Clima Now

Deep Dive
Blue Carbon

Abstract

The global oceans serve as a habitat for millions of species and play a crucial role in human livelihood and climate change mitigation. Since the 1970s, they have **absorbed over 90% of anthropogenic excess heat in the climate system**, placing oceanic mechanisms like solubility and the biological pump under great stress.

Due to the vast size and density of seawater (1’000 times more than air), oceans offer significant potential for carbon dioxide storage (15 gigatons per year) as well as removal (CDR). Scientific attention has increased in the last 15 years, leading to more research institutions, public entities, NGOs, and startups entering the blue carbon space. These ocean CDRs not only address atmospheric CO2 reduction but also combat climate effects such as ocean acidification while offering benevolent effects on marine life and localized relief.

Ocean CDR can be divided into nature-based removals (NBR) and technology-based removals (TBR). NBRs such as mangrove restoration are cost-effective and ecosystem-friendly but face scalability issues (limited land/coastal mass available) and long-term restoration challenges. TBRs, on the other hand, provide durable removals but encounter higher costs and potential environmental impact risks. Within the technology-based removals, no single TBR outperforms across all criteria and can be deemed a universal solution, but ocean Alkalinity Enhancement and Electrochemical CDR (Direct Ocean Capture) show the most promising potential due to their efficacy and scalability, provided they can mitigate potential environmental risks. Nevertheless, the optimal blue carbon strategy integrates both categories, considering their varied performance across efficacy, scalability, and environmental risks. At this stage, full-scale deployment especially of TBRs is still not possible since continued research, development, and regulatory decisions are required.

On top, blue carbon projects still face manifold challenges that require ongoing attention to balance scientific, private, and public (governance) interests. These challenges include timing tension, permitting problems, scientific uncertainty, the MRV conundrum, and public perception issues. Addressing these challenges demands enhanced research funding, streamlined regulatory processes, advanced monitoring technologies, and comprehensive public engagement. With only 408m USD invested globally in marine carbon dioxide removal ventures, which is low compared to Direct Air Capture (3.3bn USD) and Reforestation/Afforestation ventures (2.6bn USD), unlocking the full market potential will also require strategic financial backing, rigorous environmental impact evaluation, and a robust governance framework. Societal acceptance through engagement and interdisciplinary dialogues is deemed crucial as well.

1. Introduction

The global ocean covers 71% of the Earth surface and contains about 97% of the Earth's water while supporting unique habitats and being interconnected with other components of the climate system through global exchange of water, energy and carbon. Ocean habitats such as seagrasses and mangroves, along with their associated food webs, can sequester carbon dioxide from the atmosphere at rates up to four times higher than terrestrial forests can and on the order of around 50x more carbon than is currently in the atmosphere[1].

While oceans and coastal regions play a vital role in our daily lives and survival, it's only recently that they have gained significant attention in climate change policy. This newfound focus on the *blue oceans* emerged with the release of the IPCC Special Report on the ocean and cryosphere in 2019, followed by the Chilean Presidency's emphasis on oceans during the COP25, famously termed *Blue COP*. This spotlight has spurred discussions on harnessing the ocean as a tool for climate mitigation.

The IPCC report highlighted alarming trends: Global oceans have been steadily warming since the 1970s, absorbing over 90% of the excess heat within the climate system[2]. This absorption has translated to approximately 20-30% of total anthropogenic CO2 emissions since the 1980s. Consequently, the ocean has experienced heightened surface acidification, leading to a decline in surface ocean pH across more than 95% of its area, surpassing natural background variability. Notably, *Eastern Boundary Upwelling Systems (EBUS)* like the Californian west coast, renowned for their productivity due to nutrient-rich upwelling, are facing severe threats from increasing ocean acidification and oxygen loss. These changes have disrupted the ecosystem's structure, negatively impacting biomass production and species composition. Furthermore, warm-water coral reefs and rocky shores inhabited by calcifying organisms such as corals, barnacles, and mussels are being severely affected by extreme temperatures and this ocean acidification. Instances of marine heatwaves have triggered widespread coral bleaching events since 1997 leading to global reef degradation, with recovery (if it happens) taking more than 15 years. Rocky shore ecosystems also face significant risks from prolonged exposure to high temperatures and dehydration of organisms.

These environmental changes not only endanger nature but also pose a serious threat to the global population. Ocean warming throughout the 20th century and beyond has led to a decline in the catch potential of fish stocks, compounding the impacts of overfishing in some regions. Declines in the abundance of fish and shellfish stocks due to the direct and indirect effects of global warming and biogeochemical changes have contributed to reduced fisheries catches. In tandem, vegetated coastal ecosystems which are vital for protecting coastlines from storms, erosion and the impacts of rising sea levels, have significantly declined. Nearly half of these ecosystems have been lost over the past century due to a combination of local human activities, rising sea levels, warming trends, and intensified extreme weather events[3]. When degraded or destroyed, their benefits are reduced and/or lost and they can become significant sources of greenhouse gas emissions. Thus, several efforts have been made to conserve and sustainably manage blue carbon ecosystems (BCEs) since it has the potential to address both climate mitigation and adaptation challenges.

Directly harnessing the ocean's immense capacity for CO2 storage represents an unparalleled opportunity in combating climate change. Unlike land-based methods, ocean carbon dioxide removal (CDR) doesn't encroach upon critical land usage. Instead, it capitalizes on the vastness of the ocean, facilitating and expediting natural sequestration processes[4]. Remarkably, these approaches not only target the reduction of atmospheric CO2 but also contribute to mitigating ocean acidification, providing localized relief to affected areas. The ocean, therefore, emerges as a crucial arena for implementing CDR strategies, offering multifaceted benefits that address the interlinked challenges of carbon reduction and environmental preservation. But at large scape and open system, it is difficult to anticipate

[1] Biodiversity - our strongest natural defense against climate change | United Nations
[2] https://www.ipcc.ch/srocc/chapter/summary-for-policymakers/
[3] https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter11.pdf
[4] https://www.climateworks.org/report/ocean-carbon-dioxide-removal-the-need-and-the-opportunity/

the ripple effects caused by adjusting the chemistry or biology of marine ecosystems for accelerated carbon sequestration purposes. Just measuring the efficacy and durability of carbon removal remains a huge challenge, considering oceans cover ~70% of the planet with constantly shifting currents.

2. Ocean Principles (mechanism)

In this chapter, we delve into the intricate mechanisms governing the ocean's pivotal role as a solubility pump and a biological pump. Exploring these mechanisms illuminates how the oceans actively sequester carbon through physical and biological processes, illustrating their significant contribution to global carbon cycling and climate regulation.

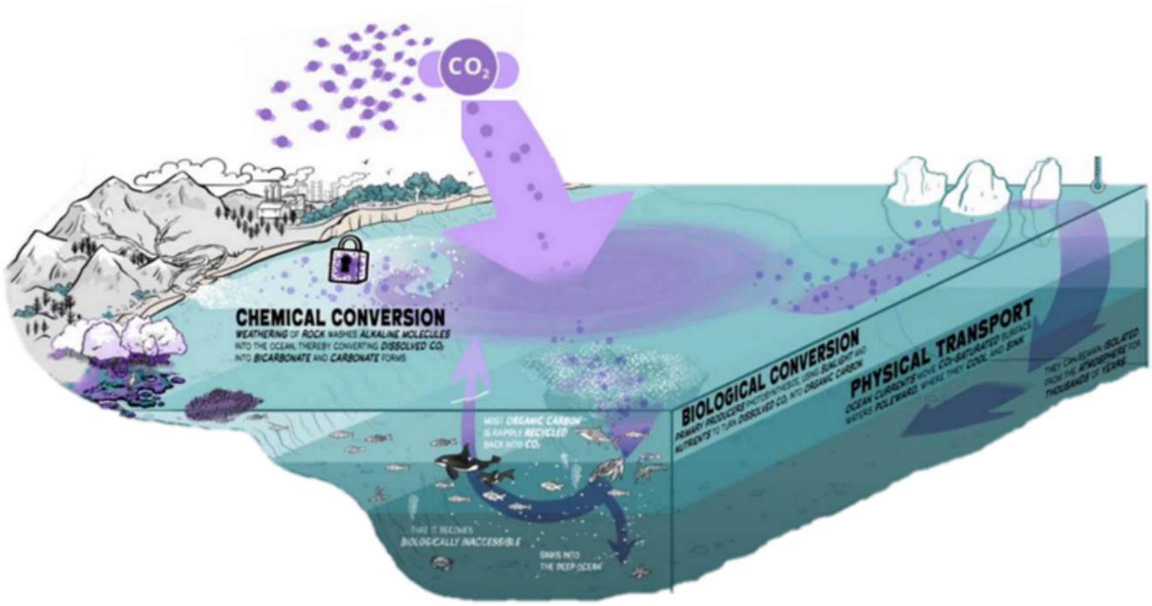

Illustration 1. Oceanic Carbon Pumps (source: www.oceancdr.net)

2.1 The Solubility Pump

Through the solubility pump, the ocean physically uptakes atmospheric CO2 and chemically converts it into dissolved inorganic carbon that is transported to the deep ocean via mixing and currents. As part of the natural pre-industrial carbon cycle, the solubility pump was in equilibrium with the atmosphere (the same amount of CO2 enters and goes out). However, anthropogenic emissions beginning in the industrial period have modified this equilibrium: For every 1 part per million (ppm) increase of atmospheric CO2, the ocean uptakes an extra 0.97 ± 0.40 Gt C (gigaton carbon) comparable to the extra induced CO2 uptake by land vegetation via photosynthesis. Without the solubility pump, atmospheric CO2 levels (which reached 414 ppm in 2020) would be 75 ppm higher. Via the solubility pump, the **ocean has thus provided a buffer for human-caused climate change absorbing 25% of all the human-induced carbon emissions over 1850-2019**[5]. Another 33% of anthropogenic carbon emissions were taken up by land vegetation, while 42% accumulated in the atmosphere. The ocean is hence taking up more carbon now than in the pre-industrial period, but this ocean sink is projected to become less effective with increasing cumulative CO2 emissions which effectively translates into greater atmospheric CO2.

The efficiency of the solubility pump varies with physical factors such as pH, temperature, and ocean circulation. As atmospheric CO2 enters the ocean, ocean pH decreases. This causes more dissolved inorganic carbon (not part of living organisms) to exist in the form of aqueous CO2 which is limiting the

[5] https://www.frontiersin.org/articles/10.3389/fmars.2022.851448

ocean's ability to absorb more atmospheric CO2 while simultaneously leading to ocean acidification. It is estimated that ocean acidification has reduced the pH of the ocean by 0.1 units since the pre-industrial period, with negative consequences for corals and calcifying organisms, as well as the wider marine ecosystem. The ocean has also taken up 91% of anthropogenic heat increasing ocean temperatures and reducing the solubility of CO2, as water's capacity to hold dissolved gasses decreases with increasing water temperatures[6]. Faster warming of the surface ocean has also enhanced water column stratification, hindering the mixing and transport of CO2 from the surface to the deep ocean and therefore limiting solubility pump efficiency. Due to these factors, the solubility pump is decreasing by a rate of 17.2 ± 5.0 Gt C per °C of increased global near surface air temperature since pre-industrial times.

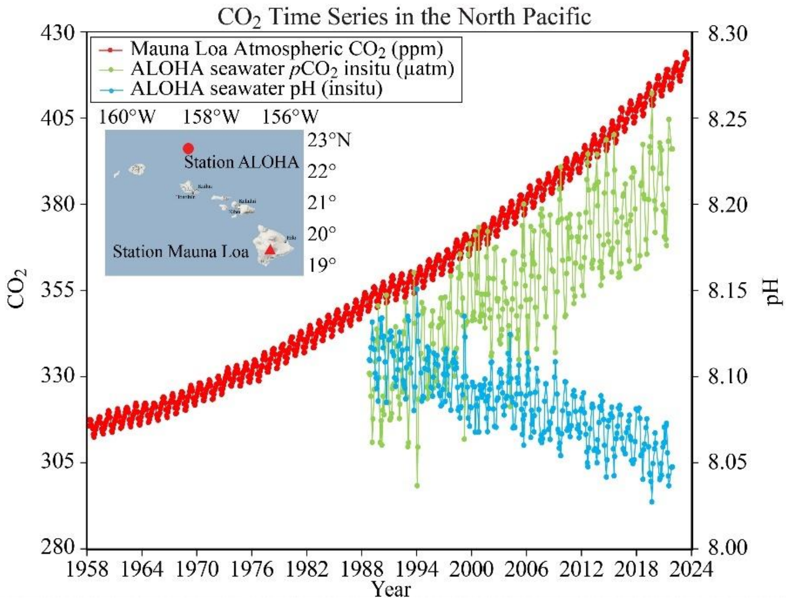

Illustration 2. Atmospheric CO2 (red), seawater CO2 (green) and PH value (blue) in the North pacific showing the acidification of oceans (source: NOAA)

2.2 The Biological Pump

The ocean also absorbs carbon through the biological pump, in which phytoplankton photosynthesis transforms CO2 into organic matter (biomass) that is then exported from surface waters to the deep ocean. Though phytoplankton (~1 Gt C standing biomass) account for less than 0.5% of the weight of all photosynthesizing plants of the world but they synthesize organic carbon at an annual rate similar to that of all terrestrial plants combined and form the base of the food chain that sustains almost all marine animals[7].

From a carbon sequestration standpoint, it is critical to understand how much of this transformed organic carbon (net primary production, NPP) is exported out of the euphotic zone (top 100m of the ocean receiving sunlight constantly mixing with the atmosphere) and into deeper ocean layers, where it can remain stored for longer timescales away from atmospheric interaction. Exported material consists of both particulate organic carbon (POC) and dissolved organic carbon (DOC). Particulate organic carbon (POC) refers to organic carbon in the form of floating particles, while dissolved organic carbon (DOC) denotes organic carbon dissolved in seawater. POC accounts for most of the biological carbon pump. The magnitude of the POC flow out of the euphotic zone has been estimated to be between 8-24% of the annual NPP rate. Globally, 13% and 5% of the POC exported out of the euphotic zone makes it to

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6 https://www.researchgate.net/publication/253941764_Convergence_of_atmospheric_and_North_Atlantic_CO2_trends_on_multidecadal_timescales

7 https://www.pnas.org/doi/full/10.1073/pnas.1711842115

1’000 m depth and 2’000 m depth respectively where it decopmposes and remineralizes through microbial respiration[8]. Therefore, a very small fraction of the organic carbon formed at the surface ultimately sinks to the sea floor, where it can be sequestered for millennia.

Dissolved organic carbon (DOC) globally accounts for about 15% of export flow out of the euphotic zone. DOC is especially important in nutrient-depleted waters of the subtropical which are projected to expand with climate change and where DOC can account for roughly half of total export[9]. The open ocean biological pump is an important part of the natural carbon cycle, but unlike the solubility pump, has not played an appreciable role in anthropogenic carbon uptake. The current strength of the biological pump is unaffected by direct changes in atmospheric CO2 concentrations because phytoplankton productivity is limited by availability of nutrients and light rather than CO2 or dissolved inorganic carbon concentrations[10]. Even so, indirect changes to ocean conditions brought on by increases in atmospheric CO2 concentrations can affect the strength of the biological pump. For example, warmer temperatures will increase both phytoplankton primary productivity and bacterial remineralization rates, but remineralization rates are predicted to increase more quickly due to remineralization’s higher sensitivity to temperature changes, resulting in a net decrease in exported POC fluxes[11]. Moreover, global warming stratifies the water column, hindering the upwelling of nutrients needed by phytoplankton at the surface. This decreases NPP and favors small, slower-sinking phytoplankton that grow better in nutrient-depleted waters, both of which result in less carbon sinking to depth. On a global scale, POC export flux out of the euphotic zone is expected to decrease under a business-as-usual scenario resulting in a relatively small reduction in ocean carbon storage by 2100 (~1 GtC yr-1 below the euphotic zone). These predicted changes in the strength of the biological pump due to climate warming-induced changes in light or nutrient availability will thus be small compared to atmospheric CO2-induced changes in the solubility pump.

The biological pump would only offer additionality for climate mitigation if it was modified in a significant way that brings it out of its existing natural equilibrium into a new equilibrium where more net carbon is sequestered on long timescales. Carbon Dioxide Removal (CDR) methods to increase the efficiency of the solubility and biological pumps (such as fertilization, see chapter 3.2.2) will be discussed in detail but also reveal large uncertainties remain around climate feedbacks and wider social and ecological implications of CDR.

Coastal ecosystems (mangroves, salt marshes, seagrass meadows): Coastal vegetated ecosystems possess the capacity to sequester substantial amounts of carbon owing to their elevated productivity. This carbon capture ability is a result of their soil conditions which decelerate the decomposition of organic matter and restrict the emission of potent greenhouse gases like methane (CH4) typically generated in freshwater wetland ecosystems. Mangroves serve as crucial carbon sinks due to their biomass productivity, comparable to that of tropical forests, and their tendency to maintain high levels of soil carbon. Salt marshes exhibit a varied biomass productivity influenced by climate and dominant species but excel in carbon accumulation within the soil. While seagrass carbon stocks and coverage are less extensively studied compared to mangroves and salt marshes, estimates indicate significant differences between seagrass productivity and overall carbon stocks, suggesting substantial export of produced biomass, potentially into shelf sediments and the deep sea[12].

Because of their capacity to store carbon in both biomass and soil, the protection, preservation, and revival of these ecosystems have been acknowledged to aid in mitigating climate change, offering numerous additional advantages for adaptation. Nevertheless, genuine reductions in emissions can solely be attained by preventing the deterioration or destruction of coastal ecosystems, given that the yearly emissions resulting from their decline are estimated to match 3–19% of the annual greenhouse

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[8] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016GB005551
[9] https://www.nature.com/articles/s41467-017-02227-3
[10] https://www.mdpi.com/2071-1050/10/3/869
[11] https://www.nature.com/articles/s41467-019-12668-7
[12] https://www.researchgate.net/publication/343486022_Blue_Carbon_Coastal_Sequestration_for_Climate_Change_Mitigation_2

gas emissions from worldwide deforestation. Furthermore, the potential for carbon sequestration differs among regions, and climate change itself is affecting these ecosystems. Climate-related risks like rising sea levels, escalating temperatures, and extreme weather events can influence productivity and alter species composition, ultimately modifying the quantity of carbon stocks within coastal ecosystems. In addition to carbon sequestration, coastal ecosystems also provide numerous adaptation services, such as buffering severe coastal storm impacts, mitigating floods, protecting against accelerated sea level rise, and supporting coastal water quality and food security. Despite their ecological and climate-regulating value, coastal ecosystems continue to disappear at a fast pace, releasing stored carbon into the atmosphere. Barriers to proper preservation, conservation, and restoration, such as habitat unsuitability and lack of community engagement, must be addressed to make carbon dioxide removal (CDR) projects more complex.

Macroalgae comprise the most extensive and productive vegetated marine habitats globally - widely distributed across coastal latitudes including kelp forests in cold, coastal waters and sargassum in tropical and temperate coastal areas. Macroalgae are identified as important carbon sinks. These highly productive yet rootless macroalgal communities generate less on-site carbon burial and export more of their carbon away from the site of origination. Kelp and other macroalgae are gaining attention due to their highly recalcitrant (difficult to decompose) organic matter, and their ability to grow quickly and capture significant amounts of atmospheric carbon in their biomass. The global average stocks of macroalgae are only recently being assessed and are estimated to account for 30% of blue carbon stocks demonstrating how significant this carbon pool can be. However, these systems are not yet adequately managed or protected by current policies as only a portion of macroalgal-carbon is sequestered and stored in ocean sediments through on-site burial[13]. It is estimated that 80-90% of macroalgal carbon production leaves the original site and is incorporated into the marine food web and eventually buried at depth putting great question marks on the MRV. Science estimates that through vertical macroalgal carbon export 69% of the macroalgae carbon at surface will sink below 1’000 m - close to permanent sequestration and storage depths, and 24% will reach deep seafloor sediments (>4’000m). Although these ecosystems do not yet fit well in current carbon accounting frameworks, as the amount of carbon carried away and buried into ocean sediments is not easily measured and monitored, their high sequestration rates at depth are promising. Understanding of macroalgal carbon cycling and their potential role in ocean carbon dynamics is growing quickly as well as interest in seaweed farming for climate mitigation.

Shelf Sediments: Offshore or shelf sediments represent a long-term carbon stock comparable to that in tropical forests[14]. However, the precise ability of these sediments to store carbon depends on the type of and there is a lack of site-specific knowledge necessary for accounting. Disturbing shelf sediments leads to sediment resuspension that results in remineralization of the component particles thereby releasing soil carbon that had accumulated over centuries to millennia. It is estimated that 1.3% of the global ocean is trawled each year resulting in 1.47 Gt of aqueous CO2 emissions which is higher than the simulated global natural carbon accumulation into sediments through export of particulate organic carbon via the biological pump. Other research[15] notes that trawling may lead to sediment erosion comparable to highly deteriorated agricultural fields on land.

Marine Organisms: Organisms such as krill, larger fish, and whales play a significant role in fertilizing phytoplankton, thereby impacting the biological carbon cycle. Additionally, their daily movements, fecal products, and deceased bodies contribute to the downward movement of carbon. Research has also delved into the ability of calcifying organisms such as coral and oyster reefs to capture and retain carbon. It's important to note that while the biological pump primarily involves the movement of carbon out of the euphotic zone, only a portion of this exported carbon stays out of the atmosphere for climate

[13] https://www.wwf.org.uk/sites/default/files/2020-11/WWF_blue_carbon020.pdf
[14] https://www.sciencedirect.com/science/article/pii/S2212041618300536
[15] https://scholar.google.ch/scholar_url?url=https://www.pnas.org/doi/full/10.1073/pnas.1405454111&hl=en&sa=X&ei=RlqeZfeDHPOsy9YPpICg4AQ&scisig=AFWwaebHPWJgGIz__KimQavdPanF&oi=scholarr

regulation, and an even smaller fraction reaches the ocean floor, where carbon can be preserved for extended periods spanning centuries to millennia.

Zooplankton feeds on surface phytoplankton before carrying carbon down the water contributing significantly to the biological pump by moving carbon through digestion, breathing, and mortality. This process moves carbon to depths exceeding 1'000m and accounts for 16-18% of the total carbon export flow. Below this depth, zooplankton's active transport escalates carbon export by at least 0.44 Gt C/yr. Understanding the global impact of zooplankton's active transport on the biological carbon pump remains a subject of ongoing research.

Krill, a crucial zooplankton shrimp species are under increasing scrutiny for their role in the biological carbon pump. Despite theoretical suggestions regarding the significant carbon export by krill, quantification remains highly uncertain. With a global population of 400 Mt, krill face threats from ocean acidification, warming waters, and changes in sea ice dynamics, potentially causing their population decline and migration towards the continent.

Fish, much like zooplankton, play a role in the biological carbon pump by engaging in vertical migration and aiding in passive transport through sinking fecal pellets. The effects of safeguarding and replenishing fish populations on this pump's function are not yet fully understood. Nevertheless, the practice of industrial fishing has notably decreased the quantity of fish carcasses reaching the ocean floor. Research indicates that ceasing industrial fishing could store an additional 1.09 MtC/yr in large fish biomass, with approximately 0.6 MtC/yr sequestered via carcass deadfall[16]. Climate change and fishing pressure are projected to decrease fish biomass by 10 to 25%, posing severe threats to biodiversity, ecosystem resilience, and coastal communities.

Whales play a crucial part in the biological pump through their contribution of iron-rich excrement that fertilizes the ocean, resulting in the rapid sinking of organic carbon particles. Moreover, when whale carcasses sink to the ocean floor, they also contribute to carbon burial (whale fall). Reinstating whale populations to their pre-whaling levels has the potential to sequester an estimated 0.16 - 6.7 MtC annually. However, challenges such as climate impacts, shipping activities, and pollution pose threats to their populations. Despite their importance, whales' impact on carbon sequestration is currently considered limited.

Calcifying organisms, such as oysters and coral reefs also contribute to carbon sequestration. Oysters, by filtering and excreting organic carbon, have the potential to offset their carbon emissions resulting from respiration and shell formation. Covering approximately 52.7 million hectares globally, coral reefs might contain about 31 Mt carbon[17]. However, they are perceived as a minor net source of CO_2, mainly because calcification surpasses dissolution. Comparable calcification processes are observed in other coastal ecosystems like seagrasses. Accurate assessments of carbon in these systems necessitate evaluations specific to each site to determine the balance between the production and sequestration of organic and inorganic carbon. Although their direct impact on climate mitigation might be modest, both oysters and coral reefs offer various ecosystem services and warrant protection.

[16] https://www.science.org/doi/10.1126/sciadv.abb4848
[17] https://www.frontiersin.org/articles/10.3389/fmars.2022.851448/full

3. Blue Carbon or Oceanic CDR

The term *blue carbon* was coined in 2009 to refer to the organic carbon sequestered and stored by coastal vegetation including mangrove forests, seagrass meadows and salt marshes. Collectively, they are referred to the already mentioned blue carbon ecosystems (BCEs) and have been recognized globally for their vital role in climate change mitigation while delivering other essential ecosystem services such as food and livelihood provision of local populations, coastal protection and source of recreation. The IPCC has made it clear that blue carbon CO2 removal (CDR) is a critical tool for achieving net zero by 2050, because it could enable businesses to neutralize residual carbon emissions once all emission reductions efforts have been exhausted. Thus, by 2050, CDR competency could be a core part of management responsibilities across all sectors. Closing the removals gap to achieve net zero would require a range of CDR solutions comprising both nature-based removals (NBR) and technology-based removals (TBR) which are discussed in detail below.

3.1 Nature-based carbon removals (NBR)

NBRs remove carbon by restoring, enhancing, or actively managing ecosystems such as wetlands. Because they tend to cost less per metric ton of CO2 removed than emergent TBR, NBR could offer a more cost-effective path to increasing near-term CDR capacity. NBR could also play a role in removals over the long term to ensure flexibility and balance in removals capacity. The most common NBR are mangrove forests, salt marshes, and seagrass beds grow where land meets the sea and store carbon in their vegetation and underlying sediments/soils. The sediments/soils can store both organic and inorganic carbon as already discussed. Of these three ecosystems, in terms of current global extent, current carbon storage, and carbon sequestration potential, mangrove forests are the best understood followed by salt marshes. Seagrass beds are the least well understood both in spatial extent and ultimate carbon sequestration potential.

3.1.1 Mangroves: Planting mangrove seedlings and restoring hydrology through reversing drainage or removing tidal restrictions.

Illustration 3. Mangrove forest in Kenya (source: Unsplash)

Permanence: 1'000 years

CDR Potential (p.a.): 0.2 gigatons

Cost: 4-18 USD per t CO2

Benefits: Coastal tidal protection, biodiversity support, water quality improvements

Challenges: Setting baseline & carbon accounting for restoration objectives, production of GHG (methane, nitrous oxide) in mangroves, restoration management (long-term)

3.1.2 Salt Marshes: Restoring including recovery of tidal exchange (hydrology) and removal of non-native vegetation / planting of native vegetation.

Illustration 4. Salt Marsh in Southern California (source: Unsplash)

Permanence: 1'000 years **CDR Potential (p.a.):** 0.01 gigatons **Cost:** 4-18 USD per t CO2 **Benefits:** Coastal tidal protection, biodiversity support, water quality improvements **Challenges:** Little potential for expansion of current habitats due to extensive land conversion, setting baseline & carbon accounting for restoration objectives

3.1.3 Seagrass Beds: Unlike salt marshes and mangrove forests, seagrass beds remove carbon from seawater, creating a disequilibrium in the CO_2 concentration between the seawater and atmosphere. The resulting flux from the atmosphere into the seawater replenishes the deficit in dissolved inorganic carbon due to seagrass photosynthesis. In theory, restoration (seed/seedling dispersal or planting) is the most likely mechanism for CDR, however, efforts to date are often unsuccessful yet.

Illustration 5. Seagrass Bed Conservation in Indonesia (source: Unsplash)

Permanence: 1'000 years **CDR Potential (p.a.):** 0.02 gigatons **Cost:** 43 USD per t CO2 **Benefits:** Nutrient cycling, fish stocks (fishing), biodiversity support, water quality improvements **Challenges:** Seagrass restoration efforts are often unsuccessful, high variability in carbon burial rates, high restoration cost

3.2 Technology-based carbon removals (TBR)

Technology-based removals (TBR) on the other hand generally deliver more durable removals by **storing CO2 permanently with minimal risk of re-release into the atmosphere**. Durable solutions are generally preferable to ensure removals efforts remain effective in the long term, so increasing volumes of such solutions would be needed. Accelerating the scale-up of durable TBR will require near-term investment and innovation to reduce their relatively higher cost (*see also chapter 4. CDR Challenges and Requirements*).

3.2.1 Macroalgae Cultivation and Carbon Sequestration: Seaweed (macroalgae) are fast-growing marine organisms that use photosynthesis to incorporate carbon from seawater into their living tissue. Macroalgae flourish in coastal and open ocean environments and a portion of the seaweed produced is exported naturally to the deep sea where it may be buried or remineralized by marine food webs (biological pump). There is also the opportunity to harvest algae for bioenergy production, biochar or production of bioplastics. The startup Running Tide for example seeds carbon buoys with selected species of algae. Macroalgae such as kelp and sea lettuce grow rapidly, converting nutrients to biomass in the surface ocean and fixing dissolved CO2 as organic carbon. Certain types of macroalgae are up to three times more efficient than phytoplankton at fixing carbon, due to macroalgae's higher carbon-to-nutrient (nitrogen, phosphorus) ratios[18]. These ratios cause macroalgae to sequester more carbon for the same nutritional input. As macroalgae are comparatively large and negatively buoyant, when attached to a carbon buoy they sink through the water column more rapidly than phytoplankton, enhancing the biological carbon pump by increasing the efficiency of nutrients to carbon transported into slow cycle reservoirs in the deep ocean.

Illustration 6. Sargassum farm (Seafields) in the Caribbean Sea

Permanence: less than 1'000 years **CDR potential (p.a.):** Theoretically scaled to 10 gigatons but ocean surface is competitive (shipping, fishing, protection areas) -> realistically up to 1 gigaton **TRL:** 7 **Cost:** 25-150 USD per t CO2 **Benefits:** Enhanced oceanic carbon uptake & counter ocean acidification, metal uptake of polluted coastal waters, creation of marine life habitats **Challenges:** Production of methane and other potentially hazardous gases, CO_2 outgassing from pumping deep water to the surface (artificial upwelling) to supply needed nutrients, reduced phytoplankton production **Startup Example:** Seafields, Phykos, Running Tide

[18] https://www.runningtide.com/blog-post/white-paper-sustainably-amplifying-the-natural-carbon-cycle#:~:text=Certain%20types%20of%20macroalgae%20are,for%20the%20same%20nutritional%20input

3.2.2 Microalgae Cultivation and Carbon Sequestration (Fertilization): Microalgae are fast-growing single-cellular organisms that convert carbon dioxide (CO_2) into biomass and various other organic compounds through photosynthesis. These biomasses then sink to the ocean floor and trap the carbon dioxide at the ocean floor until it's slowly converted into mineral resources such as fossil fuels (oil and natural gas). Microalgae cultivation approaches are done via direct addition of nutrients into ocean waters (e.g. fertilization ships) as well as artificial upwelling (AU; *see 3.2.5 Artificial Upwelling and Downwelling*) of nutrient-rich deep open waters to the surface via wave pumps to increase algae growth. Microalgae Cultivation with iron, nitrogen, and/or phosphorus has been tested in the field and shown to boost phytoplankton blooms in areas where such nutrients limit primary production (1/3 of world oceans). However, it is unclear whether microalgae cultivation results in increased carbon export to the deep ocean or not - which is necessary in order to qualify as an ocean-based CDR method. Liquid Trees for example cultivates microalgae that release oxygen while doubling in size every day while cleaning polluted waters. The microalgae then start sinking once pollutant density is too low for replication and ultimately, sediments such as clay or sand bury the microalgae.

Illustration 7. A "red tide" after oceanic iron fertilization done by ships (source: SERC Carleton)

Permanence: less than 1'000 years **CDR potential (p.a.):** Several gigatons **TRL:** 7-9 (fertilization) but unresolved CDR questions **Cost:** below 100 USD per t CO2 **Benefits:** Enhanced oceanic carbon uptake & counter ocean acidification, metal uptake of polluted coastal waters, creation of marine life habitats **Challenges:** Production of methane and other potentially hazardous gases, harmful algal bloom, impact on ecosystem (biodiversity) and food web structure, harvest & transport of nutrients **Startup Example:** Brilliant Planet, Liquid Trees

3.2.3 Ocean alkalinity enhancement (incl. weathering): Ocean Alkalinity Enhancement is a method aiming to bolster the ocean's natural capacity to absorb carbon dioxide by introducing substances that increase its alkalinity. This process involves the addition of alkaline materials like crushed rocks or minerals to seawater enhancing its ability to sequester CO2 (startup Limenet). Other approaches such as Pronoe deploy automated water treatment systems that turn the liquid discharge of coastal industries into less acidic more alkaline flows through electrochemical processing. By elevating the pH levels of the ocean, both techniques facilitate the absorption and storage of carbon dioxide, mitigating its impact on the atmosphere as well as boosting the ocean solubility pump increasing the total carbon content of sweater.

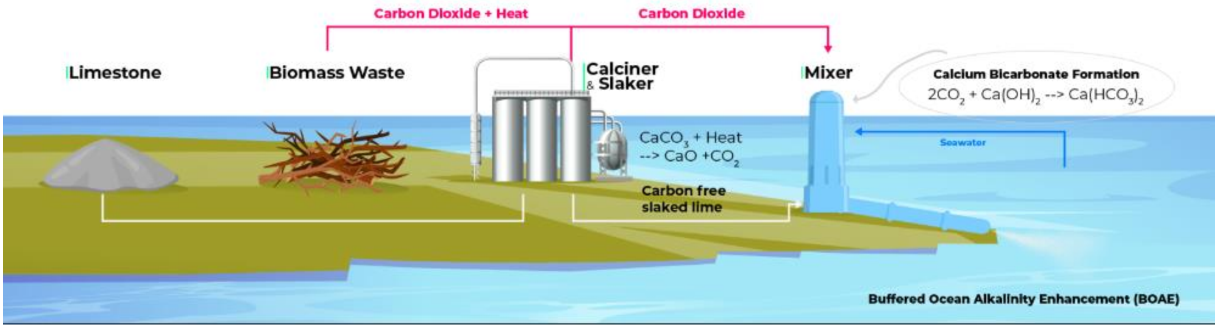


Illustration 8. Visualization of Limenet's alkalinity enhancement process (BOAE)

Permanence: >1'000 years
CDR Potential: Due to vast quantities of alkaline rocks and ocean very large potential to capture tens of gigatons annually (up to 15Gt)[19]
TRL: 3-5[20]
Cost: Estimated between 50-300 USD per t CO2
Benefits: Enhanced oceanic carbon uptake & counter ocean acidification, fertilizer for plankton populations
Challenges: Effects on marine ecosystems from alkaline (release of ecotoxicological trace metals in minerals), MRV, regulatory uncertainty in international water / benevolent nations, sustainable sourcing of alkaline materials
Startup Example: Limenet, Planeteers (limestone weathering); Pronoe, Ebb Carbon (electrochemical treatment)

3.2.4 Artificial Upwelling and Downwelling: As already indicated in the microalgae cultivation, CDR methods also evolve around the artificial up- and downwelling of waters. Artificial downwelling refers to the downward transfer of surface water and carbon to the deep ocean. Downwelling could be induced by pumps, artificially cooling surface waters, or increasing salinity through thickening of sea ice. Artificial upwelling, on the other side, refers to pumping up cooler, nutrient-rich waters from the deep to stimulate phytoplankton activity and draw down carbon dioxide. Both technologies are still at the theoretical stage and haven't been tested in real life scenarios. Also, the overall CO2 removal potential is low compared to the other technologies mentioned in this report[21].

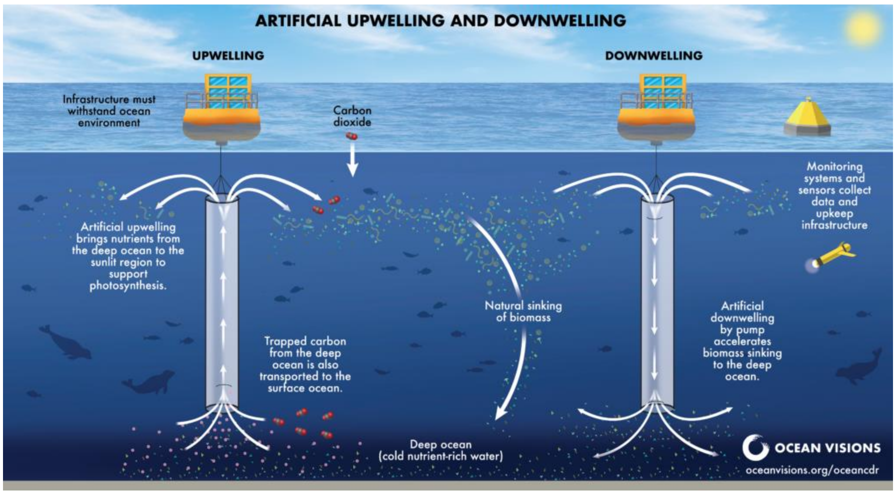


Illustration 9. Artificial Up / Downwelling Principle (source: Ocean Visions)

[19] https://www.noaa.gov/news-release/carbon-dioxide-removal-as-tool-to-mitigate-climate-change
[20] https://www2.oceanvisions.org/roadmaps/ocean-alkalinity-enhancement/state-of-technology/#technologyreadiness
[21] https://oceanvisions.org/artificial-downwelling/

Permanence: Unclear / low
CDR Potential: Unclear
TRL: 1-2
Cost: Unclear but showing complex operations (high maintenance/cost)
Benefits: Cooling surface waters, increased salinity, nutrient-rich surface water for marine life
Challenges: Unknown ecological impact, potential influence on weather, complex operations

3.2.5 Direct Ocean Capture (electrochemical CDR): DOC as the oceanic counterpart to Direct Air Capture (DAC) encompasses electrolytic techniques that capture and remove dissolved inorganic carbon from seawater (either as CO2 gas or as calcium carbonate) and then long-term storage and/or produce a CO2-reactive chemical base. That chemical base can be distributed in the surface ocean to ultimately consume atmospheric CO2 and convert it to long-lived, dissolved, alkaline bicarbonate. The process uses electrochemistry and vacuum to alter the carbonate equilibrium of the existing dissolved carbon in water to enable CO_2 extraction in gas form, which is then permanently stored in geological formations or put into products such as concrete. Direct ocean capture presents several advantages compared to Direct Air Capture (DAC): Seawater contains high concentrations of CO2 that are bound within it, making it a potential source for extraction using direct ocean capture technology. Moreover, given that seawater is approximately 1'000 times denser than air and the required system size for extraction facilities might be smaller. Additionally, the geographical flexibility of direct ocean capture is notable. Implementation could take place offshore, leveraging abandoned oil platforms or other offshore structures, thereby circumventing land use concerns.

Permanence: >1'000 years
CDR Potential: Immense stocks of dissolved inorganic carbon in seawater (30'000 Gt) but limited by access to low/zero-carbon energy
TRL: 2
Cost: 100-350 USD per t CO2
Benefits: Enhances oceanic carbon uptake & counter ocean acidification
Challenges: Marine life mortality (pumps), permanence storage, low effects on marine ecosystems (no toxicity as alkalinity enhancement)
Startup Example: Captura, SeaO2

3.3 CDR Method Comparison

Overall, **nature-based CDR shows high-cost effectiveness but possess limited scalability** as shown on illustration 10 below (dependency on coastal areas) as well as profound restoration and MRV challenges. **Technology-based removals (TBR) on the other side indicate great scalability potential but higher cost, technical complexities and uncertain impacts on nature** equilibrium and marine life. It is therefore favorable to pursue a comprehensive strategy that integrates both nature-based and technology-based methods. At this stage, TBR is not deployable at full scale since continued research, development and regulatory decisions must be made (see TRL for each method and *chapter 4. Challenges*). Additional Ventures has undertaken an assessment of various Carbon Dioxide Removal (CDR) methods, as depicted in illustration 11. Their evaluation highlights that no single method can be deemed a universal solution, given their diverse performance across efficacy, scalability, and environmental risk factors. However, with current science understanding, both Ocan Alkalinity Enhancement and Electrochemical CDR (Direct Ocean Capture) show the most promising potential based on efficacy and scalability – given that these technologies are able to mitigate potential environmental risks.

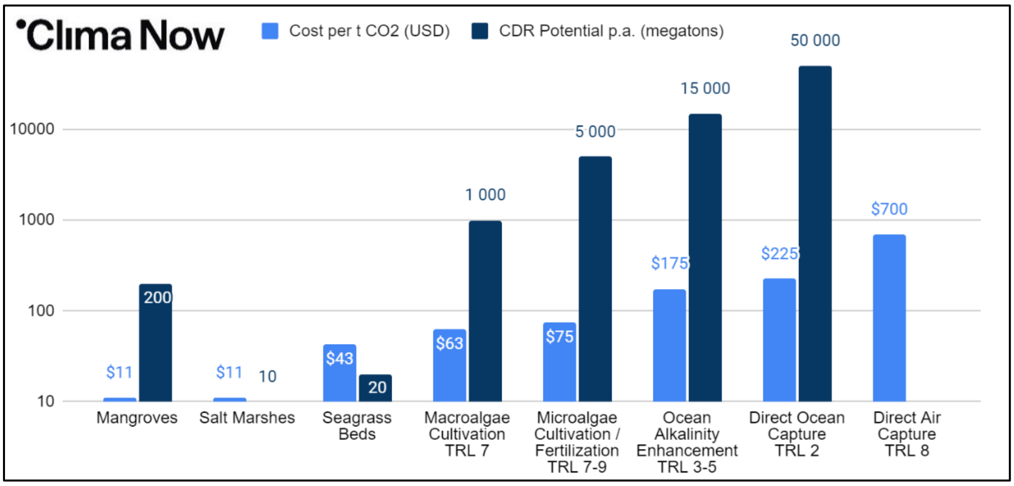


Illustration 10: Overview CDR Methods; The Y-axis has been logarithmically scaled to accommodate a wide range of values (source: Clima Now based on McKinsey 2023 & Ocean Visions 2023)

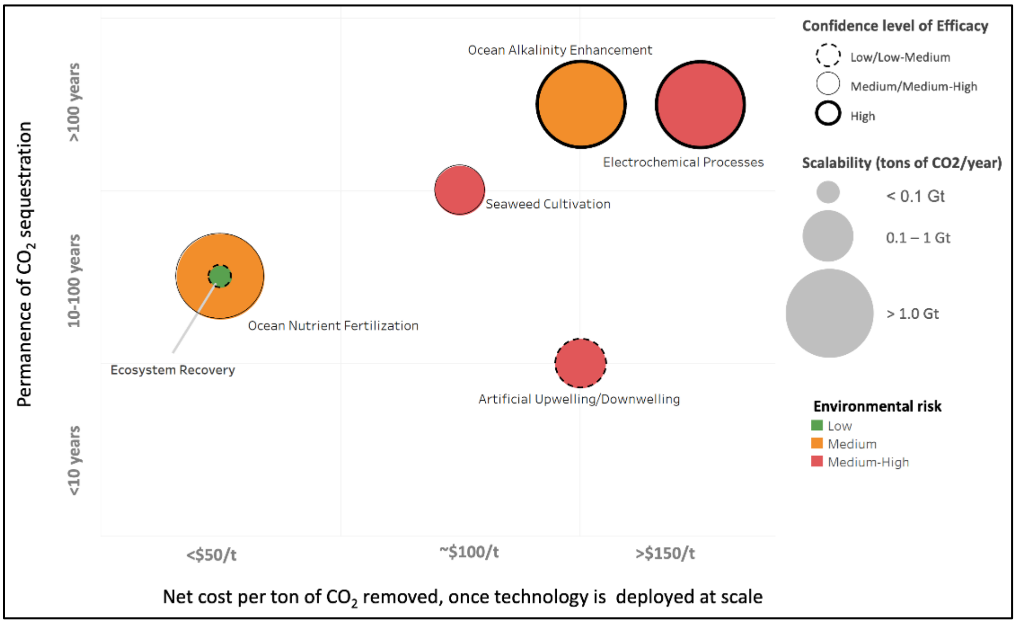


Illustration 11: Overview CDR Methods based on efficacy, scalability and risks (source: Additional)

4. CDR Challenges and Requirements

This chapter scrutinizes the multifaceted challenges that impede the effective deployment of Ocean Carbon Dioxide Removal (CDR) methods. These approaches hold promise for mitigating climate change but confront a labyrinth of complexities which have already been indicated in the overview before: From scientific uncertainties to regulatory hurdles and public perception, each aspect poses a unique barrier.

4.1. Timing Tension: The efficacy of ocean CDR methods and their potential impacts on marine ecosystems pose critical uncertainties. The varying readiness levels of these technologies accentuate the lack of comprehensive data on their effectiveness and environmental consequences. Addressing these knowledge gaps demands substantial research funding and concerted efforts from esteemed research institutions, startups and investors. Adequate baseline measurements and comprehensive understanding of the impacts at larger scales are crucial to assess efficacy and prevent inadvertent harm on marine ecosystems.

4.2. Permitting Problems: Navigating through the bureaucratic maze of permits and regulations presents a significant barrier to the deployment of ocean CDR projects. Some ventures aim at operation in international waters, others follow a process of engaging with national stakeholders. Coordination among multiple federal and state agencies is cumbersome and impedes timely project approvals. Establishing a centralized lead agency, along with global agreements on CDR policies, is crucial to streamline and expedite the permitting process, which is vital for conducting crucial field tests and demonstration projects. Successful lighthouse projects and policies are required to set the stage for coming CDR advancements.

4.3. Scientific Uncertainty: The enormity of the ocean and the complexity of its systems pose significant challenges in comprehending the carbon cycles, ecosystems and acidification dynamics. Limited observational data hinders a comprehensive understanding of the broader implications of ocean CDR methods at scale since systematic and scientific exploration of the oceans began to gain significant momentum only in the late 19th and early 20th centuries. Historically, Blue Carbon has been driven mostly by research institutions and not the private sector so far. Several 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. This includes the efficacy of OAE, the environmental impact of various agents, as well as technoeconomic analyses. However, research projects remain small (< 1m USD) and limited in scope but the totality of ongoing research projects will provide a robust roadmap for the next 7-10 years of medium to large scale research necessary to test viability and environmental risks of the different ocean CDR (illustration 12)[22].

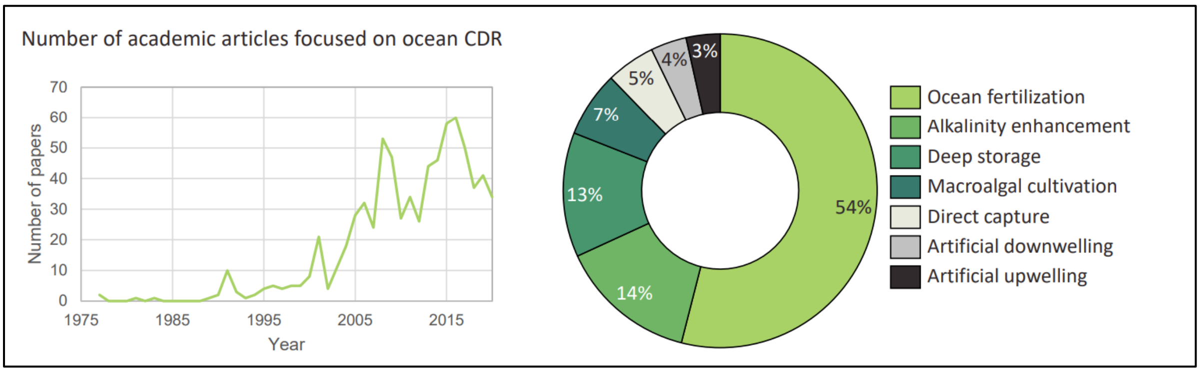


Illustration 12. Academic research in the field o ocean CDR (source: Climateworks)

More extensive research and observational efforts are imperative to address these uncertainties and

[22] https://www.climateworks.org/wp-content/uploads/2021/02/ClimateWorks-ocean-CDR-primer.pdf

predict potential impacts accurately. Scientific research such as environmental impact assessments must scale safely and incrementally from laboratory to mesocosm (experimental outdoor system that examines the natural environment under controlled conditions) to small-scale field trials[23].

4.4. The MRV Conundrum: Monitoring, reporting, and verifying (MRV) carbon removal in ocean environments is an intricate task due to the sheer magnitude and movement of the oceans. Enabling technologies, such as advanced sensors and agreed-upon standards for MRV, are essential to measure and validate the volume of CO2 removal. Expanding existing ocean-sensing efforts and developing trustworthy verification methods, informed by early testing observations, are critical steps in achieving reliable MRV in ocean CDR. Verra launch of an ocean carbon working group in September 2023 or Planetary publishing their first MRV protocol can be seen as positive development for paving the path.

4.5. Public Perception: The unknowns surrounding ocean CDR's broader effects, coupled with concerns for fragile ecosystems and vulnerable coastal communities, necessitate robust public engagement. Establishing relationships, environmental justice frameworks, and community understanding in areas targeted for CDR deployment are crucial for responsible and accepted project execution. Effective public engagement, education, and community involvement are essential to gain local support and manage potential changes in marine environments.

In conclusion, the challenges surrounding ocean-based Carbon Dioxide Removal methods demand multi-dimensional solutions, including enhanced research funding, streamlined regulatory processes, advanced monitoring technologies, and comprehensive public engagement. Addressing these challenges is pivotal to successfully harnessing the potential of ocean CDR while ensuring responsible and sustainable implementation.

[23] https://www.climateworks.org/wp-content/uploads/2021/02/ClimateWorks-ocean-CDR-primer.pdf

5. Market Potential

The potential of ocean carbon dioxide removal (ocean CDR) presents a promising yet undercapitalized avenue in the broader landscape of carbon removal solutions. Despite the vastness of the world's oceans covering 71% of the Earth's surface, investments in marine carbon dioxide removal ventures remain comparatively low when juxtaposed against direct air capture and reforestation/afforestation projects. So far, 408m USD has been invested into marine carbon dioxide removal ventures globally. This capital is light when compared to Direct Air Capture (3.3bn USD) and Reforestation/Afforestation ventures (2.6bn USD). However, in 2023, several noteworthy investments drove forward ocean carbon dioxide removal initiatives. Frontier allocated USD 7 million in carbon removal purchases, supporting companies like Banyu Carbon and Carbon Blue, employing innovative methods for seawater CO2 removal. Equatic received USD 30 million for its seawater electrolysis technology, partnering with Boeing for carbon-negative hydrogen. SeaO2 secured USD 2.35 million, while Ebb Carbon obtained USD 20 million for electrochemical CDR. Captura's USD 12 million Series A round led to a partnership with Deep Sky, installing a direct ocean capture pilot facility in Quebec. These investments highlight the growing interest and support for diverse ocean-based carbon removal solutions and need to overcome expressed challenges.

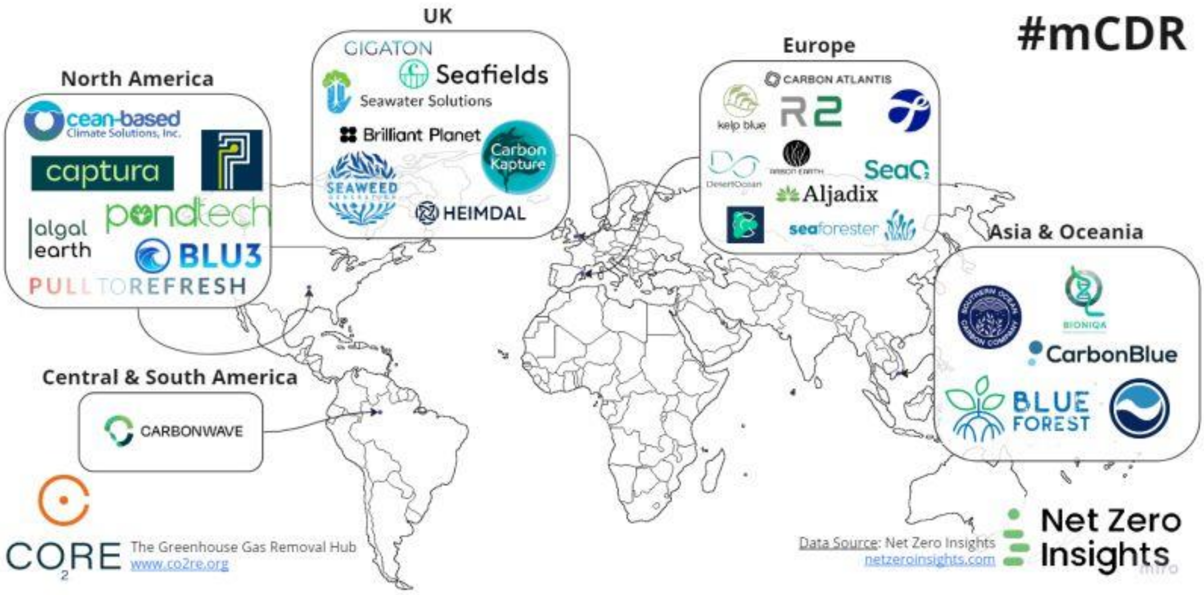
5.1 Navigating the Path to Market Potential

In the realm of climate change mitigation, unlocking the market potential for ocean-based Carbon Dioxide Removal (CDR) approaches requires a strategic and multi-faceted approach. One crucial aspect is securing the necessary **financial backing** (e.g. in the form of philanthropic grants) to propel promising concepts from the drawing board to pilot-scale proof of concept. This initial financing supports key CDR approaches, facilitating their transition from theoretical concepts to robust proposals as well as bringing **ocean stakeholders and industry partners** in the field.

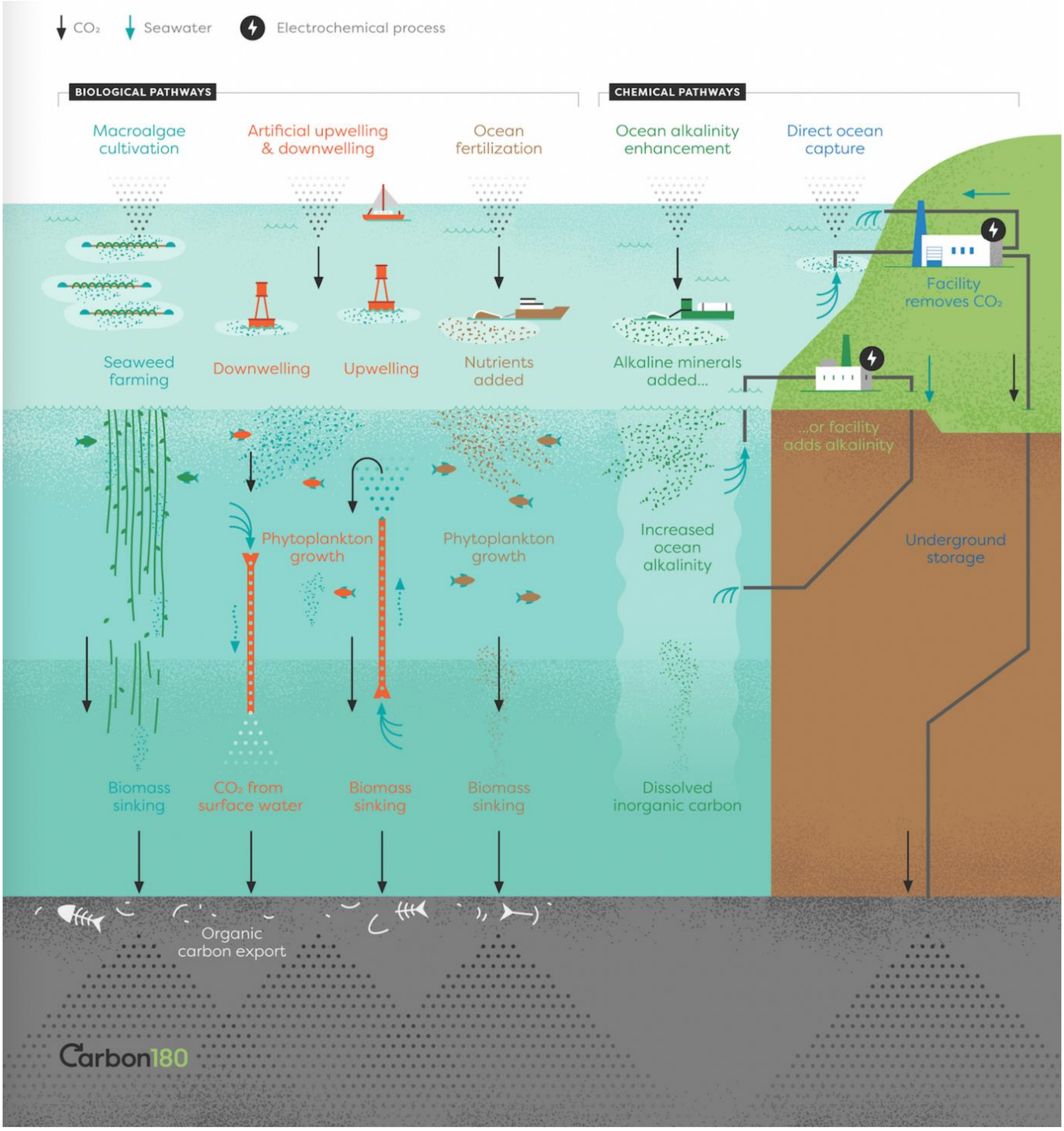
The journey towards market potential involves not only mere financial support but also a continuous evaluation of environmental impacts. This evaluation takes place through rigorous lab experiments and mesocosm/small field trials. Assessing the feasibility and effectiveness of these approaches is vital in steering them towards broader acceptance and adoption. A parallel funding stream is directed towards the development of standardized Life Cycle Assessments (LCAs), ensuring a comprehensive cradle-to-grave understanding of the CO2 footprint associated with different methods. As financial backing propels the proof-of-concept forward, **technoeconomic analyses** come into play, marking a collaborative effort with industry partners. The goal is to identify opportunities for cost reduction and scalability drivers, making these innovative approaches not only effective but also economically viable on a larger scale. However, entering uncharted waters, particularly when it comes to manipulating the Earth's climate, demands a governance framework that goes beyond existing structures. The current international and national regulations for ocean activities fall short in comprehensively and proactively addressing the nuances of ocean CDR approaches. The imperative lies in integrating responsible research and pilot testing into governance systems.

However, the journey towards market potential also underscores the importance of societal acceptance. Engaging non-governmental organizations (NGOs) and the broader public becomes pivotal in driving this acceptance. Interdisciplinary dialogues play a central role in building consensus, understanding risks, and resolving concerns. These dialogues extend to local, national, and international levels, clarifying and strengthening governance regimes to provide adequate guardrails for at-sea testing and potential large-scale deployment. Governance, in the context of ocean CDR, goes beyond mere regulation. It involves active public policy participation, equitable benefit sharing, and transparent access to information. In essence, the path to market potential demands a delicate balance between scientific innovation, responsible governance, and societal acceptance. Navigating this path requires a collective effort that transcends disciplinary boundaries and embraces the complexity of our interconnected world. This multifaceted approach is not just a scientific or regulatory challenge but a shared responsibility requiring collaboration, transparency, and inclusivity.

Appendix I. Startup Map

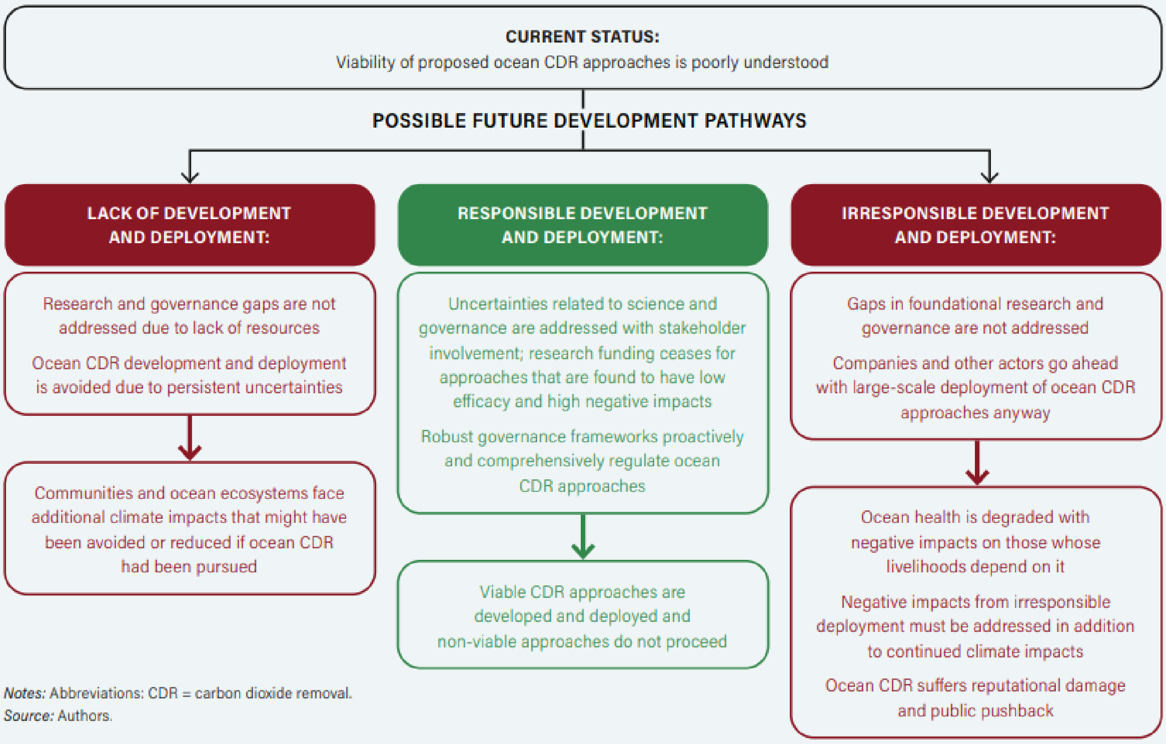


Appendix II. Carbon 101 (Methods)



Appendix III. Responsible Development of Ocean CDR

FIGURE ES-2 | The Case for Responsible Development of Ocean CDR



Notes: Abbreviations: CDR = carbon dioxide removal.
Source: Authors.

Appendix IV. Ocean CDR Philanthropic Funding (ClimateWorks)

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