedbacks” such as drought, fire, and pests already are impairing the ability of land-based solutions such as trees to remove as much CO_2 as once hoped



“The committee recognizes that oceanic options for CO_2 removal and sequestration which fall outside the scope of its task, could sequester an enormous amount of CO_2 and that the United States needs a research strategy to address them.”

“Safe potential rate of CO2 removal possible given current technology and understanding at <\$100/t CO2”



Donut sums to 20 bn tons

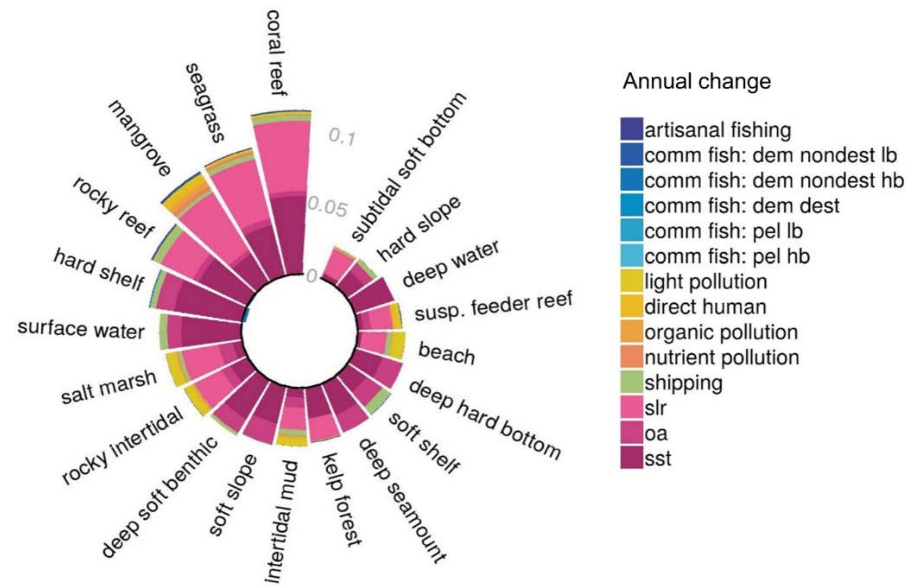
Sources: NASEM 2019. The National Academies Press. https://doi.org/10.17226/25259; https://physicsworld.com/a/carbon-removal-requires-multiple-technologies/

Climate change is the biggest and fastest growing threat to oceans

Biodiversity in the ocean has evolved in the absence of human-induced stressors such as overfishing, pollution, shipping, habitat destruction and fragmentation, and invasion of new species. Even without the impacts of climate change and ocean acidification (OA), this ‘cumulative human impact’ (CHI) on the ocean has considerably diminished marine biodiversity.

Unfortunately, the effects of climate change have now become the biggest and fastest-growing contributors to CHI. A recent report from the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) found that approximately one million plant and animal species are threatened by extinction, many within decades, and that human activities have significantly altered two-thirds of the ocean.

As a result, many prominent efforts to safeguard biodiversity, sustainably manage fisheries and alleviate poverty in coastal communities around the world are at risk due to climate change: we can work locally and nationally to reduce the detrimental effects of pollution, overfishing or habitat destruction, but OA, rising temperatures, sea level rise, and hypoxia are largely outside of our control. A quick and determined global effort to remove hundreds of billions of atmospheric CO2 is an important part of the solution set currently overlooked



Annual change in 14 impact variables comprising the “cumulative human impact” for each ecosystem

Sources: Halpern, B. et al. (2019). Recent pace of change in human impact on the world’s ocean. Sci Rep 9, 11609

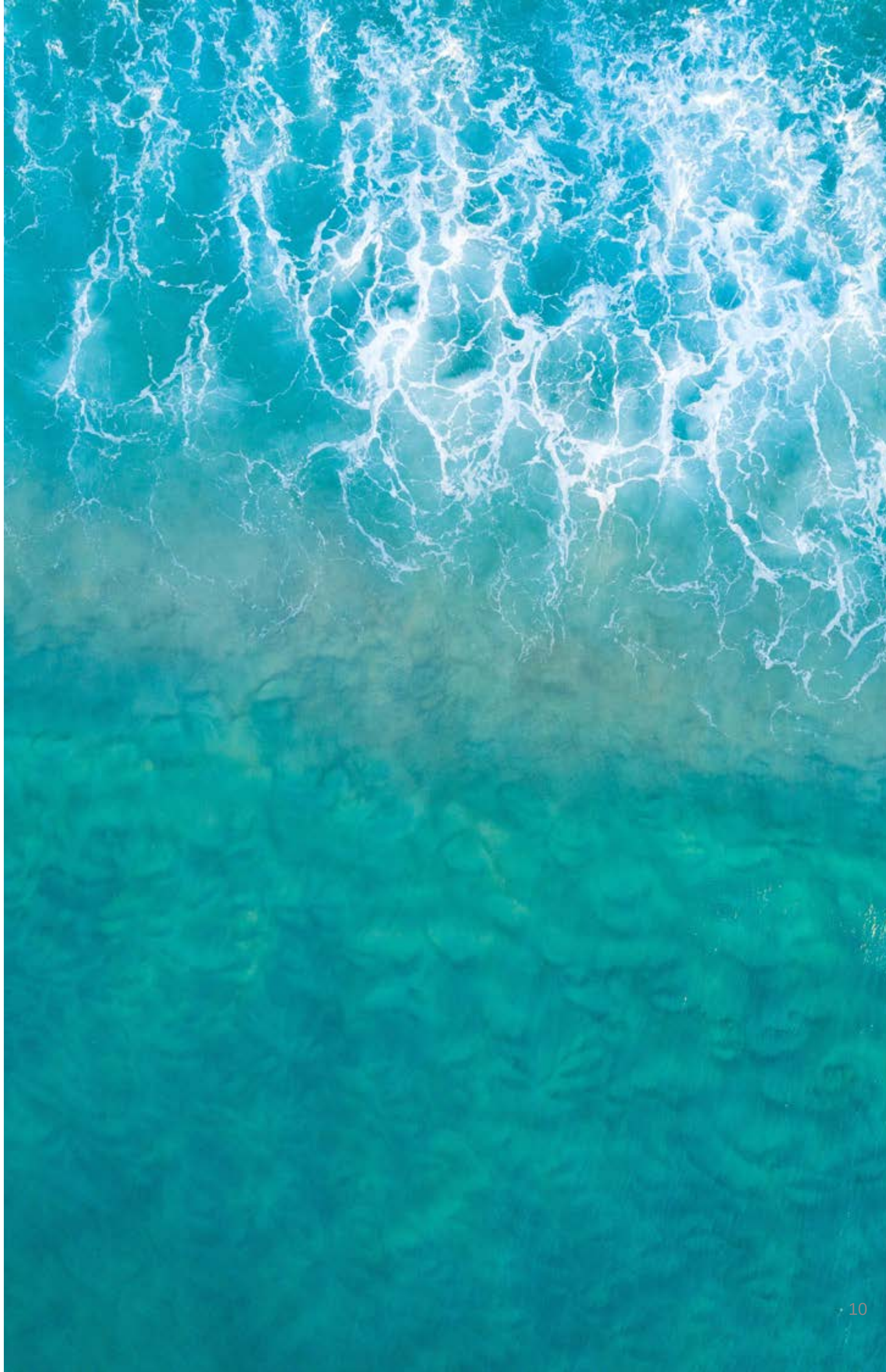
Section 2

Rationale for Ocean-based CDR

The ocean cannot be ignored given its role as one of Earth's biggest carbon sinks. Through the slow cycling of carbon through earth, air, and water, much of our carbon emissions are ultimately destined to be stored in the ocean. However, natural processes of the carbon cycle are far too slow to lessen, let alone reverse, our climate change trajectory over the next decades. Accelerating the rate by which the ocean can safely take up and store CO_2 will help achieve climate goals, if at the same time emissions are ceased.

Use of the ocean for CDR has several advantages:

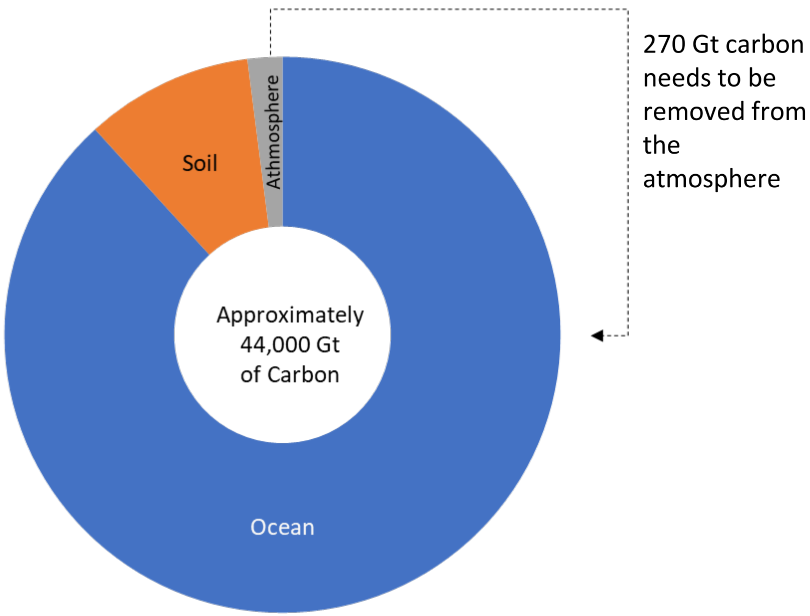
1. The ocean has a virtually unlimited potential for CO_2 storage
2. Ocean CDR does not compete for space with other land uses
3. Ocean CDR targets and accelerates natural sequestration processes
4. Some approaches mitigate ocean acidification locally



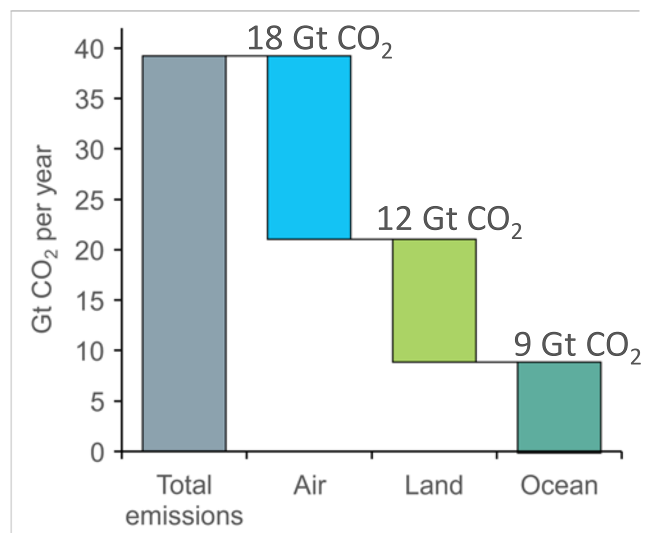
Restoring current atmospheric CO_2 to preindustrial levels via ocean CDR would increase total ocean carbon content by less than 1%

The ocean is the largest carbon reservoir on Earth. 38,000 Gt Carbon is stored in the ocean in the form of Dissolved Inorganic Carbon (DIC)* and only 860 Gt Carbon is stored in the atmosphere in the form of CO_2 (equivalent to 3,096 Gt CO_2). Return to preindustrial atmospheric CO_2 levels, a decrease from 410 to 280 ppm CO_2, requires removing 270 Gt of carbon from the atmosphere. This represents 0.7% of all carbon currently stored in the ocean. **The ocean absorbs 9 Gt CO2 every year**. This represents approximately 23% of annual emissions. Currently, the majority of our emissions remain in the atmosphere. In the absence of active CDR, much of the atmospheric CO2 will eventually be absorbed by the ocean anyway, but with detrimental effects.

Global Carbon Inventory (not including rocks)



Current Destination of CO_2 Emissions

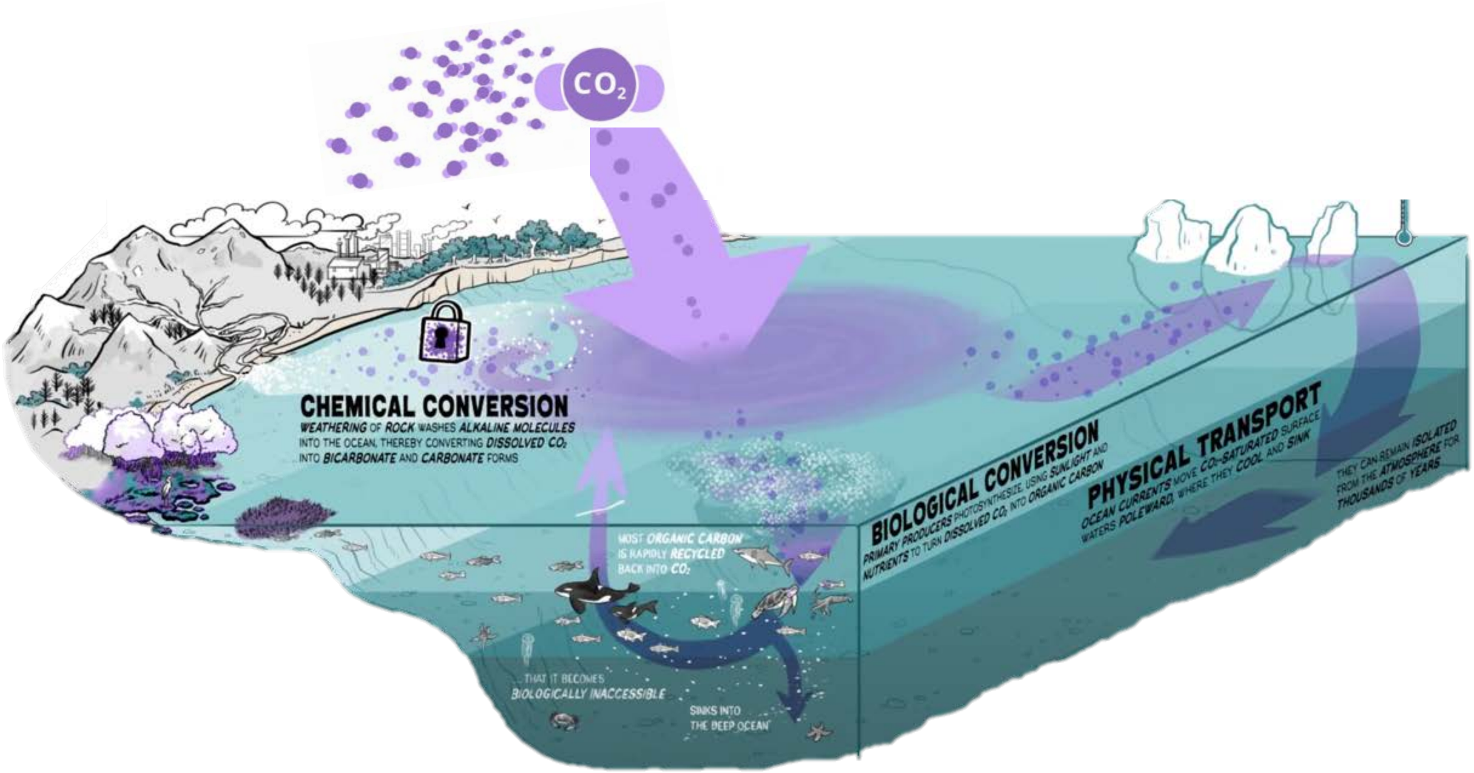


Source: Friedlingstein et al. 2020

*DIC represents the three forms of carbon in the ocean: dissolved CO_2, bicarbonate, and carbonate ions

Ocean carbon pumps continuously pull CO_2 from the atmosphere into the ocean

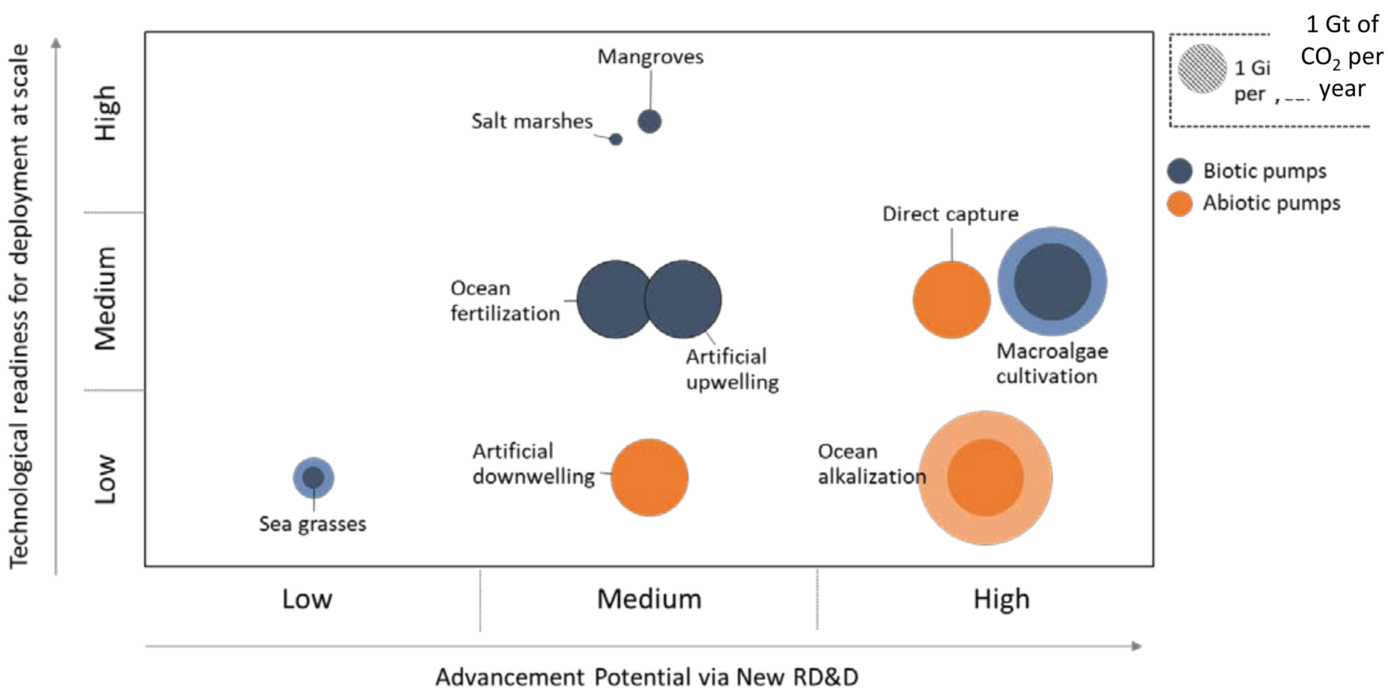
When CO_2 is more abundant in the atmosphere than in the ocean, CO_2 diffuses into the surface ocean. This is called the ‘solubility pump’. Once dissolved, additional powerful carbon pumps remove CO_2 from the surface, pulling yet more of it into the ocean. This includes the **physical transport** of ocean currents that ultimately pull CO_2 into the deep ocean; **chemical conversion** of CO_2 into bicarbonate and carbonate forms as a result of weathered rock that washes into the ocean; and **biological conversion** of CO_2 into organic carbon, some of which escapes the food web and is sequestered in the deep ocean and ocean sediments.



- Source: https://www.youtube.com/watch?v=brl4-xa9DTY;

So far, current research points to several promising ocean-based approaches that may be able to achieve CDR at a multi-gigaton scale

A handful of ocean-based methods to remove CO_2 from the atmosphere are being explored. Evaluation in terms of CDR potential, Research and Development needs, and technological readiness vary widely at this time. However, some of these approaches could potentially remove multi-gigatons of CO_2 every year if implemented at the right scale. With a portfolio approach, this could theoretically lead to the additional removal of up to 10 Gt CO_2 annually, thereby doubling the current rate by which oceans absorb atmospheric CO_2.



Sources:

- Hoegh-Guldberg O. et al. (2019). The Ocean as a Solution to Climate Change: Five Opportunities for Action. Report, Washington DC, World Resources Institute.
- Gattuso, J.-P., et al. (2018). Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems. Frontiers in Marine Science 5:337.
- Energy Futures Initiative (2020). Uncharted Waters: Expanding the Options for Carbon Dioxide Removal in Coastal and Ocean Environments.
- National Academies of Sciences, Engineering, and Medicine [NASEM] (2018). Negative Emissions Technologies and Reliable Sequestration: A Research Agenda.

Section 3

CDR: Enhancing the biological carbon pump

- **The ocean's Biological Pump transports CO_2 from surface waters into the deep ocean and marine sediments.** In the sunlit surface ocean, photosynthesis by marine plants and algae converts dissolved CO_2 into organic carbon. While most of this carbon is recycled back into CO_2 by the food web, a fraction is exported to the deep ocean where it can remain for hundreds of years, or if trapped in sediments, for tens of thousands of years.
- **Ocean CDR approaches that target the biological pump aim to boost primary production** to increase export of organic carbon to the deep ocean and sediments or create harvestable biomass that can be used in other carbon storage approaches. Approaches include artificial upwelling and ocean fertilization to increase nutrients in surface oceans, cultivation and harvest of seaweed, and conservation and restoration of blue carbon ecosystems (seagrass, mangroves, salt marshes).

"CO_2 removal based on photosynthesis"

Blue Carbon: Low global CDR potential but highly beneficial for local marine biodiversity and coastal communities, and methods are well established

Coastal vegetated marine ecosystems, including salt marshes, mangrove forests, and seagrasses meadows, capture CO_2 by photosynthesis and trap organic carbon in marine sediments for thousands of years. Loss of Blue Carbon (BC) ecosystems leads to rapid emissions of carbon stocks accumulated in biomass and soils, while also eliminating the system's continued sequestration potential. Reforestation of degraded BC ecosystems can restore sequestration rates and, in some cases, also prevent the emission of soil carbon from recent degradation. Conservation and reforestation safeguards BC's many ecosystem services and biodiversity value and is considered a 'no regrets' climate action.

Best guess drawdown potential*

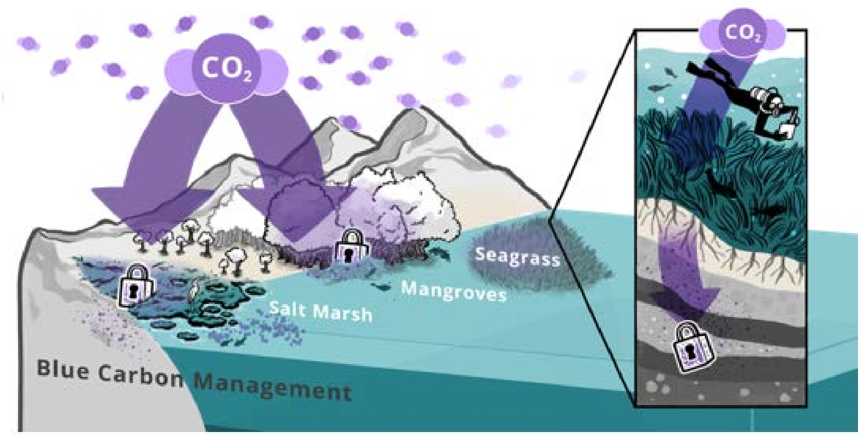
- Low: <1 Gt CO_2 per year
- Area available for restoration is limited
- BC is negatively impacted by climate change
- By area, BC restoration has 10x greater CDR potential than tropical rainforest restoration

Environmental impacts

- Boosts biodiversity & habitat for fished species
- Provides coastal protection from storms and sea level rise
- Competes for other land uses

Cost considerations

- Low to High: >$125 per ton CO_2 removed
- Restoration actions are being integrated into carbon markets which can help finance projects



Source www.OceanCDR.net; EFI 2020. https://energyfuturesinitiative.org/efi-reports
*Drawdown potential for all ocean CDR approaches is based on preliminary modeling and rough extrapolations

Macroalgal Cultivation: High CDR potential but significant development is needed to ensure viable economic pathways for use of biomass

Seaweed cultivation can contribute to net carbon removal in three major ways. First, a portion of cultivated biomass that is lost before harvest is buried in sediments or sequestered in the deep sea. Second, biomass can be converted into long-lived bioproducts (plastics, biochar) or used for biofuel with carbon capture (BECCS). Third, the macroalgal biomass could be harvested, compressed, and sunk to the deep ocean, where the organic carbon is effectively sequestered. While methods for macroalgal cultivation are well established, there is currently no focus on CDR and infrastructure would need to be greatly scales and adapted for the offshore ocean environment.

Best guess drawdown potential*

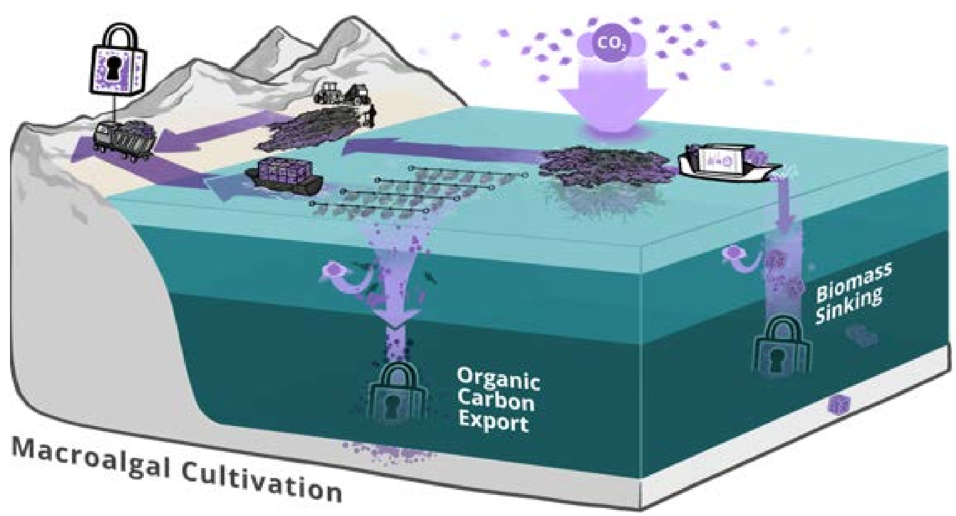
- Moderate to High: 1 to >5 Gt CO_2 per year
- Space is not limited for offshore cultivation
- Pathways for biomass use are underdeveloped

Environmental impacts

- Co-benefit of boosting seafood production and potentially local biodiversity
- Nutrient competition with the local ecosystem
- Risk of material loss, entanglement of marine life
- Biosecurity risks (disease, genetic mixing, invasive species)

Cost considerations

- Moderate: \$25-\$125 per ton CO_2 removed
- New infrastructure required for offshore environment
- CDR products and economies of scale do not currently exist



Source www.OceanCDR.net; EFI 2020. https://energyfuturesinitiative.org/efi-reports

Artificial Upwelling: Moderate CDR potential despite many uncertainties, but could have important co-benefits for seafood production

Natural upwelling moves deep, nutrient and CO_2-rich water upwards and stimulates photosynthesis by phytoplankton or macroalgae in sunlit surface waters. Artificial upwelling, using pipes or other methods, could be used to boost such primary production and increase CO_2 removal from surface waters. Theoretically, the carbon fixed during photosynthesis could contribute to organic carbon export to the deep ocean, where it is effectively sequestered from the atmosphere. Alternatively, artificial upwelling may boost the production of macroalgal biomass that can be harvested and used in other carbon storage or mitigation pathways. Field trials testing artificial upwelling are currently being planned.

Best guess drawdown potential

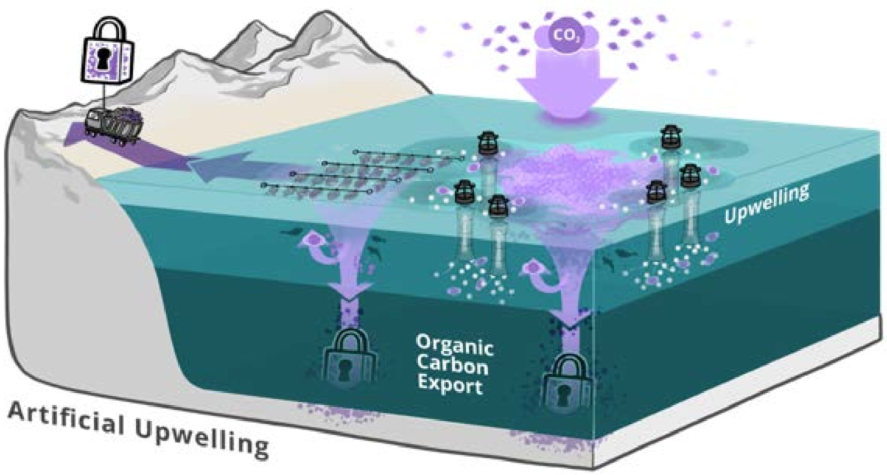
- Moderate: 1 to 5 Gt CO_2 per year
- Field trial show boost in phytoplankton blooms but carbon drawdown remains uncertain
- Upwelling also releases CO_2 to the atmosphere

Environmental impacts

- Could boost local fisheries or seafood production
- Local cooling and changes in seawater chemistry
- Unknown impact of diverting deep water from it's original upwelling destination where it would have contributed to CDR naturally

Cost considerations

- Low to Moderate: <$125 per ton CO_2 removed
- Highly dependent on pumping methods, operational costs, and monitoring needs



Source: www.OceanCDR.net; EFI 2020. https://energyfuturesinitiative.org/efi-reports

Ocean Fertilization: Large-scale research in the 1990s and 2000s was discontinued after some poorly managed experiments. Time to reconsider?

Primary production in the surface ocean is largely limited by the availability of nutrients. Fertilizing nutrient-poor surface waters with limiting nutrients such as iron (Fe), phosphorus (P), and nitrogen (N), can stimulate photosynthesis and fixate excess amounts of CO_2 in living biomass of phytoplankton or macroalgae. Increasing net primary production this way could theoretically lead to increased export of organic carbon to the deep ocean. Since 1990, 13 large-scale ocean iron fertilization experiments have been conducted and they have failed to provide conclusive evidence of net carbon export except for one trial in the Southern Ocean. While these findings do not disqualify the effectiveness of ocean (iron) fertilization altogether, they point at the complex nature of the biological pump which is still not fully understood.

Best guess drawdown potential

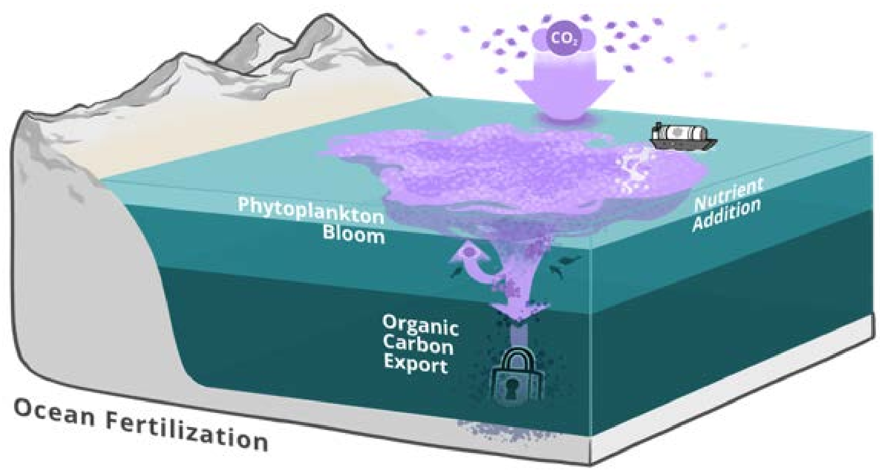
- Moderate: 1 to 5 Gt CO_2 per year
- Nutrient additions boosts primary production but tracking carbon export remains a challenge
- Likely inefficient method for CDR due to the small additional carbon export

Environmental impacts

- Ecosystem impacts are largely unknown but likely include changes in the food web structure and potentially increases in toxic algal blooms
- Production of other greenhouse gases by phytoplankton species

Cost considerations

- Moderate: \$25-\$125 per ton CO_2 removed



Source: www.OceanCDR.net; EFI 2020. https://energyfuturesinitiative.org/efi-reports

Section 4

CDR: Enhancing the abiotic carbon pumps

- The Solubility Pump transports carbon from the ocean's surface to its interior. Atmospheric CO_2 diffuses into the surface layer of the ocean. As CO_2 -saturated surface waters travel poleward, they cool and sink, pulling our emissions into the deep ocean where they can remain for thousands of years. This causes acidification of the entire ocean.
- The Carbonate Pump buffers ocean acidification and increases uptake of CO_2. When calcifying marine organisms (e.g., corals, shellfish, coccolithophores) die, they sink to the ocean floor, are buried in sediments, and, over geologic time scales, resurface as limestone. Weathering of limestone by rain and CO_2 dissolves the rock, forming alkaline carbonate and bicarbonate compounds that are transported back to the ocean through rivers and groundwater. The increased alkalinity in seawater shifts dissolved CO_2 into more stable forms of carbon (bicarbonate and carbonate), which have a lifetime of approximately 10,000 years.
- Ocean CDR approaches that target abiotic processes in the carbon cycle aim to increase the amount of CO_2 that can be stored in seawater and marine sediments/rock. Most prominently, this includes increasing ocean alkalinity which also reverses ocean acidification.

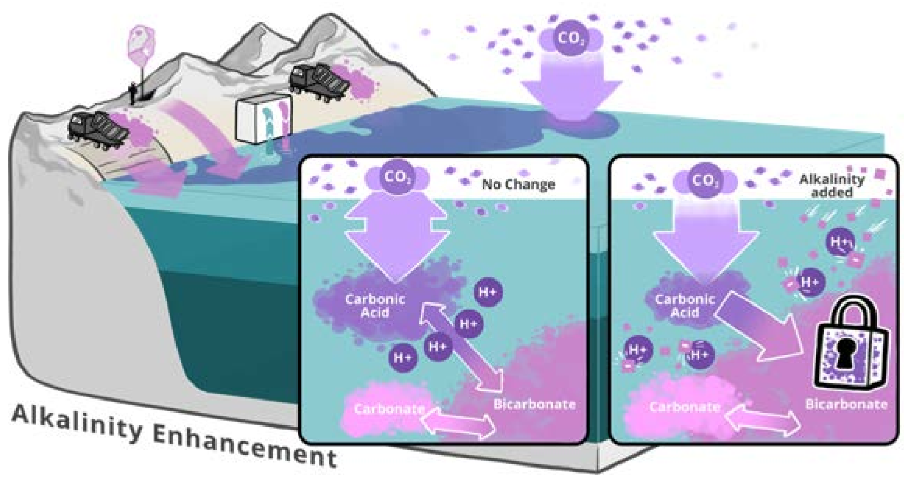
"CO_2 removal based on chemical and physical processes"

Alkalinity Enhancement: High CDR potential with few limitations but more research and field trials are needed to identify environmental impacts

Alkalinity is produced naturally through the weathering of alkaline minerals such as limestone or basalt. Weathering consumes hydrogen ions (H+), causing an increase in seawater pH. This chemical change shifts the carbonate chemistry equilibrium from dissolved CO_2 and carbonic acid (H_2O+CO_2) to bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions. The conversion of dissolved CO_2 into bicarbonate creates a CO_2-deficit in surface waters, thereby pulling more atmospheric CO_2 into the ocean. Accelerated weathering of alkaline rock or addition of manufactured alkalinity products boosts the ocean's solubility pump and increases the total carbon content of seawater. The residence time of carbon in the form of bicarbonate is on the order of ten thousand years. Lab experiments assessing ecosystem impacts are currently underway.

Best guess drawdown potential

- Moderate to High: 1 to >5 Gt CO_2 per year
- Rock resources are essentially unlimited
- Scaling of extraction/production and distribution of alkaline materials currently limit this approach



Environmental impacts

- Ecosystem impacts from mineral dissolution byproducts (e.g., silica, magnesium, and trace metals)
- Co-benefit of local reversal of ocean acidification, which is likely to benefit marine species

Cost considerations

- Low to High: <\$25 to >\$125 per ton CO_2 removed
- Cost drivers include material production and transport

Source: www.OceanCDR.net; EFI 2020. https://energyfuturesinitiative.org/efi-reports

Direct Capture: Moderate CDR impact, possibly with minimum environmental impact; beneficial use for extracted CO_2 needed.

Similar to Direct Air Capture, CO_2 can be directly removed from seawater using electrochemical methods. Here, electrical current is used to, transiently, split H_2O to create acidic (excess H^+ ions) and basic (excess OH^- ions) effluent streams. The acidic stream can be used to degas CO_2 from seawater for storage or use elsewhere. It can be used to weather alkaline rocks to increase alkalinity. The basic stream can be used to absorb CO_2 directly (e.g., from the atmosphere, or industrial flue gas streams), stabilizing dissolved CO_2 as bicarbonate and carbonate ions, or to precipitate carbonate minerals out of the seawater, thereby stabilizing carbon in a durable solid form. To ensure that the processed water discharged will absorb atmospheric CO_2, an electrochemical process operating on seawater must either remove acid (e.g., remove only CO_2), generate alkalinity, or both. Direct Capture has been performed in the lab but requires pilot scale studies.

Best guess drawdown potential

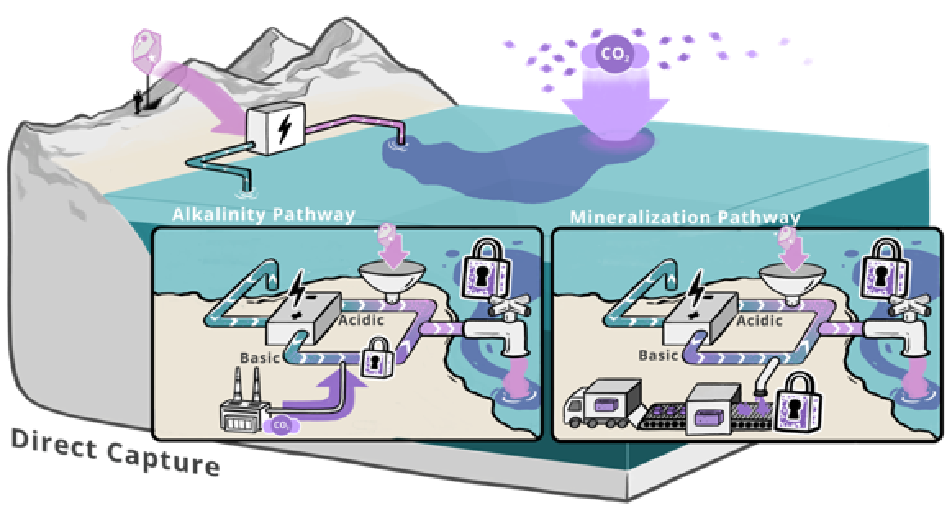
- Moderate: 1 to 5 Gt CO_2 per year
- In some cases, captured CO_2 still requires permanent storage

Environmental impacts

- Local mitigation of ocean acidification
- In some cases, captured CO_2 still requires permanent storage
- Impacts of seawater pumping, depending on the volume processed daily

Cost considerations

- Moderate to High: $25 to >$125 per ton CO_2 removed
- Energy input are high and so require renewable energy
- Byproducts such as hydrogen gas could offset costs



Source: www.OceanCDR.net; EFI 2020. https://energyfuturesinitiative.org/efi-reports

Artificial Downwelling: Theoretically can boosts CO_2 transport to the deep sea; high energy requirements likely disqualify this approach

Enhanced downward transport of cold CO_2-saturated surface waters aims to enhance the solubility pump and thermohaline transport of atmospheric CO_2 down to the deep ocean for storage for up to hundreds to thousands of years. Downwelling of surface waters in polar regions would laterally pull warmer waters poleward which would then cool and absorb more CO_2 from the atmosphere. Downwelling could theoretically be boosted via artificial cooling of surface waters or increasing salinity by thickening seasonal sea ice. Artificial downwelling has not been pursued beyond a theoretical framework as it has been determined to be energetically too expensive. However, artificial downwelling using tubes (opposite to Artificial Upwelling) has also been proposed as a way to enhance sinking of organic carbon produced by phytoplankton blooms, which could be a cheaper approach. In this case, Artificial Downwelling would boost the ocean's biological pump, rather than the abiotic pump.

Best guess drawdown potential

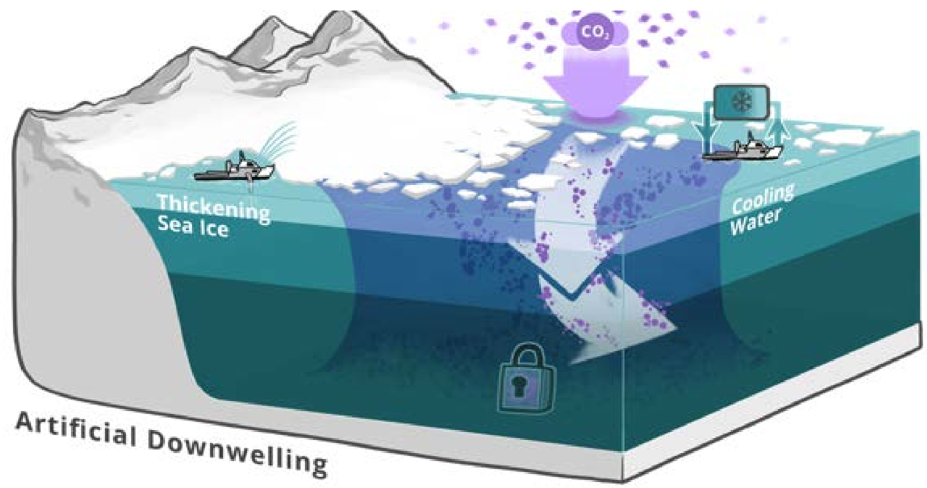
- Low

Environmental impacts

- Unknown, but likely include changes in ecosystem primary production and phytoplankton community structure

Cost considerations

- High: >$125 per ton CO_2 removed



Source: www.OceanCDR.net; EFI 2020. https://energyfuturesinitiative.org/efi-reports

Deep Storage: Ocean interior and geological formations provide ample space for long-term storage of concentrated CO_2

Stationary emission sources represent approximately a quarter of global CO_2 emissions, and carbon capture and storage (ccs) at stationary sources are crucial in achieving a 1.5-degree-pathway. Saline aquifers and depleted gas fields are among the most promising geological storage sites and could safely store trillions of tons of CO_2. Sub-seabed geological formations are, in some cases, preferable to terrestrial storage sites given their remoteness. Only 1 million tons CO_2 are stored in sub-seabed formations (Norway), with ambitions to scale to 10-20 million tons in the next 1-2 decades (Norway and Netherlands).

At sufficient depth, CO_2 could also be stored in the water column or on the sea bed. Similarly, bulk biomass from agricultural production or seaweed farming could be sunk to deep oceans where the organic carbon remains isolated from the atmosphere for hundreds of years to thousands of years.

Best guess drawdown potential

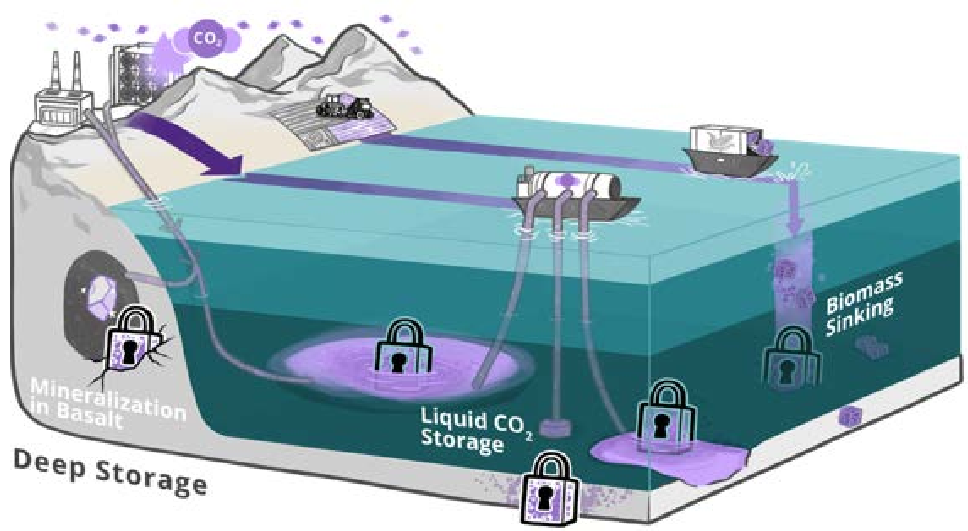
- Theoretically unlimited
- Technical potential is limited by collection and concentration of liquid CO_2

Environmental impacts

- Highly dependent on storage form (solid or liquid) and location (water or sub-seabed)
- Local acidification of seawater with liquid CO_2

Cost considerations

- Moderate: \$25-\$125 per ton CO_2 stored
- Offshore transport and storage is expected to be more expensive than onshore alternatives



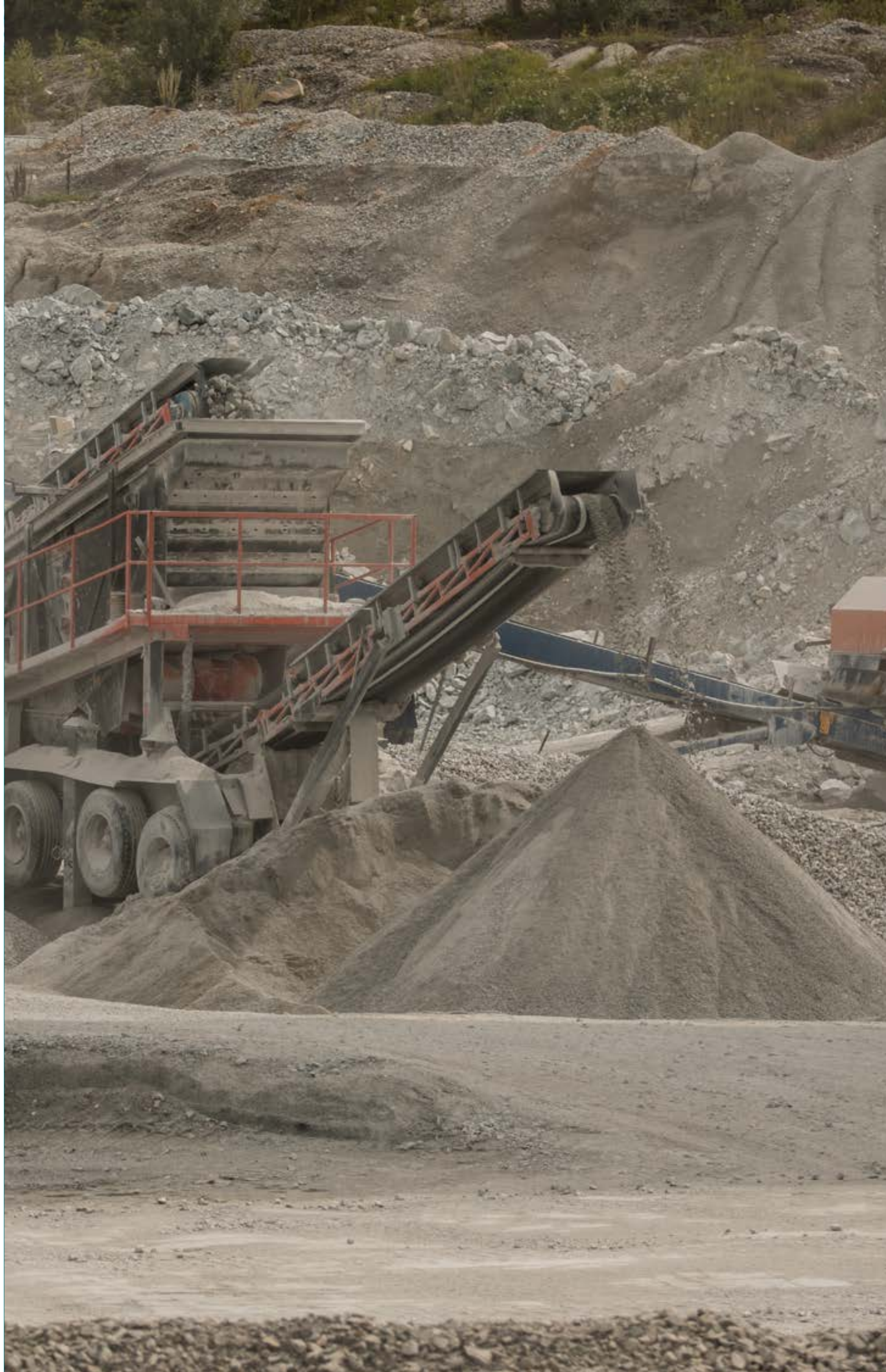
Source: www.OceanCDR.net

Case Study: Ocean Alkalinity Enhancement

Ocean alkalinity enhancement (OAE) stands out as a promising ocean-based CDR approach for several reasons:

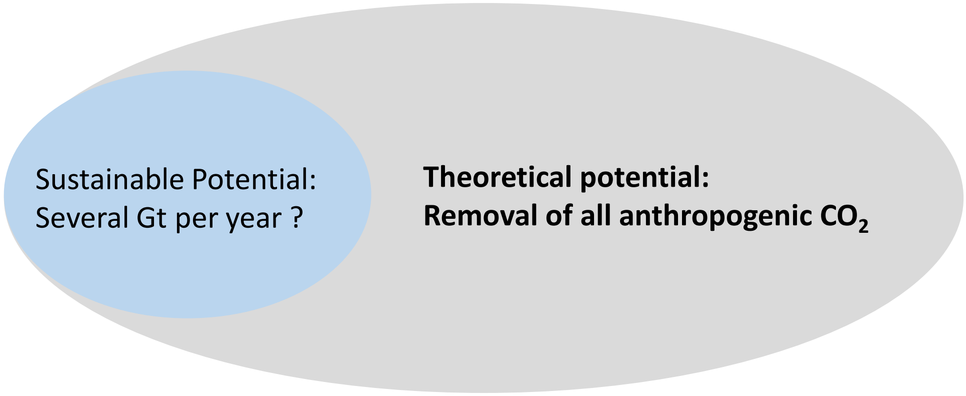
- High potential for large-scale CO_2 drawdown
- Carbon storage is stable on the order of 10,000s of years
- OAE boosts the carbon pump that naturally will remove CO2 over the period of millennia
- There are many methods to achieve OAE, ranging from natural weathering of rock to electrochemical production of alkalinity

Significant challenges include: cost and energy intensive, development of methods and implementation techniques, assessment of environmental benefits and risks.



Theoretical drawdown potential and constraining factors

Due to the near limitless quantities of alkaline rocks on Earth, ocean alkalinity enhancement via rock weathering has the theoretical potential to capture a dozen gigatons of carbon dioxide annually. This estimate, however, is only theoretical and based on modeling. Real-world limitations such as shipping capacity to distribute materials, mining operations, and optimal ocean areas for alkalinity addition are all influential factors. Nonetheless, annual removal of several gigatons CO_2 per year is considered feasible. Drawdown potential must also be evaluated by the CO_2 footprint of the overall process and supply chain (e.g., production or mining and distribution of material).



Constraining factors:

- Shipping capacity / other technological limitations
- Mineral dissolution kinetics & aragonite saturation
- Public acceptance, Policy, & Governance
- Who will pay for it? How is accounting done?
- Biological impacts

Source: D. Keller

How do we get the alkalinity into the ocean?

Mineral Sources. Naturally, rivers and groundwater deliver alkalinity from weathered rock on land to the ocean. To boost this slow geologic process, alkaline minerals can be ground to fine particles and distributed directly into the ocean on beaches or via ships, thereby bypassing the need for land-based weathering and freshwater transport. In the ocean, the minerals dissolve due to physical and chemical degradation by seawater, which produces alkalinity and increases the CO_2 absorption capacity of the seawater.

Natural and manufactured (quicklime) sources of alkaline minerals.

Source: CEA Consulting

Electrochemistry. Alkalinity can also be generated via electrochemical treatment of either fresh or salt water. Here, electricity is used to split and rearrange water and salt molecules to create acidic and basic effluent streams. Removing the acidic solution and returning the basic solution to the ocean would increase seawater alkalinity. Dilution and slow addition of the basic solution to the ocean is necessary in order to ensure that seawater pH remains safe for marine organisms. Proper disposal or use of the acid will be necessary and several options are being explored.

Laboratory electrochemical system using seawater.

Source: Matt Eisaman

What do we and don't we know about environmental impacts?

Alkalinity enhancement could locally mitigate ocean acidification impacts as the addition of alkalinity increases seawater pH. This could, for example, directly benefit aquaculture farms that have suffered economic losses due to corrosive seawater conditions over the last few years.

Large swings in pH could be harmful for marine organisms. Two decades of ocean acidification research has quantified marine species' sensitivity to changes in seawater pH. Large and rapid changes in pH due to the addition of alkalinity could thus pose an environmental risk. Methods than maintain pH within the bounds of natural pH variability are likely to have lower environmental risks.

Different sources of alkalinity will likely pose different environmental risks. For example , dissolution of silicate rock introduces trace metals at levels that could be harmful to phytoplankton species. Dissolution of calcium carbon rock could benefit phytoplankton that build $CaCO_3$ shells, such as coccolithophores, while silicate rock could benefit phytoplankton that build silicate shells, such as diatoms. Both organisms are prevalent in the ocean but large changes in phytoplankton community structure could have knock-on biogeochemical and ecological implications.

Environmental impact assessments must scale safely and incrementally from laboratory, to mesocosm, to small-scale field trials.

Source: https://www.ceaconsulting.com/wp-content/uploads/Ocean-Alkalinity-Enhancement-CEA-proceedings-doc..pdf; OceanVisions Workshop proceedings unpubl.

How cost-effective is OAE to permanently draw down CO_2 ?

Technoeconomic assessments of ocean alkalization proposals are currently based on idealized assumptions and derived from overall energy and carbon balances. Pilot-stage tests will need to be performed to reduce uncertainties. Nonetheless, current estimates (ranging from $10-$200 per net ton of carbon sequestered), suggest a level of competitiveness with "conventional" methods of mitigation.

An important consideration is a "threshold" imposed by the energy intensity of carbon emissions derived from fossil fuels (i.e., the inverse of the carbon intensity of fuels; italicized in Table 3). Surpassing 10 GJ t CO2 of thermal energy or 3 GJ t CO2 of electrical energy, then it may be more reasonable to decommission a coal fired power station than to run the negative emission technology

Table 3. Comparison of Electrical and Thermal Energy Requirements and Financial Costs of Ocean Alkalinity Carbon Storage Technologies[a]

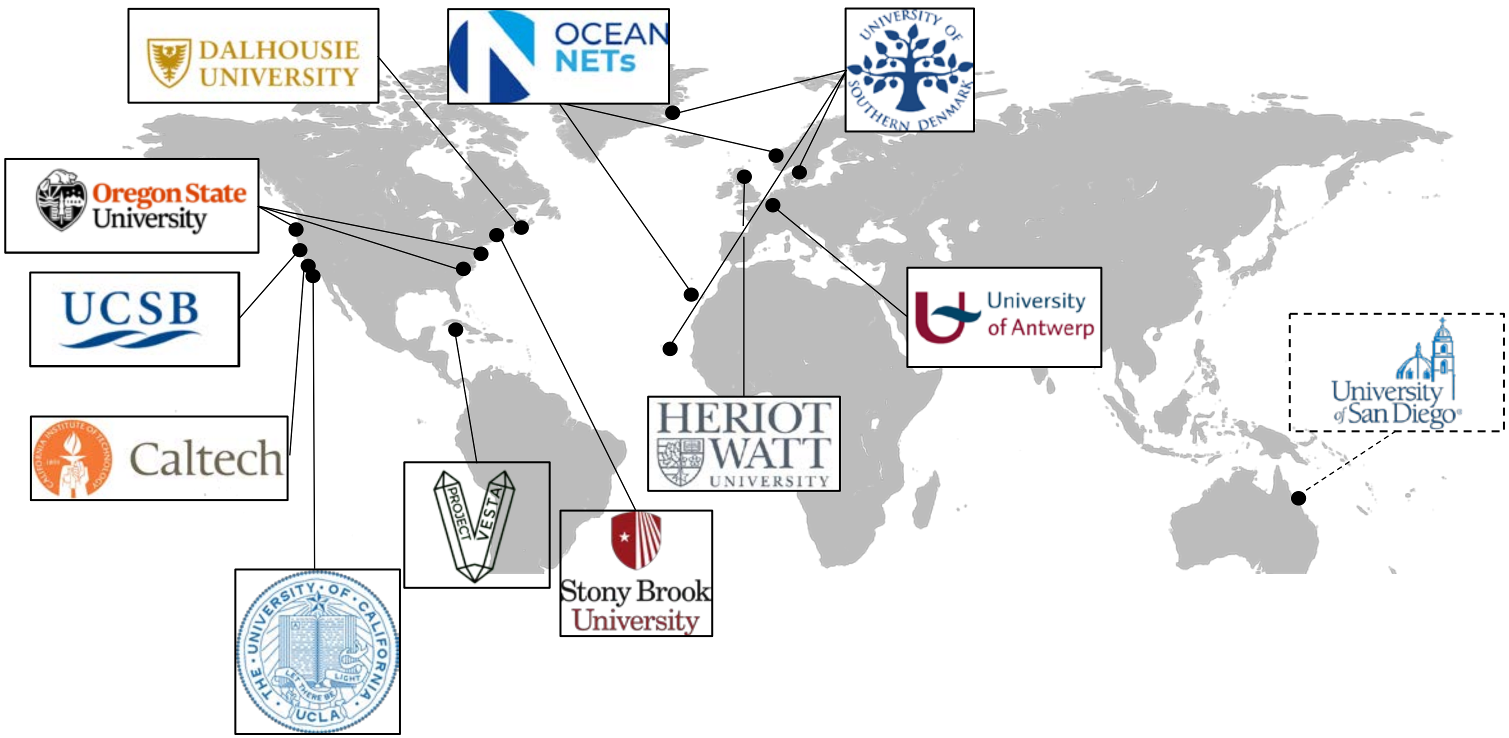
	GJ tCO_2^{-1b}		
Technology	Electricity	Thermal	US$ tCO_2^{-1b}
Ocean liming (Oxy-fuel flash calciner: limestone)	1.3	4.8	126
Ocean liming (Endex CFC: limestone)	−0.1	5.5	100
Ocean liming (Oxy-fuel flash calciner dolomite)	0.7	3.2	95
Ocean liming (Endex CFC: dolomite)	−0.1	4.2	72
Ocean liming (Solar calciner: limestone)	0.4	0.6[c]	159
Electrochemical weathering (Mg-Silicate)	5[d]		86–154
Electrochemical weathering ($CaCO_3$)	5[d]		14–190
Electrochemical weathering (NaOH production)	3–18		–
Direct carbonate addition to upwelling regions	<0.1	3.6	–
Mineral carbonation/ocean liming	2.2	5.0	
Accelerated weathering of limestone			10–40
Enhanced weathering	0.1–8.4	0.8–4.2	20–600
Direct air capture	7.5–10		100–1000
Typical cost of "conventional" CCS	6.7		30–100
Energy cost of decommissioning coal	*3*	*10*	

[a] [*Renforth et al.*, 2013; *Renforth and Kruger*, 2013 and references therein].
[b] Per net ton of carbon dioxide sequestered.
[c] Additional thermal requirements from fossil fuels.
[d] Per ton of CO_2 extracted rather than net sequestration.

Source: Renforth P. and G. Henderson (2017). Assessing ocean alkalinity for carbon sequestration. Reviews of Geophysics 55 (3)

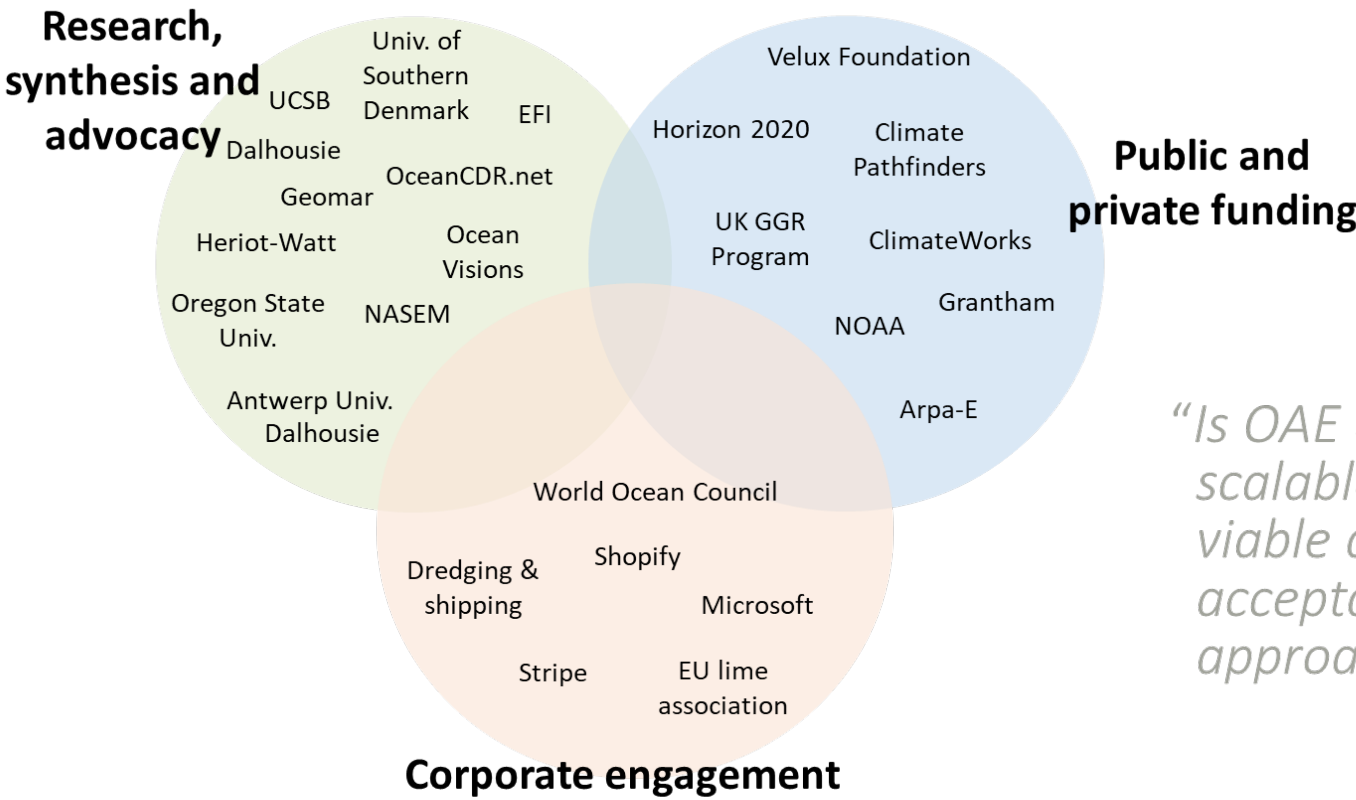
Research projects in the US and the EU are starting to emerge

More than a dozen projects have emerged in the past two years that are now conducting lab, mesocosm and field testing to address some of the biggest open questions in the field of ocean alkalinity enhancement. This includes the efficacy of OAE, the environmental impact of various alkalinity agents, as well as technoeconomic analyses. Research projects remain small (<1M$ for most projects) and limited in scope. However, the totality of ongoing research projects will provide a road map for the net 10 years of medium-to large scale research necessary to test the viability and unintended consequences of ocean alkalinity enhancement.



Source:

Interest of OAE is spilling over to a larger network of players



"Is OAE a safe, effective, scalable, economically viable and socially acceptable CDR approach?"

Source:

What are the most urgent philanthropic investments?

Continued assessments of environmental impacts through lab and mesocosm tests and small field trials

Pilot-scale proof of concept of key approaches to move hopeful concepts to robust proposals.

Reflecting the need of responsible research and pilot tests in governance systems

Engagement of NGOs and broader public to drive social acceptance of responsible research

Technoeconomic analyses (in collaboration with industry) to ID opportunities for cost reduction

Section 6

Case Study: Macroalgal Cultivation

Macroalgae are fast-growing, CO_2 consuming, marine plants that have many uses and benefits for society. Exploring CDR based on large-scale macroalgal cultivation has several advantages:

- There is deep knowledge on seaweed biology, cultivation practices are already implemented globally, and the industry is growing
- Scaling of cultivation practices to offshore areas is considered feasible
- Cultivation does not compete with land-based methods and does not require freshwater or synthetic fertilizers
- Large-scale cultivation of seaweed for food is still likely to contribute to CDR
- There is a high potential for societal acceptance as it is a 'nature-based' approach and follows on the heels of the blue carbon movement.

What are current and proposed farming technologies?

Cultivation of seaweed is implemented around the world but is often restricted to coastal zones that are protected from storms and waves. These requirements limit the scaling of such methods for cultivation needed to achieve multi-gigaton CO_2 removal. As such, a diverse portfolio of new culture techniques are being explored that will scale farms from a few hectares to 1000s of hectares in the offshore environment. These include:

- Fixed cultivation: lined array anchored to the seafloor
- Fixed or autonomously towed arrays that lift seaweed to the surface for photosynthesis during the day, and sink at night to access nutrients
- Autonomous free floating systems that releases seaweed for subsequent collection or to sink seaweed to deep ocean for permanent sequestration.
- Management and harvest of natural free-floating *Sargassum*

Small scale farming in the Philippines
https://geographical.co.uk/nature/oceans/item/1960-seaweed-success-sustainability-in-aquaculture

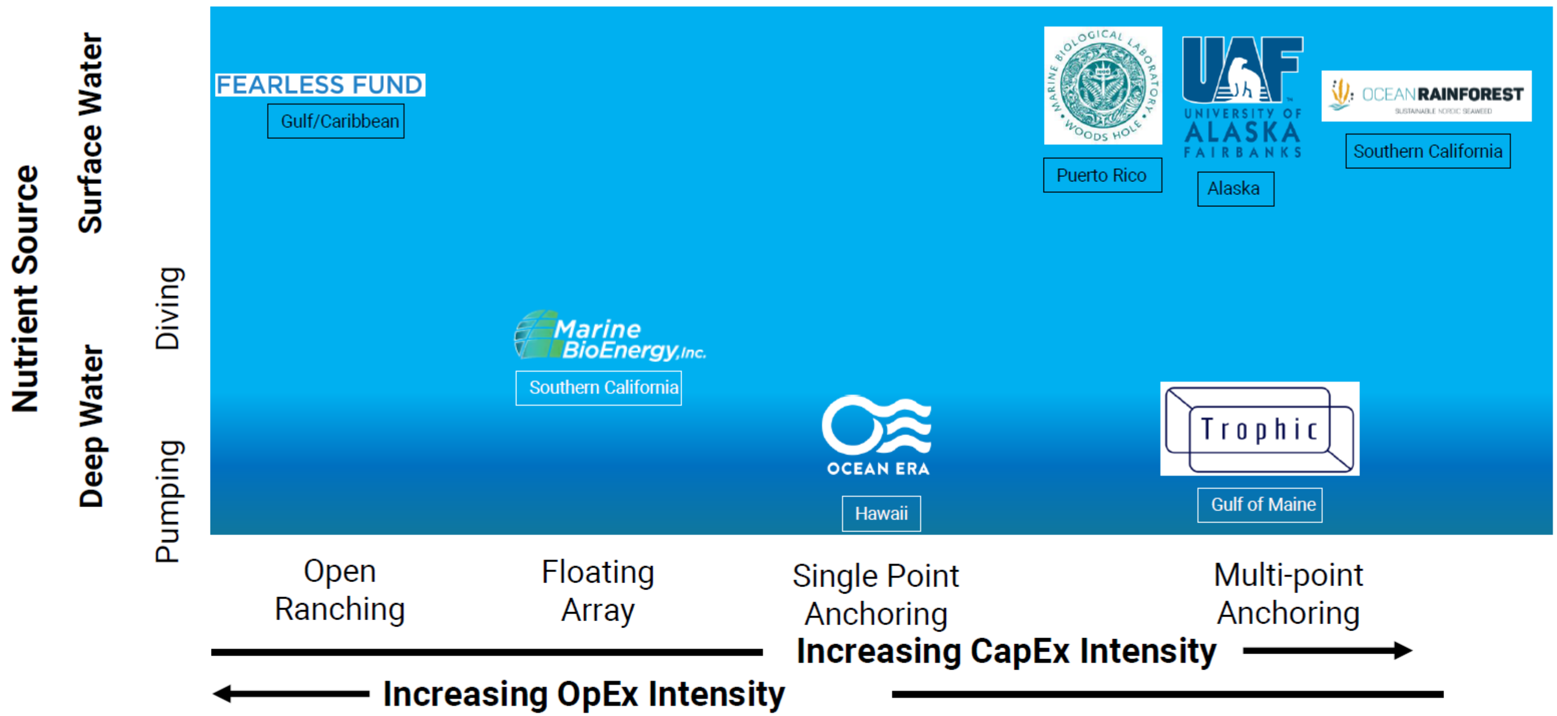
Industrial scale farming in China
https://phys.org/news/2016-09-experts-booming-seaweed-industry.html

Harvest of free floating Sargassum
The Ocean Cleaner, https://www.youtube.com/watch?v=PEdjKlGiHy8

Source: APRA-e MARINER Programs, https://arpa-e.energy.gov/technologies/programs/mariner

Diverse cultivation approaches to anchoring and nutrients are being explored by MARINER to scale production

The projects that comprise ARPA-E's MARINER (**Macroalgae Research Inspiring Novel Energy Resources**) program seek to develop the tools to enable the United States to become a global leader in the production of marine biomass. ARPA-E estimates the United States has suitable conditions and geography to produce at least 500 million dry metric tons of macroalgae per year. Such production volumes could yield about 2.7 quadrillion BTUs (quads) of energy in the form of liquid fuel, roughly 10% of the nation's annual transportation energy demand.



Projects listed are part of ARPA-E MARINER program

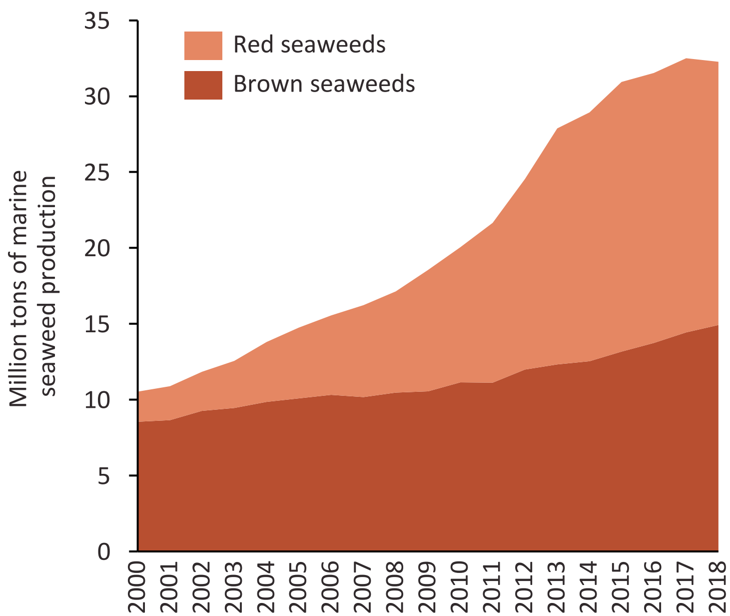
arpa·e CHANGING WHAT'S POSSIBLE

Source: Courtesy of ARPA-E's Mariner program

How useful is current seaweed production for carbon mitigation or removal?

CO_2 is fixated in seaweed biomass during photosynthesis. **Pre-harvest sequestration**: A portion of this carbon-rich biomass falls off the main stem and sinks to the ocean bed or is transported to deeper ocean areas. Some of this material is permanently sequestered in deep ocean areas or sediments (estimated 11% of production).

Post-harvest mitigation/removal: Once harvested, seaweed biomass can be used in different forms. Net atmospheric CO_2 removal only occurs if long-term cradle-to-grave emissions are negative. Mitigation occurs if the use of seaweed allows to decrease emissions that would have occurred in the absence of seaweed production/consumption



- Seaweed production has tripled since 2010, now exceeding 30 million tons per year
- 99.5 percent of seaweed is produced in Asia, largely in very small-scale production close to the coast
- 95 percent of seaweed production is used for Carrageenan, most of the remainder is either consumed by humans or animals
- Both carrageenan and human/animal consumption lead to re-release of CO2 fixated in seaweed leaves.
- As such, post- harvest seaweed production currently does not contribute to CDR
- Pre-harvest CDR likely occurs and Oceans2050 is currently leads a global team to increase robustness of initial estimates

Source: FAOSTAT.ORG; Oceans2050.org

Potential product pathways and their CDR argument

Product	Use of seaweed	CO_2 fate
BECCS	One example: anaerobig digestion releases Methane, which is used to produce energy	Captured during both digestion and combustion, then stored in geologic formations
Biofuels	Biogas, bioethanol, biodiesel and syn-gas bio-oil biochar derived from high carbon content/ low lignin biomass	Replaces fossil fuels. Depending on use, the released CO_2 can be captured and stored.
Cattle feed	Supplementing cattle feed with selected seaweed species such as asparagopsis	CO_2 is eventually released back into atmosphere but methane emissions of ruminants is decreased due to its effect on the digestive system.
Meat supplements	Similar to soy, use seaweed as supplement for CO_2-intense meat	CO_2 is released back into atmosphere but CO2 production of meat supply chain is decreased
Sinking of seaweed	Harvest the seaweed and sink it to the deep ocean floor	CO_2 fixated in plant material is isolated from atmosphere for several thousands of years.

What is the theoretical drawdown potential and what are limiting factors?

The CO_2 drawdown potential of macroalgae is considered moderate to high (1 to >5 Gt CO2 per year) as CO2 removal is primarily driven by biological characteristics of the seaweed (growth rate, carbon content, etc.) and environmental conditions (nutrient availability, seawater temperature, and sunlight).

The theoretical scale of biomass production is immense. However, the realized scale is constrained by current limitations on large-scale, offshore infrastructure, competition for space with other ocean industries and stakeholders (shipping, MPAs, tribal rights), practical constraints with cultivation in remote areas (e.g., far offshore), and the need to develop uses for harvested biomass that ensures a net-negative CO2 footprint.

Model framework indicating the variables that control seaweed's drawdown potential (UCI, Davis et al. (unpublished))

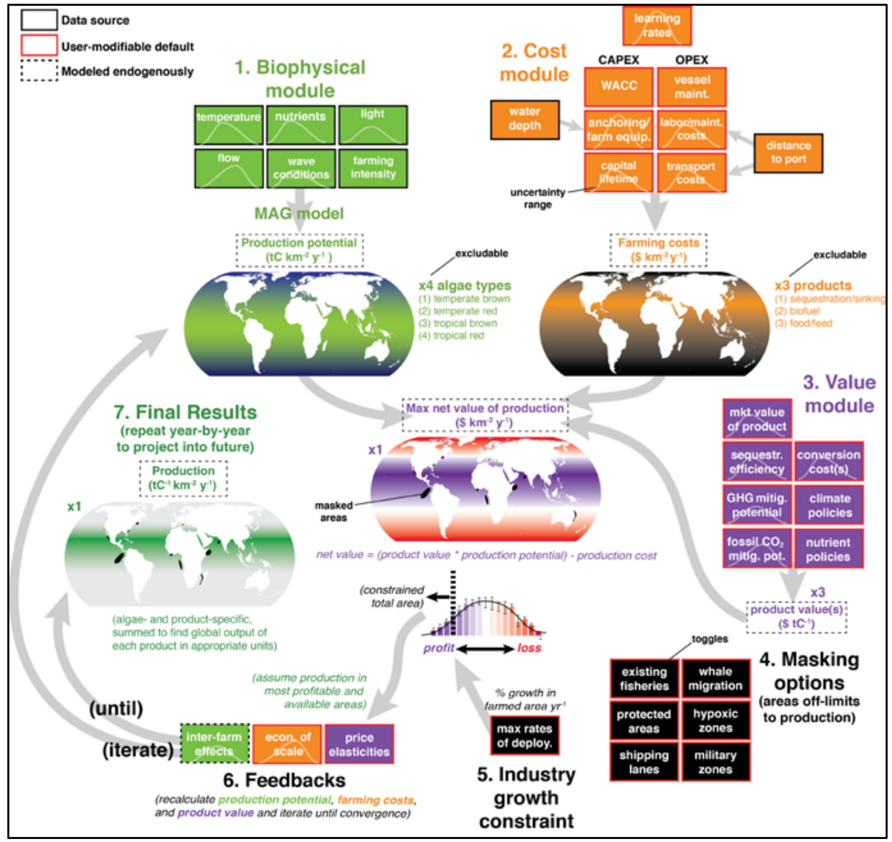
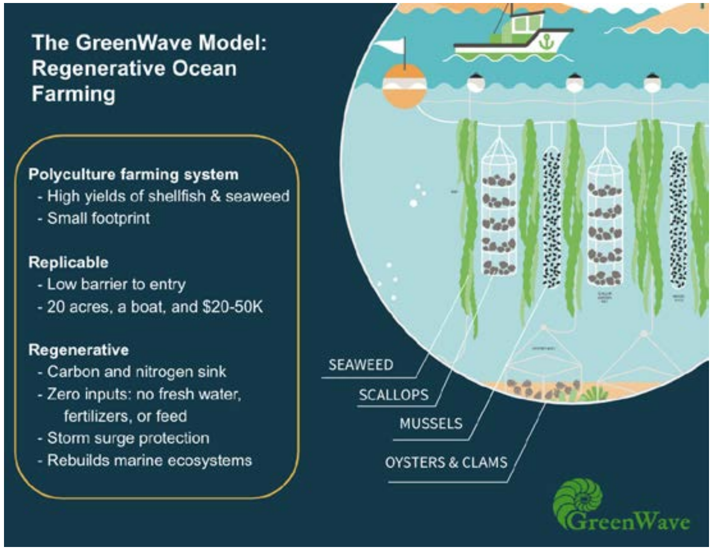


Figure: Courtesy of Prof. Steve Davis at the University of California, Irvine | Dept. of Earth System Science

What do we and don’t we know about environmental impacts?

Assessing environmental impacts of multi-1000 hectare macroalgal cultivation still requires research and field experiments. Modeling efforts can aid in understanding physical (e.g., wave attenuation), nutrient, and biogeochemical impacts while field trials will be necessary to better understand biodiversity impacts of adding new 3-dimensional habitat to the ocean ocean environment. Field trials of polyculture, such as growing oysters alongside kelp are underway.

Example model of seaweed polyculture



Source: https://www.greenwave.org/our-model

Potential environmental impacts of large-scale seaweed

Co-benefits	Risks and Hazards
Local mitigation of ocean acidification, hypoxia, and coastal eutrophication (for cultivation in coastal waters)	Biosecurity risks: genetic mixing with local species, spread of diseases and parasites, and creation of stepping stones for invasive marine species.
Coastal protection by wave attenuation (for cultivation in coastal waters)	Entanglement of marine life and contributions to marine debris
Enhanced seafood production of species co-located with seaweed farms (e.g., polyculture)	Nutrient competition with the local ecosystem
Increase in local biodiversity due to the creation of new habitat	Entanglement of marine life and contributions to marine debris

How is the seaweed landscape evolving?

While seaweed farming has a long tradition, particularly in Asia and South East Asia, its potential usefulness to mitigate emissions and/or draw down atmospheric CO2 has only emerged as a prominent idea around 2010. Notwithstanding, the „seaweed landscape“ is quickly evolving, including public, private and NGO attention. A strong focus remains on the beneficial use of seaweed biomass for biofuels and bioenergy with carbon capture and storage, although increasing attention is given to the possibility of sinking biomass to the deep sea for long-term sequestration.

Public and Private funding & technical support

Gvt

Multilateral

Private

Knowledge generation and exchange

Research

NGOs

Accelarators

Supply Chain

Investors

Startups

Corporations

- Exemplary organizations, not comprehensive

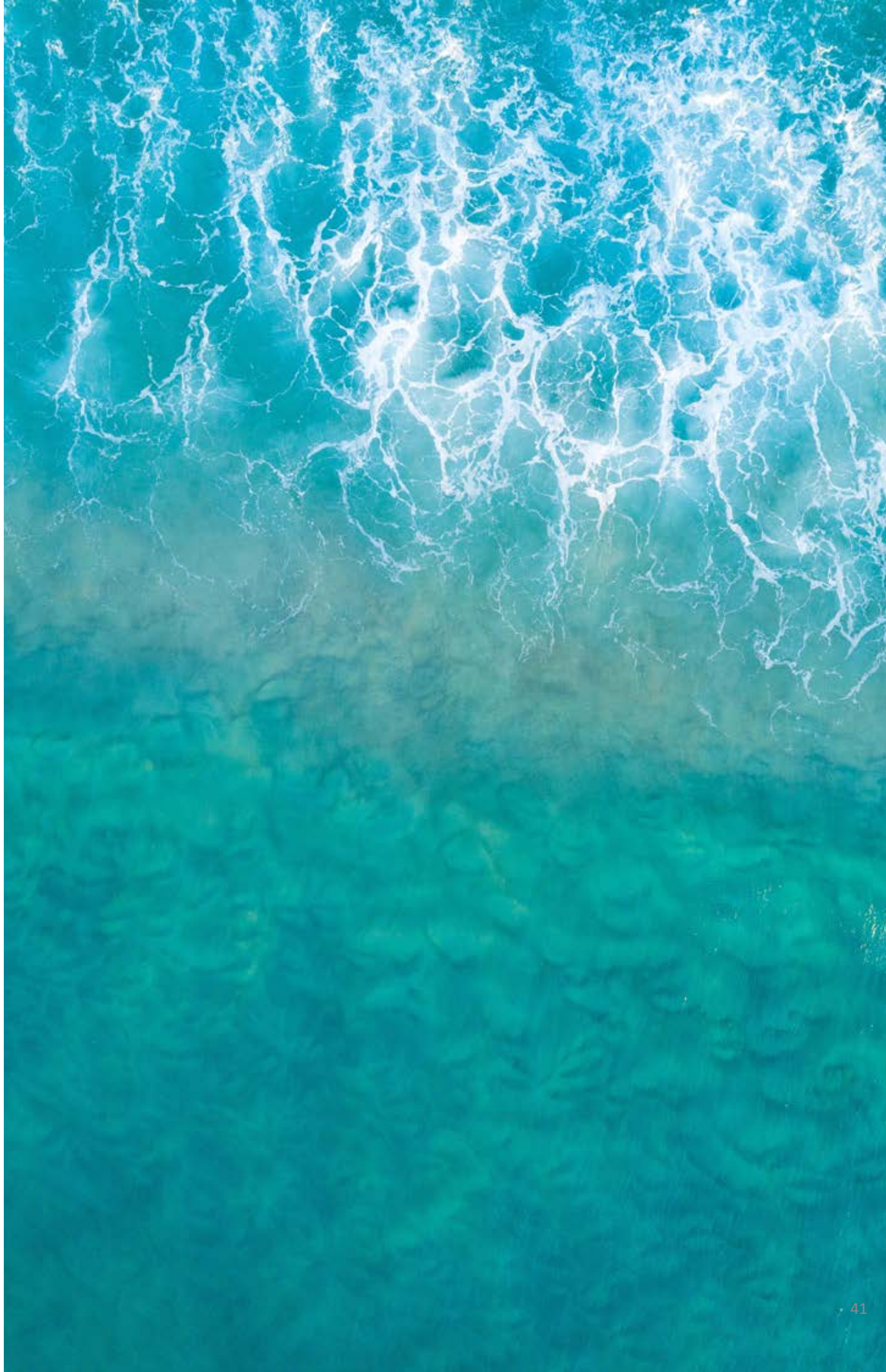
What are the most urgent philanthropic investments?

- **Lifecycle assessments**
  - Fund the development of standardized LCAs that transparently show the cradle-to-grave CO2 footprint of different product pathways dependent on production method and geography.
- **Environmental impacts**
  - Fund monitoring and evaluation studies to study the impact of seaweed farms on local ecosystems (seagrass, corals) and its effect on nutrient depletion.
  - Fund well designed field studies to monitor fate of sinking seaweed and potential ecosystem consequences in deep sea. How permanent is deep storage?
  - Fund large-scale studies to further explore mitigation potential of asparagopsis and other species for cattle feed (-> methane mitigation)
- **BECCS and biofuels pathways**
  - Fund macroalgae-based biorefinery development to demonstrate sustainable value creation from marine biomass while sequestering carbon
- **New cultivation techniques**
  - Fund field trials to study benefits of polyculture by partnering with existing farms
  - Fund biophysical modeling studies to improve understanding of environmentally-sustainable production ceilings
  - Fund tech advances to access deeper water nutrients, minimize environmental impact and
- **Field building**
  - Support pre-competitive industry collaborations to allow for industry-driven development of transparency and sustainability standards
  - Support environmental NGOs with “blue carbon” experience to productively link into the conversation, including science and policy.

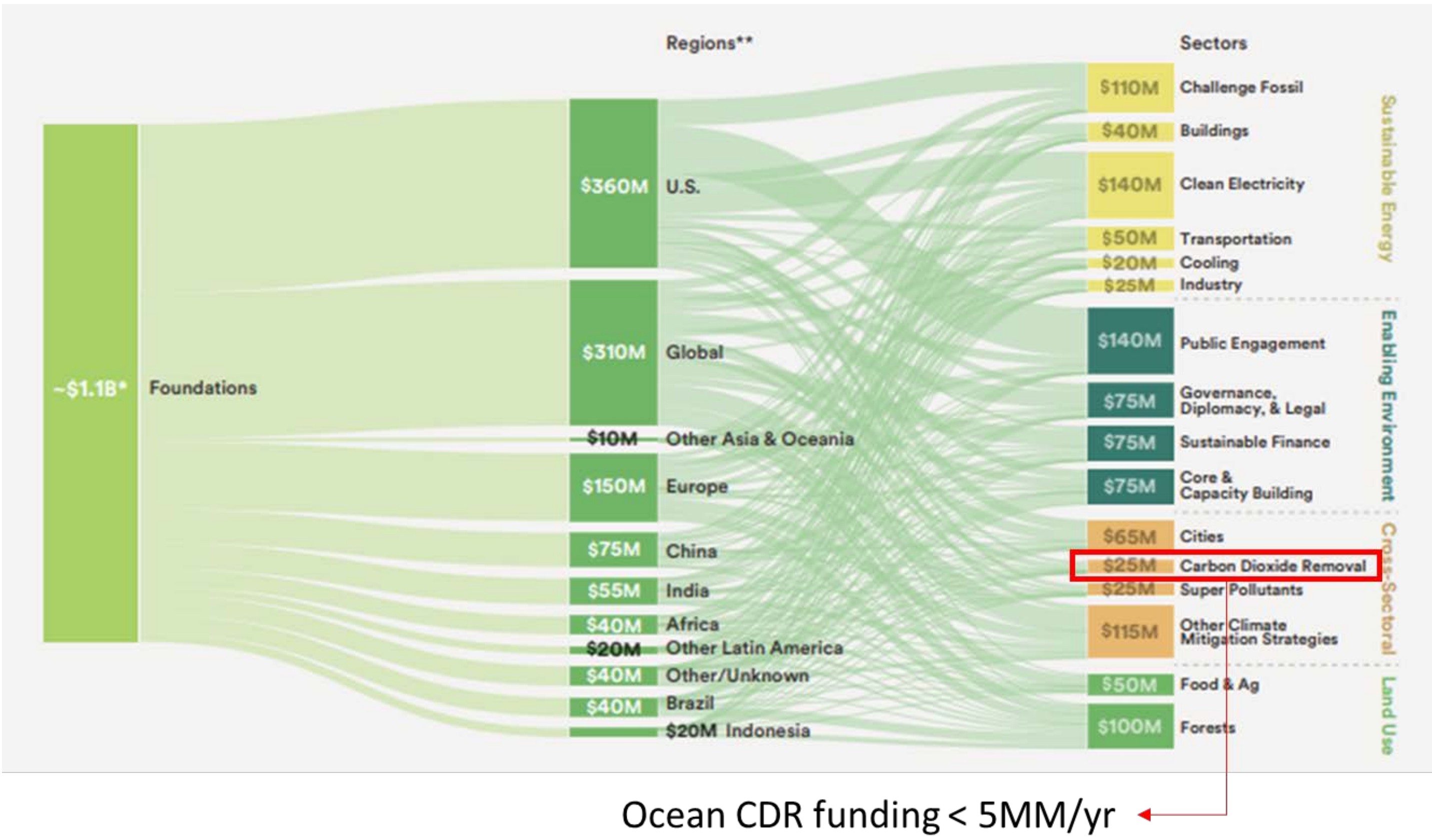
Section 7

Cross-cutting

The following slides touch on recent developments in the growing field of ocean CDR and discusses risks of (philanthropic) action vs. inaction.



Philanthropic funding: Foundations have been very slow in warming up to CDR and even slower in embracing ocean CDR



Source: https://www.climateworks.org/report/funding-trends-climate-change-mitigation-philanthropy/

Philanthropic Funding: Priority areas of funding

Philanthropy can support the stepping stones necessary to achieve multi-billion dollar public funding that will be necessary to achieve CDR at a global and climate-relevant scale.

Research & pilots: Fund demonstration projects, make it effective, cheap, and safe, support development of monitoring methods

Field building: Increase knowledge exchange, build networks with other ocean stakeholders and industries, continue to support exploratino of new ocean CDR approaches (EFI report)

Governance: Permitting structures for research and pilots

Policy: unlock public funding for large-scale research and development

Communications: Build awareness and create social acceptance for responsible research

Corporate partnerships: pre-competitive partnerships at supply and demand end

Risks of action vs. inaction: Rationale for philanthropic engagement

Ocean funders have traditionally deferred to the climate and energy funding communities to address and avert the worst effects of climate change. However, there is compelling rationale to believe that ocean funders should increase their efforts to directly address climate change and its impacts to the oceans, rather than count on other actions to arrive in time. These reasons include:

- Climate change has already altered the physical and biogeochemical state of the ocean and will continue to do so for centuries to come unless we effectively reduce atmospheric CO_2 and other greenhouse gas concentrations.
- To avert the worst consequences of climate change, every sector in the global economy must aggressively decrease current emissions. In addition, society needs to remove and sequester 100–1000 billion tons of carbon dioxide (CO2) from the atmosphere by 2100, just to keep warming to 1.5 degrees Celsius.
- The ocean conservation community is an important stakeholder in many important mitigation and sequestration “wedges.” These includes the conservation of carbon-rich coastal ecosystems, direct engagement with ocean-related industries (e.g., shipping), and exploration of ocean-based carbon dioxide removal opportunities.
- The marine community has increasing desire to engage in the broader climate dialogue to ensure that the ocean is not inadvertently sacrificed in our search for solutions (e.g., Solar Radiation Management).

Risks of action vs. inaction: Unintended consequences and philanthropy's role in supporting the maturation process of promising approaches

Environmental concerns Ocean-based CDR covers a range of approaches, from the conservation of mangrove forests to seaweed farming to alkalinity addition and iron fertilization. The large-scale interventions required to draw down gigatons of CO2 per year has environmental advocates concerned about CDR's deleterious impact on specific marine species or even irreversible ecosystem change.

The need for responsible research and governance systems: There is no path to meeting our climate goals through mitigation pathways alone, and recent IPCC modeling strongly suggests that only a combination of aggressive mitigation efforts and ambitious CDR can help us stay within relatively safe bounds of CO2 concentrations. In the absence of quickly scaled responsible research and development in the field of CDR, we risk that less tested and potentially more risky geoengineering approaches are deployed (such as solar radiation management) down the line. The nascent nature of most approaches and the many open questions call for a coordinated effort to test effectiveness, evaluate potential environmental risks, and work closely with coastal communities. Philanthropy's role will be crucial in supporting the maturation process of promising approaches while building the safety rail guards that prevent irresponsible deployment.

Risks of action vs. inaction: Does CDR pose a moral hazard problem?

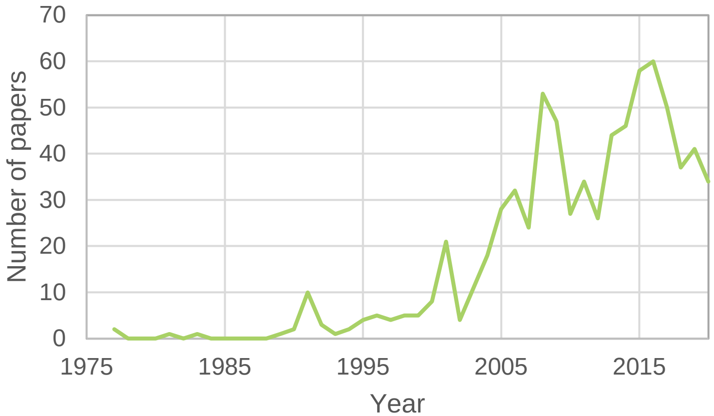
Brad Ack is an environmental innovator with nearly 30 years of creative contributions for a more sustainable and biologically diverse world. He has worked for both government and NGOs at senior levels, in concert with the private sector, designing and implementing innovative conservation and sustainability initiatives.

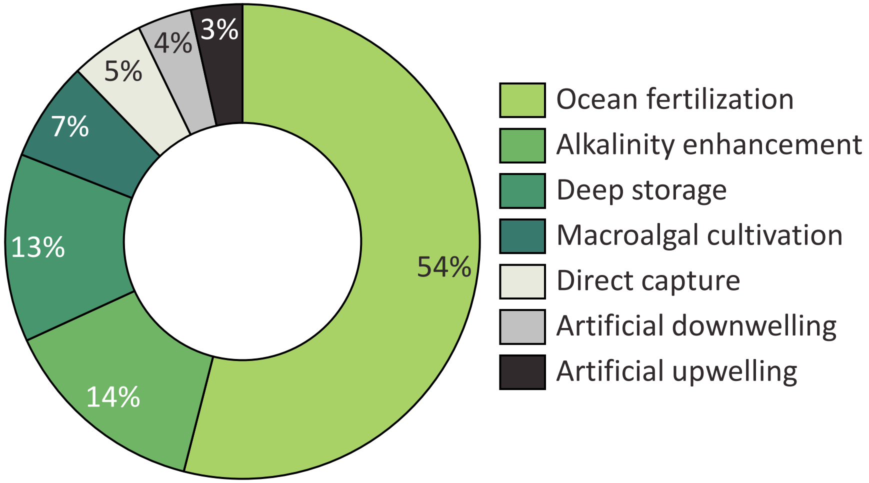
"Some people have argued that pursuing CDR creates a "moral hazard", giving license to the fossil fuel industry to continue emitting CO_2. But the approach of not actively working on negative emissions has had no perceptible effect on the fossil fuel industry so far -- fossil fuel use and emissions have continued to grow year on year. The real moral hazard at this point is to not take any and all available steps to reduce atmospheric CO2 – the true enemy here. Focusing only on new emissions is like stopping a breach in the hull of a boat but not bailing it out…"

"Enviros who do accept CDR as a critical part of the path forward tend to advocate only for nature-based solutions, such as reforestation. The fossil-fuel sector, meanwhile, is focused on direct carbon capture and storage. The ideological divide between these two camps has hindered progress on either approach, as well as others such as ocean pathways. It is urgent that we build greater consensus that CDR is critical, and embrace RD&D on all possible pathways, because we are deep into the climate crisis."

A growing field: Academic research in the field of ocean CDR is only slowly emerging, with particular focus on x and y

Number of academic articles focused on ocean CDR





Source: S. Gill et al., unpublished

A growing field: The National Academies of Science has appointed an ad-hoc committee to explore ocean-based approaches to CDR

Description:

With the goal of reducing atmospheric carbon dioxide, an ad hoc committee will conduct a study exclusively focused on carbon dioxide removal and sequestration conducted in coastal and open ocean waters to:

A. Identify the most urgent unanswered scientific and technical questions, as well as questions surrounding governance, needed to: (I.) assess the benefits, risks, and potential scale for carbon dioxide removal and sequestration approaches; and (ii.) increase the viability of responsible carbon dioxide removal and sequestration;
B. Define the essential components of a research and development program and specific steps that would be required to answer these questions;
C. Estimate the costs and potential environmental impacts of such a research and development program to the extent possible in the timeframe of the study.
D. Recommend ways to implement such a research and development program that could be used by public or private organizations.

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

The carbon dioxide removal approaches to be examined include:

- Recovery of ocean and coastal ecosystems, including large marine organism
- Iron, nitrogen or phosphorus fertilization
- Artificial upwelling and downwelling
- Electrochemical ocean CDR approaches
- Seaweed cultivation
- Ocean alkalinity enhancement

Prepublication due: September 2021

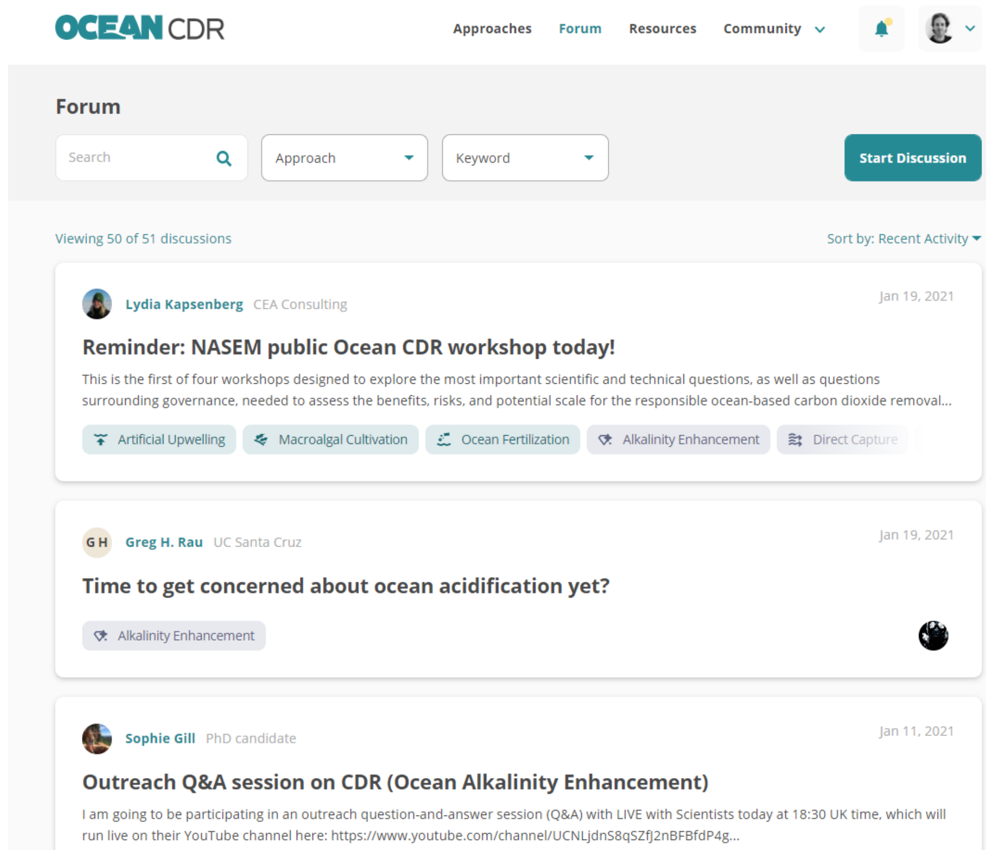
Source: https://www.nationalacademies.org/our-work/a-research-strategy-for-ocean-carbon-dioxide-removal-and-sequestration

A growing field: A growing community of experts, entrepreneurs, funders and investors are exchanging ideas on www.oceancdr.net

Description:

OceanCDR was launched in 2020 following a growing need for a multidisciplinary information exchange focused on ocean-based carbon dioxide removal (CDR) approaches. This is funded by ClimateWorks Foundation.

This knowledge hub brings together all ocean CDR stakeholders, including scientists, entrepreneurs, funders, NGOs, among others, to advance the state of knowledge, build bridges across disciplines, and help the field move towards evaluating, testing, and piloting the safest and most promising ocean CDR approaches.

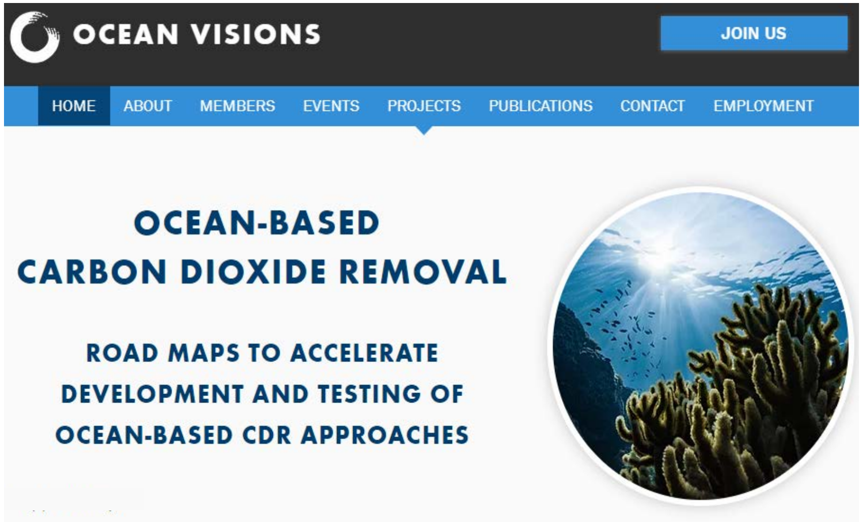


A growing field: Ocean Visions convenes experts and interested parties in development of road maps to identify the needed steps to accelerate development and testing of the most viable ocean-based CDR approaches

Description:

Ocean Visions is facilitating an open process to engage actors across diverse disciplines and sectors towards collaborative development of detailed, "living" road maps to advance promising ocean-based carbon dioxide removal (CDR) approaches.

These road maps are intended to identify critical paths forward to accelerate development and testing of various ocean-based CDR approaches. Road maps will identify the current state of technology readiness, the scale potential for CDR, key uncertainties, obstacles, opportunities, and priorities from a range of perspectives and disciplines, including natural sciences, engineering, policy, governance, economics, social equity and others. The road maps will be grounded in an evidence-based, precautionary approach towards implementation.



To date:

- 5 workshops held with 136 attendees in total coming from 16 countries (6 continents)
- 5 synthesis reports produced, one from each workshop, opened to public comment
- 3 open expert review panels convened to review synthesis documents in detail
- Version 1 of digital roadmaps planned for May 2021

https://www.oceanvisions.org/task-force-ocean-cdr