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The Climate Technology Progress Report 2026

Navigating Ocean-based Technologies

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Annex A

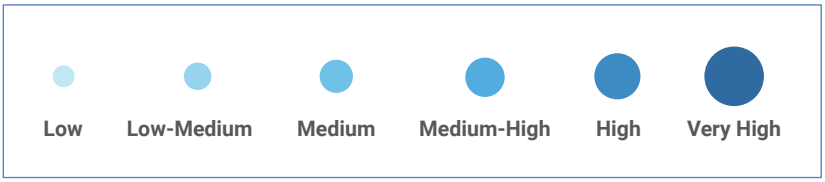
Full Comparison of the climate mitigation potential and technological readiness of chemical, biological, and physical mCDR techniques

Adapted from Doney et al. (2025).

Reference:

Doney, S., Lebling, K., Ashford, O.S., Pearce, C.R., Burns, W., Nawaz, S. et al. (2025). Principles for Responsible and Effective Marine Carbon Dioxide Removal Development and Governance. Washington, DC: World Resources Institute. https://doi.org/10.69902/84b3a9a8.

TRL Levels	
Basic Research	1: Initial idea
Applied Research	2: Application formulated (technology concept and application of solution formulated)
	3: Concept needs validation (solutions need to be prototyped and applied)
	4: Early prototype (prototype proven in test conditions)
	5: Full prototype at scale (components proven in conditions to be deployed)
Demonstration	6: Full prototype at scale (prototype proven at scale in conditions to be deployed)
	7: Pre-commercial demonstration (solutions working in expected conditions)
	8: First-of-a-kind commercial (commercial demonstration, full scale deployment in final form)
Deployment	9: Commercial operation in early environment (solution is commercial available, needs evolutionary improvement to stay competitive)
	10:Integration needed at scale (solution is commercial and competitive but needs further integration efforts)
	11: Proof of stability reached (Predictable growth)



Biological mCDR

Macroalgae Growth

Farming and deep-sea depositoin
Sargassum sinking

Stock	Efficacy	Durability	Sequestration Potential	Cost	TRL
Low (<1 GtC)	Medium	Medium-Long (decades to millennia)	Medium-Large (0.1 to 5 Gt CO^2/yr)	Medium (50 to 100 $t/$CO^2$)	3 (Concept needs validation)

Technology & Infrastructure Capacity Requirements		Seaweed farming is established for other sectors, and the processes that control growth and CO^2 uptake are well understood The potential for increasing seaweed growth at scale, plus the efficacy of carbon sinking and burial in manipulated settings remains uncertain.
Scientific Principles Understanding Gaps		Commercial seaweed farms are already operational. Field trials and technologies for depositing harvested seaweed in deep-sea settings are currently in development. The need for nutrient replenishment in surface waters and deposition of harvested material into deep-sea environments mean substantial material and energy requirements are likely associated with farming at scale.
Environmental Implications Co-benefits Impacts		Seaweed farms may create beneficial habitats for other species and sectors (e.g. fisheries) but may also impact nutrient availability and seawater chemistry with detrimental consequences for phytoplankton-based food-webs due to nutrient robbing. The deposition of harvested material into deep-sea environments is also likely to impact seafloor ecosystems, with potential effects including physical smothering and expansion of oxygen deficient conditions.
MRV Readiness (carbon crediting mechanisms)		The amount of carbon captured within the seaweed can be quantified, but it is difficult to relate that to atmospheric CO^2 uptake into seawater. The fate of carbon deposited into deep-sea environments is also very challenging to monitor, and significant uncertainty exists in the nature and scale of MRV required for deep-sea deposition.
General Comments		Whilst seaweed farming can be considered a mature technology, its potential use for mCDR is unproven and significant uncertainties exist on the wider ecological consequences if conducted at scale.

Phytoplankton Growth

Iron Fertilisation
Nutrient Fertilisation

Stock	Efficacy	Durability	Sequestration Potential	Cost	TRL
Medium (1 to 100 GtC)	Medium	Medium-Long (decades to millennia)	Medium-Large (0.1 to 5 Gt CO^2/yr)	Low-High (<50 to 500 $t/$CO^2$)	4 (Early prototype)

Technology & Infrastructure Capacity Requirements		The general mechanisms that influence the ocean's biological pump are well understood, but there is significant spatial variability in natural phytoplankton growth. The potential for manipulation at scale plus the efficacy of carbon sequestration in manipulated settings remains uncertain.
Scientific Principles Understanding Gaps		Several iron fertilisation field trials were conducted between 1990 and 2009. Further iron/nutrient fertilisation trials are currently being planned or assessed. Substantial material and energy requirements associated with placing the nutrients into the photic zone (including shipping, aerial deployment and/or in situ infrastructure).
Environmental Implications Co-benefits Impacts		The intentional modification of marine phytoplankton productivity will have an array of cascading environmental impacts, with potential effects including biodiversity changes, nutrient robbing, seawater chemistry perturbation (including O2 reduction and N2O production), adjusted sea surface albedo and effects from nutrient dispersal infrastructure (ships/pipes). However, the severity and ecological consequences of these impacts if conducted at-scale remain unknown.
MRV Readiness (carbon crediting mechanisms)		Phytoplankton productivity can be monitored using both in situ and remote observation (satellite) techniques. However, it is very challenging to relate the extent of phytoplankton activity to carbon export and atmospheric CO^2 removal, owing to the large spatial scales involved, effects of marine circulation, carbon tracing through the food web and water column and delay in CO^2 uptake into seawater.
General Comments		Despite its prominence in mCDR discussions and potential for implementation over large spatial scales, a number of critical knowledge gaps and uncertainties remain.

Blue Carbon Ecosystems

Mangroves
Seagrass Meadows
Saltmarsches

Stock	Efficacy	Durability	Sequestration Potential	Cost	TRL
Low-Medium (<1 to 100 GtC)	Low	Short-Medium (years to centuries)	Small-Medium (<0.1 to 1 Gt CO^2/yr)	High-Very High (100 to >500 $t/$CO^2$)	6 (Full prototype at scale)

Technology & Infrastructure Capacity Requirements		The processes that influence organic carbon accumulation in coastal ecosystems are relatively well understood. Knowledge gaps remain regarding the spatial and temporal heterogeneity in sequestration and the extent to which other greenhouse gas emissions (CH4; NOx) and carbonate production may impact efficacy.
Scientific Principles Understanding Gaps		Blue carbon ecosystem management strategies are well established and supported by a large network of international organisations. Low energy requirements minimise costs when implemented for wider ecosystem benefits, though potential trade-offs with other marine spatial uses may need to be considered
Environmental Implications Co-benefits Impacts		The management and restoration of blue carbon environments has an array of recognised ecosystem benefits that may outweigh the net CDR benefit. Potential negative impacts from mismanagement (perturbations in O2 availability, release of other greenhouse gases etc) are generally well characterised.
MRV Readiness (carbon crediting mechanisms)		Whilst the carbon content of coastal sediments can be directly measured, it is extremely challenging to quantify the additional extent of atmospheric CO^2 uptake into Blue Carbon Ecosystems as a function of management interventions.
General Comments		Whilst Blue Carbon Ecosystem management is technologically the most mature mCDR approach with well-characterised co-benefits, it has limited potential for at-scale implementation as a mCDR strategy alone.

Chemical mCDR

Ocean Alkalinity Enhancement

Coastal Enhanced Weathering
Mineral dissolution
Ocean liming

Stock	Efficacy	Durability	Sequestration Potential	Cost	TRL
Very Large (>1000 GtC)	High	Long (centuries to millennia)	Large-Very (1 to >5 $GtCO^2$/yr)	Medium-High (50-500 $t/$CO^2$)	5 (Full prototype)

Technology & Infrastructure Capacity Requirements		Marine carbonate systematics are generally well understood and characterised. Uncertainties persist in mineral dissolution rates and the implications of strong chemical gradients close to the point addition on sequeuestration efficiencies and biogeochemical processes.
Scientific Principles Understanding Gaps		Small scale field trials are being conducted with further in situ experiments planned, though the scalability of the approaches taken in these pilot study remains unclear. Substantial material and energy requirements will be associated with the acquisition, preparation, transportation and deployment of alkalinity sources, though they will vary by technique. Electrochemical OAE methods are also expected to have high energy demands and will generate acidic waste.
Environmental Implications Co-benefits Impacts		Increases in pH may counteract ocean acidificaiton. Elevated seawater pH and strong chemical gradients may negatively impact organisms. Mineral-based methods may introduce harmful trace minerals, impact nutrient availability that affect phytoplankton and the wider food web, and yield precipitates that reach the seafloor. Seawater intake and discharge required for electrochemical methods may affect ecosystems.
MRV Readiness (carbon crediting mechanisms)		Sensors and platforms are available for conducting in situ observations of marine carbonate chemistry. Challenges persist in linking the added alkalinity to CO^2 removal from the atmosphere (as this does not necessarily happen at the point of application), though advanced numerical modelling approaches are being developed.
General Comments		One of the more advanced mCDR techniques with field trials starting to address key knowledge gaps.

Direct Ocean Carbon Capture

Electrolysis
Electrodialysis

Stock	Efficacy	Durability	Sequestration Potential	Cost	TRL
N/A	High	Long (centuries to millennia)	Large-Very Large (1 to >5 $GtCO^2$/yr)	Medium-High (50 to 500 $t/$CO^2$)	4 (Early prototype)

Technology & Infrastructure Capacity Requirements		Marine carbonate systematics are generally well understood and characterised. Uncertainty with the potential implications of strong chemical gradients close to the point discharge on sequeuestration efficiencies and biogeochemical processes.
Scientific Principles Understanding Gaps		Small scale field trials are being conducted with further in situ experiments planned, though the scalability of the approaches taken in these pilot study remains unclear. Substantial material and clean-energy requirements associated with the extraction and subsequent transportation and long-term storage of CO^2. Acidic by-products need to be used/disposed of appropriately.
Environmental Implications Co-benefits Impacts		Increases in pH may counteract ocean acidificaiton. Strong chemical gradients at the point of discharge may negatively impact marine organisms. Seawater intake and discharge may affect ecosystems.
MRV Readiness (carbon crediting mechanisms)		Sensors and platforms are available for conducting in situ observations of marine carbonate chemistry. Challenges persist in determining the rate of CO^2 removal from the atmosphere (if this does not happen prior to discharge), though advanced numerical modelling approaches are being developed.
General Comments		One of the more advanced mCDR techniques with pilot plants and field trials starting to address key knowledge gaps, though challenges remain regarding energy and infrasturcture requirements

Physical mCDR

Artificial Downwelling

Pumps, Pipes & Turbines

Stock	Efficacy	Durability	Sequestration Potential	Cost	TRL
N/A	Low	Medium-Long (decades to millennia)	Medium (0.1 to 1 Gt CO^2/yr)	High (100-500 $t/$CO^2$)	1-2 (Application formulated)

Scientific understanding / Knowledge gaps	Technical capacity / Infrastructure requirements	Environmental co-benefits / Environmental impacts	MRV Readliness
			

Stock: Amount of carbon currently stored globally in that ocean reservoir. Low (<1 GtC); Medium (1-100 GtC); Large (100-1000 GtC); Very Large (>1000 GtC)
Efficacy: Level of confidence that the technology will remove atmospheric CO_2 and increase ocean carbon storage. Low; Medium; High
Durability: Likely duration over which CO_2 is expected to be removed from the atmosphere and stored away from the surface ocean. Short (years-decades); Medium (decades-centuries); Long (centuries-millennia); Permanent (>10,000 yrs)
Sequestration potential: Anticipated maximum extent of net annual CO_2 removal that could be achieved by the technology if conducted globally at appropriate locations in the future. Small (<0.1 Gt CO_2/yr); Medium (0.1-1 Gt CO_2/yr); Large (1-5 Gt CO_2/yr); Very Large (>5 GtCO_2/yr)
Estimated cost at scale: Approximate cost (dollars per metric ton CO_2) for deployment at scale in the future, excluding the cost of MRV and associated development. Low (<50 $t/$CO_2$); Medium (50-100 $t/$CO_2$); High (100-500 $t/$CO_2$); Very High (>500 $t/$CO_2$)
TRL: Technology Readiness Level, based on IPCC AR6 WGIII scheme (defined above)
Note: The current state of progress/understanding regarding the Technology & Infrastructure, Scientific Principles, and Environmental Implications of each mCDR approach have been indicatively ranked out of 3 (Low; Medium; High) for both positive (green) and negative (red) considerations. The relative current state of MRV readiness is represented using a single scale out of 6 (Low; Low-Medium; Medium; Medium-High; High; Very High).

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