THE ABDULLAH BIN HAMAD AL ATTIYAH FOUNDATION

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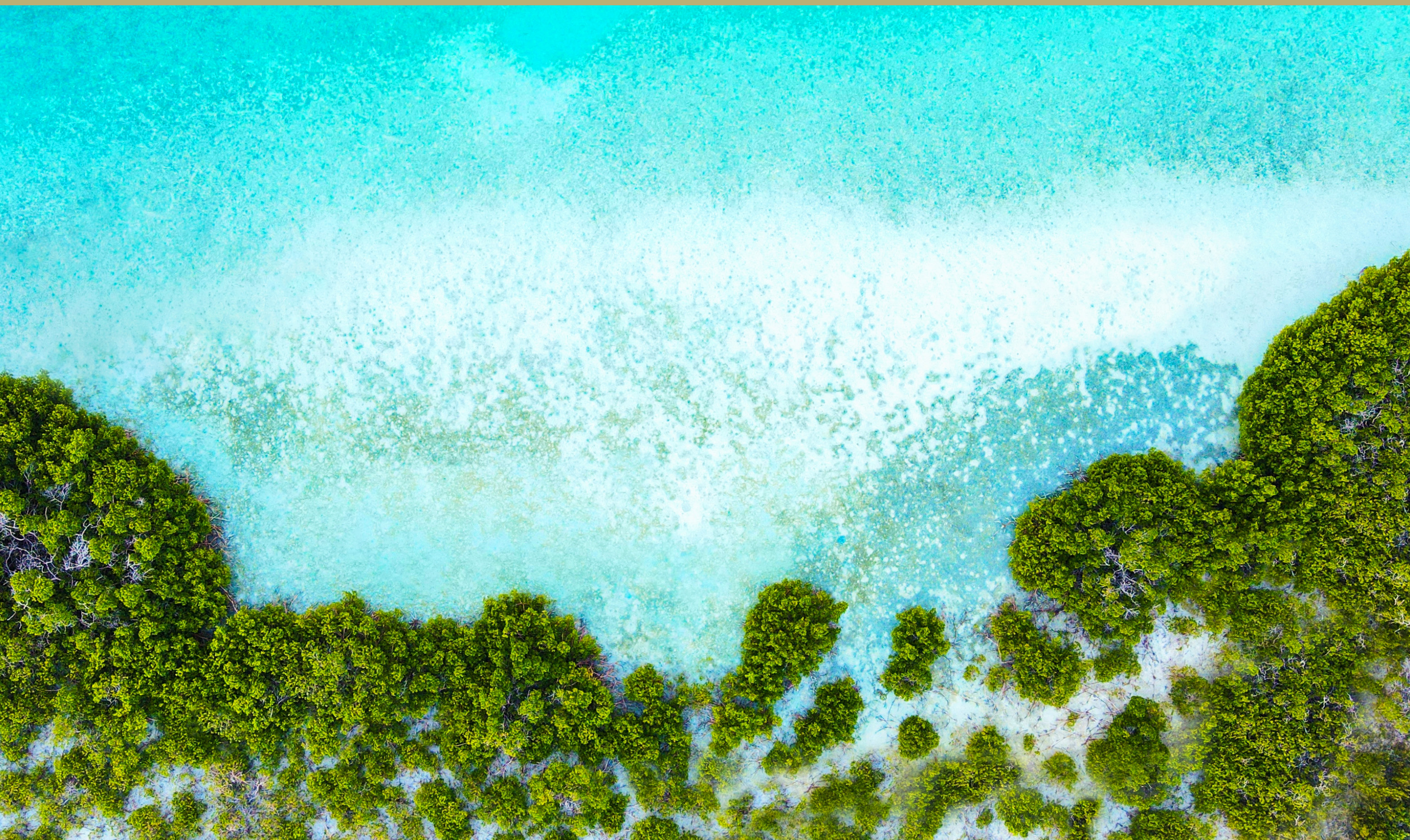
Marine Carbon Dioxide Removals (mCDR) – Emerging Technologies and Regulation at Various Levels



Sustainability Research Paper

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INTRODUCTION

Alongside substantial and rapid emissions reductions, Carbon Dioxide Removal (CDR) is necessary to keep global warming to well below the 2°C temperature goal set by the Paris Agreement. The Intergovernmental Panel on Climate Change (IPCC) and the global community have emphasised the importance of CDR to reduce atmospheric CO2 and manage potential overshoot scenarios. While the attention has so far predominantly focused on land-based CDR methods, marine CDR (mCDR) approaches have increasingly moved into the spotlight. What significant challenges does the implementation of mCDR methods face? How can dedicated political solutions help address the challenges associated with mCDR? What are the strengths and limitations of the most prominent mCDR approaches?

SUSTAINABILITY RESEARCH PAPER

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03 EXECUTIVE SUMMARY

- To meet the Paris Agreement´s temperature goals, substantial amounts of CDR are required alongside emissions reduction.
- Marine CDR (mCDR) has potential, but also faces significant challenges, with most of the attention focussed on land-based CDR methods to date.
- Different approaches are being developed, with unique characteristics and challenges.
- Policy challenges include moderating land-use issues, MRV ability of mCDR methods and lack of legal frameworks in domestic as well as international contexts.

BACKGROUND

To prevent dangerous levels of climate change, the parties to the Paris Agreement have committed to limiting the global average temperature increase to well below 2°C, while pursuing efforts to limit warming to 1.5°C above pre-industrial levels. Reaching these goals depends on the near-term plateauing of anthropogenic greenhouse gas emissions followed by rapid emissions reductions. However, the growing delays in reducing emissions, coupled with the need for a net-negative emissions balance to reach net-zero emissions in the second half of the century, make this goal unachievable without the deployment of substantial amounts of Carbon Dioxide Removal (CDR), as affirmed by the Intergovernmental Panel on Climate Change (IPCC) in its Special Report on global warming of 1.5°C1 and its recent Sixth Assessment Report[2]. Only with CDR can we further address the increasingly likely overshoot scenarios, in which temperatures temporarily exceed the Paris targets before being reduced again.

Among the various CDR approaches, marine Carbon Dioxide Removal (mCDR) has significant potential. Innovations in coastal, nearshore, and offshore areas offer promising avenues for carbon sequestration in marine environments. However, the implementation of these methods is fraught with challenges, including regulatory issues, particularly in high seas, environmental concerns stemming from existing knowledge gaps, and complexities related to Measurement, Reporting, and Verification (MRV) and accounting.

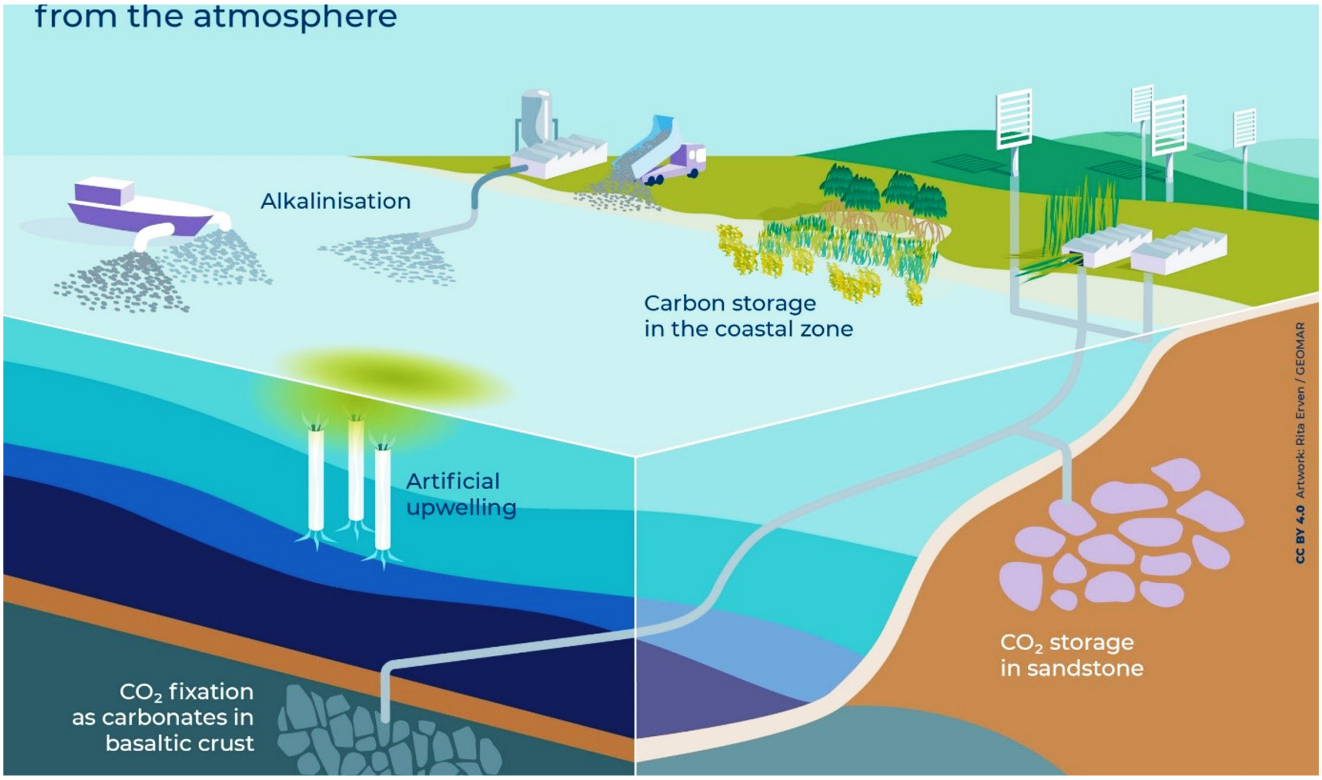
This paper aims to provide an overview of existing mCDR methods, exploring their potential and examining the regulatory and governing challenges associated with their deployment.

There are various methods of mCDR, ranging from ecosystem-based approaches to technical methods including artificial upwelling and downwelling, ocean alkalinity enhancement as well as direct ocean capture. What the various methods have in common is their approach to mimicking and enhancing existing biological and geochemical processes in the ocean to remove atmospheric CO2, and in most cases, sequester the captured carbon in different ways in the ocean. While these approaches show promise in contributing to net-zero emissions, most are still in the early stages of development. Thus, it is crucial to understand their potential strengths, weaknesses, and the challenges they face before considering large-scale deployment.

Ecosystem-based approaches of mCDR leverage the natural ability of marine organisms to capture and sequester CO2. In coastal ecosystems, marine vegetation absorbs CO2 through the air via photosynthesis or from water via their roots. The carbon is then stored in their biomass or in the surrounding sediment. Three primary ecosystems are commonly discussed for mCDR and they are as follows:

Seagrasses are underwater flowering plants found in shallow coastal waters, that through photosynthesis, absorb CO2, storing it in their leaves, roots, and surrounding sediments. This process depletes CO2 in surface waters, prompting further atmospheric CO2 to dissolve into the ocean via air-sea gas exchange. Despite covering only 0.1% of the ocean floor, seagrass meadows account for 10–18% of oceanic carbon storage, sequestering 48 to 112 teragrams of carbon annually, making them highly effective carbon sinks.[4]

Figure 1: Visualisation of the Different mCDR Methods



Source: Keller et al. (2022)[3]

Kelp forests, formed by large brown algae, represent another promising natural method for ocean-based carbon sequestration. Growing in nutrient-rich, cooler coastal waters, kelp absorbs CO2 during photosynthesis and stores it in its biomass. When parts of the kelp break off, they sink to the ocean floor, where the carbon they contain is sequestered for long periods. This natural process not only captures atmospheric CO2 but also provides essential ecosystem services, including habitat and food for a diverse array of marine species.[5]

Mangrove forests are highly efficient carbon sinks capable of storing large amounts of carbon both in their biomass and, more significantly, in the underlying soil. Unlike other forests, mangroves' waterlogged soils slow the decomposition process allowing organic matter to accumulate as peat rather than releasing stored carbon back into the atmosphere.

Beyond their carbon storage capabilities, mangroves provide vital ecosystem services, such as preventing coastal erosion, protecting shorelines from storm surges, supporting biodiversity, and purifying water.[6]

Technical Approaches involve human-engineered solutions to enhance the ocean's capacity to absorb and store CO2, usually requiring advanced technology and infrastructure.

Artificial Upwelling involves pumping nutrient-rich cold water from the ocean's depths to the surface, where the combination of sunlight and nutrients stimulates the growth of microalgae. These algae absorb CO2 through photosynthesis, and, when they die, their biomass sinks to the seafloor, storing carbon in the deep ocean.

Downwelling, on the other hand, works by moving carbon-rich surface water to deeper layers, where the carbon is stored over longer time scales. This process can be achieved through cooling, increasing water salinity, or using mechanical pumps to drive the water downward.[7]

Ocean Alkalinity Enhancement (OAE) aims to increase the ocean's natural ability to absorb and store CO2 by raising the pH and alkalinity of seawater. This is typically achieved through processes such as accelerated mineral or rock weathering, where minerals like olivine are introduced to seawater to chemically alter its composition, or through electrochemical methods.[8]

Direct Ocean Capture (DOC) is a fully engineered process designed to extract CO2 directly from seawater, similar to the concept of Direct Air Capture (DAC).

The aim is to chemically remove dissolved CO2 from the ambient marine environment for long-term storage, typically in geological reservoirs. One method involves inducing pH swings, where changes in water acidity allow for CO2 extraction, while another approach uses specific solvents to capture CO2. Once extracted, the CO2 can be transported for storage in geological formations beneath the seabed or converted into carbonates, which can be safely stored in the ocean.[7]

Table 1. Overview of Advantages, Disadvantages and Challenges of Different mCDR Approaches[3,7]

mCDR approach	Working principle	Advantages	Challenges
Ecosystem-based methods in coastal zone	Biota (typically seagrass, macroalgae, mangroves) take up CO_2 via photosynthesis; storage in soil, water, biosphere	• Methods already established • Often co-benefits (biodiversity, tourism, fisheries, coastal protection) • Coastal zone regulated on national level	• Conflicts of interest regarding land use • Limited potential • Stocktake currently incomplete
Artificial upwelling and down-welling	Enhancing the natural ocean circulation to increase the upwelling of nutrient-rich waters or downwelling of surface waters to sequester carbon	• Potential co-benefits (fisheries and source of cold water for seawater-based air conditioning)	• Low technology readiness level • Large infrastructure required • Low CO_2 removal potential • Potential threat that dissolved CO_2 re-enters atmosphere • Environmental impacts unknown: changing seawater temperature and salinity might affect ecological cycles and climate • Legal frameworks needed
Ocean Alkalinity Enhance-ment	Adding alkaline substances to ocean waters to increase their capacity to absorb CO_2 and form stable carbonate minerals	• High durability and efficacy • Reduce ocean acidification locally (beneficial for certain organisms)	• Low to medium technology readiness level • Expansion of mining operations • Lack of public acceptance • Weathering of alkaline minerals may release byproducts, with unforeseen ecosystem impacts • Interactions between OAE and other ocean-based activities will also need to be considered • Legal frameworks needed
Direct Ocean Capture	Capturing CO_2 directly from the ocean and storing it either in the ocean or on land	• High precision in CO_2 capture • High durability and efficacy	• Complex and high energy demand to drive the deployment • More costly than other mCDR technologies • Potential impacts on marine ecosystems • Legal frameworks needed

Source: Authors

Ecosystem-Based Approaches

From a technological readiness perspective, ecosystem-based approaches are both cost effective and poised for immediate implementation, as many of these methods have already been proven and could be operational within relatively short timelines. Additionally, when executed with appropriate care and continuous management, these approaches can yield significant co-benefits including enhancements in biodiversity, improvements in fisheries, boosts to tourism, and better water quality.

However, despite their cost effectiveness and ease of implementation, ecosystem-based approaches face several key challenges. Adequate MRV involves dealing with high temporal and spatial variability and the complex carbon cycles in marine ecosystems. Coastal ecosystems, in particular, experience highly variable light and temperature conditions due to turbulent mixing from waves and tides, which can affect the consistency of carbon sequestration potential.7 Additionally, the fluxes of other greenhouse gases and carbonate dynamics are not always fully accounted for, and the long-term security of carbon storage may be threatened by future climate change or direct anthropogenic influences.[9, 10]

Moreover, while these approaches offer the potential for job creation and economic opportunities, such as in seaweed cultivation, their potential is further limited by competing land and coastal uses.9

Technological Approaches

Large-scale technological approaches to CDR exhibit substantial theoretical potential. Ocean alkalinity enhancement and direct ocean capture promise a high efficacy and durability, making them promising solutions in the pursuit of net-zero goals.

While some technological approaches are relatively straightforward to deploy, they often come with considerable energy requirements and infrastructural demands. Deploying these methods requires investment not only in the removal technologies themselves but also in the supporting infrastructure along the value chain, such as for alkalinity enhancement the mineral extraction, transport, and storage. Therefore, the cost of mCDR technologies is estimated to be rather expensive ranging from $100/tCO2 to well over $2,500/tCO2, excluding additional expenses for MRV.[7]

The deployment of technological mCDR methods further carries significant, yet largely uncertain, environmental risks. For instance, increasing ocean alkalinity could inadvertently alter biogeochemical processes, affect phytoplankton species composition, and introduce trace minerals into marine systems. Similarly, artificial upwelling and downwelling may affect seawater temperature and salinity, potentially disrupting ecological cycles and influencing climate patterns. In addition, the expansion of mining operations and resource extraction required for these technologies may lead to both environmental and climatic side effects.[7,11]

The uncertainty surrounding these technological approaches is substantial, primarily due to the lack of long-term, large-scale research. This uncertainty spans various aspects, including the feasibility of MRV, as well as regarding the timescales of carbon storage. Additionally, issues related to termination effects, similar to those discussed in Solar Radiation Management (SRM), require further investigation.

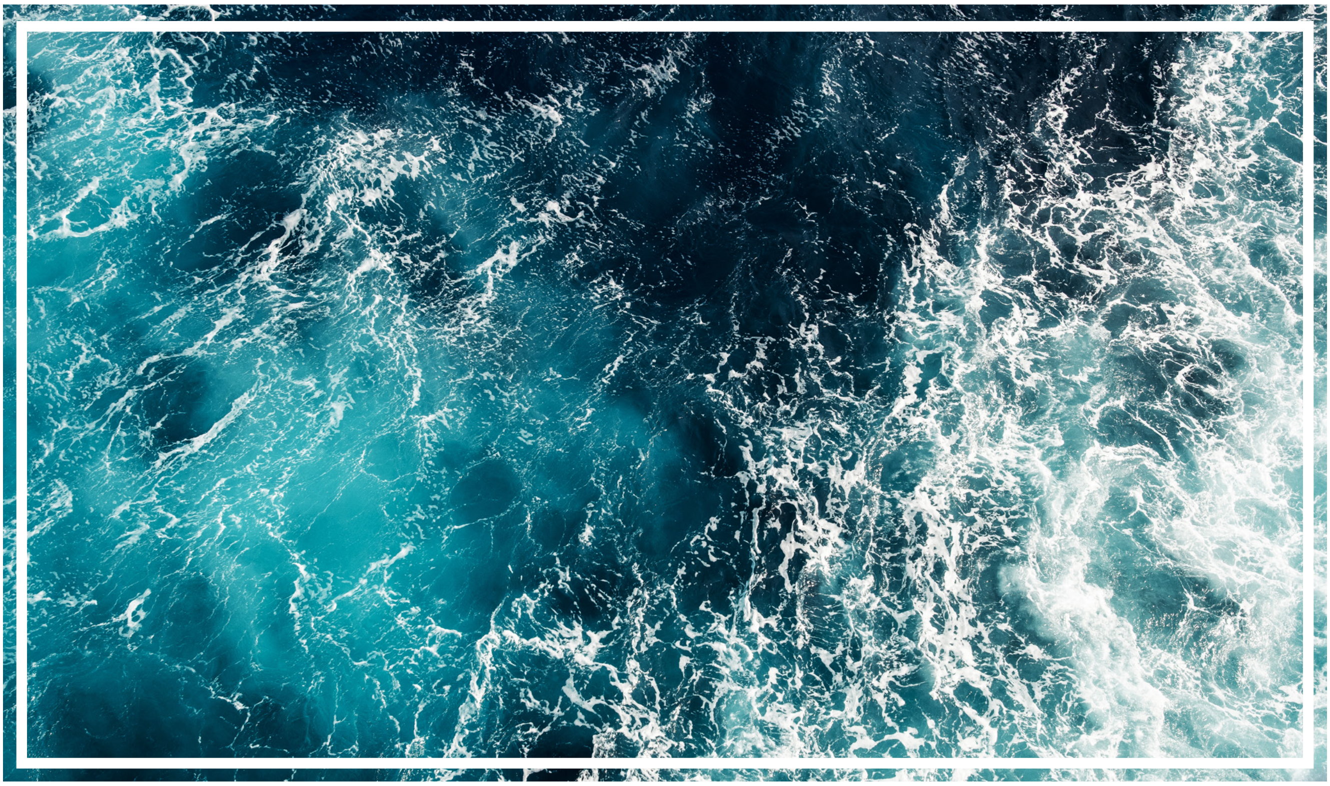
Effective governance of mCDR involves the consideration of numerous ethical dimensions, regarding the choice of appropriate mCDR methods as well as policy instruments and frameworks. [12, 13, 14]

At the local level, Exclusive Economic Zones (EEZs) are usually relevant when governing marine activities, as within these zones (up to 370 km from a countries coastline), national or local authorities have special rights regarding the exploration and use of marine resources. In the U.S., for example, proposals for mCDR projects within the EEZ could fall under existing laws such as the Marine Protection, Research, and Sanctuaries Act, the Coastal Zone Management Act, and Section 10 of the Rivers and Harbours Act of 1899.15 To specifically address mCDR challenges, existing regulations need to be adapted to avoid conflicts of interest and ensure that local livelihoods are considered. Therefore, involving local communities and stakeholders in decision-making processes is crucial to address their concerns, incorporate their knowledge, and gain public acceptance.

Nationally, it is imperative to integrate mCDR into broader climate strategies, such as net-zero emissions plans, to enhance the overall effectiveness of climate mitigation efforts. Governments need to carefully evaluate and decide which mCDR methods to apply, considering factors such as environmental impact, scalability, and cost effectiveness. Developing policies to incentivise these methods is crucial for their widespread adoption. This could involve financial incentives, such as grants and tax credits, to lower the initial investment costs, subsidies to make mCDR technologies more accessible, and regulatory measures that mandate or encourage the use of specific mCDR methods.[16]

At the international level, a cohesive approach is necessary to manage high-risk applications of mCDR, similar to the ongoing discussions around SRM. Marine CDR must align with international law, particularly the 1982 United Nations Convention on the Law of the Sea (UNCLOS), which provides a legal framework for all marine activities. Ocean-based methods that involve adding substances to the marine environment, such as ocean alkalinity enhancement and iron fertilisation, are regulated by the London Convention and its 1996 Protocol, which aim to prevent marine pollution. In 2013, the London Protocol was amended to include "marine geoengineering," making it the first binding international regulation on ocean-based CDR.3 However, only ocean iron fertilisation has been added to the list of regulated activities, and the amendment has not yet entered into force. There are also concerns about whether the existing regulatory frameworks are both flexible and precautionary enough to accommodate the challenges such as liability, risk mitigation, and the necessary MRV associated with mCDR.

11 CONCLUSION



mCDR offers significant potential but varies widely across different methods in terms of removal potential, technology readiness, societal acceptance, and regulatory clarity. Coastal ecosystem-based approaches often present co-benefits and are easier to regulate, but they face challenges related to land use, local livelihoods, and overall effectiveness.

On the other hand, technical methods applied in international waters offer greater potential due to their scalability, yet they come with higher levels of uncertainty, lower public acceptance, and complex regulatory challenges. To maximise mCDR's potential, policy frameworks are needed at local, national, and international levels to address these diverse challenges and guide responsible deployment.

1. Masson-Delmotte, V., Zhai, P., Pörtner, H. O., Roberts, D., Skea, J., & Shukla, P. R. (2022). Global Warming of 1.5 C: IPCC special report on impacts of global warming of 1.5 C above pre-industrial levels in context of strengthening response to climate change, sustainable development, and efforts to eradicate poverty. Cambridge University Press. https://doi.org/10.1017/9781009157940

2. IPCC (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115. https://doi.org/10.59327/IPCC/AR6-9789291691647

3. Keller, D., Ketelhake, S., Meyer, J., Neumann, B., Oschlies, A., Proelß, A., Rickels, W. (2022). Achieving Climate Neutrality and Paris Agreement Goals: Opportunities for Ocean-Based Methods of Carbon Dioxide Removal, Science Policy Brief, DOI: 10.3289/cdrmare.oceannets_1

4. Greiner, J. T., McGlathery, K. J., Gunnell, J., & McKee, B. A. (2013). Seagrass restoration enhances "Blue carbon" sequestration in coastal waters. PLoS ONE, 8(8), e72469. https://doi.org/10.1371/journal.pone.0072469

5. Alongi, D. M. (2018). Blue carbon: Coastal sequestration for climate change mitigation. Cham, Switzerland: Springer.

6. Friess, D. A., Krauss, K. W., Taillardat, P., Adame, M. F., Yando, E. S., Cameron, C., Sasmito, S. D., & Sillanpää, M. (2020). Mangrove blue carbon in the face of deforestation, climate change, and restoration. Annual Plant Reviews Online, 427–456. https://doi.org/10.1002/9781119312994.apr0752

7. National Academies of Sciences, Engineering, and Medicine. (2022). A research strategy for ocean-based carbon dioxide removal and sequestration. https://nap.nationalacademies.org/catalog/26278/a-research-strategy-for-ocean-based-carbon-dioxide-removal-and-sequestration?utm_source=nationaltribune&utm_medium=nationaltribune&utm_campaign=news

8. 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

9. Mengis, N., Paul, A., & Fernández-Méndez, M. (2023). Counting (on) blue carbon—Challenges and ways forward for carbon accounting of ecosystem-based carbon removal in marine environments. PLOS Climate, 2(8). https://doi.org/10.1371/journal.pclm.0000148

10. Williamson, P., & Gattuso, J. (2022). Carbon removal using coastal blue carbon ecosystems is uncertain and unreliable, with questionable climatic Cost-Effectiveness. Frontiers in Climate, 4. https://doi.org/10.3389/fclim.2022.853666

11. Lebling, K., Northrop, E., McCormick, C., & Bridgwater, L. (2022). Toward responsible and informed ocean-based carbon dioxide removal: Research and governance priorities. towards-responsible-and-informed-ocean-based-carbon-dioxide-removal.pdf (wri.org)

12. Baatz, C. et al. (2024). A Holistic Assessment Framework for Marine Carbon Dioxide Removal Options. Unpublished Manuscript.

13. Holland-Cunz, A., Baatz, C. (submitted). How to govern Carbon Dioxide Removal: An Assessment Framework for Policy Instruments. Submitted to Climate Policy.

14. Honegger M., Baatz C., Eberenz S., Holland-Cunz A., Michaelowa A., Pokorny B., Poralla M. and Winkler M. (2022). The ABC of Governance Principles for Carbon Dioxide Removal Policy. Frontiers in Climate 4:884163. https://doi.org/10.3389/fclim.2022.884163

15. Keating-Bitonti, C., Jordan, M., Gatz, L., Marshak, A. (2024). Selected Potential Considerations with Respect to Marine Carbon Dioxide Removal: In Brief https://crsreports.congress.gov/product/pdf/R/R48159

16. Winkler, M., Holland-Cunz, A., Honegger, M., Oh, S., Poralla, M., Vollmer, A., Michaelowa, A. (submitted). Exploring Key Dimensions of Policy Instruments for Carbon Dioxide Removal. Submitted to Climate Policy.

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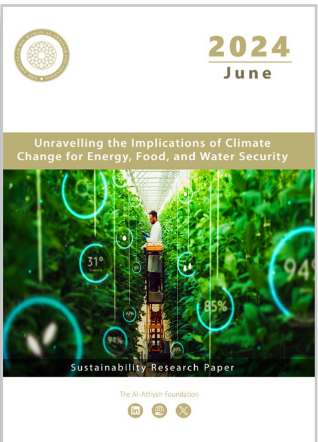

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