Marine Carbon Dioxide Removal (mCDR) in Canada: Opportunities and Challenges

Waterloo Climate Institute Policy Brief

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ABSTRACT

Marine carbon dioxide removal (mCDR) techniques could play an important role in helping Canada reach its net-zero emissions goal. However, these techniques also come with environmental, political, and social challenges. Since Canada has the world's longest coastlines, and an increasing number of private sector actors actively engaged in the research and development of mCDR, there is a pressing need for a clear and proactive federal strategy on mCDR. This policy brief highlights the current state of mCDR in Canada, the key uncertainties and challenges, and offers specific recommendations for a national mCDR strategy.

Keywords: Canada; climate mitigation; marine carbon dioxide removal; ocean policy

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KEY MESSAGES

- Marine carbon dioxide removal (mCDR) approaches are emerging and could make significant contributions to achieving net-zero GHG emissions but they face critical scientific, social, and regulatory challenges.
- Canada needs to act quickly to create a mCDR research strategy, including research priorities and associated funding, and ensuring regulatory oversight of field experiments.
- Public engagement and transparency in research governance must be included in both project-level processes and Canada's overarching mCDR strategy.
- While carbon dioxide removal may play an important role in meeting Canada's climate commitments, it comes with significant risks and should not replace efforts to reduce emissions .

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INTRODUCTION

Exploring the Pros and Cons of Marine CDR Implementation.

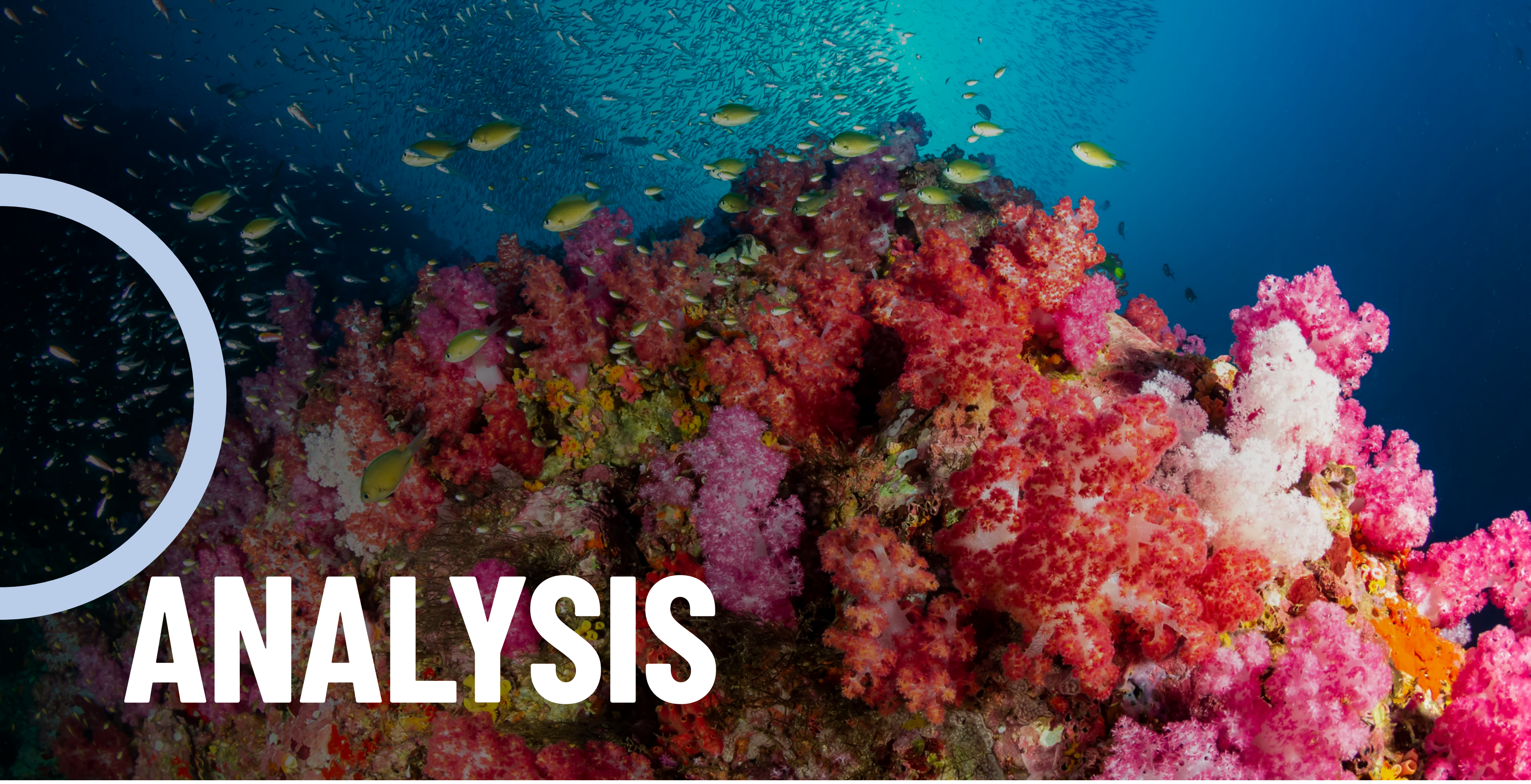
Canada has committed to reach net-zero greenhouse gas (GHG) emissions by 2050 as part of its most recent Nationally Determined Contribution.[1] Net-zero emissions does not mean zero emissions, since this commitment anticipates that by 2050 Canada will still emit 100 to 300 metric tonnes (Mt) of CO2 from hard to reduce emission sources (e.g., aviation, cement production) and from ongoing fossil fuel use in certain sectors of Canada's economy.[2] To reach net-zero, Canada must deploy carbon dioxide removal (CDR) techniques at large scales to offset these remaining emissions. While emissions reductions prevent new GHGs from entering the atmosphere, CDR removes CO2 from the atmosphere and stores it in geological or biological reservoirs.[3]

The Intergovernmental Panel on Climate Change (IPCC) in its most recent Assessment Report (AR6) underscored the need to scale up CDR techniques to limit global warming to 2 degrees Celsius compared to pre-industrial levels.[4] Specifically, IPCC scenarios that limit warming to 1.5-degrees project an average annual removal of around 7.3 gigatons (Gt) of CO_2 by 2050. This is roughly equal to the current CO_2 emissions from global production of oil (4Gt) and gas (3Gt) combined, and far more than current practices.[5] Canada can and should make a significant contribution to this removal effort.

Most of the CDR approaches, such as afforestation and reforestation (A/R) (planting trees) or using direct air capture and storage (DACCS), currently being considered and deployed at small or medium scales are land-based. However, concerns such as competition for land use, biodiversity impacts, and energy input requirements, have led to a significant shift towards exploring ocean-based or marine carbon dioxide removal (mCDR) approaches.[6] Since the ocean covers approximately 70% of the Earth's surface and absorbs approximately a quarter of GHG and related emissions, enhancing the ocean's capacity to absorb CO2 through biological and chemical processes has the potential to provide gigaton scale CDR.[7] This has sparked rapid interest from both government and industry in mCDR research and development.

However, intervening in the ocean raises significant concerns. Some mCDR processes involve adding substances to the marine environment, which could pose environmental risks.[8] There are also questions about the effect of mCDR activities have on other ocean users, such as fisheries, as well as the potential impacts on coastal communities.[9] With the ocean already under significant stress from climate change, overfishing, pollution, and other factors, large-scale mCDR deployment introduces complexity to the challenges for ocean health and governance.[10] Moreover, relying on CDR as a climate response is controversial as it risks diverting attention and funding from essential GHG reduction efforts, a phenomenon known as 'mitigation deterrence.'[11]

The stakes for mCDR are high. Canada, with the longest coastline in the world and strong expertise in ocean science, is uniquely positioned to lead in mCDR research and development. However, managing the risks and rewards of mCDR responsibly is crucial not only for Canadian climate policy and ocean health, but also for the nation's ocean innovation sector. This policy brief provides an overview of Canada's emerging mCDR landscape and the key issues facing regulators.

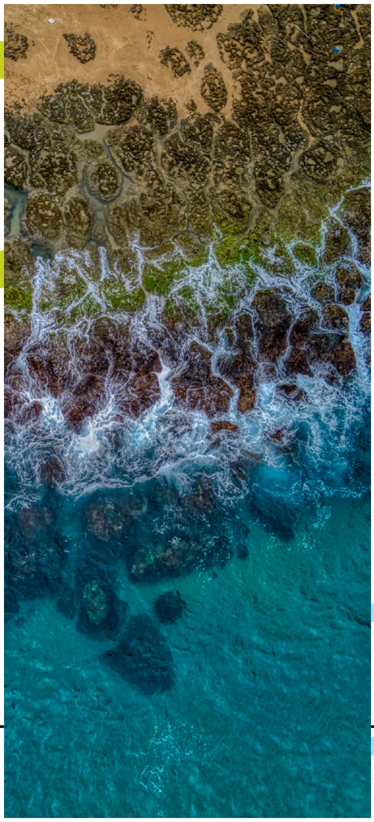


ANALYSIS

Marine carbon dioxide removal (mCDR) encompasses a diverse array of methods that leverage the ocean's physical, geochemical, and biological processes to accelerate carbon removal and storage (see the descriptions of different processes in Box 1). Table 1 presents a summary of knowledge regarding important characteristics for the proposed mCDR methods. The data presented in Table 1 was compiled using key reports and sources evaluating mCDR methods from 2022-2024.

More Research is Needed to Address the Uncertainties of Marine Carbon Dioxide Removal

The current understanding of most mCDR methods, with the exception of coastal blue carbon, is low. Marine CDR methods are experimental and require a significant amount of further research to better understand their effectiveness and attendant risks.[13] The technological readiness level (TRL), which is measured on a scale of 1 (lowest) to 9 (highest), generally indicates that these technologies require significant further investigation and therefore their deployability remains uncertain.[14] *cont'd on page 7*



BOX 1 : OVERVEIW OF MARINE CARBON DIOXIDE REMOVAL METHODS

Marine carbon dioxide removal methods are categorized into three categories:

1. BIOLOGICAL CARBON PUMP ENHANCEMENT: These methods aim to increase the ocean's natural biological pump capacity. The biological carbon pump is part of the oceanic carbon cycle where inorganic carbon is fixed into organic matter via photosynthesis and then sequestered from the atmosphere generally by transport into the deep ocean. There are four methods which fall under this category:

- **Ocean Nutrient Fertilization (ONF):** The addition of nutrients (i.e., iron, nitrogen, phosphorus) to nutrient-poor surface level ocean waters to stimulate phytoplankton activity to enhance carbon sequestration via photosynthesis.
- **Artificial Upwelling/Downwelling:** The use of mechanical pumps to bring nutrient-rich deep ocean waters to the surface (upwelling) to stimulate phytoplankton activity or transport of surface waters rich in CO2 to deep ocean layers (downwelling) to increase sequestration permanence.
- **Macroalgae Cultivation:** Large-scale seaweed/kelp farming in the open-ocean via structures (ropes, nets, buoys, floating platforms) to absorb CO2 through photosynthesis. The seaweed is then sunk to the deep ocean for sequestration.
- **Ecosystem Recovery/Coastal Blue Carbon:** Restoration projects that aim to enhance the ability of coastal and marine ecosystems, such as mangroves, salt marshes, and seagrasses, to sequester carbon dioxide.

2. CHEMICAL MCDR: These methods use chemical processes to enhance the ocean's ability to absorb and store CO2. The primary method is **Ocean Alkalinity Enhancement (OAE)**, which involves adding alkaline substances to seawater via open-ocean distribution or the use of wastewater treatment discharge. The added alkalinity converts dissolved CO2 to bicarbonates, which in theory increases the capacity of the ocean to absorb more carbon dioxide from the atmosphere at a faster rate, facilitating long-term storage of CO2 in seawater.

3. ELECTROCHEMICAL MCDR: These methods involve using electricity to drive chemical reactions to either enhance the ocean's ability to uptake CO2 or to remove CO2 from the seawater. There are two methods which fall under this category:

- **Electrochemical OAE**: This method uses electrical energy to drive chemical reactions within a unit that either produces alkaline substances or removes acidic compounds from the seawater. This method can be conducted onshore, where seawater is pumped in, treated, then discharged back into the ocean in a neutralized state, or on units that can be installed on offshore platforms or ships.
- **Direct Ocean Capture (DOC)**: Technologies designed to directly extract or 'strip' CO2 from seawater using electrochemical and physical processes. One variation passes seawater through an electrodialysis unit where electric fields are used to separate and remove CO2 by splitting water molecules. The released CO2 is then captured and can be stored either in terrestrial reserves or injected into the deep ocean. Neutralized seawater is then released back into the ocean.

Table 1. This table presents data about important characteristics of mCDR methods that policymakers need to consider. The data was compiled using six leading reports and sources that analyze mCDR technologies [A: NASEM, 2022; B: IPCC AR6, 2023; C: State of CDR, 2024; D: NOAA, 2023; E: Ocean Visions, 2024; F: CICE/IBET, 2024].[12]

Key Characteristics of MCDR Methods- An Overview

	Ocean Nutrient Fertilization	Artificial Upwelling /Downwelling	Seaweed Cultivation	Ecosystem Recovery/Blue Carbon	Ocean Alkalinity Enhancement	Electrochemical Processes
Knowledge Base	Medium-High [A]	Low-Medium [A]	Medium-High [A]	High [A]	Low-Medium [A]	Low-Medium [A]
Technology Readiness Level (TRL)	1-2 [B]; Low [C] Moderate [D]; 5 [E]	Low [D]; 4 [E]	Moderate [D]	2-3 [B]; High [C, D]	1-2 [B]; Low [C]; Low-Moderate [D]; 6 [E]	Low [C[; Low-Moderate [D]; 5 [E]
Durability of storage (Years)	10-100 [A, B, E,F]; 100-1000 [C]	10-100 [A,D,E,F]	10-100 [A,D,F]; 100-1000 [E]	10-100 [A, C, D,E,F]	>100 [A]; >1000 [C, F]; >20,000 [D,E]	>100 [A]; >1000 [C]; 10000 [E, F]; >10000 [D]
Scalability (GtCO_2/year)	0.1-1 [A, D, E, F]; 1-3 [B]; 3-9 [C]	0.1-1 [A,D, F]; <0.1 [E]	0.1-1 [A,E,F]; 0.1-0.6 [D]	0.1-1 [A, B, F]; <3 [C]; 0.1-0.4 [D]; 0.008-0.117 [E]	0.1-1 [A]; 1-100 [B]; >9 [C]; >1 [F]; 1-15 [D,E]	0.1-1 [A]; >9 [C]; 1-10 [D, E]; <1 [F]
Costs (US/tCO_2$)	<50 [A]; 50-500 [B]; 50-125 [D]; Insufficient data [F]	> 100-150 [A]; 100-150 [D]; Insufficient data [F]	100 [A]; 100-400 [F]; 25-125 [D,E]	<50 [A]; 100-1000 [B]; 10-50 [D,F]	100-150 [A]; 40-260 [B]; 160 [D,E]; 100-130 [F]	150-2500 [A]; 400-600 [D]; 100-350 [E]; 250-290 [F]
Environmental Risks	Medium [A]	Medium-High [A]; Uncertain but likely high [E]	Medium-High [A]	Low [A]	Medium [A]	Medium-High [A]
Co-benefits	Medium [A]; Unknown [E]	Medium-High [A]; Unknown [E]	Medium-High [A]	High [A]	Medium [A]	Medium-High [A]
Monitoring, Regulation and Verification (MRV) challenges	Medium [A]; Difficult [F]	High [A]; Difficult [F]	Low-Medium [A]; Medium [F]	High [1]; Difficult [E, F]	Low-Medium [A]; Medium [F]	Medium [F]
Other resources	Low-Medium [A]	Medium-High [A]	Medium [A]	Low [A]	Medium-High [A]	Medium-High [A]

More Research is Needed to Address the Uncertainties of Marine Carbon Dioxide Removal

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The research needs vary depending on the technology, but many uncertainties will need more field testing to assess their efficacy and evaluate what risks they pose under real-world conditions. Field experiments should focus on identifying potential test sites and a clear approvals process that includes public consultation. The environmental risks associated with mCDR are currently estimated to be medium or high for most approaches and would largely be dependent on scale and site-specific characteristics of the intervention. The uncertainty surrounding the environmental implications of mCDR is exacerbated by the complexity of ocean ecosystems.

A critical research area is understanding the technological and economic characteristics of different technologies to better inform integrated assessment models (see Box 2). These models provide insight into the broader impacts of different social and technological pathways to meeting climate goals. At present, mCDR methods are not represented in these models, creating a significant gap in our understanding of the future role for mCDR. Reliance on unproven mCDR approaches in mitigation planning exercises may lead to lower ambitions on emission reduction efforts. Developing and funding a focused research strategy is an important early step to reduce these critical uncertainties to assess mCDR's potential.

BOX 2 : MCDR AND INTEGRATED ASSESSMENT MODELS

Currently, the potential role that mCDR may play in Canadian mitigation strategies is unknown. Policymakers use integrated assessment models (IAMs) to provide insight into economically and technologically feasible pathways to achieve climate goals, such as meeting the net-zero target by 2050. In the latest Intergovernmental Panel of Climate Change (IPCC) Assessment Report (AR6), all 330 scenarios capable of achieving the 1.5-degree Celsius target include forms of CDR, but none of these scenarios accounted for mCDR specifically. Despite progress, the representation of mCDR methods in modeling remains under-developed compared to land-based methods.[15] Given the crucial role of IAMs in facilitating policy discussions on the relative efficacy of different interventions, there is an urgent need to incorporate a broad spectrum of mCDR techniques into models to avoid the oversimplification and overreliance on singular technologies.[16] For example, two recent studies introduced mCDR techniques such as direct ocean capture and ocean alkalinity enhancement into their models with the results suggesting a limited role for mCDR.[17]

Incorporating a diverse array of mCDR techniques into IAMs is favored over a constrained set. We emphasize the need for modeling studies to include mCDR methods in their models. However, modelers must proceed with careful consideration of the assumptions associated with these methods, as most are still emerging and need further investigation into their techno-economic characteristics.

Public Support and the Method of mCDR Determine the Scalability of Its Implementation

The ability to scale mCDR methods is highly variable and there remains disagreement among experts on how scalable these approaches really are. Ocean alkalinity enhancement appears to be the only method able to scale at levels that would make significant CDR contributions on a global scale.[18] Other methods may have potential to scale, but there is no consensus on this and, given the early stage of development of mCDR methods, the estimates of scalability must be treated with caution. The complexity of ocean processes raises the likelihood that impacts from mCDR may not scale in a linear fashion, requiring attention to experimentation across multiple scales. The assessment of scalability in Table 1 focuses on the physical attributes of the mCDR methods, but social acceptability of different approaches will be an important contributing factor to scaling mCDR.[19] Public support for mCDR will depend on benefit/risk trade-offs, and the public's understanding of the complex ethical and social questions that large-scale interventions in the ocean raise.[20] Public engagement and outreach, particularly in coastal communities, is critical for any mCDR governance framework.[21] Furthermore, consultation with Indigenous communities is especially important, given the strong cultural and economic ties that many coastal Indigenous groups have to the ocean. This includes the Crown's constitutional and human rights obligations to Indigenous groups, including commitments made under the *United Nations Declaration on the Rights of Indigenous Peoples Act*.[22]

Co-Benefits May Support Faster Implementation of mCDR

Marine CDR has the potential to generate co-benefits which could improve its social acceptability and provide additional economic and environmental justification for deployment. For example, blue carbon - despite its limited scalability and durability - may be justified on the basis of its benefits to coastal climate adaptation and resilience.[23] Ocean alkalinity enhancement uses chemical processes that reduce ocean acidification, an effect that is getting worse by increasing amounts of CO2 in the atmosphere. This is harming coral reefs and organisms with calcium-based shells (calcareous organisms).[24] The co-benefits of mCDR are identified in Table 1. These focus primarily on physical benefits, but a scaled-up mCDR industry in Canada has the potential to drive innovation, create jobs, and generate economic benefits.

Credibility of Monitoring, Reporting and Verification (MRV) methods and the role it plays in mCDR

Another key research area is developing improved methods to understand how much carbon is removed from the atmosphere through mCDR.[25] The process pathways are complex, and difficult to monitor and verify. For example, mCDR methods tend to remove carbon dioxide indirectly by affecting the amount of CO2 in the water column, which in turn influences the ability of the oceans to absorb CO2 from the atmosphere via natural processes. It is also important to note that the permanence of carbon removal varies across different mCDR methods, which must be accounted for in any credible MRV system.[26] The credibility of MRV methodologies is essential for the integration of mCDR into carbon pricing mechanisms. This will, in turn, influence the investment levels in mCDR research and development. An emerging source of research funding for mCDR is through the pre-purchase of carbon credits (on the voluntary market) generated through experimental activity.[27] However, there is an ongoing debate about whether scientific research ought to be funded through the sale of carbon credits or similar funding mechanisms, as it may create incentives to publicize positive results to secure more funding at the expense of disclosing negative findings.[28] Ensuring the integrity of early-stage carbon credits should be a high priority. If MRV is not robust it could result in eroded public confidence in mCDR, stop investments, and slow the integration of CDR into climate policy.

An Analysis of Canada's mCDR Research and Development Efforts

Canada hosts a growing number of active interest groups for mCDR (see Appendix, Table 1 & Figure 1) including private technology developers, academic institutions, civil society organizations, industrial and philanthropic funders, federal government and national science agencies. Research and development (R&D) in Canada is widespread, encompassing all mCDR techniques with the exception of artificial upwelling and downwelling (see Appendix, Figure 2). Nonetheless, R&D in Canada is currently largely focused on macroalgae cultivation and ocean alkalinity enhancement (including electrochemical OAE), with 5 ongoing projects each (3 private, 2 research for macroalgae cultivation; 2 private, 3 research for OAE methods).

Most activities are concentrated on the east and west coasts, with little formal collaboration between the coastal networks. National coordination of mCDR research and development activity would help facilitate consensus on research priorities, best practices, and innovation on how to communicate mCDR to the public.

At present, Canada lags behind the United States and Europe in providing specific supports for mCDR research and innovation. For example, in 2023 alone, U.S. federal agencies awarded over $60M in funding for mCDR research, and as of May 2024, the U.S. Department of Energy announced an additional $1.2M to accelerate the CDR industry, including support for mCDR pilots.[29] U.S. regulators are also advancing inter-agency collaboration to support R&D infrastructure and the development of protocols addressing ecosystem safety, social benefit, and economic viability.[30]

Considerations for a mCDR regulatory framework

Due to the potential risks involved, mCDR activities require regulatory oversight. Internationally, the focal point of regulation has been the London Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter.[31] This Treaty, to which Canada is a party, addressed "marine geoengineering" in a 2013 amendment to the Protocol (not yet in force).[32] It defined marine geoengineering as a "deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, lasting or severe."[33] The amendment created an Annex which lists marine geoengineering techniques that are either prohibited or can be authorized by a permit. Currently, ocean fertilization is prohibited unless it qualifies as 'legitimate scientific research', meets specific assessment criteria, and is authorized by a permit. The amendment also created a generic assessment framework for marine geoengineering activities.[34] The parties to the London Protocol are currently considering listing other forms of mCDR within the amendment, including ocean alkalinity enhancement and biomass sinking.[35] Other international instruments, such as the Paris Agreement and the United Nations Convention on the Law of the Sea, will influence the development of mCDR activities, though they are not anticipated to directly regulate mCDR activities.

Canada fulfills its commitment under the London Protocol through the Disposal at Sea provisions of the Canadian Environmental Protection Act,1999 (CEPA).[36] However, Canada has not yet ratified the 2013 amendment to the London Protocol and does not have specific regulations for mCDR. Some mCDR activities may be considered 'disposal' under CEPA and would require a disposal at sea permit, while others may be exempt (For example, CEPA does not apply to deposits from land-based outfalls). These activities could still trigger other regulatory requirements, such as those under the Fisheries Act.[37] There may be a benefit in providing technology-neutral assessment standards that provide some broader uniformity to the regulation of mCDR activities.

There are specific regulatory challenges to address, such as how to balance the potential benefits of climate mitigation efforts with potential risks to ecosystems. There are risks to the global environment in not fully exploring potential mitigation solutions. This trade off needs to be accounted for, but assessment approaches that balance different forms of risk do not easily fit into existing regulatory frameworks. Another issue is generating carbon credits from experimental activity. According to the London Protocol assessment framework, research activity should not involve financial gain.[38] Generating carbon credits to finance research could be seen as a form of economic gain, which needs to be carefully managed, especially if the pre-purchase of carbon credits provides an avenue of financing R&D activity – a practice that appears to be happening in Canada. The provision within the assessment framework limiting the financial interests in research is meant to prevent research design and outcomes from being unduly influenced by economic interests. This could be addressed through transparency disclosure mechanisms, and by offering public funding opportunities that reduce reliance on private funding sources.

MCDR FUTURES

Marine CDR may support pathways toward net-zero emissions that should be explored and assessed by the Government of Canada.

IMPLEMENTING MCDR POLICY

1. Develop and fund a national mCDR research strategy and platform that leverages pre-existing expertise and encourages international, cross-country, and interdisciplinary collaboration.

2. Public education and outreach on mCDR should focus on engaging Indigenous and coastal communities to help them understand and assess the social, economic, and political dimensions of mCDR research and deployment. These efforts should also provide opportunities for public input on the future direction of mCDR activities in Canada.

3. Domestic regulation of mCDR should align with Canada's international legal commitments.

POLICY RECOMMENDATIONS

Research and development on marine carbon dioxide removal (mCDR) in Canada is progressing quickly, but in an uncoordinated fashion. Our analysis shows that Canada is well positioned to take the lead in the responsible development and assessment of mCDR techniques. However, to do so, Canada needs a more intentional and strategic approach to mCDR policy. The following policy recommendations identify key elements in such a strategy.

1. Develop and fund a national mCDR research strategy and platform that leverages pre-existing expertise and encourages international, cross-country, and interdisciplinary collaboration.

Canadian expertise in mCDR is spread across industry, government, academia, and civil society. To identify research needs and funding priorities, an inclusive approach is needed. Dedicated workshops and communities of practice can provide a platform for collaboration and the co-development of a science-driven and fair research strategy.

2. Public education and outreach on mCDR should focus on engaging Indigenous and coastal communities to help them understand and assess the social, economic, and political dimensions of mCDR research and deployment. These efforts should also provide opportunities for public input on the future direction of mCDR activities in Canada.

Public awareness of mCDR is currently low. Incorporating public outreach initiatives can help build support for mCDR experimentation and create mCDR policies that are responsive to the needs of affected groups and communities at local and national scales.

Public consultation should be incorporated, where appropriate, into field experiment approval processes. National outreach efforts, such as consultations through the Net-Zero Advisory Board, should begin to incorporate discussion of mCDR pathways in their work.

3. Domestic regulation of mCDR should align with Canada's international legal commitments.

Public oversight of mCDR experimental activities is essential to protect the ocean environment and to maintain public confidence in the research process. The London Protocol 2013 amendment and its associated assessment process offer a sound, internationally accepted approach to governing mCDR field experiments and should guide Canada's regulatory approaches. Defining the pathways that would lead to commercial deployment will reduce regulatory risk and contribute to a more stable investment environment for private capital.

CONCLUSION

Marine CDR may support pathways toward net-zero emissions that should be explored and assessed by the Government of Canada. While mCDR is potentially significant to addressing climate mitigation and may provide important environmental co-benefits, it has environmental and social risks. Marine CDR should not be understood as a substitute for GHG emission reductions. A coordinated national research strategy on mCDR will enable future policy decisions regarding this complex and controversial response to climate change.

REFERENCES

1 Government of Canada, 2021, Canadian Net-Zero Emissions Accountability Act, Target 6. https://laws-lois.justice.gc.ca/eng/acts/c-19.3/fulltext.html.

2 T. Bushman & N. Merchant, 2023, Ready for Removal: A Decisive Decade for Canadian Leadership in Carbon Dioxide Removal, Carbon Removal Canada, p. 12. https://carbonremoval.ca/reports-resources/.

3 See official definition: 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, p. 121.

4 Ibid, p. 85.

5 K. Riahi, R. Schaeffer, et al., 2022, "Mitigation pathways compatible with long-term goals," In: IPCC, 2022, Climate Change 2022: Mitigation of Climate Change, Contribution of Working Group III to the Sixth Assessment Report, ISBN 978-92-9169-160-9, pp. 295-408; CICE & IBET, 2024, Catalyzing Carbon Dioxide Removal at Scale: A techno-economic analysis of gigatonne opportunities, p. 123. https://cice.ca/knowledge-hub/catalyzing-carbon-dioxide-removal-at-scale-report/

6 K. De Pryck & M. Boettcher, 2024, The rise, fall, and rebirth of ocean carbon sequestration as a climate 'solution', Global Environmental Change, Vol. 85, p. 7. https://doi.org/10.1016/j.gloenvcha.2024.102820

7 O. Hoegh-Guldberg, K. Caldeira, T. Chopin, et al., 2023, The Ocean as a Solution to Climate Change: Five Opportunities for Action, In: J. Lubchenco & P.M. Haugan (eds.), The Blue Compendium, Springer Publishing, p. 620. https://link.springer.com/book/10.1007/978-3-031-16277-0

8 See: Levin, Lisa A., et al. 2023, Deep-sea impacts of climate interventions. Science 379.6636: 978-981; L.T. Bach, S.J. Gill, et al., 2019, CO2 Removal with Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-Benefits for Marine Pelagic Ecosystems, Frontiers in Climate, Vol. 1, https://doi.org/10.3389/fclim.2019.00007; L. Duan, J. Song, X. Li, et al., 2023, Potential risks of CO2 removal project based on carbonate pump to marine ecosystem, Science of the Total Environment, Vol. 682, https://doi.org/10.1016/j.scitotenv.2022.160728; J. Wu, D.P. Keller, A. Oschiles, 2023, Carbon dioxide removal via macroalgae open-ocean mariculture and sinking: an Earth system modeling study, Earth Systems Dynamics, 14:1, pp. 185-221, https://esd.copernicus.org/articles/14/185/2023/; M.W. Silver, S. Bargu, et al., 2010, Toxic diatoms and domoic acid in natural and iron enriched waters of the oceanic Pacific, Proceedings of the National Academy of Sciences of the United States of America, 107 (48), https://www.pnas.org/doi/full/10.1073/pnas.1006968107#:~:text=https%3A//doi.org/10.1073/pnas.1006968107.

9 N.J. Bennett, 2019, In political seas: engaging with political ecology in the ocean and coastal environment, Coastal Management, Vol. 47, pp. 67-87, https://doi.org/10.1080/08920753.2019.1540905; M. Barbesgaard, 2018, Blue growth: saviour or ocean grabbing, The Journal of Peasant Studies. 45:1, pp. 139-149, https://doi.org/10.1080/03066150.2017.1377186; L. Ertör & M. Madjimichael, 2020, Blue degrowth and the politics of the sea: rethinking the blue economy, Sustainability Science, Vol. 15, pp. 1-10, https://doi.org/10.1007/s11625-019-00772-y.

10 IOC-UNESCO, 2024, State of the Ocean Report, Paris, IOC-UNESCO, IOC Technical Series, 190, https://doi.org/10.25607/4wbg-d349.

11 M. Boettcher, F. Chai, et al., 2023, A Code of Conduct for Marine Carbon Dioxide Removal Research,

REFERENCES

12 National Academies of Sciences, Engineering, and Medicine (NASEM), 2022, A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration, Washington, DC: The National Academies Press, https://doi.org/10.17226/26278; Intergovernmental Panel on Climate Change (IPCC), 2023, Climate Change 2022: Mitigation of Climate Change, Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Table TS.7, pp. 115-116; J.N. Cross, C. Sweeny, E.B. Jewett, et al., 2023, Strategy for NOAA Carbon Dioxide Removal Research: A White Paper documenting a potential NOAA CDR Science Strategy as an element of NOAA's Climate Interventions Portfolio, NOAA Special Report, NOAA, Washington DC, Table 1, p. 22. DOI: 10.25923/gzke-8730; B.C. Centre for Innovation and Clean Energy (CICE) & Innovative Breakthrough Energy Technologies (IBET), 2024, Catalyzing Carbon Dioxide Removal at Scale: A techno-economic analysis of gigatonne opportunities, Figure 20 - Ocean CDR Comparison Chart, p. 62; S.M. Smith, O. Geden, M.J. Gidden, et al., (eds.), 2024, The State of Carbon Dioxide Removal 2024 - 2nd Edition, Figure 1.4, p. 27, DOI 10.17605/OSF.IO/F85QJ; Ocean Visions, 2024, Ocean-Based Carbon Dioxide Removal: Road Maps. https://www2.oceanvisions.org/roadmaps/

13 For an overview of further research required see: Ocean Visions, 2024, Ocean-Based Carbon Dioxide Removal: Road Maps, https://www2.oceanvisions.org/roadmaps/. Select a mCDR method to enter its road map and then select 'Development Gaps and Needs.'

14 The concept of Technology Readiness Level (TRL) was first developed by NASA (1995) and is now widely taken as the basis philosophy for new technology graduation development stages by many agencies and organizations worldwide. The classification reflects the state of development results for wide production and/or application. See: NASA, 2017, Technology Readiness Level Definitions, https://esto.nasa.gov/trl/.

15 W. Rickels, C. Merk, F. Reith, et al., 2019, (Mis)conceptions about modeling of negative emissions technologies, Environmental Research Letters, 14:10, 104004, https://www.ifw-kiel.de/publications/misconceptions-about-modelling-of-negative-emissions-technologies-22147/.

16 L. Van Beek, J. Oomen, M. Hajer, et al., 2022, Navigating the political: An analysis of political calibration of integrated assessment modelling in light of the 1.5-degree Celsius goal, Environmental Science & Policy, Vol. 133, pp. 193-202, https://doi.org/10.1016/j.envsci.2022.03.024.

17 D.R. Morrow, R. Apeaning, & G. Guard, 2023, GCAM-CDR v.1.0: Enhancing the representation of carbon dioxide removal technologies and policies in an integrated assessment model, Geoscientific Model Development, Vol. 16, pp. 1105-1118, https://doi.org/10.5194/gmd-16-1105-2023; J. Fuhrman, C. Bergero, et al., 2023, Diverse carbon dioxide removal approaches could reduce impacts on the energy-water-land system, Nature Climate Change, 13:4, pp. 341-350, https://doi.org/10.1038/s41558-023-01604-9.

18 For example, in the CICE/IBET 2024 report 'Catalyzing Carbon Dioxide Removal at Scale', the authors note: "Of all the approaches we studied, Ocean Alkalinity Enhancement (OAE) was estimated to have the highest potential for multi-Gt scale of removals" (p. 17) and "OAE is one of very few engineered approaches with potential for multi-Gt scalability at or near $100/tCO2 cost" (p. 66).

19 G. Andersen, C. Merk, M.L. Liones, & M.P. Johannessen, 2022, Interim report on public perceptions of marine CDR, OceanNETS, Kiel, Germany, https://oceanrep.geomar.de/id/eprint/57226/.

20 T. Satterfield, S. Nawaz, & M. Boettcher, 2023, Social considerations and best practices to apply to engaging publics on ocean alkalinity enhancement, In: A Oschiles, A. Stevenson, L.T. Bach, K. Fennel, R.E.M. Rickaby, T. Satterfield, R. Webb, & J.P. Gattuso (eds.), Guide to Best Practices in Ocean Alkalinity Enhancement, Copernicus Publications, State Planet, https://doi.org/10.5194/sp-2-oae2023-11-2023.

21 M. Boettcher, F. Chai, et al., 2023, A Code of Conduct for Marine Carbon Dioxide Removal Research, Aspen Institute.

22 Government of Canada, 2021, United Nations Declaration on the Rights of Indigenous Peoples Act, SC. 2021, C. 14, https://laws-lois.justice.gc.ca/eng/acts/U-2.2/.

REFERENCES

23 N. Hilmi, R. Chami, M.D. Sutherland, et al., 2021, The Role of Blue Carbon in Climate Change Mitigation and Carbon Stock Conservation, Frontiers in Climate, Vol. 3, https://doi.org/10.3389/

24 J-P. Gattuso, A.K. Magnan, L. Bopp, et al., 2018, Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems, Frontiers in Marine Science, Vol. 5, https://doi.org/10.3389/fmars.2018.00337; ang T.P. Hughes, M.L. Bellwood, D.R. Cinner, et al., 2017, Coral reefs in the Anthropocene, Nature, 546, pp. 82-90, https://doi.org/10.1038/nature22901; S.C. Doney, V.J. Fabry, R.A. Feely, & J.A. Kleypas, 2009, Ocean Acidification: The Other CO2 Problem, Annual Review of Marine Science, Vol. 1, pp. 169-192, https://doi.org/10.1146/annurev.marine.010908.163834.

25 S.M. Smith, O. Geden, M.J. Gidden, et al., (eds.), 2024, The State of Carbon Dioxide Removal 2024 – 2nd Edition, Chapter 10: ”Monitoring, Reporting, and Verification”, https://www.stateofcdr.org/.

26 Ibid.

27 S.M. Smith, O. Geden, M.J. Gidden, et al., (eds.), 2024, The State of Carbon Dioxide Removal 2024 – 2nd Edition, Chapter 4: ”The Voluntary Carbon Market.”

28 J.C. Long and D. Scott, 2013. Vested interests and geoengineering research. Issues in science and technology, 29(3), pp.45-52.

29 NOAA Ocean Acidification Program (OAP), September 7, 2023, Announcing $24.3M Investment Advancing Marine Carbon Dioxide Removal Research, https://oceanacidification.noaa.gov/fy23-nopp-mcdr-awards/; ENERGY.GOV, October 26, 2023, DOE Announces $36 Million to Advance Marine Carbon Dioxide Removal Techniques and Slash Harmful Greenhouse Gas Pollution, https://www.energy.gov/articles/doe-announces-36-million-advance-marine-carbon-dioxide-removal-techniques-and-slash; ENERGY.GOV, May 28, 2024, DOE Announces $1.2 Million to Accelerate America’s Carbon Dioxide Removal Industry, https://www.energy.gov/articles/doe-announces-12-million-accelerate-americas-carbon-dioxide-removal-industry.

30 Memorandum of Agreement between Department of Energy and National Oceanic and Atmospheric Administration, June 5, 2024, https://www.noaa.gov/sites/default/files/2024-06/EXEC-2024-003330-Final_NOAA-DOE_MOA_05222024_GR_RS_Signed.pdf.

31 7 November 1996, 1996 Protocol to the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, [2006] ATS 11,

32 Resolution LP.4(8), Amendment to the 1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972 to Regulate Marine Geoengineering (adopted 18 October 2013, not in force). Available via IMO Website: https://www.imo.org/en/OurWork/Environment/Pages/geoengineering-Default.aspx

33 Ibid, Annex, Article 1.

34 Ibid Annex 5.

35 International Maritime Organisation, 30 June 2023, Progress Report from the Legal Intersessional Correspondence Group on Marine Geoengineering, LC 45/5/1, annex, 10-12.

36 Government of Canada, 1999, Canadian Environmental Protection Act, 1999 (S.C. 1999, c. 33), https://laws-lois.justice.gc.ca/eng/acts/c-15.31/.

37 Government of Canada, 1985, Fisheries Act (R.S.C., 1985, c. F-14), https://laws-lois.justice.gc.ca/eng/acts/f-14/.

38 International Maritime Organization, 14 October 2010, Resolution LC-LP.2 (2010) on the Assessment Framework for Scientific Research Involving Ocean Fertilization.

APPENDIX

Figure 1. A pie chart of categories of mCDR actors in Canada to provide an alternative visualization of the data presented in Appendix Table 1. This visualization demonstrates that nearly 50% of mCDR actors in Canada are in organizations that engage primarily in research activity – outlining that mCDR is still in an early phase in Canada.

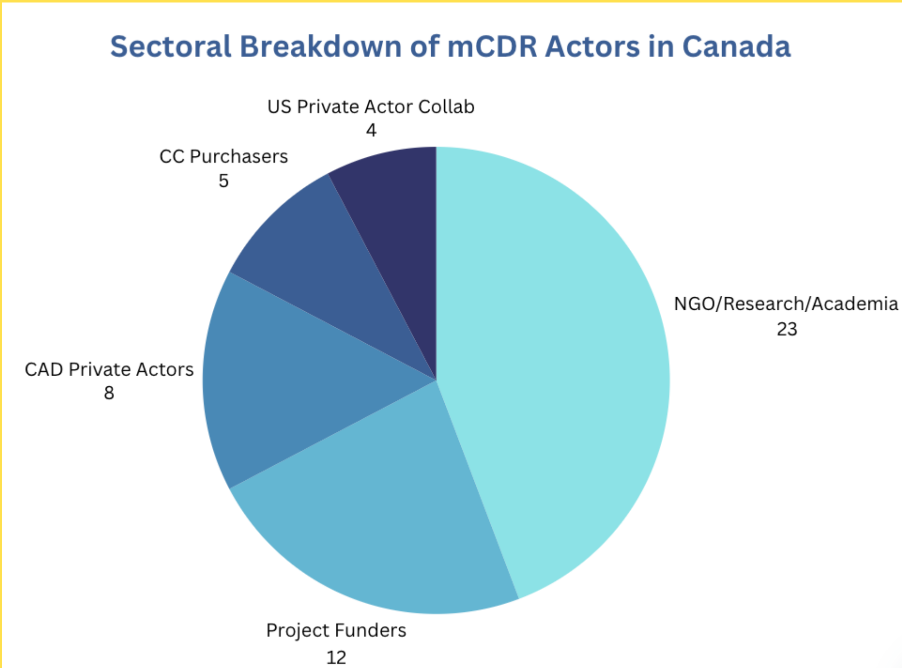
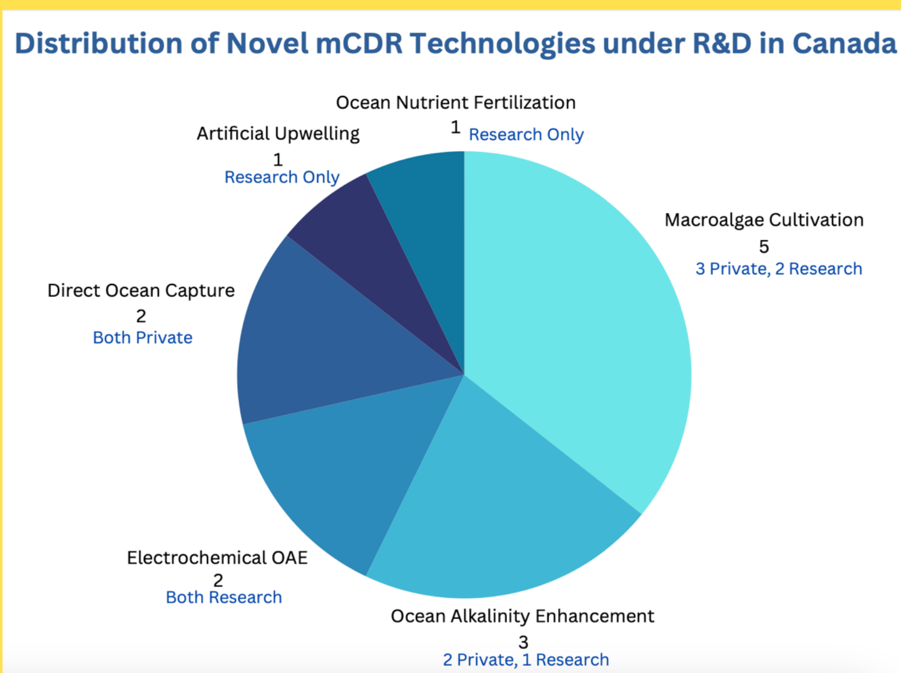


Figure 2. This pie chart visualizes non-conventional mCDR technologies currently under R&D in Canada. This list is not exhaustive. Macroalgae cultivation and ocean alkalinity enhancement methods appear to be the leading focus of mCDR R&D in Canada.



APPENDIX

Table 1. This table categorizes a non-exhaustive list of names of actors, relevant stakeholders, and government bodies and agencies engaged in the support of marine carbon dioxide removal in Canada. Most notably, it does not include many groups associated with coastal restoration/blue carbon initiatives in Canada. For information regarding the landscape of blue carbon actors/activity in Canada, consult WWF-Canada's 2023 report entitled "Coastal Blue Carbon in Canada: State of Knowledge."

PRIVATE ACTORS	FUNDERS & CARBON CREDIT (CC) PURCHASERS	NGO/NOT-FOR-PROFIT/RESEARCH	OTHER STAKEHOLDER GROUPS	RELEVANT GOV. AGENCIES/BODIES
Planetary Technologies	Shopify (CC)	Ocean Wise	Greenpeace Canada	Ocean Program-National Research Council
Running Tide (U.S.)	MaRS Discovery District (CC)	Dalhousie University	PEW Conservation Canada	Innovation, Science, and Technology
Solid Carbon	Frontier (CC) (Global)	Carbon Removal Alliance (U.S.)	Oceans North	Environment and Climate Change Canada
CarbonRun	Stripe (CC) (U.S)	Carbon to Sea (U.S.)	Oceana Canada	Natural Resources Canada
Cascadia Seaweed	BDC Climate Tech Fund	Ocean Frontier Institute	Living Oceans Society	Department of Fisheries and Oceans
Equatic (U.S.)	RBC Foundation (CC)	Canada's Ocean Supercluster	Canadian Climate Institute	Impact Assessment Agency of Canada
Deep Sky	Peter Gilgan Foundation	Ocean Networks Canada	Canadian OA Community of Practice	Canadian Conservation Institute
atdepth MRV (U.S.)	Consecon Foundation	COAST	Canadian Wildlife Federation	Environmental Protection Review Canada
ONT Holdings Inc.	Investissement Québec	B.C. Centre for Innovation and Clean Energy (CICE)	CPAWS	Natural Sciences and Engineering Research Canada
Pro Oceanus	Brightspark Ventures	Pacific Institute for Climate Solutions		Transport Canada
Coastal Carbon	Whitecap Venture Partners	Reseau Quebec Maritime		Ocean Research in Canada Alliance
Captura (U.S.)	OMERS Ventures	Université du Québec à Rimouski (ISMER)		Canadian National Ocean Decade Committee
	XPRIZE Climate (U.S.)	Carbon Removal Canada		
	Invest Nova Scotia	MEOPAR		
	Lafarge Canada	University of Calgary- PEACH		
	Sustainable Development Technology Canada	WatCISL		
	Scotiabank Net Zero Research Fund	Pembina Institute		
	Thistledown Foundation	The De Lannoy Lab – McMaster University		
		Tula Foundation – Hakai Institute		
		Blue Carbon Canada		
		WWF-Canada		
		COVE		
		Ocean Alk-Align		