The advantages, limitations, and the future of marine carbon dioxide removal (mCDR) techniques

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This review provides a comprehensive analysis of marine carbon dioxide removal (mCDR) methods aimed at combating climate change. This paper examines a range of techniques, including ocean fertilization, artificial upwelling and downwelling, ocean alkalinity enhancement, coastal blue carbon ecosystem restoration, and direct ocean air capture (DOAC). Each method is evaluated based on its technical feasibility, scalability, costs, and potential environmental impacts. The discussion highlights ocean fertilization's ability to stimulate phytoplankton growth for carbon uptake, balanced by ecological risks such as the potential for harmful algal blooms. Artificial upwelling and downwelling, while promising in theory, face uncertainties regarding their effectiveness and ecological consequences. Ocean alkalinity enhancement emerges as a viable long-term solution for carbon storage, although the high cost presents significant challenges. The restoration of coastal blue carbon ecosystems is recognized for its dual benefits of carbon sequestration and ecosystem service provision, albeit with limitations in scalability. DOAC is assessed for its high potential for durability and scalability, though it currently encounters economic barriers and environmental concerns. This paper underscores the necessity for robust monitoring and verification systems to evaluate the performance of mCDR techniques effectively. It advocates for an integrated approach that combines multiple mCDR strategies to maximize carbon removal while minimizing ecological risks, emphasizing the need for ongoing research and technological advancements to enhance the viability of marine carbon removal in addressing global climate challenges.

Keywords:
Ocean fertilization, Artificial Upwelling, Artificial Downwelling, Ocean Alkalinity Enhancement, Coastal blue carbon, Direct Ocean Air Capture

1. Introduction:

Over the past few hundred years, atmospheric levels of carbon dioxide (CO_2) and other greenhouse gasses have increased because of the burning of fossil fuels and alterations of the terrestrial biosphere. Fossil fuels are burned primarily for energy production and transportation, releasing significant amounts of CO_2 and other greenhouse gases into the atmosphere from various sources such as transportation systems, energy generation, industrial processes, and agricultural practices. Due to fossil fuel burning, excessive carbon and other greenhouse gasses trap heat inside of our atmosphere, gradually warming the planet (Kweku et al, 2018).

The surge in CO_2 levels since the Industrial Revolution is unprecedented; in just a few centuries, atmospheric CO_2 has risen over 40%, reaching 400 ppm from 280 ppm (EPA, 2022). This level was last seen 5 to 3 million years ago (NOAA, 2024) (Figure 1), highlighting the unprecedented change over a remarkably short time period.

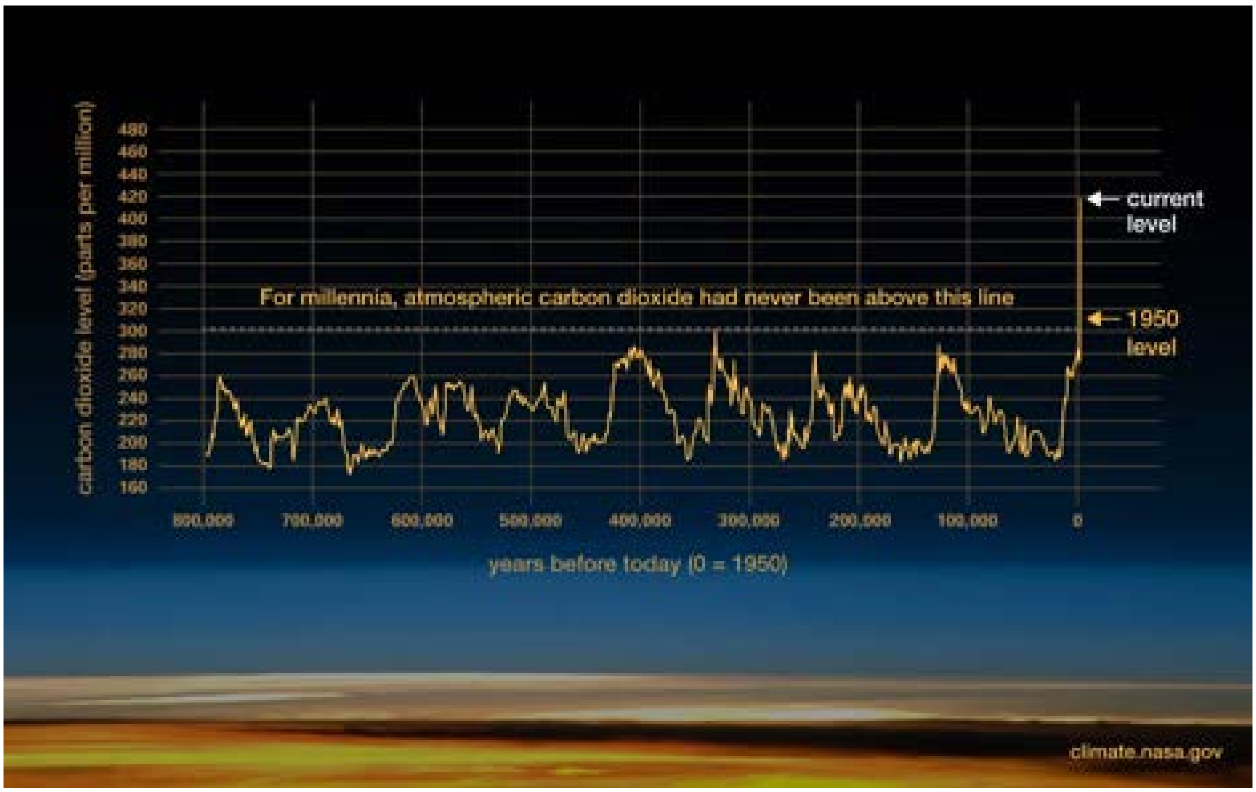

Figure 1 Diagram of atmospheric CO_2 levels over the past 800,000 years. This diagram demonstrates the periodic rises of atmospheric CO_2 followed by the unprecedented increase from anthropogenic emissions.(NASA, 2013)

Human-driven CO_2 emissions have led to substantial global warming, causing various environmental shifts. Anthropogenic climate change refers to alterations in temperature patterns, weather events, and climate conditions on Earth due to human actions. Over the past century the effects of climate change have become more severe and increasingly unbearable for vulnerable populations. Climate change has many detrimental impacts. Rising global temperatures lead to more frequent and intense heat waves, droughts, and wildfires, posing risks to human health, agriculture, and water resources (Hardy J. T., 2003). Ice caps and glaciers contribute to sea-level rise, threatening coastal communities and ecosystems (Mimura N. 2013). Climate change also disrupts weather patterns, leading to extreme weather events like hurricanes and heavy rainfall, causing widespread destruction (NOAA 2021). Additionally, climate change causes a multitude of impacts on oceans, including ocean acidification, intensifying marine heatwaves, and coral bleaching events, all of which threaten marine ecosystems and biodiversity (Hoegh-Guldberg, O., & Poloczanska, E. S. 2017). The consequences of climate change extend beyond environmental issues and affect various aspects of human society as well including economic stability, food security, and geopolitical tensions.

This rapid increase in CO_2 and harmful consequences underscore the urgent need for effective climate change mitigation strategies (Monroe, 2020). Taking a stand against climate change now is important to mitigate the threats. Addressing climate change requires the reduction of greenhouse gas emissions, a transition to clean and renewable energy sources, the promotion of sustainable practices, and adoption of climate-resilient strategies. While multiple countries have agreed to the Paris Agreement, which aims to hold the increase in global average temperature to 2 °C, we are unlikely to reach this goal given our current rate of emissions reduction (IPCC). According to the 6th IPCC report, it is necessary to remove excess carbon dioxide to reach the goals set by the Paris Agreement. Carbon Dioxide Removal (CDR) technologies play a vital role in addressing climate change and this current challenge. By removing carbon from the atmosphere or expanding the ocean's capacity to absorb carbon, CDR can help remove excess carbon from the atmosphere.While CDR technologies can be implemented in the atmosphere, marine CDR (mCDR) technologies have a high yet underutilized potential. mCDR refers to the process of capturing and storing carbon dioxide from the ocean, contributing to the reduction of greenhouse gas concentrations in the atmosphere. The oceans already act as a significant sink for carbon dioxide, absorbing almost 25% (Emerson & Hodge, 2008) of the carbon emissions generated by human activities. In addition, mCDR can mitigate the severity of ocean acidification by either sequestering the carbon or solidifying it.

2. Marine Carbon Dioxide Removal (mCDR) Techniques

2.1 Ocean Fertilization

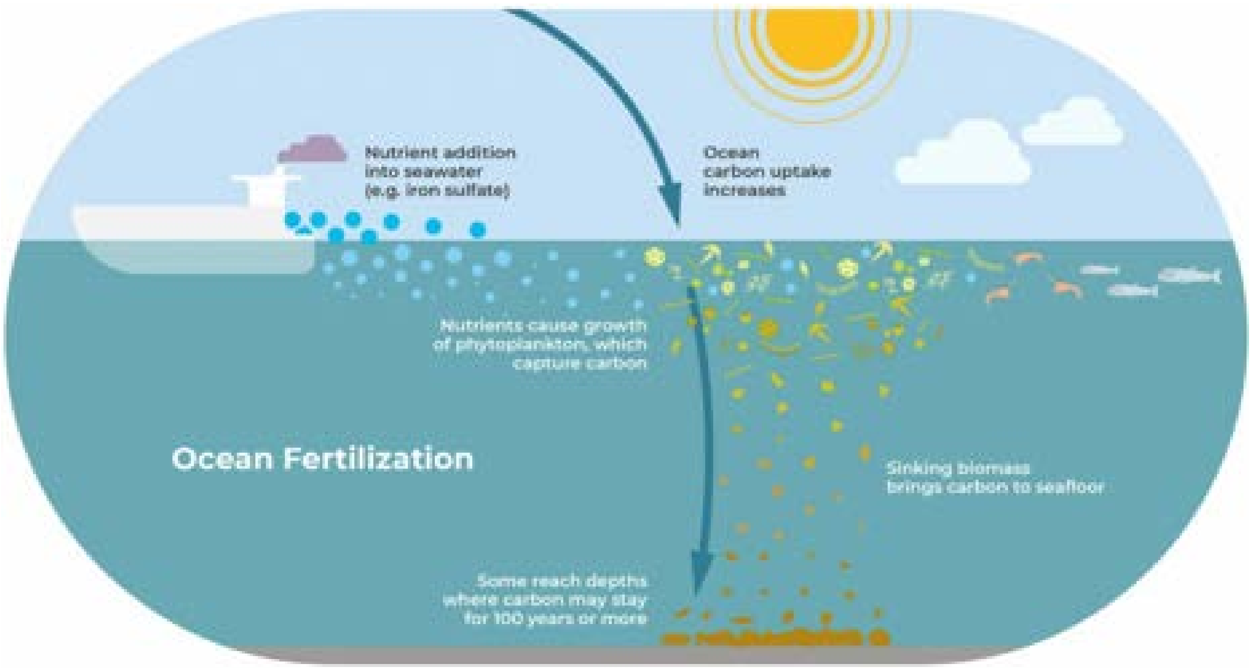

Figure 2 Illustrative diagram of the processes in ocean fertilization. Nutrients, such as iron sulfate are added to the seawater on the surface, which leads to increased photosynthesis in phytoplankton. This causes increased carbon capture, which then leads to carbon sequestration when the biomass sinks with its increased carbon. (OceanNets, 2024)

Ocean fertilization is a well-researched and established mCDR technology, which involves adding micronutrients, such as iron, or macronutrients, such as phosphorus and nitrogen, to the surface of the ocean (NASEM Committee, 2022). The goal is to increase the growth of marine phytoplankton, which first increases the absorption of carbon dioxide in the surface waters, and secondly, facilitates the sequestration of the newly formed organic carbon to the deep sea away from the surface layer exposed to the atmosphere (fig. 2). This occurs as the phytoplankton photosynthesize, where carbon is absorbed in the form of CO_2 and O_2 is released. The first step of increased photosynthesis is achievable in areas where phytoplankton growth is limited by nutrients, except in nutrient-rich regions near coastlines. There is still scientific uncertainty regarding the second step of increased sequestration (Fig. 2), which depends on factors like location, depth of carbon export, and the rate at which sinking particles break down (Aumont and Bopp, 2006). Ocean fertilization aims to enhance the ocean's natural biological carbon pump, utilizing solar energy and nutrients from within or outside the ocean. Fertilization with micronutrients like iron requires relatively small amounts of nutrients compared to potential carbon sequestration, while the amount of nitrogen, phosphorus, or silicate needed for fertilization would be significantly larger.

2.2 Artificial Upwelling and Downwelling

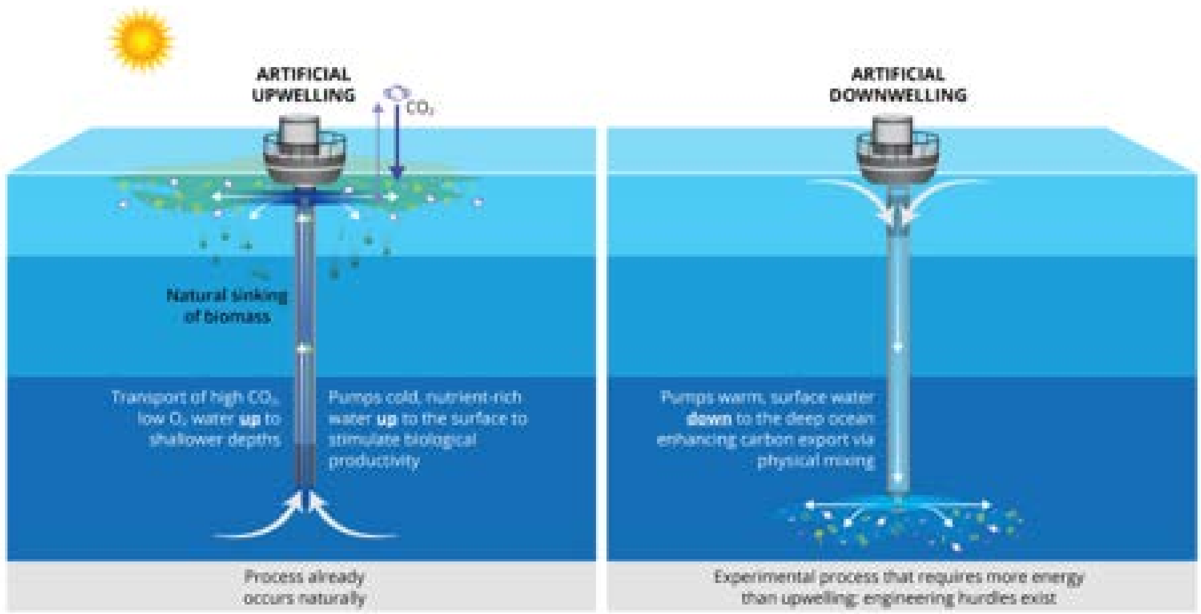

Figure 3 Illustrative diagram of the processes of artificial upwelling and downwelling. Artificial upwelling involves pumping cold, nutrient-rich water up to the surface, while allowing the natural sinking of biomass. Artificial downwelling allows for warm surface water to be pumped down, enhancing carbon sequestration. (Cross et. al, 2022)

Another mCDR method is artificial upwelling and downwelling, which imitates a natural process. Natural upwelling and downwelling play a crucial role in transferring heat, salt, nutrients, inorganic and organic carbon, and energy between the different depths of the ocean. Scientists have been trying to replicate its effects artificially through artificial upwelling and downwelling. Artificial upwelling aims to supply essential nutrients to the upper ocean, promote increased primary production, and enhance carbon sequestration (NASEM, 2021). Achieving this increased carbon sequestration requires that the biological production of carbon surpasses the input of dissolved inorganic carbon from the upwelled water source. This would mean that the downwelled water would contain more carbon, than the upwelled water source, which is supplying nutrients, but also some inorganic carbon. Upwelling has also been suggested to sustain fisheries and aquaculture, generating energy, providing cold water for seawater-based air conditioning, and even mitigating the formation or severity of typhoons (Oschlies, et al, 2010). Artificial downwelling of oxygen-rich surface water has been proposed to counteract eutrophication and hypoxia in deeper depths by providing oxygen through a downward flow (Liu, 2020). Both of these artificial mechanisms when combined can enhance the ocean sequestration of atmospheric carbon dioxide.

2.3 Ocean Alkalinity Enhancement

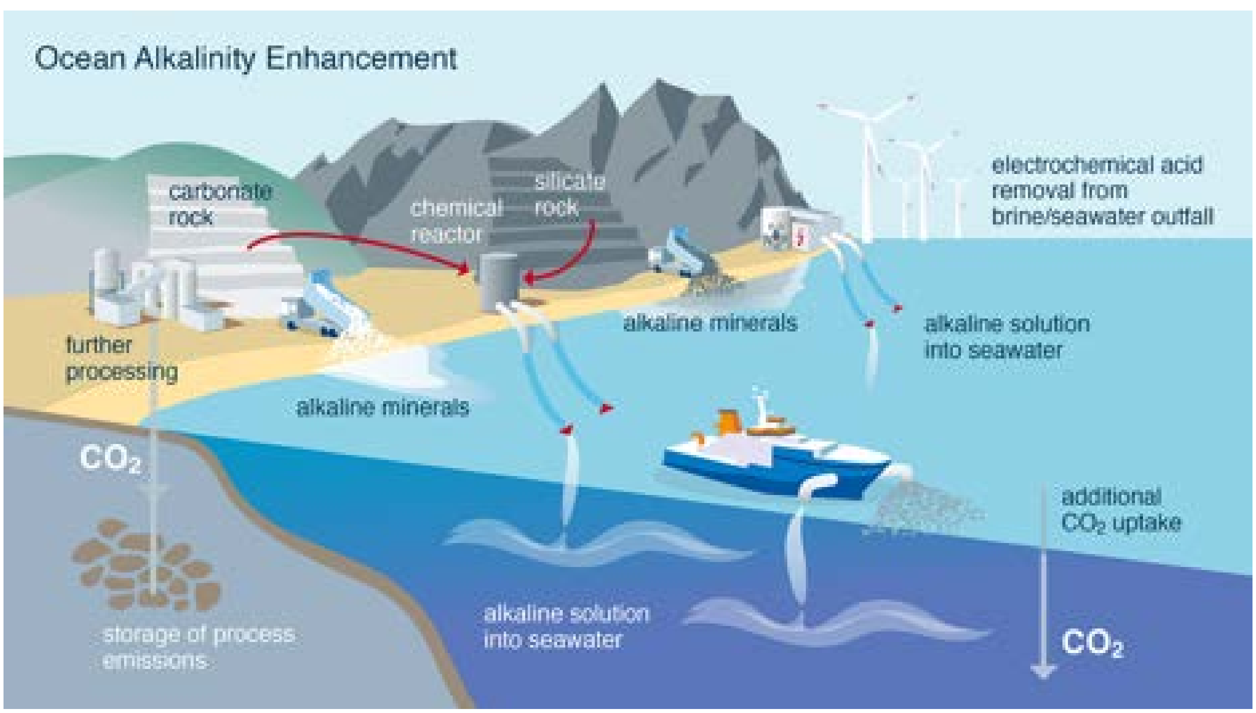

Figure 4 Illustrative diagram of ocean alkalinity enhancement. This diagram demonstrates the weathering of carbonate and silicate rock to create an alkaline solution. This

solution allows for the increase in the pH level of water, which promotes the conversion of dissolved carbon dioxide into bicarbonate ions. (State Planet, 2023)

An additional mCDR technique is ocean alkalinity enhancement, which aims to increase the ocean's alkalinity and therefore enhance the ocean as a carbon sink. This technique involves adding alkaline substances to the ocean, such as crushed rocks or minerals rich in calcium and magnesium (Hartmann et. al, 2023). When these alkaline materials dissolve in seawater, they increase its alkalinity and raise the pH level, promoting the conversion of dissolved carbon dioxide into bicarbonate ions. This process ultimately leads to the long-term storage of carbon dioxide in the form of bicarbonate compounds. Ocean alkalinity enhancement has the potential to effectively remove carbon dioxide from the atmosphere on a large scale. However, careful consideration must be given to the potential ecological impacts and the selection of suitable alkaline substances to ensure responsible implementation and harm reduction for marine ecosystems. Continued research and collaboration are necessary to fully understand the potential of ocean alkalinity enhancement as a viable CDR technique and its implications for global climate change mitigation efforts (NASEM Committee, 2022).

2.4 Coastal Blue Carbon

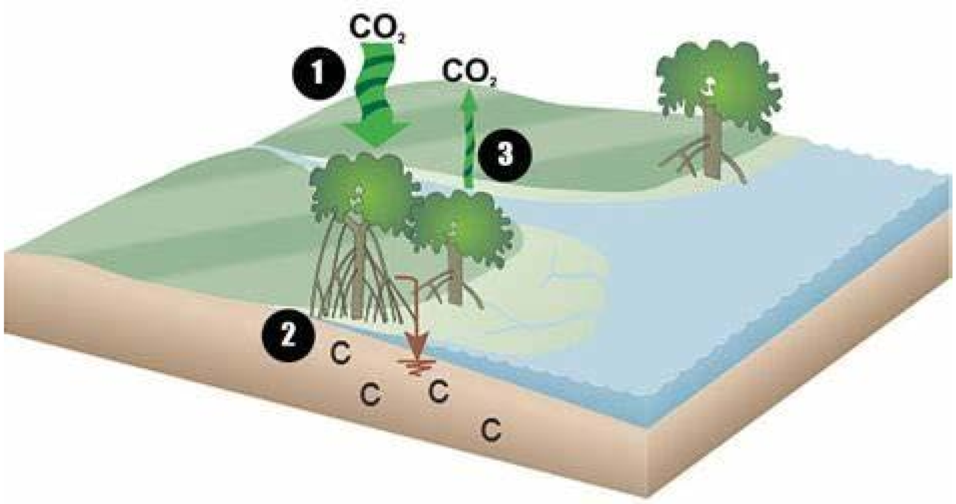

Figure 5 Illustrative diagram of coastal blue carbon. This diagram shows the increased uptake in carbon dioxide by coastal ecosystems that are either conserved or restored. (NOAA, 2022)

Coastal blue carbon refers to the carbon captured by coastal ecosystems such as mangroves, tidal marshes, and seagrasses (Siikamäki, 2013). These ecosystems can sequester and store large amounts of carbon both above and below ground. Mangroves, for instance, are highly efficient in trapping carbon in their biomass and sediments due to their dense root systems and slow decomposition rates in anaerobic conditions (Alongi, 2020). Tidal marshes and seagrasses similarly contribute to carbon sequestration through the accumulation of organic matter in their soils.

Implementation of coastal blue carbon strategies involves the conservation, restoration, and sustainable management of these coastal ecosystems to enhance their carbon sequestration potential. This may include activities such as reforestation of mangrove forests, restoration of degraded tidal marshes, and protection of seagrass beds from coastal development and pollution (Tang et. al, 2018). By conserving and restoring these ecosystems, coastal blue carbon initiatives not only contribute to carbon dioxide removal but also provide additional ecosystem services such as coastal protection, habitat for biodiversity, and support for fisheries.

2.5 Direct Ocean Air Capture

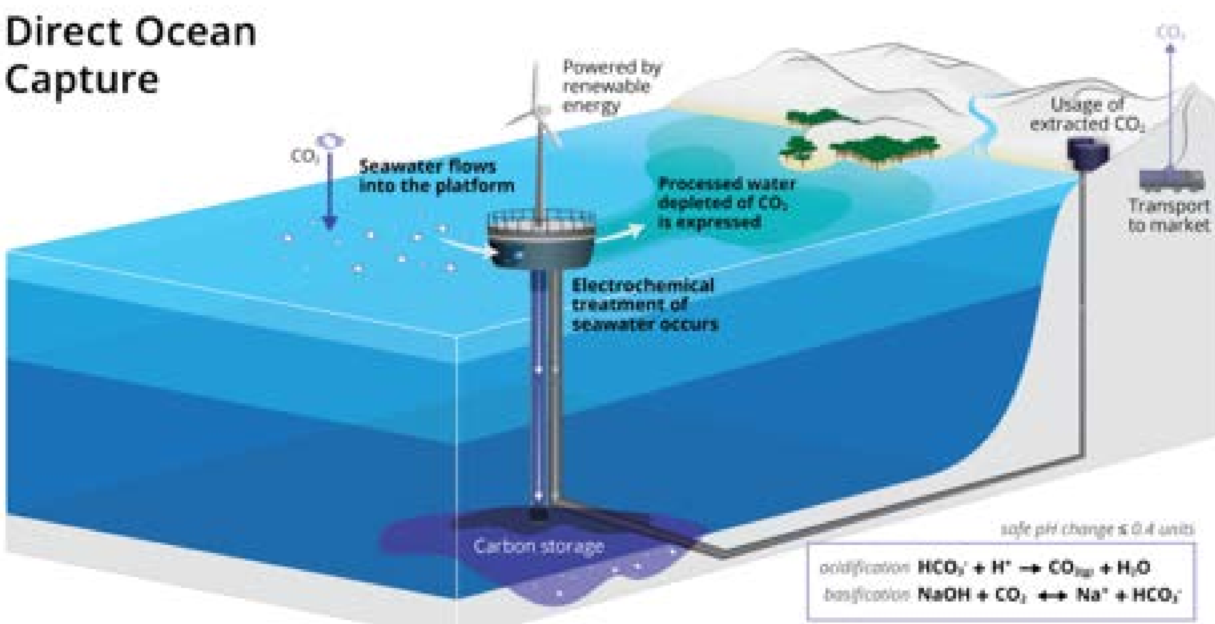

Figure 6 Illustrative diagram of direct ocean capture. Seawater is treated by offshore stations through electrochemical treatment, which removes and stores carbon dioxide. (Cross et. al, 2022)

Direct Ocean Air Capture (DOAC) is an emerging technology that involves capturing carbon dioxide directly from the atmosphere using ocean-based systems. Unlike land-based Direct Air Capture (DAC) technologies, which typically rely on chemical sorbents or solvents to capture CO_2, DOAC utilizes the natural alkalinity of seawater to absorb and chemically bind carbon dioxide . One proposed method for DOAC involves the deployment of floating platforms equipped with large fans or sprayers that draw in atmospheric air and expose it to a solution of alkaline substances, such as sodium hydroxide or calcium hydroxide (Ametistova, 2002). The alkaline solution reacts with the carbon dioxide in the air to form bicarbonate ions, which are then transported into the ocean where they can be stored as dissolved inorganic carbon.

2.6 Method of Analysis

These mCDR techniques will be analyzed and evaluated using a variety of factors that include their maturity, cost, environmental effects, and effectiveness. The category of maturity will be measured based on our amount of data and research on a certain technique and how developed it is. Cost will be measured on its cost to implement, cost to scale, and cost of monitoring. Environmental effects will be measured on the environmental risks and benefits of each method, determining how it would disrupt different ocean ecosystems or the chemistry of the environment. Finally, effectiveness will be determined based upon the scalability of each technique, the length of time of the removal of carbon, and confidence in the method's ability to remove atmospheric CO_2.

3. Comparison among mCDR Techniques:

Figure 7 Global Distribution of mCDR studies This figure demonstrates the global distribution of various mCDR studies. (Ocean Vision, 2024)

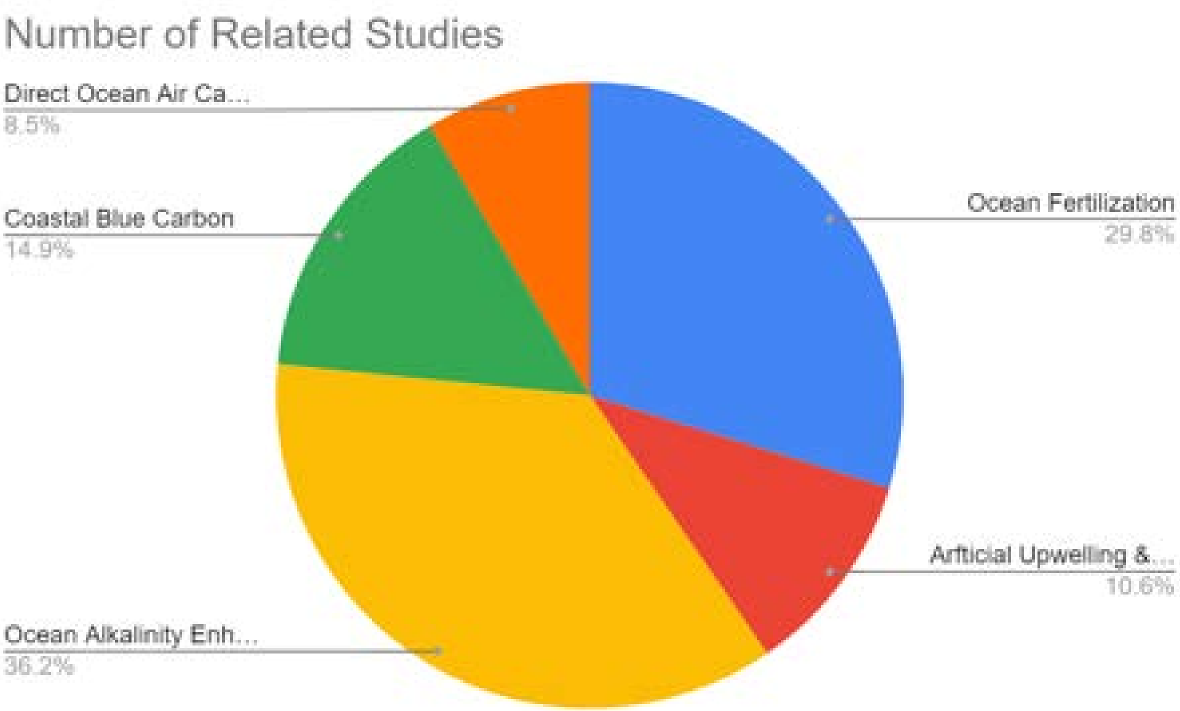

Figure 8 Distribution of mCDR studies This figure demonstrates the distribution of each mCDR technique in the 47 known studies on mCDR.(Ocean Vision, 2024)

Table 1 mCDR Methods Analysis: Maturity represents the amount of research on each method based on Figure 8. Durability represents how long the carbon is sequestered. Scalability represents the maximum amount of carbon dioxide sequestered with global scale implementation. Cost of scaling represents the increased cost per ton of CO2. (NASEM Committee, 2022)

Method	Ocean Fertilization	Artificial Upwelling/Downwelling	Ocean Alkalinity Enhancement	Blue Coastal Carbon	Direct Ocean Air Capture (DOAC)
Maturity	4 (Medium to High)	2 (Low)	5 (Medium to High)	3 (Low to Medium)	3 (Low to Medium)
Durability	3 (10 to 100 years)	2 (Less than 10 to 100 years)	5 (High; over 100 years)	4 (10 to over 100 years)	5 (High; over 100 years)
Scalability	4 (Medium to High; >0.1 to 1.0 Gt/year)	2 (Uncertain; requires pilot trials)	3 (Medium; >0.1 to 1.0 Gt/year or more globally)	2 (Low to Medium; <0.1 to 1.0 Gt/year)	4 (Medium to High; >0.1 to 1.0 Gt/year)

Cost of Scaling	2 (<$50 per ton CO2)	3 ($100 to $150 per ton CO2)	3 ($100 to $150 per ton CO2)	2 (<$50 per ton CO2)	5 ($150 to $2,500 per ton CO2; potentially <$100)
Environmental Risks	4 (Medium to High risk of algal blooms, oxygen depletion)	4 (Medium to High risk due to altering ocean density fields)	3 (Medium; potential toxic effects, bio-optical impacts)	2 (Low; positive impacts on biodiversity expected)	4 (Medium to High; effluent discharge impacts)
Carbon Accounting Challenges	4 (High difficulty in tracking sequestration beyond application)	4 (High due to nutrient displacement impacts)	3 (Medium due to tracking changes in alkalinity)	5 (High due to complexities in monitoring biomass)	2 (Low to Medium; simpler due to engineered systems)
Recommended Environment	Open ocean, areas with low iron levels (HNLC regions)	Coastal regions, upwelling zones	Open ocean, coral reef areas	Coastal wetlands, mangroves, seagrass beds	Enclosed engineered systems, near industrial hubs

4. Discussion:

Ocean fertilization leverages extensive research on phytoplankton growth response to nutrient addition, making it a well-understood and potentially effective method for enhancing the biological carbon pump (BCP) (Figure 8). It has a large scalability potential, capable of removing 0.1 to 1.0 gigatons of CO_2 per year, and is cost-effective (Table 1). However, the technique carries significant ecological risks, including the possibility of harmful algal blooms and oxygen depletion (Table 1). There are also uncertainties surrounding the fate of sequestered carbon and the long-term impact on marine ecosystems, which complicate carbon accounting and monitoring efforts (Table 1). Ocean fertilization is best suited for regions where phytoplankton growth is nutrient-limited, offering a cost-effective method for large-scale carbon removal (Table 1). However, its implementation should be coupled with rigorous monitoring to mitigate ecological risks and ensure environmental balance.

Artificial upwelling and downwelling have the potential to enhance primary production and carbon sequestration by mimicking natural ocean processes. This technique is versatile, with potential applications in sustaining fisheries, generating energy, and even mitigating the severity of typhoons. However, the maturity of this technique is limited, and there is low confidence in its effectiveness, particularly due to uncertainties about the counteraction of CO_2 upwelling (Figure 8). The scalability is uncertain, and the environmental risks, including potential alterations in ocean density and temperature, are non negligible (Table 1). This technique would be particularly useful in regions where additional benefits, such as sustaining fisheries, can be realized alongside carbon sequestration.

Ocean alkalinity enhancement offers long-term carbon storage lasting over 100 years, with a significant scalability potential (Table 1). The technique is based on well-understood chemical processes and can remove over 0.1 to 1.0 gigatons of CO2 per year on a global scale (Table 1). However, this technique is expensive and carries some environmental risks, particularly concerning potential toxic effects and bio-optical impacts (Table 1). Additionally, there are uncertainties regarding the aggregation and export of altered ocean chemistry (Table 1). Ocean alkalinity enhancement is best suited for large-scale deployments in regions where the long-term durability of carbon storage is a priority. It should be implemented with careful consideration of potential ecological impacts and in conjunction with monitoring programs.

Coastal blue carbon strategies are highly effective in sequestering carbon and provide additional ecosystem services such as coastal protection, habitat for biodiversity, and support for fisheries. The environmental risks are low, and the cost is relatively affordable (Table 1). The scalability of these efforts is limited, with the potential to remove less than 0.1 to 1.0 gigatons of CO2 per year (Table 1). Additionally, the complexity of marine ecosystems and challenges in accurately quantifying carbon sequestration outcomes pose significant challenges (Table 1). Coastal blue carbon strategies are best used in regions where conservation and restoration of coastal ecosystems can provide multiple environmental and economic benefits. This technique is ideal for local-scale projects with the potential for positive ecological and carbon sequestration outcomes.

DOAC offers high durability, with carbon storage lasting over 100 years, and has a significant scalability potential (Table 1). The technique is based on well-understood chemical processes and provides high confidence in CO2 monitoring within an engineered system (Table

1).The current costs are high and the energy and water requirements may limit large-scale deployment (Table 1). There are also significant environmental risks, particularly related to effluent discharge and the treatment of by-products. DOAC is best suited for regions where controlled and measurable CO_2 removal is critical, particularly in areas where the infrastructure and energy resources are available to support large-scale operations (Table 1). This technique may be most effective as part of a diversified approach to carbon removal, complementing other mCDR methods.

The future of marine carbon dioxide removal (mCDR) techniques is likely to be shaped by continued advancements and innovations across multiple fronts. One promising trend is the development of hybrid approaches that combine elements from different mCDR techniques to optimize carbon sequestration and minimize environmental risks. For instance, integrating ocean alkalinity enhancement with artificial upwelling could simultaneously enhance carbon uptake and address nutrient limitations, potentially increasing overall efficiency.

Advancements in monitoring and verification technologies are poised to play a crucial role in the broader adoption of mCDR techniques. Enhanced remote sensing tools, coupled with AI-driven data analysis, will improve the accuracy of carbon sequestration tracking, reducing uncertainties and building confidence in methods like ocean fertilization and coastal blue carbon, where carbon accounting has been a challenge. Research into sustainable and less ecologically disruptive materials for ocean alkalinity enhancement is also advancing, potentially expanding its use while minimizing harm to marine ecosystems. Additionally, refinements in DOAC systems to reduce energy and water demands could make these methods more efficient, scalable, and affordable.

Currently, mCDR technologies are primarily concentrated in wealthier nations due to high costs and infrastructure needs (Figure 7). However, as these technologies evolve and become more cost-effective, there is potential for their broader adoption in developing countries. This would create more equitable global participation in climate mitigation efforts, ensuring a wider distribution of both the benefits and responsibilities of carbon removal. As accessibility improves, these technologies could play a critical role in achieving international climate goals.

In conclusion, the future of mCDR techniques is poised for significant growth, driven by innovation, interdisciplinary collaboration, and a growing understanding of the ocean's role in global carbon cycles. As these techniques continue to evolve, they will become increasingly integral to global climate change mitigation efforts.

References:

Alongi, D. M. (2020). Global Significance of Mangrove Blue Carbon in Climate Change Mitigation. *Sci*, *2*(3), 67. https://doi.org/10.3390/sci2030067

Ametistova, L., Twidell, J., & Briden, J. (2002). The sequestration switch: removing industrial CO2 by direct ocean absorption. *Science of the Total Environment*, *289*(1), 213–223. https://doi.org/10.1016/S0048-9697(01)01048-8

Aumont, O., & Bopp, L. (2006). Globalizing results from ocean in situ iron fertilization studies. *Global Biogeochemical Cycles*, *20*(2), n/a-n/a. https://doi.org/10.1029/2005gb002591

Bijma, J., Pörtner, Hans-O., Yesson, C., & Rogers, A. D. (2013). Climate change and the oceans – What does the future hold? *Marine Pollution Bulletin*, *74*(2), 495–505. https://doi.org/10.1016/j.marpolbul.2013.07.022

Coastal Blue Carbon. (2014). Noaa.gov. https://oceanservice.noaa.gov/ecosystems/coastal-blue-carbon/?n=@

Cross, J., Gledhill, D., Sweeney, C., Butler, J., Jewett, E., Feely, R., Theuerkauf, S., Stein, T., Kitch, G., Alin, S., Barbero, L., Briggs, R., Carter, B., Chu, S., Dunne, J., John, J., Harris, J., Hollarsmith, J., Krepp, A., & Longmire, K. (2022). *NOAA Carbon Dioxide Removal Research: A White Paper documenting a Potential NOAA CDR Science Strategy as an element of NOAA's Climate Mitigation Portfolio Executive Writing Team: NOAA National Marine Fisheries Service (NMFS) NOAA National Ocean Service (NOS) NOAA Affiliates*. https://sciencecouncil.noaa.gov/wp-content/uploads/2022/09/Clean-copy-of-Draft-CDR-Research-Strategy.pdf

Emerson, S., & Hedges, J. (2008). *Chemical Oceanography and the Marine Carbon Cycle*. Cambridge University Press.

Hardy, J. T. (2003). *Climate change : causes, effects, and solutions*. J. Wiley.

Hartmann, J., Suitner, N., Lim, C., Schneider, J., Marín-Samper, L., Arístegui, J., Renforth, P., Taucher, J., & Riebesell, U. (2023). Stability of alkalinity in ocean alkalinity enhancement (OAE) approaches – consequences for durability of CO2 storage. *Biogeosciences*, *20*(4), 781–802. https://doi.org/10.5194/bg-20-781-2023

Hoegh-Guldberg, O., & Poloczanska, E. S. (2017). Editorial: The Effect of Climate Change across Ocean Regions. *Frontiers in Marine Science*, *4*. https://doi.org/10.3389/fmars.2017.00361

IPCC. (2023). *CLIMATE CHANGE 2023 Synthesis Report A Report of the Intergovernmental Panel on Climate Change*. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_FullVolume.pdf

Jayarathna, C., Maelum, M., Karunarathne, S., Andrenacci, S., & Haugen, H. A. (2022). Review on direct ocean capture (DOC) technologies. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4282969

Lindsey, R. (2024, April 9). *Climate Change: Atmospheric Carbon Dioxide*. Climate.gov; National Oceanic and Atmospheric Administration. https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheri c-carbon-dioxide

Liu, S., Zhao, L., Xiao, C., Fan, W., Cai, Y., Pan, Y., & Chen, Y. (2020). Review of Artificial Downwelling for Mitigating Hypoxia in Coastal Waters. *Water*, *12*(10), 2846. https://doi.org/10.3390/w12102846

Mimura, N. (2013). Sea-level rise caused by climate change and its implications for society. *Proceedings of the Japan Academy, Series B*, *89*(7), 281–301. https://doi.org/10.2183/pjab.89.281

Mitchell, J. F. B. (1989). The “Greenhouse” effect and climate change. *Reviews of Geophysics*, *27*(1), 115–139. https://doi.org/10.1029/rg027i001p00115

NASA. (2013, August 29). *Graphic: The relentless rise of carbon dioxide*. Science.nasa.gov. https://science.nasa.gov/resource/graphic-the-relentless-rise-of-carbon-dioxide/

NASEM Committee. (2022). *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration*. National Academies Press. https://doi.org/10.17226/26278

Ocean Fertilization – OceanNETs. (n.d.). Www.oceannets.eu. https://www.oceannets.eu/ocean-fertilization/

Ocean Visions | mCDR Field Trial Database. (2024, September 9). Ocean Visions. https://oceanvisions.org/mcdr-field-trials/

Oschlies, A., Bach, L. T., Rosalind, Satterfield, T., Webb, R., & Gattuso, J. (2023). Climate targets, carbon dioxide removal, and the potential role of ocean alkalinity enhancement. *State of the Planet*, *2-oae2023*, 1–9. https://doi.org/10.5194/sp-2-oae2023-1-2023

Oschlies, A., Pahlow, M., Yool, A., & Matear, R. J. (2010). Climate engineering by artificial ocean upwelling: Channelling the sorcerer’s apprentice. *Geophysical Research Letters*, *37*(4). https://doi.org/10.1029/2009gl041961

Rise of Carbon Dioxide Unabated. (2020, June 4). Scripps Institution of Oceanography. https://scripps.ucsd.edu/news/rise-carbon-dioxide-unabated

Siikamäki, J., Sanchirico, J. N., Jardine, S., McLaughlin, D., & Morris, D. (2013). Blue Carbon: Coastal Ecosystems, Their Carbon Storage, and Potential for Reducing Emissions.

Environment: Science and Policy for Sustainable Development, *55*(6), 14–29. https://doi.org/10.1080/00139157.2013.843981

United Nations Treaty Collection. (2015). *UNTC*. Un.org. https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-d&chapter=27&clang=_en

US EPA. (2017, January 23). *Climate Change Indicators: Atmospheric Concentrations of Greenhouse Gases | US EPA*. US EPA. https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases