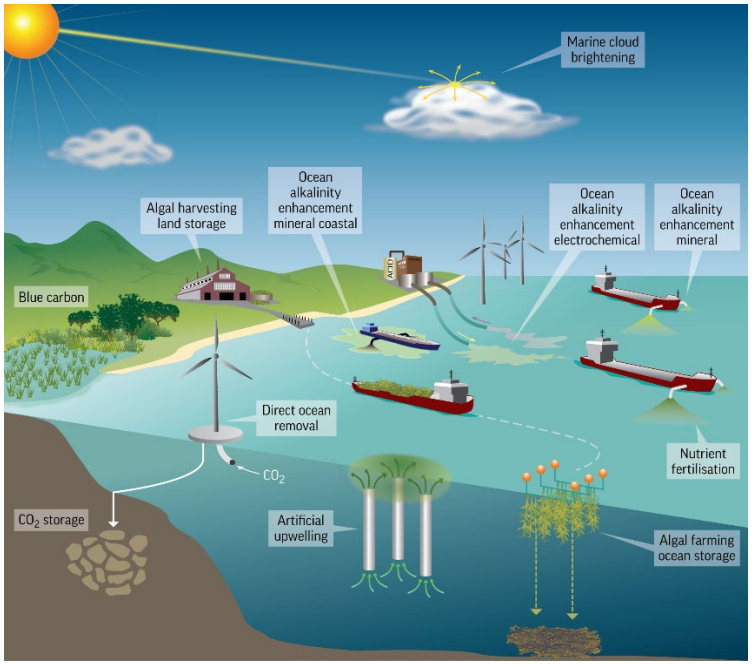
Summary

Marine climate intervention refers to ocean-based approaches that may help to mitigate climate change. These can be divided into two main categories: one focuses on reducing atmospheric greenhouse gas concentrations through enhancing ocean carbon uptake and storage, and the other aims to reduce or ameliorate the effects of rising greenhouse gases. Although most marine climate intervention methods are still in their early stages, significant international investment and growing pressure to act are already being exerted by proponents as global temperatures continue to rise.

For Australia, with our vast marine estate, it is critical to develop the knowledge to make informed decisions based on the best science available, and to work with other international partners to advance this. Over the next decade, this knowledge base needs to expand and address not only the technical issues of marine climate intervention but also the social, cultural, and governance challenges that will shape whether, how, and at what scale these approaches may be deployed.



Marine climate intervention approaches

This white paper identifies three strategic priorities for marine climate intervention in Australia, each with corresponding actions and recommendations for the next decade:

1. Expand and intensify research into current and future marine climate interventions.

2. Develop and expand Australia's monitoring, reporting, and verification (MRV) capabilities underpinned by sustained observations and model advances.

3. Advance Research to build the understanding of social acceptance and governance, including amongst communities and First Nations.

Marine Climate Interventions

Lead authors: Kerryn Brent[1], Lennart Bach[2], Andrew Lenton[1], Bronte Tilbrook[1]

Contributing authors: Harris Anderson[1], Mark Baird[1], Erin Bohensky[1], Philip Boyd[2], Damon Britton[2], Joey Crosswell[1], Perran Cook[4], Michael Elwood[3], Clothilde Langlais[1], Nadine Lehmann[2], Yuwan Malakar1, Jan McDonald[2], Mathieu Mongin[1], Elizabeth Shadwick[1], Manon Simon[2], Pete Strutton[2], Tyler Rohr[2]

Reviewing authors: Waye Dillon[1], Thomas Holmes[2], Sarah Polanco[5]

1. CSIRO
2. University of Tasmania
3. Australian National University
4. Monash University
5. University of Sydney

Glossary

Active Carbon Reservoir: A reservoir that exchanges with the atmosphere on timescales that matter to humans

Additionality: The principle that a climate intervention should result in reduced radiative forcing than would have occurred without the intervention.

Carbon Dioxide Removal (CDR): Processes designed to extract carbon dioxide from the atmosphere and store it durably

Climate Intervention: Deliberate actions aimed at altering the climate system to reduce or ameliorate climate change effects.

Durability: The longevity and stability of the climatic benefits provided by a climate intervention.

Environmental Safety: Ensuring that climate interventions minimise harm to ecosystems or human health.

Governability: The ability to manage and regulate climate interventions effectively.

Mitigation deterrence: Refers to situations where the pursuit or promise of one climate action reduces the motivation to pursue other necessary mitigation efforts, often unintentionally.

Predictability: The extent to which the outcomes of a climate intervention can be reliably and accurately forecast.

Solar Radiation Management (SRM): Methods to reflect a small percentage of the sun's light and heat back into space, thereby reducing global warming.

Scalability: The potential for a climate intervention to be expanded in scope or size to achieve significant impact.

Technological readiness: Refers to how mature or developed a technology is—essentially, how close it is to being practically deployed or implemented. It is often evaluated using Technology Readiness Levels (TRLs), which are widely used in research, industry, and government.

1. Introduction

Marine climate intervention could significantly assist Australia to meet its net-zero targets and help vulnerable ecosystems adapt to climate change. Climate Interventions are deliberate actions aimed at altering the climate system to reduce or ameliorate climate change effects. Marine-based carbon dioxide removal (mCDR) approaches are being developed to enhance the capacity of Australia's vast marine estate to sequester carbon dioxide (CO_2). These methods address residual and hard-to-abate emissions and can enable Australia to meet its international climate commitments. Marine-based solar radiation management (mSRM) methods could bolster Australia's adaptation capacity by shading vulnerable ecosystems, such as the UNESCO World heritage sites of the Great Barrier Reef (GBR) and Ningaloo Coast.

Marine climate intervention methods are largely in the early stages of development. How research is progressed over the coming decade will be critical to overcoming technical, social, and governance challenges, and enabling responsible research and deployment. This white paper identifies strategic research priorities for marine climate interventions.

The Australian coastline extends approximately 34 000 kilometres (excluding all small offshore islands), hosts 87% of the population, and there are 8.2 million square kilometres of Exclusive Economic Zone. Australia is also bordered by the Indian, Pacific and Southern Oceans which are considered prime locations for mCDR. The vast and diverse coast and offshore waters represent opportunities that could play an important role in helping Australia and the world reach globally agreed climate goals. Engagement in the development, research, and governance is also important to identify the potential for climate interventions to impact Australia's marine ecosystems and their sustainability.

This paper describes the potential role of climate intervention methods in contributing to the mitigation of climate change (section 1), aspects that determine: their feasibility (section 2); their environmental safety (section 3); verification of their success (section 4); their acceptance by the public (section 5); governance needs around them (section 6). Section 7 n concludes with a potential timeline of overarching priorities in the immediate (1-3 years), mid (3-5 years), and long (5-10 years) term, with a set of Actions and Recommendations for:

- Research in Marine Climate Intervention
- Monitoring, Reporting and Verification
- Governance and Social Acceptance

1.1 The role of marine carbon dioxide removal activities in addressing climate change

CDR is a key pillar of international and national climate change policy

Under the Paris Climate Change Agreement, the international community has committed to limit global temperatures to well below 2°C above pre-industrial levels, with a further ambition

to aim for not more than 1.5°C. Rapid and significant mitigation of greenhouse gas (GHG) emissions at the source is essential but is insufficient. According to the Intergovernmental Panel on Climate Change (IPCC, 2022), it is also necessary to remove CO_2 directly from the atmosphere on a large scale to counterbalance hard-to-abate residual GHG emissions. This is known as carbon dioxide removal (CDR). CDR differs from other carbon management methods that capture anthropogenic CO_2 from point sources (i.e. carbon capture, utilisation and storage (CCUS)) before it enters the atmosphere, in that CDR aims to remove anthropogenic CO_2 that is already in the atmosphere.

The amount of CDR required globally is immense. Based on the amount of carbon dioxide already in the atmosphere, the scale of hard-to-abate emissions, and the fact that emissions from other sectors are still increasing, it is likely that around 7-9 $GtCO_2$/yr of CDR will be required by 2050 to achieve net-zero (Smith et al., 2024). Leading reports by the IPCC (2022), the United Nations Environment Program, and the International Energy Agency all recognise CDR as an essential international requirement.

CDR is also essential for Australia to deliver on its net-zero commitments. In addition to reducing GHG emissions at the source, Australia must remove an additional 133 $MtCO_2$-e/yr by 2050 (Climate Change Authority, 2024). Australia's current National Science and Research priorities recognise developing CDR at scale as a significant and urgent priority. Conventional land-based CDR already plays a role in Australian climate policy, with reforestation/afforestation and soil carbon sequestration incentivised under the Australian Carbon Credit Unit scheme (ACCU; https://cer.gov.au/schemes/australian-carbon-credit-unit-scheme). However, the extent to which these methods can contribute to Australia's net-zero objectives is limited by competing land use and vulnerability to climate change and extreme events, such as fires and droughts (Abram et al., 2021; Canadell et al., 2021). While the ACCU scheme does include inter or subtidal restoration of blue carbon ecosystems, many other mCDR approaches are not included. CDR methods are being considered for inclusion in the National Accounts in the 2027 Methodology Reports of IPCC Task Force 1 (e.g. ocean alkalinity enhancement, direct ocean removal, blue carbon including seaweeds; Table 1 https://www.ipcc-nggip.iges.or.jp/public/mtdocs/pdfiles/2410_CDR_CCUS_Scoping_Report.pdf). This in turn may allow new methods to be included under the ACCU or other Australian Government crediting schemes.

The oceans have significant CDR potential

mCDR is being developed to enhance the ocean's uptake of CO_2. The oceans are the world's largest active carbon reservoir. The oceans naturally slow the rate of climate change by absorbing about 26% of the annual anthropogenic CO_2 emissions (Friedlingstein et al., 2025). Over very long timescales (>>1000 years), the oceans will also take up more than 90% of anthropogenic CO_2 emissions. mCDR approaches could accelerate this uptake and storage of atmospheric CO_2, thereby slowing the rate and magnitude of climate change (e.g. GESAMP 2019, Cross et al., 2023).

Internationally, mCDR is in its early stages. The potential of mCDR has been considered in numerous international reports, including by the UN GESAMP (2019), US National Academies (2022) and, most recently, the World Resources Institute (2025). Publicly and privately funded research programs are being conducted worldwide, including in China, the USA, Europe, and Australia. Several countries, alongside commercial and non-commercial operators, have also published mCDR Roadmaps (e.g., Ocean Visions), and business start-ups have begun with small scale deployments to sell carbon credits on voluntary carbon markets (e.g. puro.earth, https://puro.earth/buy-carbon-credits; planetary, https://www.planetarytech.com)

Australia has the world's third-largest marine exclusive economic zone and significant potential to contribute to mCDR development and deployment. Australia's draft Sustainable Ocean Plan (2024) recognises the need to develop ocean-based climate actions, including mCDR. Australian universities, CSIRO, and for-profit organisations are currently developing and conducting mCDR research programs, although existing efforts are uncoordinated. Strategic research coordination, funding and policy leadership is needed over the next decade to realise the significant climate and economic benefits that mCDR could provide for Australia. This includes attracting investment, creating new jobs, and positioning Australia to assist other nations in meeting their net-zero commitments through international trading mechanisms, such as Article 6 of the Paris Agreement and Voluntary Carbon Markets.

Current Marine CDR Approaches

There are many proposed mCDR approaches (Figure 1). Each had a variety of pathways and reservoirs/fluxes in the ocean carbon cycle that influence storage potential, storage durability time scales, feasibility, and requirements for monitoring, reporting, and verification (Table 1).

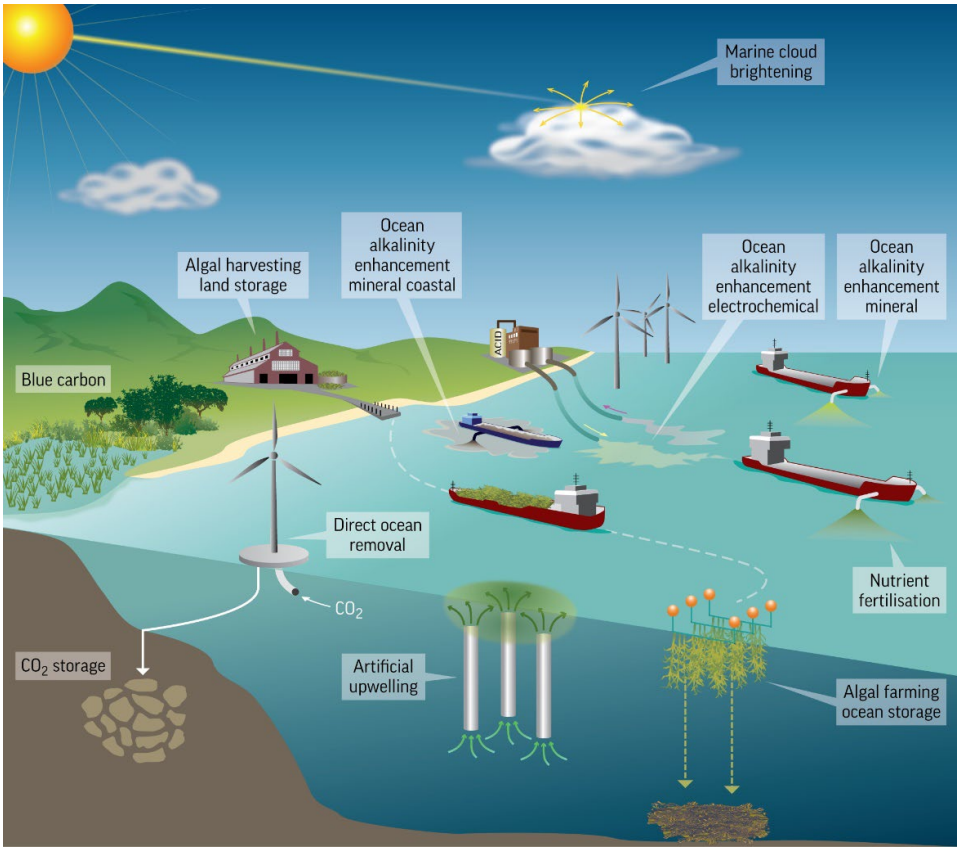


Figure 1. Illustration of proposed marine climate intervention approaches adapted from Cross et al. (2023) and Oschlies et al. (2025).

Biotic approaches use photosynthesis to convert CO_2 from the atmosphere into organic material in the ocean or on land. This organic carbon can be harvested, buried in the sediment, or can sink passively into the deep ocean (i.e. accelerating the ocean's biological carbon pump). Nutrient fertilisation is one example whereby iron or other key nutrients are added to the water column to promote additional CO_2 uptake through photosynthesis.

Abiotic approaches alter ocean carbonate chemistry to increase inorganic carbon storage. For example, ocean alkalinity enhancement involves adding alkaline minerals or electrochemically increasing seawater alkalinity to enhance the ocean's capacity to take up and store more CO_2. Abiotic approaches typically offer greater scaling potential, more durable removal, and less anticipated negative impacts on marine ecosystems than biotic approaches (Table 1).

Table 1. Abiotic and biotic methods for mCDR with assessments of the feasibility (adapted from Cross et al. 2023) and potential ecological impacts. For each method, potential scalability refers to the global potential to remove CO_2, durability refers to the likely time scale of the anthropogenic removal, and predictability refers to the current ability to estimate removal and impacts. Governability and additionality also influence the feasibility (Section 2) and can vary widely with environmental and societal factors. Open systems refer to ocean or seafloor storage of captured CO_2. Closed systems refer to storage of the captured CO_2 either on land with removal from exchange with the atmosphere, or in geological structures.

Method	**Feasibility**			**Ecological Impact**	**System**
	Potential Scalability ($GtCO_2$/yr)	**Durability (Years)**	**Predictability**		
Abiotic methods					
[1,2,3,11]Ocean alkalinity enhancement - solid phase (mineral addition)	Moderate - High (1 - 15+)	High (>20,000)	Moderate - High	Low - Moderate	Open
[4,5,11]Ocean alkalinity enhancement - liquid phase (electrochemical)	Moderate - High (1 - 15+)	High (>20,000)	High	Low	Open
[6,11]Direct ocean removal with geological storage	Moderate (1 - 10)	High (>20,000)	High	Low	Closed
Biotic methods					
[6,7,11]Nutrient fertilisation	Low (0.1 - 1+)	Low (10 -100)	Low	High	Open

[8,9,11]Blue carbon (mangroves, tidal marshes, seagrass)	Low (0.1 - 0.4)	Moderate (100-1000)	Low	Moderate	Open
[10,11]Algal cultivation with land disposal	Low (0.1 - 0.6)	Low (10 – 100)	Low - Moderate	Moderate - High	Closed
[6,10,11]Algal cultivation with ocean disposal	Low (0.1 - 0.6)	Low (10 – 100)	Low	Moderate - High	Open
[6]Artificial Upwelling	Low (0.1 - 1)	Low (10 -100)	Low	High	Open

[1]Fuss et al., 2018; [2] Lenton et al., 2018; [3]Bach et al., (2019); [4]Eisaman et al., 2023; [5]Rau et al., 2018; [6]NASEM, 2022; [7]Bach et al., 2023; [8]McCreadie et al., 2019; [9]Williamson and Gattuso, 2023;[10]Krause-Jensen and Duarte, 2016; [11]Roberts et al., 2025

1.2 Marine-based solar radiation management

SRM is distinct from CDR as it does not seek to sequester atmospheric CO_2. Instead, SRM aims to cool temperatures at a local, regional or global scale by reducing the amount of net solar radiation (sunlight) absorbed by the Earth's atmosphere. mSRM proposals include brightening clouds over the ocean (Figure 1 "marine cloud brightening") and surface albedo modification using microbubbles or reflective surface films to reflect more solar radiation away from the water surface (UNEP, 2023).

While some SRM activities have been proposed to affect temperatures on a global scale, there is increasing interest in the potential for mSRM to be used on a local or regional scale to protect vulnerable ecosystems from rising temperatures, such as the Great Barrier Reef (Hernandez-Jaramillo et al., 2025), to reduce the risk of coral bleaching through cooling and shading. Globally, six mSRM studies have been trialled at regional scale, including one under the Australian Reef Restoration and Adaptation Program (Baresi er al., 2025). Importantly mSRM does not address the changes in the marine environment such as ocean acidification which is already impacting the long-term viability of marine ecosystems (Hurd et al, 2018).

Like mCDR, mSRM methods are at an early stage of R&D. In some respects, they share similar research priorities, such as responsible governance of research and deployment, and community engagement and social acceptance. However, the fundamental difference between these technologies means that some research priorities discussed below (section 2-6) are distinct to mCDR.

Before examining these research priorities, we acknowledge that there are other proposals to develop marine-based technologies for climate adaptation purposes. For example, artificial upwelling has been proposed to mitigate hurricanes by pumping cool deepwater to the ocean's surface to slow/prevent their evolution (Hlywiak and Nolan, 2022). There are also proposals to slow or stop the melting of Antarctic glaciers and subsequent sea level rise by building submarine walls (Moore et al., 2018). While the investigation of emerging ideas should be encouraged to determine impacts and feasibility (e.g. Hlywiak and Nolan, 2022), they are not near-term research priorities and are not considered further in this white paper.

2. Feasibility

This section examines research priorities that relate to the feasibility of marine climate interventions. Along with safety (Section 3), feasibility is essential to determine whether a marine climate intervention is possible and desirable. The early stage of mCDR development means that numerous questions are outstanding concerning the following key aspects of feasibility:

1. Additionality
2. Durability
3. Scalability
4. Predictability
5. Governability

2.1 Additionality

Methods are essential for measuring the additionality of marine climate interventions. Additionality determines if the intervention provides a net climate benefit. For mCDR, additionality refers to a net increase in CO_2 sequestration compared to no intervention (Gustavsson et al., 2000; Michaelowa et al., 2019). For mSRM, additionality refers to the induced cooling compared to no intervention, with warming reduction or reduced degree heating days being the expected benefit. Additionality is reduced when feedback mechanisms in the Earth system respond to the anthropogenic intervention in a way that reduces their natural carbon sequestration or cooling effect. The variety of feedback mechanisms affecting the additionality of climate intervention methods scales with their complexity (see section 2.4). The assessment of additionality needs to integrate sufficiently large temporal and spatial scales as some climate-relevant feedback, like nutrient robbing (Tagliabue et al., 2023; Oschlies et al., 2025) could unfold years (or more) later, and likely be geographically distant from the climate intervention deployment (Bach et al., 2024).

Quantifying additionality will require rigorous observational, experimental and modelling approaches (see section 2.4). For instance, observational work must provide monitoring data to determine the baseline against which the intervention is contrasted. Likewise, experimental work must identify and constrain the dominant feedback mechanisms that could compromise additionality for each intervention method. Modelling approaches must then skilfully incorporate these mechanisms to simulate counterfactual baselines that necessarily can’t be observed.

2.2 Durability

The durability of marine climate interventions will affect the feasibility of climate intervention approaches. Durability refers to the duration a climate intervention method will maintain its climate effect after being deployed. Durability is a particular concern for mCDR, as methods need to store carbon on a long timescale to deliver a meaningful climate benefit. The durability

of mCDR methods varies (Table 1). For example, carbon storage durability in coastal Blue Carbon biomass is on the order of decades to hundreds of years (Johanessen and Christian, 2023), while the durability of ocean alkalinity enhancement can approach ~100,000 years (Sarmiento and Gruber 2006; Middelburg et al., 2020). For mSRM methods, the regional interventions are designed to counteract the negative effect of marine heatwaves and to reduce coral bleaching over months-long duration deployment. The durability of the cooling effect would depend on how long the mSRM method reduces radiative forcing, for example, equivalent to the lifetime of a modified (reflective) cloud or sea ice.

2.3 Scalability

Understanding the extent to which a climate intervention method can be scaled will be key to determine if it is feasible and desirable. Scalability refers to the ability to expand the deployment of techniques so that it can have an effect at the desired scale. For mCDR, scalability is a question of how much atmospheric CO_2 a method could remove within reasonable practical constraints (Table 1). In the context of mSRM, scalability refers to the extent to which a method would need to be implemented to have a cooling effect at the desired scale (i.e. at a local, regional or global level).

To support effective deployment, research must identify and address the specific constraints and externalities that limit the scale of individual methods. These range from ecological boundaries, such as spatial limits for Blue Carbon, to industrial demands, such as resource extraction and renewable energy inputs for ocean alkalinity enhancement.

Equally important is research into the enabling conditions for scale: financial mechanisms, public acceptance, and supportive policy environments. For Australia, there is a unique opportunity to explore how the country's extensive resource base, renewable energy potential, and diverse marine environments can be leveraged to support future scaled deployments.

Understanding scalability also means recognising that not all methods need to scale equally to be valuable. Research should assess the role of smaller-scale interventions that offer co-benefits, such as Blue Carbon through *Natural Capital Accounting*, or pathways for local communities to meet smaller scale regional net-emissions targets, while also identifying which approaches can contribute meaningfully to national climate targets through large-scale deployment (see Table 1).

2.4 Predictability

Targeted experimentation and the subsequent development of models are needed to enhance the capacity to predict mCDR and mSRM approaches. Predictability refers to the ability of scientists and decision-makers to forecast the outcomes of an intervention that has not happened or simulate the outcomes of an intervention that cannot be observed. This must be done across a sufficiently large area and timescale. For example, the sequestration of CO_2 for mCDR and the reduction in short-wave radiation for mSRM.

Predictability is crucial for assessing effectiveness and risk prior to deployment, facilitating investment prior to commercialisation and scaling, improving monitoring, regulatory compliance and ultimately governance of ongoing deployments. If an intervention is not adequately predictable, it is unlikely to gain public, commercial, or regulatory acceptance.

Predictability of marine climate interventions can be strengthened through the combined use of multi-scale modelling and sustained observations. Earth system models, such as those informing IPCC AR7, generally provide robust representations of atmospheric dynamics and large-scale ocean circulation. However, they often lack the resolution or parameterisation needed to capture the specific mechanisms of interventions and their impacts on marine biological systems and carbon cycling. These include more sophisticated ecosystem components (Rohr et al., 2023), inorganic carbon cycling components (Hinrichs et al, 2023), and coupled sediment models, especially near the coasts (Fennel et al., 2023).

High-resolution regional and local models are capable of resolving the finer-scale processes that determine ecological and place-based outcomes; however, they remain limited in terms of spatial and temporal scope. Integrating these approaches through nested, regional-global scale models with two-way biogeochemical tracer coupling and increasing resolution and/or complexity near the coasts (Wang et al., 2025) is essential to improve confidence in assessing both large-scale effectiveness and local consequences of marine interventions. In the case of mSRM, the complexity of the MCB intervention requires regional coupled ocean-atmosphere models, with detailed representation of aerosol and cloud microphysics in the atmosphere.

Furthermore, these models must be constrained by observations. The biogeochemical processes in these models, particularly the many feedback that govern additionality, will need both mature laboratory-based and field experiments. Further, the emergent properties of these models (i.e. the model output) must be evaluated against long-term observational data sets.These models will need to be rigorously evaluated across the range of Australian marine coastal and open ocean regions, where climate intervention may be implemented.

2.5 Governability

Governability refers to the extent to which legal frameworks and other measures can mitigate the risks and realise the benefits of marine climate intervention implementation.Governability research priorities are discussed in greater detail in Section 6 below. However, we consider governability here as a key component of feasibility and whether approaches can be scaled and deployed.

The governability of marine climate intervention methods is generally positively influenced by its level of predictability (Bach et al., 2024). Less predictable methods (e.g. those with many or poorly understood feedback pathways and interactions) will require more complex governance, regulatory control, and adaptive management strategies (if they are allowed at all). This is because uncertain outcomes and poor controllability compared to potentially large risk for the environment strongly influence public and political acceptance (Bellamy et al., 2017; Shrum et al., 2020; Dooley et al., 2021; Cooley et al., 2023) and raise ethical

considerations (Baatz et al., 2016; Hale and Dilling, 2020). To accommodate these considerations, marine climate intervention needs an adaptive management framework capable of observing and responding to unpredictable impacts. Such a framework will also require a robust system for monitoring and reporting the impacts of a given deployment across appropriate space and time scales.

3. Safety, environmental impacts and co-benefits

Climate interventions must be environmentally safe (NASEM 2022, Cross et al. 2023) to avoid risk to Australia's marine systems and the services they provide. Environmental effects can occur at the species and community level and include impacts on natural biogeochemical cycles and water quality (e.g., pH, O_2, turbidity and metal toxicity), as well as physical parameters (e.g. light/temperature reduction in mSRM). These effects can also have social consequences when environmental change affects or is perceived to affect human activities (e.g., impacts on fisheries).

Processes need to be developed to minimise negative effects of climate interventions and balance them against potential co-benefits and climate benefits.

3.1 Identifying environmental change

Marine climate interventions could have wide-ranging effects on the ecosystem, its species and food web interactions, with some benefiting and others being negatively affected. For example, an mCDR-induced change in the composition of a marine ecosystem could enhance commercial fish production at the expense of endemic biodiversity. For mSRM, cooling might benefit corals, but the reduced light might decrease primary productivity (i.e. phytoplankton). Assessment criteria should consider safety from all viewpoints (section 5).

Methods that induce minimal permanent change or perturb the system within predetermined guidelines are likely to be seen as most desirable, socially safe and acceptable. There are existing guidelines/regulations for many of the chemical and physical effects that will need to be updated alongside regulatory development (e.g. Aus/NZ Water Quality Guidelines - ANZG 2018). Research should focus on developing safe thresholds for mCDR and mSRM methods based on a mixture of laboratory, field studies, monitoring, and regional modelling approaches. These thresholds should be based both on near-term, readily observable impacts on individual species and long-term, cascading ecosystem impacts. The assessment of long-term impacts require direct ongoing monitoring and inference from mechanistic models. However, most current earth system and marine ecosystem models do not include sufficient complexity to simulate the full impact of many climate interventions and thus require further development (Section 4; Roberts et al., 2025).

3.2 Balancing intervention risks against the risks of climate change

While climate interventions present various risks, doing nothing (i.e. not developing them) is not "risk neutral" (NASEM 2022, Brent, 2023). Without climate interventions, it will be near impossible to keep warming below 2°C and avoid the worst impacts of climate change (IPCC 2023). For example, coral bleaching events due to climate change-induced heat stress are already widespread and are likely to increase in severity in the future (e.g., Mellin et al., 2024). Novel "risk trade-off" assessment methods are needed to support such complex decision making. This includes approaches to weigh up competing risks that may be dissimilar in nature, severity, and likelihood, and affect different populations and ecosystems (Felgenhauer et al, 2025; Brent, 2023).

There is a wealth of knowledge projecting how climate change will impact marine systems, and there are clear research opportunities to incorporate new data on the effects of climate interventions into these projections. As interventions are scaled, their environmental effects may not scale linearly, resulting in unpredictable outcomes. To support risk trade-off decision-making, research into safety should aim to scale as methods increase in their technological readiness.

3.3 Balancing local effects against global benefits

Climatic and co-benefits are also relevant to assessing the safety of climate interventions. Climatic benefits are reductions in atmospheric CO_2 or reduced radiative forcing. In assessing safety relative to climatic benefit, there will likely be a scale mismatch between an intervention's intended beneficial effect on climate (global scale) and it's unintended, possibly adverse side-effects (local scale). There are significant challenges in determining how to reconcile this mismatch. For example, ocean alkalinity enhancement might lead to localised regions of low pCO_2 near injection sites, with effects on primary producers in the immediate vicinity. However, effects will dissipate quickly beyond this point source and the amount of CO_2 removed further downstream could be high with global impact. Alternatively, for interventions such as MCB, there may be regional cooling effects (Latham et al. 2013), yet minimal global effects.

Co-benefits are additional and potentially complementary to climatic benefits, such as enhancing biodiversity (i.e., restoring a Blue Carbon ecosystem) (Macreadie et al. 2021), or reducing the impact of ocean acidification in OAE (Renforth and Henderson 2017, Bach et al. 2019). Co-benefits could increase the desirability of a method to a broader range of stakeholders. Research investigating environmental safety should aim to present both the localised effects, co-benefits and estimate the regional and global climatic benefits to ensure a balanced assessment of safety.

4. Monitoring, reporting and verification

Monitoring, reporting, and verification (MRV) are essential for evaluating the success of marine climate interventions, from field trials to large-scale applications, and for detecting and responding to any unintended consequences (McDonald, 2018; NASEM, 2022; Cross et al., 2023; Bach et al., 2024). For mCDR, continuous monitoring and verification of net carbon uptake are crucial for assessing both durability (e.g., Burke and Schenuit, 2023) and additionality (Bach et al., 2024). Developing robust, internationally accepted MRV protocols is vital to ensure that Australian CDR claims are credible worldwide, both in compliance/voluntary offset markets and/or within other financing frameworks (Boyd et al., 2023a). For both mCDR and mSRM, MRV plays a key role in preventing transboundary impacts, including those from activities conducted by other nations or actors in neighbouring waters.

Monitoring requirements will vary depending on the climate intervention. Understanding the site-specific physical dynamics, marine chemistry, and biology is essential (e.g. Burt et al., 2012). For assessing additionality of mCDR, baseline observations must be highly accurate and comprehensive to identify small changes in net carbon uptake amid high background levels and variability of dissolved inorganic carbon. To evaluate the magnitude and regional effects of chemical and ecosystem responses, integrated modelling and observational strategies are necessary, including sensor development at various scales to capture local and broader impacts. High-quality observations are also vital for confirming the permanence of carbon sequestration and detecting potential leakage back into the atmosphere (e.g., Boyd et al., 2022; Bach et al., 2024; Doney et al., 2025). MCB requires high-resolution satellite and insitu data (e.g. temperature and biological effects) of the intervention zone and region of influence and a comparable counterfactual over extended periods. And a comparable counterfactual over extended periods.

Ocean modelling underpinned by direct measurements will play a key role in MRV (Boyd et al., 2023; Ho et al., 2023; Fennel, 2025). mCDR activities will have effects that extend beyond specific locations and timeframes, which cannot be fully accounted for with direct measurement alone. Models can help connect spatio-temporal scales and overcome detection limit challenges, allowing for a comprehensive estimate of mCDR signal dispersal and net CO_2 uptake (Boyd et al., 2023). However, they must include all relevant feedback mechanisms that control additionality. Prior to deployment, models can also be used to predict uptake and estimates of the counterfactual state for comparison, net-uptake accounting and rigorous hypothesis testing.

Modelling should be performed across multiple scales. High-resolution regional models are essential for capturing near-field physical dynamics and complex biogeochemical feedback that larger models cannot resolve (Anderson et al., 2025; Fennel et al., 2023; Wang et al., 2025). Conversely, low-resolution global models are crucial for estimating net carbon uptake and Earth system feedback beyond the scope of regional models, which is vital for accurate carbon accounting and attribution (Fennel et al., 2023; Fennel, 2025). Integrating different scale models into global ocean simulations involves nested, downscaled resolutions, increased biogeochemical detail near coastlines, and two-way coupling of biogeochemical tracers with the open ocean. Uncertainty quantification must be applied across all scales (Fennel et al.,

2023). Model Intercomparison Programs, such as Google and Carbon to Sea's OAEMIP, are vital for establishing standardised methodologies and encouraging interdisciplinary collaboration. For MCB, ocean and atmosphere coupling, including aerosols and cloud microphysics in the atmosphere, and biogeochemical cycle in the ocean, is also required to represent crucial ocean and atmosphere processes, such as sources of marine aerosol and precursors, heat and radiation feedback, feedback on precipitation potential impact over land and biogeochemical ocean responses. Reporting will require agreement and coordination across multiple levels. At the local scale, municipalities need clear reporting standards for smallscale interventions with limited risk. At the international level, multi-lateral reporting frameworks are needed to drive accurate verification and public acceptance of global scale interventions (Boyd et al., 2023). While there is no international standard in place at present, pathways exist through the UNFCCC that may enable mCDR methodologies to be accounted for in future National Accounts through IPCC Task Force 1. This, in turn, would allow nations to incorporate these into their domestic schemes and potentially trade these internationally through Article 6 of the Paris Agreement. A considerable number of proponents have published MRV methodologies for specific markets (e.g. Carbon to Sea, https://www.carbontosea.org/oae-data-protocol; Isometrics, https://isometric.com/).

Data, including uncertainty estimates and metadata (i.e. sensors and calibrations, sampling and sequestration methods) should be made transparent and accessible in regional, national, and international repositories (Jiang et al., 2023).

Australia has considerable observational and modelling expertise to address these research priorities. Australia's Integrated Marine Observing System (IMOS) are leaders in biogeochemical and satellite observations and data delivery for the Southern Ocean and the regional seas around Australia. Significant coverage gaps remain – spatially, temporally – and in terms of variables monitored. Existing field experiments and modelling research could be built on to fill these gaps. Australia also has outstanding capacity in carbonate chemistry and biogeochemical modelling, ranging from high resolution to global scales (Mongin et al., 2021; Mongin et al., 2016; Lenton et al., 2018), which can be leveraged for mCDR/mSRM research. The Australian modelling community (ACCESS) can be utilised to improve capacity to quantify and guide MRV development of mCDR (e.g. Buchanan et al., 2025).

5. Social acceptance

Social science research has a critical role to play regarding the development and governance of marine climate interventions. Science and Technology Studies and related fields have articulated many multiple arguments for the engagement of and participation in novel technology R&D by affected publics, namely, instrumental, substantive, and normative (Fiorino et al. 1989). The normative argument views participation as a right of citizens where decisions may affect them. The substantive rationale argues that the inclusion of diverse citizens and their knowledge may lead to better outcomes. From an instrumental perspective, as the desired outcome of participation, social acceptance is a key part of the enabling environment for marine climate intervention research, including field-trials, and any eventual deployment and upscaling (Fritz, et al. 2024).

Furthermore, the expanding field of responsible research and innovation stresses that new technologies should aim to create beneficial social results (McCrea et al., 2024), including protecting environmental and community values and supporting justice within and across generations. It is important to distinguish positive social outcomes from positive climate outcomes, which should not be automatically equated. The achievement of positive social outcomes for marine climate interventions in Australia presents a significant challenge, requiring continuous attention alongside advancements in technology, science, law, and policy.

Advances have been made in the context of specific interventions. Most notably, social science research on engagement practice is being conducted as part of RRAP, on the Great Barrier Reef, including for MCB (Baresi et al., 2025a & b, Bartelet et al., 2025). Researchers in different states across Australia have also conducted empirical studies to understand stakeholder perspectives and priorities regarding Blue Carbon and other coastal restoration activities (Bell-James et al. 2023). There has otherwise been limited Australian social science research on mCDR and mSRM. Further place-based and technology-specific research is required to understand how Australian communities perceive different technologies (with different risk profiles and co-benefits), their priorities and concerns, and develop effective and diverse engagement pathways that span the participation spectrum (Vaughn and Jacquez 2020) in keeping with principles of responsible innovation. The presently early stage of R&D of many marine climate interventions affords unique opportunities for upstream engagement, prior to field testing and deployment. Interdisciplinary and transdisciplinary research (i.e. with stakeholders and partners) should seek to maximise these opportunities, to reduce social risk and path dependency (Diamond et al. 2022).

Given the potential for interventions to be deployed on Sea Country and impact on Cultural Heritage, engagement with Aboriginal and Torres Strait Islander communities is an urgent priority. Apart from research being conducted regarding Great Barrier Reef interventions, there is a significant knowledge gap concerning the potential risks and benefits of marine climate interventions for First Nations peoples, including impacts on cultural values. Co-design, partnership and Indigenous-led approaches are necessary to ensure ethical and equitable research, and to maximise beneficial outcomes (Hunter et al., 2024).

6. Domestic and international governance

To ensure environmental and human safety (including social and cultural risks) of marine climate interventions and realise potential climate and co-benefits, governance should develop in tandem with the techno-scientific research. A key distinction should be drawn between current *permitting requirements* for individual experiments or research projects and *research priorities relating to governance* of marine climate interventions. Depending on the nature, scale, and location of experiments, field tests might require legal approvals under existing state or Commonwealth law. Understanding current permitting requirements is not a research priority per se; it is a matter of legal compliance that requires expert advice from qualified lawyers.

However, there is concern that existing governance frameworks provide neither a suitable incentive framework for R&D investment, nor adequately address the risks and challenges of

marine climate interventions (McDonald et al, 2019; Brent, Simon and McDonald, 2024; Foster et al, 2025, McDonald., et al. 2023; Diamond et al 2022). Research is needed to understand what such frameworks require for both mSRM and mCDR, as well as interaction with international law, including Australia's obligations under the UNFCCC/Paris Agreement, United Nations Law of the Sea Convention, London Protocol, and the new High Seas treaty (Brent et al 2024; McDonald et al 2023). Governance is an ongoing process that must co-evolve with understandings of environmental and social risks, benefits and co-benefits of marine climate interventions, and reflect the role these technologies play in Australian and international climate policy.

A governance framework for marine climate interventions will need to provide both incentives and safeguards, as well as ensure regulatory coordination. The high cost of R&D and deployment suggests that incentives may be needed to encourage investment in mCDR development and deployment. The ACCU may provide a suitable starting point, but research will need to evaluate the economic and legal constraints of adapting Australia's carbon crediting scheme for mCDR (McDonald et al, 2023).

Legal and governance research should evaluate how best to refine current regulatory approvals and oversight to address the specific risks of different marine climate interventions in different locations (McDonald et al, 2023). Some risks, for example the risk of mitigation deterrence, are common to all technologies. Research should identify the best governance arrangements needed to support the acceleration of mitigation efforts, to avoid the risk that marine climate interventions might detract from other forms of mitigation and adaptation (Brent et al 2019; Carton et al, 2023) Other risks are site- and technology-dependent, and a generic framework may lack the necessary detail and focus.

The design of technology-specific guidelines, and robust systems for MRV is also a priority. These systems need to be tailored to Australia's diverse marine environments and power sharing arrangements over coastal waters. Other uses of Australia's oceans and coastline will also need to be considered, including fishing, tourism, and offshore energy.

The relationship between enhanced governance, engagement, and community trust and social acceptance for marine-based climate interventions is under-explored (Van Putten et al, 2018; NASEM, 2022), but there is growing appreciation that the governance of emerging technologies needs to consider public interests (Fritz et al., 2024). Responsible research recognises the importance of engaging local communities early and throughout the research process and to ensure environmental justice and minimize risks to the public and marine environment (NASEM, 2022, Baresi et al. 2025b). How best to reflect native titles and other indigenous rights holders in the governance of marine climate interventions is another key priority.

Finally, Australia has a strong interest in the development of international law that advances the dual goals of facilitating responsible marine climate interventions and avoiding or mitigating the risks. Governance research considering Australia's unique legal system, marine environments and strategic interests can inform Australia's negotiating position in respect of emerging developments under the London Protocol, the UN Environment Assembly, the World

Meteorological Organisation and other future treaty negotiations to achieve this balance (Webb, 2024).

7. Marine Climate Intervention roadmap (2025–2035)

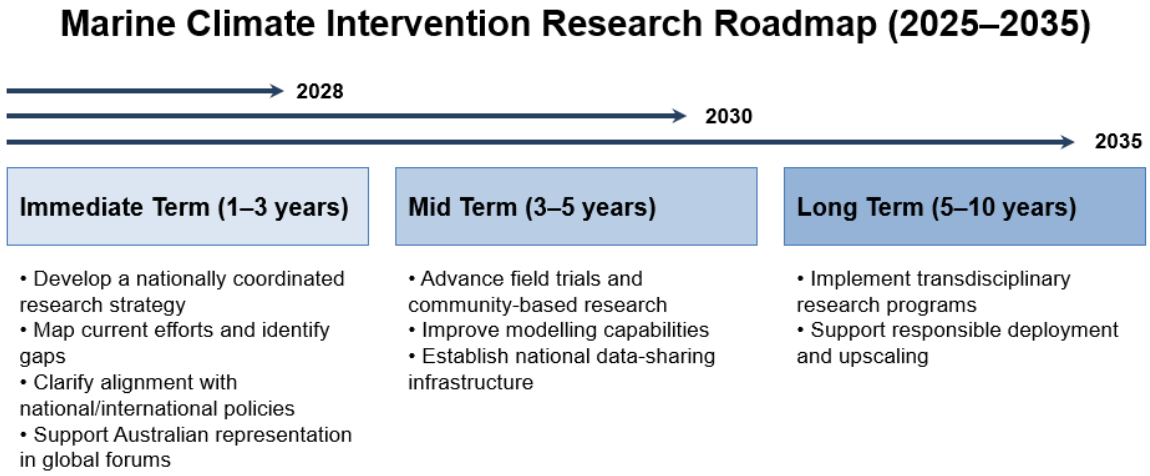


Figure 2. A suggested roadmap for Australian research into marine climate intervention.

Over the next decade, research on marine climate intervention in Australia should progress through three coordinated phases (Figure 2):

1. Immediate Term (1–3 years):

Establish a nationally coordinated research strategy or shared research agenda to map current efforts, identify critical knowledge gaps, and determine opportunities for Australia to develop marine climate interventions. The design of integrated observations and modelling and incorporating relevant mechanisms into models is important to identify optimal locations and ensure the activities in Australia's marine jurisdiction can be adequately monitored and verified, including any transboundary impacts in our regional waters. Coordination should foster collaboration with the goal to initiate transparent projects and build capacity and community engagement. The projects should first clarify how marine climate interventions align with national and international ocean, climate, and sustainability policies, and second work toward initiation of hands-on research with planning for field trials. This will help ensure Australian representatives are informed by the latest science to contribute meaningfully to global forums (e.g. London Protocol, UNCBD, UNFCCC, UNCLOS).

2. Mid Term (3–5 years):

Focus on generating real-world data through observations and field trials, while improving modelling capabilities through integration into nested global configurations. Develop a

national data-sharing infrastructure—potentially through IMOS or similar platforms—to support collaboration, transparency, and evidence-based governance.

3. Long Term (5–10 years):

Implement transdisciplinary research programs that integrate natural and social sciences to support the responsible deployment and scaling of marine climate intervention technologies. Develop pilot methods and approaches, particularly those that have the capacity to be scaled further, and those that can utilise existing marine infrastructure. Table 2 outlines long-term goals on performance parameters relevant to successful climate intervention research and potential deployment.

7.1 Actions and Recommendations

Key priorities for marine climate interventions for Australia in the next decade include:

1. Research in marine climate intervention:
    a. What are the climate intervention methods well-suited to Australia's marine estate?
    b. What is the effectiveness of different approaches under different warming levels?
    c. What are the co-benefits, synergies, trade-offs, and adverse impacts of different approaches?
    d. What is the permanence, durability and reversibility of different approaches?
    e. What is the technical potential of different approaches, their scalability, sustainability and costs?

2. Monitoring Reporting and Verification

    a. Establish rigorous baselines for biogeochemical (e.g. carbon, other greenhouse gases and biogeochemical tracers) and ecosystems monitoring.
    b. Develop and build the observational capabilities and infrastructure that can detect changes in carbon uptake, climate, and their impacts on ecosystems.
    c. Invest in new technologies, modelling capability and sensors networks to determine the fate of carbon, the risk to permanence and risk of reversals.
    d. Advance multi-scale modelling capable of simulating the physical, chemical, and ecological responses to marine climate interventions across scales from local pilot sites to regional seas and global Earth system models.
    e. Develop transparent and rigorous MRV standards, including international standards in collaboration with the international community, to ensure comparability, credibility, global acceptance, and participation in international carbon markets.

3. Governance and Social Acceptance
    a. Develop a transparent CDR Project Registry, including environmental and social impact assessments.

b. Establish guidelines and/or communities of practice to promote early, continuous and active engagement with communities and stakeholders.
c. Work with stakeholders, communities and policymakers across multiple levels of government to develop tailored governance for marine climate interventions, including incentive mechanisms, risk management processes, and transparency/oversight mechanisms.
d. Engage with First Nations communities to understand their priorities and concerns and develop Indigenous-led/co-designed climate intervention research projects, exploring Indigenous perspectives and knowledge.
e. Integrate social science and governance research into climate intervention research projects and programs, i.e., adopt test-bed approaches exploring questions of governance and social acceptance alongside field-tests and pilot studies.
f. Understanding how Australia can continue to engage in the development of international governance, promoting international cooperation and advancing Australia's national interest.

References

Abram, N.J., Henley, B.J., Sen Gupta, A. *et al.* (2021) Connections of climate change and variability to large and extreme forest fires in southeast Australia. *Commun Earth Environ,* **2**, 8. doi:10.1038/s43247-020-00065-8

Anderson, H. J., Mongin, M., & Matear, R. (2025). Ocean alkalinity enhancement in a coastal channel: Simulating localised dispersion, carbon sequestration and ecosystem impact. *Environmental Research Communications*. (In revision). CSIRO.

ANZG. 2018. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Governments and Australian State and Territory Governments.

Bach, L. T. (2024) The additionality problem of ocean alkalinity enhancement. *Biogeosciences*, 21,261-277. doi: 10.5194/bg-21-261-2024

Bach, L. T., Gill, S. J., Rickaby, R. E. M., Gore, S., & Renforth, P. (2019). CO2 Removal with Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems [Original Research]. *Frontiers in Climate*, 1. doi: 10.3389/fclim.2019.00007

Bach, L. T., Tamsitt, V., Gower, J., Hurd, C. L., Raven, J. A., & Boyd, P. W. (2021). Testing the climate intervention potential of ocean afforestation using the Great Atlantic Sargassum Belt. *Nature Communications*, 12(1), 2556.doi: 10.1038/s41467-021-22837-2

Bach, L.T., Vaughan, N.E., Law, C.L., Williamson, P. (2024) Implementation of marine CO_2 removal for climate mitigation: The challenges of additionality, predictability, and governability. *Elementa: Science of the Anthropocene* 12 January 2024; 12 (1): 00034. doi: 10.1525/elementa.2023.00034

Baresi, U., Baum, C. M., Fischer, T. B., Lockie, S., Piggott-McKellar, A., Graham., V., Bohensky, E., Fritz, L.B., Shumway, N., Harrison, D. P., Foster, R., Sovacool, B. K., Vella, K., and Ristovski, Z. 2025a. A call for strategic assessments of regional applications of solar radiation management. *Environmental Impact Assessment Review* 110. doi: 10.1016/j.eiar.2024.107701

Baresi, U., Eberhard, R., Vella, K., Gooch, M., Piggott-McKellar, A., Calibeo, D., Lockie, S., Taylor, B., Bohensky, E., Brooksbank, J.L., Curnock, M., Graham, T., Kong, T., Lyons, P., Maclean, K., Paxton, G., Schmitt, K., Siehoyono Sie, L., Stone-Jovicich, S. 2025b. Community engagement for novel ecosystem restoration and assisted adaptation interventions: observations and lessons from the Australian Reef Restoration and Adaptation Program. *Society & Natural Resources*. doi: 10.1080/08941920.2025.2463088

Bartelet et al. 2025. Public support for novel interventions to protect, restore, and accelerate adaptation to climate change in the Great Barrier Reef. Ocean and Coastal Management 107489

Bell-James et al. (2023) The permitting process for marine and coastal restoration: A barrier to achieving global restoration targets? 5(12) *Conservation Science and Practice* doi: 10.1111/csp2.13050

Boyd, P.W., Bach, L.T., Hurd, C.L. *et al.* (2022) Potential negative effects of ocean afforestation on offshore ecosystems. *Nat Ecol Evol* **6**, 675–683. doi: 10.1038/s41559-022-01722-1

Boyd, P.W., Bach, L.T. Holden, R., and Turney, C. (2023a) Redesign carbon-removal offsets to help the planet. *Nature*, 620, 948-949.

Boyd, P. W., Claustre, H., Legendre, L., Gattuso, J.-P., & Le Traon, P.-Y. (2023b). Operational monitoring of open-ocean carbon dioxide removal deployments: Detection, attribution, and determination of side effects. *Oceanography, 36*(1), 2–10. Oceanography Society. https://www.jstor.org/stable/27217363Brent, Kerryn., Burns, Wil. and McGee, J. (2019) Governance of Marine Geoengineering, CIGI https://www.cigionline.org/publications/governance-marine-geoengineering/

Brent, Kerryn. (2023) Solar Geoengineering and the Challenge of Governing Multiple Risks in the Anthropocene in P d Burdon & J Martel (eds) *The Routledge Handbook of Law and the Anthropocene* (1st ed, 2023) 257-267.

Brent, K., Simon, M., & McDonald, J. (2024). From informal to formal governance of solar radiation management. *Climate Policy*, 1–18. doi: 10.1080/14693062.2024.2430688

Britton, D., Pelletier, M., Lehmann, N., Bach, L. T. (in preparation). Effects of carbonate- and olivine-based ocean alkalinity enhancement on seafloor communities in coastal Tasmania: a field study. https://appliedbgc.imas.utas.edu.au/oae-field-study-2024/

Buchanan, P. J., Reddy, P. J., Matear, R. J., Chamberlain, M. A., Rohr, T., Squire, D., and Shadwick, E. H.: Optimisation of the World Ocean Model of Biogeochemistry and Trophic-dynamics (WOMBAT) using surrogate machine learning methods, *EGUsphere* [preprint], doi: 10.5194/egusphere-2024-4026, 2025

Burke, J. and Schenuit, F. (2023) Governing permanence of Carbon Dioxide Removal: a typology of policy measures. CO2RE – The Greenhouse Gas Removal Hub. Downloaded: https://co2re.org/wp-content/uploads/2023/11/CO2RE_Report_CDR_Permanence-FINAL-v7.pdf

Burt D.J., Fröb F. and Ilyina T. (2021) The Sensitivity of the Marine Carbonate System to Regional Ocean Alkalinity Enhancement. *Front. Clim.* 3:624075. doi: 10.3389/fclim.2021.624075

Canadell, J.G., Meyer, C.P.(., Cook, G.D. *et al.* Multi-decadal increase of forest burned area in Australia is linked to climate change. *Nat Commun* **12**, 6921 (2021). doi: 10.1038/s41467-021-27225-4

Carton, W., Hougaard, I.-M., Markusson, N., & Lund, J. F. (2023). Is carbon removal delaying emission reductions? WIREs *Climate Change*, 14(4), e826. doi: 10.1002/wcc.826

Cross, J.N., Sweeney, C., Jewett, E.B., Feely, R.A., McElhany, P., Carter, B., Stein, T., Kitch, G.D., and Gledhill, D.K., 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. doi: 10.25923/gzke-8730

Commonwealth of Australia 2024, Australia's draft Sustainable Ocean Plan, Commonwealth of Australia, Canberra, Sustainable Ocean Plan - DCCEEW

de Lannoy, C.F., Eisaman, M.D., Jose, A., Karnitz, S.D., DeVaul, R.W., Hannun, K., and Rivest, J.L. (2018) Indirect Ocean capture of atmospheric CO2: Part I. Prototype of a negative emissions technology. *International Journal of Greenhouse Gas Control,* 70: 243–253. doi: 10.1016/j.ijggc.2017.10.007

Diamond, M., Gettelman, A., Lebsock, M., McComiskey, A., Russell, L., Wood, R., and Feingold, G. (2022). Opinion: To assess marine cloud brightening's technical feasibility, we need to know what to study—and when to stop. *Proceedings of the National Academy of Sciences*. 119. e2118379119. doi: 10.1073/pnas.2118379119.

Doney, S., K. Lebling, O.S. Ashford, C.R. Pearce, W. Burns, S. Nawaz, T. Satterfield, H.S. Findlay, N.D. Gallo, J.-P. Gattuso, P. Halloran, D.T. Ho, L.A. Levin, C. Savoldelli, P.A. Singh, and R. Webb. 2025. *Principles for Responsible and Effective Marine Carbon Dioxide Removal Development and Governance*. Washington, DC: World Resources Institute. https://oceanpanel.org/publication/marine-carbon-dioxide-removal/ doi: 10.69902/84b3a9a8

Doney, S.C., Wolfe W.H., McKee, D.C., and Fuhrman J.G. (2025) The Science, Engineering, and Validation of Marine Carbon Dioxide Removal and Storage, *Annual Review of Marine Science*, 17:55–81, doi: 10.1146/annurev-marine-040523-014702

John S. Dryzek *et al.* (2020) Global citizen deliberation on genome editing. *Science,* 369,1435-1437 doi: 10.1126/science.abb5931

Eisaman, M. D., Geilert, S., Renforth, P., Bastianini, L., Campbell, J., Dale, A.W., Foteinis, S., Grasse, P., Hawrot, O., Löscher, C. R., Rau, G. H., Rønning, J. (2023) Assessing the technical aspects of ocean-alkalinity-enhancement approaches, in: Guide to Best Practices in Ocean Alkalinity Enhancement Research, edited by: Oschlies, A., Stevenson, A., Bach, L. T., Fennel, K., Rickaby, R. E. M., Satterfield, T., Webb, R., and Gattuso, J.-P., Copernicus Publications, *State Planet*, 2-oae2023, doi: 10.5194/sp-2-oae2023-3-2023

Felgenhauer, Tyler., Govindasamy Bala, Mark E Borsuk, Inés Camilloni, Jonathan B Wiener, Jianhua Xu. 2025. Practical paths to risk-risk analysis of solar radiation modification, *Oxford Open Climate Change*, Volume 5, Issue 1, 2025, kgaf012, doi: 10.1093/oxfclm/kgaf012

Fennel, K., Long, M. C., Algar, C., Carter, B., Keller, D., Laurent, A., Mattern, J. P., Musgrave, R., Oschlies, A., Ostiguy, J., Palter, J. B., & Whitt, D. B. (2023). Modelling considerations for research on ocean alkalinity enhancement (OAE). In A. Oschlies, 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 Research* (Vol. 2-oae2023, p. 9). Copernicus Publications. doi: 10.5194/sp-2-oae2023-9-2023

Fennel, K. (2025) The Verification Challenge of Marine Carbon Dioxide Removal. Annual Review of Marine Science, 18:6.1–6.24 doi: 10.1146/annurev-marine-032123- 025717

Foster, R., N. Shumway, D. Harrison and P. Fidelman (2025) *Earth System Governance* Vol. 23 Pages 100240 DOI: https://doi.org/10.1016/j.esg.2025.100240

Freidlingstein, P., O''Sullivan, M., Jones, M. W. et al. (2025) Global Carbon Budget 2024, *Earth System Science Data*, 17(3), 965-1039, doi: 10.5194/essd-17-965-2025

Fritz, L., et al. (2024) Public engagement for inclusive and sustainable governance of climate interventions." *Nature Communications* **15**(1): 4168-4168.

Fuss S., Lamb W. F., Callaghan M. W., Hilaire J., Creutzig F., Amann T., Beringer T., Garcia W. de O., Hartmann J., Khanna T., Luderer G., Nemet G. F., Rogelj J., Smith P., Vicente J. L. V., Wilcox J., Dominguez M. del M. Z. and Minx J. C. (2018) Negative emissions - Part 2: Costs, potentials and side effects, *Environmental Research Letters,* 13 063002

Hernandez-Jaramillo, D. C., Harrison, L., Gunner, G., Junkermann, W., Lieff, W., Hacker, J., Rosenfeld, D., Kelaher, B., and Harrison, D. P. (2025) *Environmental Research Letters*, 20 054065, doi: 10.1088/1748-9326/adccd7

Hinrichs, C., Köhler, P., Völker, C., and Hauck, J. (2023) Alkalinity biases in CMIP6 Earth system models and implications for simulated CO_2 drawdown via artificial alkalinity enhancement, Biogeosciences, 20, 3717–3735, doi: 10.5194/bg-20-3717-2023

Hlywiak, J and D. S. Nolan (2022) Targeted artificial ocean cooling to weaken tropical cyclones would be futile. *Communications Earth & Environment*, 3, 185, doi: 10.1038/s43247-022-00519-1

Ho, D. T., Bopp, L., Palter, J. B., Long, M. C., Boyd, P. W., Neukermans, G., & Bach, L. T. (2023). Monitoring, reporting, and verification for ocean alkalinity enhancement. In A. Oschlies, 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 Research* (Vol. 2-oae2023, p. 12). Copernicus Publications. doi: 10.5194/sp-2-oae2023-12-2023

Hunter, C et al (2024) Cultural licence to operate in the Blue Economy https://blueeconomycrc.com.au/project/cultural-licence-to-operate-in-the-blue-economy/

Hurd, C.L., Lenton, A., Tilbrook, B. & Boyd, P. W. Current understanding and challenges for oceans in a higher-CO_2 world. *Nature Clim Change* **8**, 686–694 (2018). doi:10.1038/s41558-018-0211-0

IPCC, 2022: Summary for Policymakers [P.R. Shukla, J. Skea, A. Reisinger, R. Slade, R. Fradera, M. Pathak, A. Al Khourdajie, M. Belkacemi, R. van Diemen, A. Hasija, G. Lisboa, S. Luz, J. Malley, D. McCollum, S. Some, P. Vyas, (eds.)]. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001.

IPCC, 2023: Sections. In: 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, doi: 10.59327/IPCC/AR6-9789291691647

Jiang, L.-Q., Subhas, A. V., Basso, D., Fennel, K., and Gattuso, J-P. (2023) Data reporting and sharing for ocean alkalinity enhancement research, in: Guide to Best Practices in Ocean Alkalinity Enhancement Research, edited by: Oschlies, A., Stevenson, A., Bach, L. T., Fennel, K., Rickaby, R. E. M., Satterfield, T., Webb, R., and Gattuso, J.-P., Copernicus Publications, *State Planet*, 2-oae2023, 13, doi: 10.5194/sp-2-oae2023-13-2023

Krause-Jensen, D., and C. M. Duarte. 2016. Substantial role of macroalgae in marine carbon sequestration. Nature Geoscience 9(10):737-742. doi:10.1038/ngeo2790.

Lamb, W.F., Gasser, T., Roman-Cuesta, R.M. *et al.* The carbon dioxide removal gap. *Nat. Clim. Chang.* **14**, 644–651 (2024). doi: 10.1038/s41558-024-01984-6

Latham, J., Kleypas, J., Hauser, R., Parkes, B., & Gadian, A. (2013). Can marine cloud brightening reduce coral bleaching? *Atmospheric Science Letters,* 14(4), 214-219. doi: 10.1002/asl2.442

Lenton, A., Matear, R. J., Keller, D. P., Scott, V., and Vaughan, N. E. (2018). Assessing carbon dioxide removal through global and regional ocean alkalinization under high and low emission pathways. *Earth Syst. Dyn*. 9, 339–357. doi: 10.5194/esd-9-339-2018

Macreadie, P. I., Costa, M. D., Atwood, T. B., Friess, D. A., Kelleway, J. J., Kennedy, H., Lovelock, C. E., Serrano, O., & Duarte, C. M. (2021). Blue carbon as a natural climate solution. *Nature Reviews Earth & Environment*, 2(12), 826-839.

Maynard, A.D., Dudley, S.M. Navigating advanced technology transitions: using lessons from nanotechnology. *Nat. Nanotechnol.* **18**, 1118–1120 (2023). doi: 10.1038/s41565-023-01481-5

McCrea, Rod, Rebecca Coates, Elizabeth V. Hobman, Sarah Bentley, Justine Lacey. (2024). Responsible innovation for disruptive science and technology: *The role of public trust and social expectations, Technology in Society*, Volume 79, 2024, 102709, ISSN 0160-791X, doi: 10.1016/j.techsoc.2024.102709.

McDonald, J., McGee, J., Brent, K., & Burns, W. (2019) Governing Geoengineering Research for the Great Barrier Reef 19(7) *Climate Policy* 801-11

McDonald, J., Brent K., McCormack, P., & McGee, J (2023). Greenhouse Gas Removal in Australian Climate Law: A Positive Role for Negative Emissions. *University of New South Wales Law Journal* 46(1) 79-110

Mongin, M., Baird, M.E., Tilbrook, B., Matear, R. J., Lenton, A., Herzfeld, M., Wild-Allen, K.A., Skerratt, J., Margvelashvili, N., Robson, B., Duarte, C.M., Gustafsson, M.S.M., Ralph, P.J., and Steven A. (2016) The exposure of the Great Barrier Reef to ocean acidification, *Nature Communications*, *7*, 10732, doi: 10.1038/ncomms10732

Mongin, M., Baird, M.E., Lenton, A., Neil, C., and Akl. J. (2021) Reversing ocean acidification along the Great Barrier Reef using alkalinity injection, *Environmental Research Letters.* 16, 064068, doi: 10.1088/1748-9326/ac002d

Moore, J. C., Gladstone, R., Zwinger, T. and M. Wolovick (2018) Geoengineering polar glaciers to slow sea-level rise. *Nature*, 555, 303-305, doi: 10.1038/d41586-018-03036-4

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

Ogle, S.M., Domke, G., Kurz, W.A. *et al.* Delineating managed land for reporting national greenhouse gas emissions and removals to the United Nations framework convention on climate change. *Carbon Balance Manage* **13**, 9 (2018). doi: 10.1186/s13021-018-0095-3

Oschlies A, Bach LT, Fennel K, Gattuso J-P and Mengis N (2025) Perspectives and challenges of marine carbon dioxide removal. *Front. Clim*. 6:1506181. doi: 10.3389/fclim.2024.1506181

Rau, G.H., Willauer, H.D. & Ren, Z.J. (2018) The global potential for converting renewable electricity to negative-CO_2-emissions hydrogen. *Nature Clim. Change* **8**, 621–625 doi: 10.1038/s41558-018-0203-0

Renforth, P., & Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration. *Reviews of Geophysics*, 55(3), 636-674. doi: 10.1002/2016RG000533

Roberts, K.E., Harrison, C.H., Rohr, T.W. et al. (2024) Potential impacts of climate interventions on marine ecosystems. *ESS Open Archive.* December 21, 2024. doi: 10.22541/essoar.173482381.11257447/v1

Rohr, T., Richardson, A.J., Lenton, A. *et al.* (2023) Zooplankton grazing is the largest source of uncertainty for marine carbon cycling in CMIP6 models. *Commun Earth Environ* **4**, 212 . doi: 10.1038/s43247-023-00871-w

Ross, A., Myers, J., van Ooijen, E., Greenwood, J., Ryan, T., Hughes, D., Marouchos, A., Keesing, J., Scoulding, B., and Jenkins C. (2022) M8 Synthesis report on network designs for CCS site marine measurement, monitoring and verification – Volume 1 , ANLEC R&D Project 7-0816-0305, downloaded https://anlecrd.com.au/projects/methodology-to-deploy-shallow-focused-subsea-ccs-technologies/

Schenuit, F., O. Geden, O., and G. P. Peters. 2024. Five principles for robust carbon dioxide removal policy in the G7 *One Earth,* 7(9), 1487-1491 doi: 10.1016/j.oneear.2024.08.015

Smith, S. M., Geden, O., Gidden, M. J., Lamb, W. F., Nemet, G. F., Minx, J. C., Buck, H., Burke, J., Cox, E., Edwards, M. R., Fuss, S., Johnstone, I., Müller-Hansen, F., Pongratz, J., Probst, B. S., Roe, S., Schenuit, F., Schulte, I., Vaughan, N. E. (eds.) *The State of Carbon Dioxide Removal 2024* - 2nd Edition. doi: 10.17605/OSF.IO/F85QJ (2024)

United Nations Environment Programme (2023). One Atmosphere: An independent expert review on Solar Radiation Modification research and deployment. Kenya, Nairobi

Tagliabue, A., Twining, B. S., Barrier, N., Maury, O., Berger, M., & Bopp, L. (2023). Ocean iron fertilization may amplify climate change pressures on marine animal biomass for limited climate benefit. *Global Change Biology*, 29, 5250–5260. doi: 10.1111/gcb.16854

Van Putten, I. E., Cvitanovic, C., Fulton, E., Lacey, J., & Kelly, R. (2018). The emergence of social licence necessitates reforms in environmental regulation. *Ecology and Society*, *23*(3)

Vaughn, L. and Jacquez, F. (2020). Participatory Research Methods – Choice Points in the Research Process. *Journal of Participatory Research Methods,* 1, 10.35844/001c.13244.

Wallace, D., Law, C., Boyd, P., Collos, Y., Croot, P., Denman, K., Lam, P., Riebesell, U., Takeda, S., Williamson, P., 2010. *Ocean fertilization: a scientific summary for policy makers.* UNESCO.

Wang, B., Laurent, A., Pei, Q., Sheng, J., Atamanchuk, D., & Fennel, K. (2024, October). Maximizing the detectability of ocean alkalinity enhancement (OAE) while minimizing its exposure risks: Insights from a numerical study. *ESS Open Archive*. doi: 10.22541/essoar.173013884.44766434/v1 *(Preprint, accessed 2024-11-05)*

Wang, B., Laurent, A., Pei, Q., Sheng, J., Atamanchuk, D., & Fennel, K. (2025) Maximizing the detectability of ocean alkalinity enhancement (OAE) while minimizing its exposure risks: Insights from a numerical study. *Earth's Future*, 13, e2024EF005463, doi: 10.1029/2024EF005463

Webb, Romany M. (2024) *International Governance of Ocean-Based Carbon Dioxide Removal: Recent Developments and Future Directions*, Sabin Center for Climate Change Law, Columbia Law School, April 2024 Available at: https://scholarship.law.columbia.edu/sabin_climate_change/216

Williamson P. and Gattuso J-P. (2022) Carbon Removal Using Coastal Blue Carbon Ecosystems Is Uncertain and Unreliable, With Questionable Climatic Cost-Effectiveness. *Front. Clim.* 4:853666. doi: 10.3389/fclim.2022.853666