

Ocean Alkalinity Enhancement:
A Synthesis of Research on its Climate
Mitigation Potential and International
Governance Challenges

Jenna Painter

Supervisor: Luc Juillet

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Institute of the Environment, University of Ottawa

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Executive Summary

Deploying carbon dioxide removal (CDR) technologies has been deemed necessary to complement drastic emissions reductions and limit global warming to well below 2°C compared to pre-industrial temperatures by the end of the century (IPCC, 2023). Attention has turned to deploying CDR in marine environments (mCDR) due to the ocean's natural capacity for sequestering and storing atmospheric carbon dioxide (CO₂). Ocean alkalinity enhancement (OAE) is an mCDR approach that aims to increase the ocean's chemical storage capacity for atmospheric CO₂ by adding alkaline materials to its surface to enhance its natural buffering capacity (Kheshgi, 1995; Wang et al., 2023). This scoping review synthesized the academic literature on OAE's CDR potential, climate mitigation benefits, and the opportunities and challenges associated with the international governance of OAE and mCDR approaches.

Earth model scenarios of OAE show different potentials for atmospheric CO₂ uptake and storage due to varying model parameters, such as the scale of OAE (e.g., global or regional), the location of OAE, the amount and type of alkaline material added, and the forecasted emissions pathway. Overall, model scenarios of global, regional, and coastal OAE using various natural and synthetic alkaline materials indicate that oceanic uptake and storage of atmospheric CO₂ would increase (e.g., Jin & Cao, 2023; Fakhraee et al., 2023). OAE termination scenarios indicate that once OAE ceases after a certain period, the ocean stops taking up CO₂ at an enhanced rate; however, the CO₂ previously sequestered remains in the marine environment (e.g., Ilyina et al., 2023; Keller et al., 2014). Corresponding with the enhanced oceanic CO₂ uptake and reduced atmospheric CO₂ concentrations, future projected increases in average global surface air temperature are predicted to decrease under OAE scenarios (e.g., Gonzalez et al., 2018; Sonntag et al., 2018). However, despite OAE's potential for climate mitigation, numerous knowledge gaps

remain regarding its impact on the climate system and the marine environment. Future multi-model research into the effectiveness and feasibility of OAE and its influence on the global climate system and ocean ecology is required (Butenschan et al., 2021; Lenton et al., 2018).

mCDR approaches, including OAE, have no legally binding international governance regimes (Bach et al., 2024). However, numerous frameworks likely have implicit roles in mCDR governance due to their connections to the marine environment and climate change, such as the London Protocol, Paris Agreement, United Nations Convention on the Law of the Sea, and Convention on Biological Diversity (Gambardella, 2019; McGee et al., 2018). While research on mCDR approaches is needed to evaluate their effectiveness and impacts, experimental groundwork and deploying OAE and other mCDR techniques are expected to face numerous governance challenges (Gattuso et al., 2021; Sovacool et al., 2022). Substantial challenges for mCDR governance stem from the potential of transboundary harm and the fragmented international law framework for the ocean (Boettcher et al., 2021; Roschel & Neumann, 2023). Further, mCDR research and deployment will likely have low social acceptability due to risks to the marine environment and human well-being (Cox et al., 2021). To address these challenges, transdisciplinary and inclusive research is needed to develop a governance approach that comprehensively assesses mCDR approaches (McGee et al., 2018; Roschel & Neumann, 2023).

OAE displays a strong potential for climate mitigation. Future research is needed to assess OAE's CDR potential under different earth system models and determine OAE's impact on marine ecosystems and biodiversity (Feng et al., 2017; Jin & Cao, 2023; Lenton et al., 2018). An inclusive and transdisciplinary approach to mCDR governance is required to create an extensive and foresighted framework that addresses the unique challenges and opportunities of mCDR approaches for climate mitigation (Bach et al., 2024; Loomis et al., 2022; McGee et al., 2018).

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List of Abbreviations

CBD	Convention on Biological Diversity
CDR	Carbon dioxide removal
DIC	Dissolved inorganic carbon
EEZs	Exclusive economic zones
GHGs	Greenhouse gases
IMO	International Maritime Organization
IPCC	International Panel on Climate Change
mCDR	Marine carbon dioxide removal
MRV	Monitoring, reporting, and verification
NDCs	Nationally determined contributions
NETs	Negative emission technologies
OA	Ocean acidification
OAE	Ocean alkalinity enhancement
pCO ₂	Partial pressure of carbon dioxide
RCP	Representative concentration pathway
SAT	Surface air temperature
SSP	Shared socio-economic pathway
SRM	Solar radiation management
TA	Total alkalinity
tCDR	Terrestrial carbon dioxide removal
UNCLOS	United Nations Convention on the Law of the Sea
UNFCCC	United Nations Framework Convention on Climate Change

1.0 Introduction

Anthropogenic climate change is deemed one of the greatest threats to humankind (IPCC, 2021; The Royal Society and Royal Academy of Engineering, 2018). The 2015 Paris Agreement set out the ambitious goal to limit human-induced global warming to well below 2°C above pre-industrial levels and to take further action to limit warming to only 1.5°C above pre-industrial levels by the end of the century to prevent the disastrous impacts of climate change (Goodwin et al., 2018; UNFCCC, 2015 – Art. 2(a)). Drastic and rapid emissions reductions are needed to achieve the goals outlined by international climate policy. However, the current and pledged emissions reductions, known as nationally determined contributions (NDCs), outlined by states to reach the goals set out in the Paris Agreement are predicted to result in a 2.3-3.5°C temperature increase above pre-industrial levels (Climate Action Tracker, 2017; McGee et al., 2018). Consequently, it is increasingly likely that unprecedented emissions reductions must be complemented by large-scale carbon dioxide removal (CDR) to remove historically emitted anthropogenic carbon dioxide (CO₂) from the atmosphere and limit the global average temperature increase to below 2°C (IPCC, 2018; NASEM, 2019). The most recent assessment by the International Panel on Climate Change (IPCC) shows that keeping global warming well below 2°C requires extreme emissions reductions in combination with the deployment of CDR technologies (IPCC, 2023).

There are multiple approaches to CDR, also known as negative emission technologies (NETs), that can take place in terrestrial (tCDR) or marine (mCDR) environments (NASEM, 2019). As the world's oceans are a natural CO₂ sink, having absorbed approximately 30% of historical anthropogenic CO₂ emissions from 1750 to 2020 (Friedlingstein et al., 2020), they have been an area of interest for mCDR. Specifically, mCDR approaches aim to capitalize on the

geophysical potential of enhancing the oceans as a sink for atmospheric CO₂ (NASEM, 2022). However, due to the uptake of atmospheric CO₂ from anthropogenic sources, the oceans have undergone ocean acidification (OA) due to decreasing pH (Bates et al., 2012; Carter et al., 2019; Cyronak et al., 2014). Specifically, as the ocean takes up CO₂, there is a shift in the chemical equilibrium, which reduces the carbonate ion concentration and decreases pH (Lenton et al., 2018). OA has detrimental impacts on the entire marine ecosystem by altering nutrient availability, organism growth and physiology, species composition and distribution, nutrient availability, and food web structure, ultimately destabilizing ecosystems and threatening vital ecosystem services (Doney et al., 2012; Gattuso et al., 2015). Within this century, OA will continue to intensify in proportion to anthropogenic emissions (Gattuso et al., 2015).

Ocean alkalinity enhancement (OAE), also known as ocean alkalization or artificial ocean alkalization, is an mCDR approach that could reduce OA while increasing the ocean's chemical storage capacity for CO₂ (Kheshgi, 1995; Wang et al., 2023). OAE aims to increase oceanic CO₂ uptake by adding proton-neutralizing (alkaline) materials to the ocean's surface to raise its alkalinity and neutralize OA (Kheshgi, 1995). OAE mimics the naturally occurring mineral weathering process between the land and ocean on geological timescales (10,000 to 100,000 years) through the dissolution of alkaline minerals in seawater (Gonzalez & Ilyina, 2016; Lord et al., 2016). The natural weathering process contributes to the alkalization of the ocean through weathering fluxes on land that result in large amounts of alkaline minerals entering the marine environment over multi-millennial timescales, and OAE thus aims to speed up and mimic this process (Hartmann et al., 2013; Kheshgi, 1995).

Increasing the ocean's surface alkalinity shifts the dissolved inorganic carbon (DIC) speciation from CO₂ into stable bicarbonate (HCO₃⁻) and carbonate (CO₃²⁻) ions through a series

of chemical reactions, as these are the dominant forms of seawater alkalinity (Hartmann, 2013; NASEM, 2022). As dissolved CO₂ is converted into other forms of DIC, the partial pressure of CO₂ (pCO₂) in seawater decreases (NASEM, 2022). To restore the pCO₂ equilibrium, the air-sea flux of CO₂ will be enhanced, leading to increased atmospheric CO₂ uptake by the ocean (NASEM, 2022). Overall, OAE increases the ocean's total alkalinity (TA) and buffering capacity to enhance oceanic uptake of atmospheric CO₂ and store it for long periods (Gately et al., 2023; Hartmann et al., 2013; Renforth & Henderson, 2017). In addition to decreasing the amount of atmospheric CO₂, OAE could counteract OA by increasing the pH of the ocean and the availability of carbonate ions (Doney et al., 2020; Mu et al., 2023; Wang et al., 2023).

OAE can be achieved through multiple approaches (Renforth & Henderson, 2017). There are three broad categories of OAE approaches: coastal weathering, offshore alkalinity enhancement, and electrochemical methods (Bach et al., 2024; Renforth & Henderson, 2017). Coastal weathering involves adding alkaline materials to the surface coastal waters (e.g., Feng et al., 2017; Palmieri & Yool, 2024), while offshore alkalinity enhancement takes place in open ocean surface waters (e.g., Gonzalez & Ilyina, 2016; Keller et al., 2014). Coastal and offshore OAE can be done through the dispersion of pulverized or pre-dissolved naturally occurring silicate (e.g., olivine and basalt) or carbonate (e.g., calcite and dolomite) minerals or synthetic minerals (e.g., lime and brucite) (NASEM, 2022; Renforth & Henderson, 2017). These techniques can involve the application of alkaline minerals globally or regionally in selected locations (e.g., Burt et al., 2021; Ilyina et al., 2013; Jin & Cao, 2023; Lenton et al., 2018). Electrochemical OAE involves using fuel cells on the coasts to create alkalinity in the ocean through electrolysis reactions using minerals such as calcium carbonate, magnesium silicate, or sodium chloride (Renforth & Henderson, 2017).

While OAE is not a new concept (e.g., Kheshgi, 1995), its effectiveness as an mCDR technique is still being explored and quantified. OAE approaches are in the early stages of development and require further testing to understand their effectiveness, risks, and ecological impacts (Wang et al., 2023). Current OAE studies rely on earth system models to estimate the CDR potential and quantify any potential side effects from OAE; however, these studies differ in terms of the model parameters used and associated results (Keller et al., 2014). Aside from the climate and environmental impacts of OAE, assessments of the broader technical, regulatory, and economic implications are also preliminary (Boettcher et al., 2023; Cooley et al., 2023). Regarding governance, OAE and other mCDR approaches are subject to the interconnectedness of the marine environment as well as the relationships between humankind and the oceans, thus demanding international coordination and cooperation for effective governance (Biermann et al., 2009; Boucher et al., 2014; Boyes & Elliott, 2014; Minx et al., 2018). However, the fragmented nature of the global ocean governance regime will create challenges for mCDR governance, especially regarding uncertainties and risks associated with climate change and the potential side effects of mCDR techniques on marine biodiversity and ecosystems (Haas et al., 2022; Renforth & Henderson, 2017).

Considering the apparent need for CDR to reach the goals set out by international climate policy and the ocean's natural ability to sequester and store CO₂, this scoping review will analyze the state of knowledge surrounding the CDR potential of coastal and offshore OAE and the associated impacts on the climate system. Further, this review will synthesize the existing literature on the key actors, relevant frameworks, and overall challenges associated with mCDR governance from an international perspective and highlight potential paths forward for effective future governance.

2.0 Methods

This research project was a scoping review that assessed the state of knowledge on the CDR potential and climate impacts of OAE. Additionally, this review examined literature discussing the key actors and frameworks, issues, and recommendations moving forward regarding mCDR governance from an international perspective.

2.1 Scope

This scoping review was guided by two research questions. The scope of this review was to assess the CDR potential of coastal and offshore OAE and analyze the international governance implications of mCDR techniques.

The first research question focused on synthesizing existing literature evaluating the CDR potential and carbon storage stability of OAE. Additionally, this research question sought to analyze the climate impacts of OAE, such as changes in projected temperature or precipitation patterns. OAE conducted through surface alkalinity addition in coastal or offshore zones on global or regional scales was the focus of this research question. Due to the time constraints of this research project (~4 months), studies examining electrochemical OAE were excluded. Additionally, the impacts of OAE on marine and coastal biodiversity and ecosystems, including OA, were excluded due to time constraints.

Research Question 1 was:

What is the CDR potential and stability/permanency of carbon storage using OAE in coastal or offshore areas, and what are the associated climate impacts?

The second research question aimed to synthesize literature reviewing the governance implications of mCDR approaches from an international perspective. The scope of this research question extended beyond OAE to encompass mCDR more broadly, as initial searches revealed very little academic literature discussing OAE governance exclusively. Thus, the key actors, frameworks, challenges, and opportunities for international mCDR governance were examined.

Research Question 2 was:

What are the relevant frameworks, challenges, and opportunities for the international governance of mCDR?

Considering the two research questions, several searches were conducted to retrieve recent (in the last ten years) academic reviews on the CDR potential of OAE and governance implications associated with mCDR. No published reviews were found with similar research questions, which confirmed that the scope of this review addressed a knowledge gap in academic literature.

2.2 Search Procedure

Each research question had a distinct search string and individual screening process. The first search was conducted to collect relevant studies that discussed the CDR potential and climate impacts of OAE. The second search was conducted to collect pertinent studies that analyzed the governance implications of mCDR. Each search was conducted on Web of Science and Scopus. The conditions for each search were set to provide academic, peer-reviewed articles (excluding review articles) that were available in English.

To begin developing the search strings used in this review, keywords related to mCDR and OAE were identified. As OAE is an emerging technique, broader terminology related to CDR and

geoengineering was considered. Using Scopus and Web of Science, multiple searches using various combinations of keywords were conducted to determine which terminology relating to OAE and mCDR should be included in the search strings. The first 25 papers of each search were reviewed, and the keywords were adjusted as needed.

2.2.1 Research Question 1

The first search string was associated with Research Question 1. This search string was intentionally broad and aimed to collect studies discussing OAE as an mCDR technique. The results were manually screened for relevance, and as OAE is an emerging topic, this was feasible. The first search string selected and used for this review was:

[geo*engineer* OR "climate engineer*" OR
 "carbon dioxide removal" OR "CO2 removal" OR
 "carbon removal" OR "negative emission*" OR
 "climate intervention" OR "ocean alkalinity
 enhancement" OR "ocean alkalini*ation"]
 AND [ocean*]
 AND [alkalin*]

This search was conducted on May 9th, 2024, and produced 116 results in Web of Science and 102 results in Scopus.

2.2.2 Research Question 2

The second search string corresponded to Research Question 2. This search string was less focused on OAE and instead aimed to retrieve studies discussing the governance implications of mCDR approaches. The second search string selected and used for this review was:

[geo*engineer* OR "climate engineer*" OR
 "carbon dioxide removal" OR "CO2 removal" OR
 "carbon removal" OR "negative emission*" OR
 "climate intervention" OR "ocean alkalinity
 enhancement" OR "ocean alkalini*ation"]
 AND [ocean* OR marine]
 AND [polic* OR govern* OR law*]

This search was completed on June 6th, 2024, and produced 116 results in Web of Science and 102 results in Scopus.

2.3 Selection Criteria

Individual sets of selection criteria were drafted for each research question. The selection criteria guided the screening process.

2.3.1 Research Question 1

Given the timeframe of this research project, the scope of Research Question 1 was narrowed to focus on the CDR potential and climate impacts of OAE through global or regional surface application in the open ocean, seas, or coastal zones (Table 1). Studies comparing OAE to other CDR or solar radiation management (SRM) methods were included; however, only the data

relevant to OAE was extracted. Studies reviewing electrochemical OAE or OAE conducted in freshwater bodies were excluded. Additionally, articles examining the specific weathering or deposition process involved in OAE or studies discussing technology or model development were excluded. The impact of OAE on marine biodiversity and ecosystems, as well as OA, were also excluded.

Table 1. Selection criteria for Research Question 1.

Include	Exclude
<ul style="list-style-type: none"> - Global or regional OAE application - Coastal or offshore (including seas) OAE - Surface TA addition (mineral-based) - CDR potential of OAE - Climate impacts of OAE (e.g., surface air temperature) - CO₂ storage stability/permeance in the ocean - Knowledge gaps relating to OAE - Research priorities relating to OAE 	<ul style="list-style-type: none"> - Electrochemical OAE - OAE in freshwater (i.e., rivers) - OAE weathering process - Emissions associated with OAE - Impact of OAE on marine biodiversity and ecosystems - Impact of OAE on OA - OAE technology/model development, design, comparison - Other mCDR or geoengineering techniques

2.3.2 Research Question 2

Studies discussing the key actors, relevant international frameworks, issues and uncertainties, and recommendations regarding the global governance of mCDR technologies were the focus of Research Question 2 (Table 2). Studies investigating tCDR or SRM governance were excluded. Further, studies discussing national governance implications or economic considerations were excluded.

Table 2. Selection criteria for Research Question 2.

Include	Exclude
<ul style="list-style-type: none"> - mCDR and OAE - Relevant international actors and frameworks (e.g., Paris Agreement, London Protocol, etc.) - Issues and uncertainties regarding mCDR governance through social/ethical, scientific, and policy lenses - Recommendations for the future of mCDR governance 	<ul style="list-style-type: none"> - tCDR and SRM governance - Economic implications (e.g., carbon pricing, carbon market) - National policies/governance plans

2.4 Screening

The results of each search were exported into Covidence, a software used to guide the screening process for literature reviews. The results of each search string underwent individual screening processes.

2.4.1 Research Question 1

The 218 results from Web of Science and Scopus associated with Research Question 1 were imported into Covidence. After removing 92 duplicates, 126 studies went on to the title and abstract screening. After this initial screening, 61 studies were excluded, and the remaining studies went on to the full-text review. After this second screening stage, 47 studies were excluded. The final dataset thus comprised 18 studies (Figure 1).

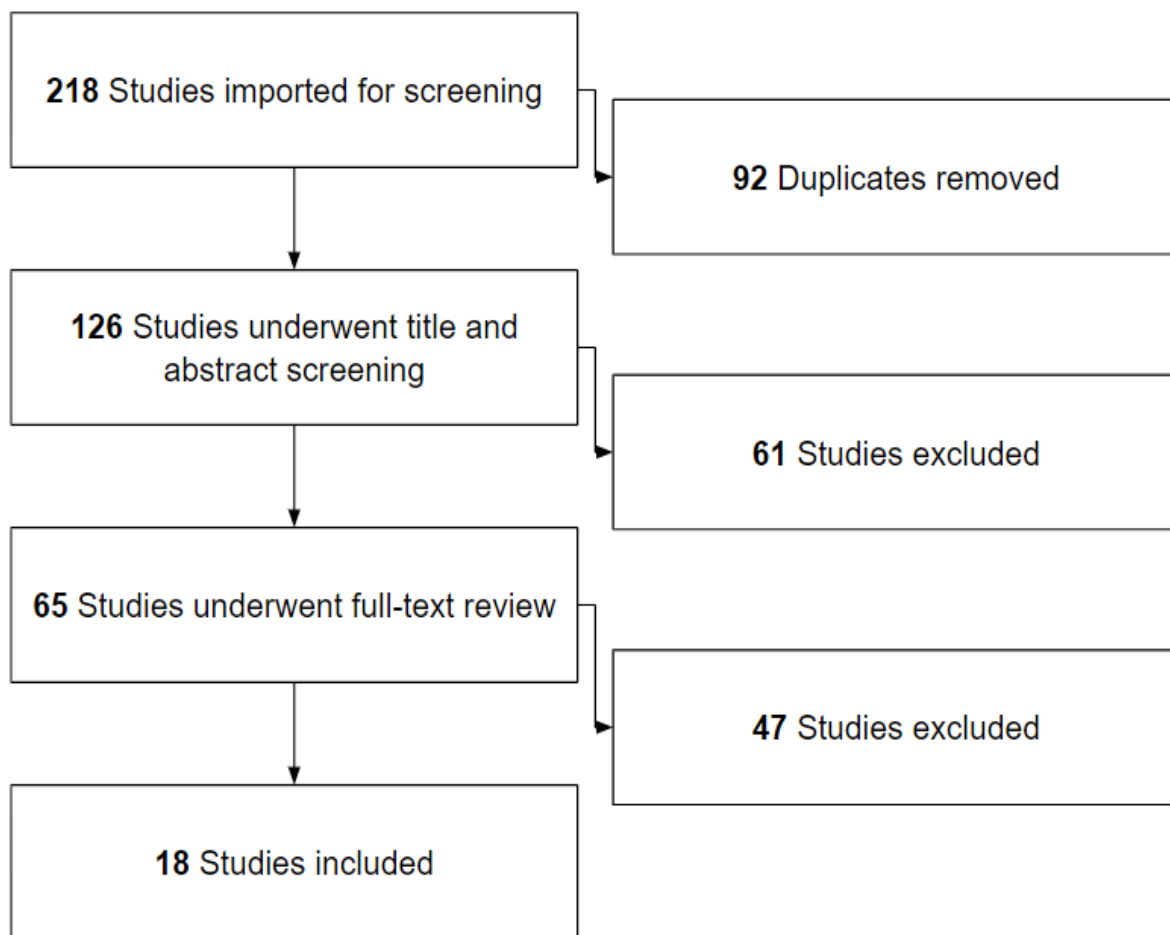


Figure 1. Flow diagram of the screening process for Research Question 1 to obtain the final dataset of 18 studies.

2.4.2 Research Question 2

The 218 results from Web of Science and Scopus associated with Research Question 2 were imported into Covidence. After removing 72 duplicates, 146 studies went on to the title and abstract screening. After this initial screening, 125 studies were excluded, and the remaining studies went on to the full-text review. After this second screening stage, 11 studies were excluded. The final dataset thus comprised 10 studies (Figure 2).

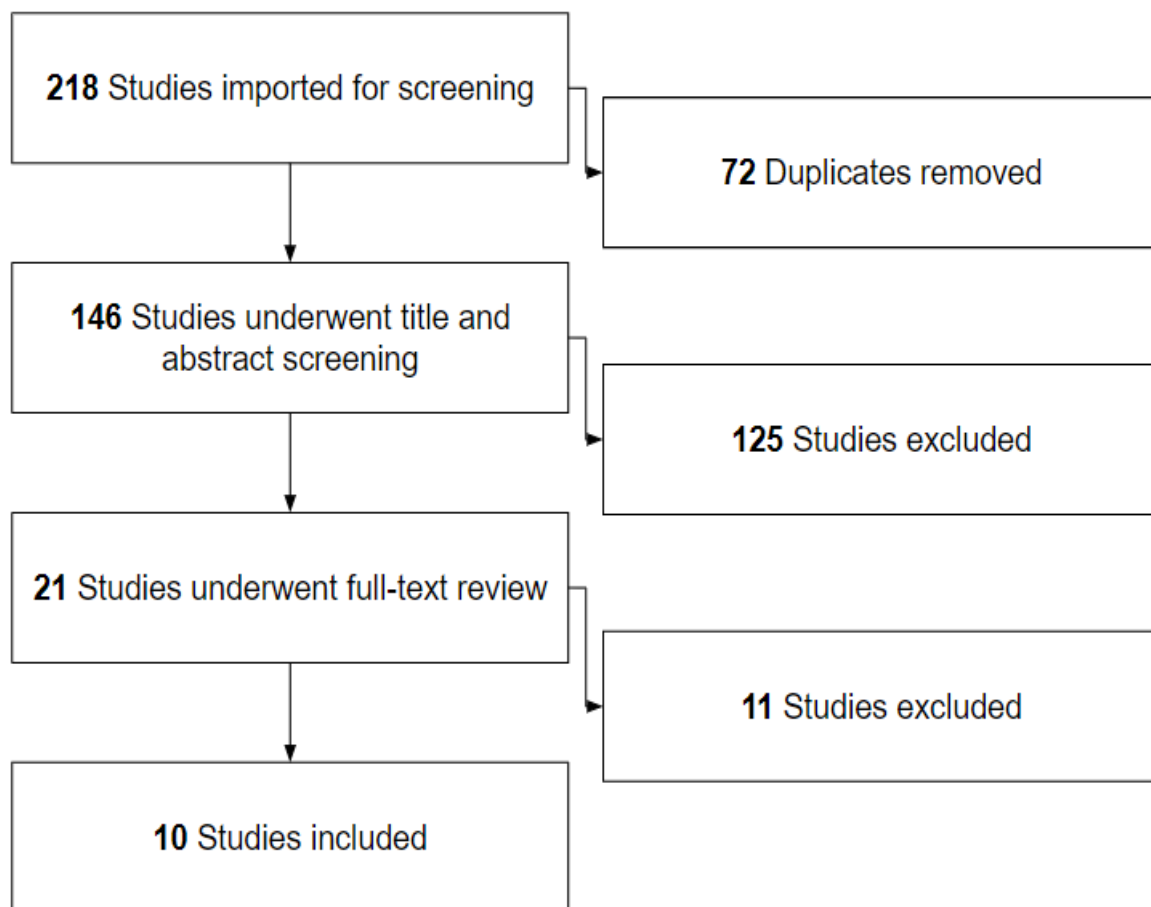


Figure 2. Flow diagram of the screening process for Research Question 2 to obtain the final dataset of 10 studies.

3.0 OAE: Implications for Climate Mitigation

The efficiency of OAE as an mCDR technique and its associated impacts on the climate system vary based on different model scenarios. The oceanic CO₂ uptake achieved by OAE can differ depending on the scale and location of the alkaline material application, as OAE can be conducted on the global surface ocean, regionally on the surface ocean or seas, or in coastal zones (e.g., Burt et al., 2021; Feng et al., 2016; Gonzalez & Ilyina, 2016; Kwiatkowski et al., 2023). Figure 3 demonstrates the number of studies in this review that modelled global, regional, or coastal OAE scenarios. The type and amount of alkaline material added can also impact CDR efficiency (e.g., Fakhraee et al., 2023; Kohler et al., 2013). Figure 4 highlights the number of studies reviewed that model OAE scenarios using different alkaline materials. In addition to the scale of application and alkaline material used in OAE scenarios, the length and termination of OAE will further influence its capacity for enhancing oceanic CO₂ uptake and storage (Gonzalez et al., 2018; Jin & Cao, 2023; Keller et al., 2014).

As OAE increases the amount of CO₂ sequestered from the atmosphere and stored in the ocean, it influences atmospheric CO₂ concentrations and can thus influence climate variables. Specifically, OAE is expected to reduce global average surface air temperature (SAT) increases compared to unmitigated high emissions scenarios (Gonzalez & Ilyina, 2016; Sonntag et al., 2018). Corresponding to the impact on global average SAT, OAE is predicted to decrease sea ice melt and associated sea level rise (Gonzalez & Ilyina, 2016). Earth system models also indicate that OAE could influence global precipitation patterns (Jin & Cao, 2023; Sonntag et al., 2018).

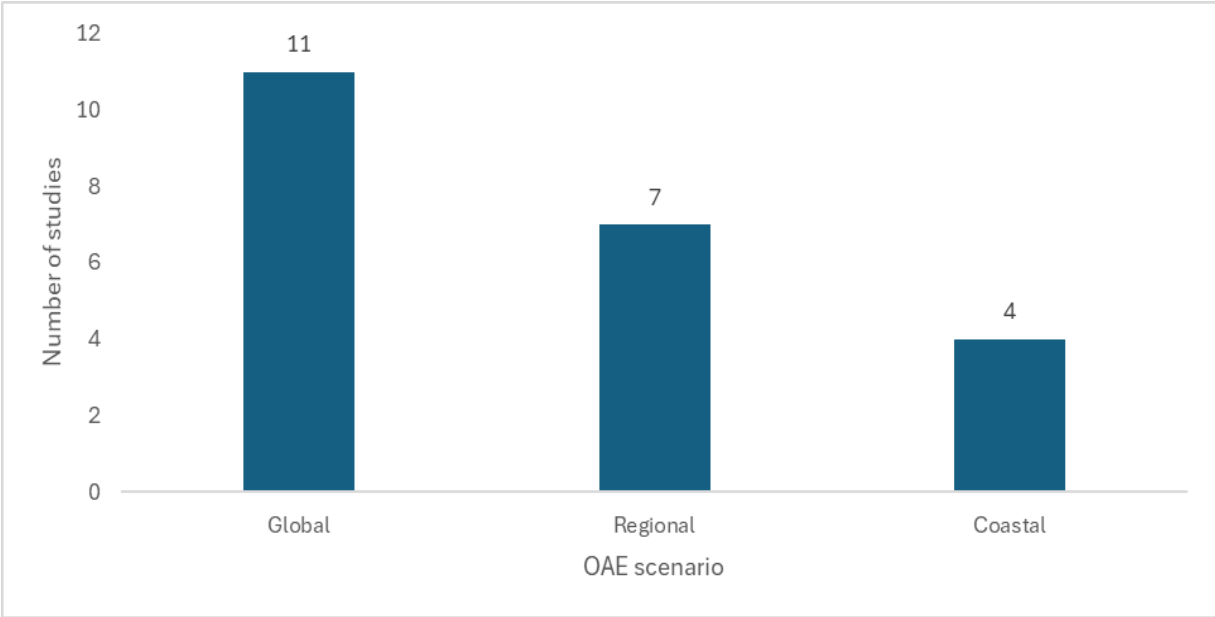


Figure 3. The number of studies investigating global, regional, and coastal OAE scenarios in the dataset for Research Question 1.

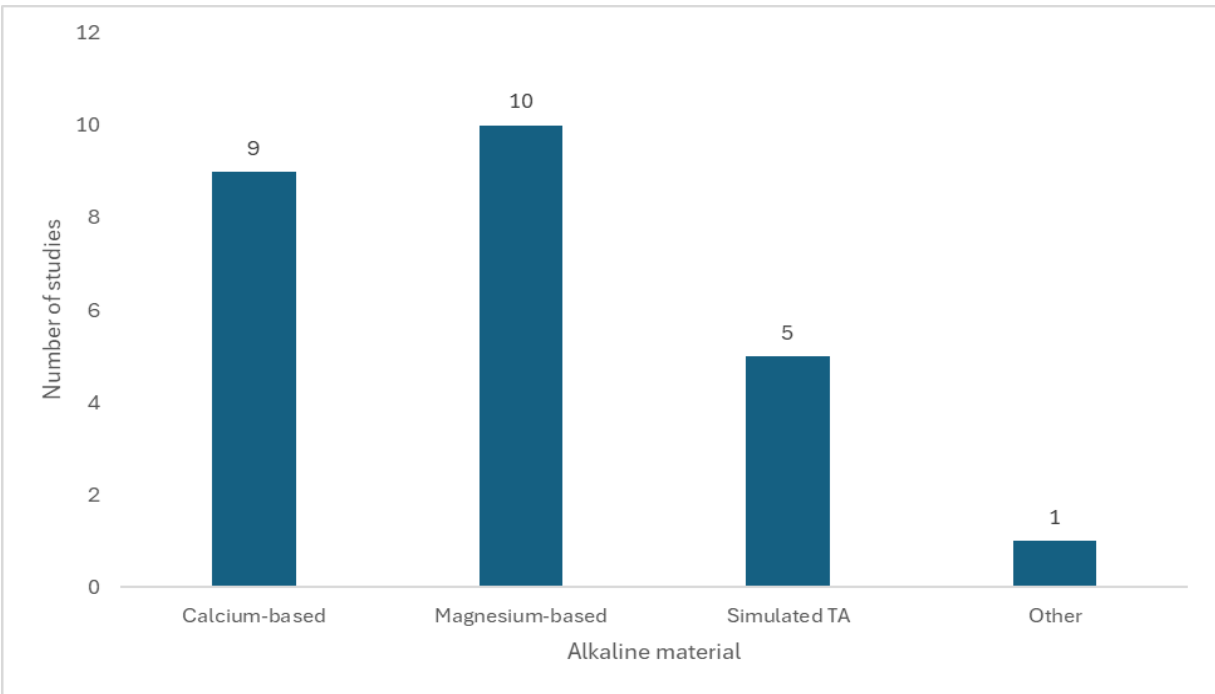


Figure 4. The number of studies investigating different alkaline materials in OAE scenarios in the dataset for Research Question 1.

While the concept of OAE is not new (e.g., Kheshgi, 1995), there are still numerous knowledge gaps relating to its CDR potential. Consequently, robust multi-model frameworks are needed to understand OAE's impact on the climate system (Caserini et al., 2021; Fakhraee et al., 2023; Keller et al., 2014; Lenton et al., 2018; Palmieri & Yool, 2024). Further uncertainties remain regarding the potential side effects of OAE on the marine environment. Specifically, knowledge gaps remain regarding OAE's impact on ocean and coastal ecosystems, biodiversity, and biogeochemistry (Butenschan et al., 2021; Caserini et al., 2021; Feng et al., 2017).

3.1 CDR Potential

The modelled increase in oceanic CO₂ uptake from OAE can differ based on application scale, location, material, amount, and rate. The alkalinity addition for OAE can be applied over the global ocean, regionally, or in coastal areas (Bach et al., 2024; Renforth & Henderson, 2017). Various alkalinity sources can be used to achieve OAE, including natural and synthetic materials (Fakhraee et al., 2023). Calcium-based and magnesium-based compounds are commonly investigated as potential alkalinity sources for OAE because these materials produce a pulse of alkalinity when they dissolve in seawater (Fakhraee et al., 2023). Alternatively, studies modelling OAE scenarios can simulate an overall increase in surface seawater TA to mimic the effects of adding an alkaline source without deliberately specifying a specific material (e.g., Burt et al., 2021; Lenton et al., 2018). Overall, modelling studies indicate OAE has a high potential for enhancing oceanic CO₂ uptake and storage, but specific estimates vary based on model parameters and OAE scenarios.

3.1.1 Global OAE Scenarios

Many studies investigating the CDR potential of OAE have modelled OAE scenarios where alkalinity addition occurs uniformly over the global, ice-free surface ocean (considered between 70° N and 60° S) (Keller et al., 2014). Table 3 shows a breakdown of the alkalinity source used in studies modelling global OAE scenarios in this review.

Table 3. The alkalinity source investigated in modelled global OAE scenarios in the dataset for Research Question 1.

Alkalinity Source		Number of Studies	References
Calcium-based	Calcium carbonate (CaCO ₃)	2	Gonzalez & Ilyina, 2016; Sonntag et al., 2018
	Calcium hydroxide/ Hydrated lime (Ca(OH) ₂)	2	Jin & Cao, 2023; Keller et al., 2014
Magnesium-based	Olivine (Mg, Fe) ₂ SiO ₄	2	Kohler, 2020; Kohler et al., 2013
	Magnesium hydroxide (Mg(OH) ₂)	1	Yang et al., 2023
Simulated increase in TA	N/A	4	Burt et al., 2021; Gonzalez et al., 2018; Ilyina et al., 2013; Lenton et al., 2018

3.1.1.1 Calcium-based OAE

Several studies have investigated the CDR potential of a global OAE scenario using calcium-based compounds as the alkalinity source. For example, Gonzalez and Ilyina (2016) modelled an OAE scenario using calcium carbonate from 2018 to 2100 to reduce the atmospheric CO₂ concentrations under a high emissions pathway (representative concentration pathway (RCP) 8.5) to those under a moderate emissions pathway (RCP4.5). Under this setting, the ocean will remove 940 GtC from the atmosphere by 2100, indicating up to 27 GtC per year could be removed by the end of the century (Gonzalez & Ilyina, 2016). Following the same OAE scenario implemented by Gonzalez and Ilyina (2016), Sonntag et al., (2018) modelled the carbon uptake potential of OAE using calcium carbonate from 2006 to 2100 and investigated the interactions of the atmospheric, oceanic, and land carbon reservoirs. The results indicate that the increased buffering capacity of the ocean under OAE strongly increases marine carbon uptake, increasing the ocean carbon reservoir by 941 GtC and decreasing the atmospheric and land carbon reservoir by 905 GtC and 36 GtC, respectively, relative to the reference RCP8.5 scenario by the year 2100 (Sonntag et al., 2018).

The carbon uptake potential using calcium hydroxide (hydrated lime) as the alkalinity source in global OAE scenarios has also been investigated. For example, Jin and Cao (2023) modelled the carbon uptake potential of OAE using calcium hydroxide from 2020 to 2100 to reduce atmospheric CO₂ concentrations under a high emissions pathway (RCP8.5) to those under a moderate emissions pathway (RCP4.5). The results indicate that this OAE scenario increases the ocean's buffering capacity and the global oceanic carbon uptake by 983 GtC by 2100 relative to RCP8.5 (Jin & Cao, 2023). Similar to Jin and Cao (2023), Keller et al., (2014) modelled the CDR potential of OAE using calcium hydroxide under RCP8.5 conditions from 2020 to 2100. The

results suggest that OAE would decrease atmospheric carbon by 166 GtC by 2100 while the ocean carbon reservoir would increase by 181 GtC relative to the RCP8.5 scenario (Keller et al., 2014).

3.1.1.2 Magnesium-based OAE

Several studies have focused on performing global OAE using olivine (a magnesium iron silicate) as the alkalinity source. For example, Kohler (2020) modelled OAE using olivine (approximately 5 Gt of olivine dissolution per year) under a high CO₂ emissions scenario (shared socioeconomic pathway (SSP) 5-85) from 2020 to 7020. The results indicate that OAE reduces the atmospheric CO₂ concentration by 200 ppm at its peak (in 2326) compared to the reference high emissions scenario with no CDR (Kohler, 2020). Under the OAE scenario, atmospheric CO₂ concentrations fall below pre-industrial values between 5500 and 6100, implying the neutralization of all anthropogenic emissions (Kohler, 2020).

Similar to Kohler (2020), Kohler et al., (2013) investigated the effects of olivine-based OAE using various model scenarios which differ in the amount of olivine dissolved (1, 3 or 10 Gt olivine per year) and the way olivine is spatially distributed over the ocean (evenly applied globally or using global ship tracks) from 2000 to 2009. The results indicate that the increase in oceanic carbon uptake for 1, 3, and 10 Gt of added olivine leads to 0.29, 0.28, and 0.27 GtC uptake per Gt olivine, respectively (Kohler et al., 2013). Under the global shipping scenario, where olivine is added to the surface ocean based on established ship track densities, the oceanic carbon uptake is 0.28 GtC per Gt olivine (Kohler et al., 2013). Thus, the oceanic carbon uptake under the shipping scenario resembles that of the global scenario using 3 Gt of olivine (Kohler et al., 2013).

In addition to olivine, magnesium hydroxide has been investigated for OAE. Yang et al., (2023) investigated the CDR potential of OAE using magnesium hydroxide through lab and wind tank experiments with seawater. The results indicate that the ocean could absorb an extra 44.4 Gt

CO₂ when approximately 34.1 Gt of magnesium hydroxide is added to the global surface ocean (Yang et al., 2023). Consequently, global OAE using magnesium hydroxide could increase the natural CO₂ sink of the ocean by 2-3.3 times (Yang et al., 2023).

3.1.1.3 Alkalinity Addition Scenario

Further studies have investigated global OAE scenarios by modelling increases in surface seawater alkalinity without specifying a particular alkalinity source. For example, Burt et al., (2021) and Lenton et al., (2018) modelled oceanic carbon uptake under an OAE scenario where 0.25 Pmol per year of alkalinity is added. Burt et al., (2021) found that this OAE scenario resulted in a carbon uptake of 157 GtC over 75 years under pre-industrial forcing conditions. Lenton et al., (2018) found that oceanic carbon uptake increases by 184.4 GtC and 143.1 GtC compared to control scenarios under a high (RCP8.5) and low (RCP2.6) emissions scenario, respectively, from 2020 to 2100. Atmospheric CO₂ concentration decreased by 82-86 ppm and 53-58 ppm under high and low emissions scenarios, respectively, compared to control runs (Lenton et al., 2018).

Similar to Burt et al., (2021) and Lenton et al., (2018), Ilyina et al., (2013) modelled the CDR impact of an OAE scenario where surface seawater alkalinity is steadily increased from 2020 to 2100 in proportion to every mol of anthropogenic CO₂ emitted. Results indicate that global OAE following a 2:1 molar ratio (TA:CO₂) can produce a CO₂ drawdown of 450 ppm under a moderate emissions scenario (IPCC A1B scenario) (Ilyina et al., 2013).

3.1.2 Regional OAE Scenarios

Studies modelling regional OAE scenarios show differences in the carbon uptake potential based on the application location. Lenton et al., (2018) evaluated the oceanic carbon uptake from 2020 to 2100 for three regional scenarios under high (RCP8.5) and low (RCP2.6) emissions

scenarios where 0.25 Pmol per year of alkalinity is added. The three regional scenarios were the subpolar Northern Hemisphere oceans (40-70° N) and the ice-free Southern Ocean (40-60° S), the subtropical oceans (15-40° N and 15-40° S), and the equatorial regions (15° N-15° S). Lenton et al., (2018) found under RCP8.5 conditions, the subpolar Northern hemisphere oceans and the Southern Ocean had the highest carbon uptake (188.1 GtC), followed by the subtropical oceans (185.1 GtC), and lastly, the equatorial regions (177.2 GtC). A similar trend was found under RCP2.6 conditions, as the subpolar Northern hemisphere oceans and the Southern Ocean had the highest carbon uptake (145.2 GtC), followed by the subtropical oceans (143.1 GtC), and lastly the equatorial regions (139.2 GtC) (Lenton et al., 2018). Similarly, Jin and Cao (2023) modelled three regional scenarios in the same locations as Lenton et al., (2018) and implemented an OAE scenario to lower atmospheric CO₂ concentrations under a high emissions pathway (RCP8.5) to those under a moderate emissions pathway (RCP4.5) from 2020 to 2100 using calcium hydroxide. Jin and Cao (2021) found results similar to those of Lenton et al., (2018), which indicate that enhancement of global oceanic CO₂ uptake is weakly dependent on where OAE occurs. Specifically, Jin and Cao (2023) found the difference in uptake is at most 10% and depends on the application site.

Similar to Lenton et al., (2018), Burt et al., (2021) modelled the CDR potential of regional OAE scenarios through a fixed alkalinity addition of 0.25 Pmol per year. Specifically, Burt et al., (2021) conducted eight regional scenarios of OAE under pre-industrial forcing conditions for 75 years. The eight regional scenarios modelled were the Indian Ocean, the Southern Ocean, the Subpolar North Pacific, the Subtropical North Pacific, the Subtropical South Pacific, the Subpolar North Atlantic, the Subtropical North Atlantic, and the Subtropical South Atlantic (Burt et al., 2021). Similar to Lenton et al., (2018), Burt et al., (2021) found the highest oceanic carbon uptake (175 GtC) was achieved under the Southern Ocean application scenario, followed by the Subpolar

North Pacific scenario (160 GtC). Burt et al., (2021) found the Subpolar North Atlantic scenario displayed the smallest carbon uptake (82 GtC).

Further, Ilyina et al., (2013) modelled the carbon uptake potential of several regional scenarios from 2020 to 2100. Ilyina et al., (2013) focused on a regional OAE scenario involving alkalinity addition over approximately 47 million km² in the Pacific and Atlantic Ocean. Five scenarios using different molar ratios of alkalinity addition (TA:CO₂) were conducted (2:1; 1.5:1; 1:1; 0.5:1, 0.2:1). The results indicate that adding alkalinity in this region in a 2:1 molar ratio of TA:CO₂ would produce a CO₂ drawdown of 450 ppm under a moderate emissions pathway (IPCC A1B scenario), which is very similar to the CO₂ drawdown under the global scenario (450 ppm) (Ilyina et al., 2013). Adding alkalinity in small amounts (i.e., 0.2:1 TA:CO₂) had little effect on atmospheric CO₂ (decrease of 72 ppm) (Ilyina et al., 2013).

Other regional OAE studies have focused on application scenarios in seas or basins. Feng et al., (2016) modelled regional OAE simulations beginning in 2020 under a high emissions scenario (RCP8.5) by adding 1-10 Gt per year of calcium hydroxide (1 Gt per year in increasing increments) in the Great Barrier Reef, Caribbean Sea, and South China Sea to evaluate OAE's carbon uptake potential. By 2099, the simulated OAE scenario results in an additional carbon uptake of approximately 15.36, 32.54, and 35.41 GtC for the Great Barrier Reef, Caribbean Sea, and South China Sea, respectively, compared to the control RCP8.5 scenario (Feng et al., 2016). Atmospheric CO₂ concentrations are drawn down by the end of 2099, relative to the control run, by about 7 ppm for the Great Barrier Reef scenario, 15 ppm for the Caribbean Sea scenario, and 16 ppm for the South China Sea scenario (Feng et al., 2016). Thus, the results indicate that OAE in these regions under these conditions would not be an appropriate means for climate remediation (Feng et al., 2016).

Further regional OAE studies have focused on the Mediterranean Sea. Butenschan et al., (2021) and Caserini et al., (2021) evaluated the carbon uptake potential of OAE scenarios implemented in the Mediterranean basin based on ship transportation networks. Butenschan et al., (2021) implemented a discharge rate of 7.58 kg of calcium hydroxide per second for each ship based on existing transportation networks. From 2021 to 2050, the cumulative lime disposal was 6 Gt, and the carbon uptake under this scenario approximately doubled compared to the control (RCP4.5) and reached 80 Mt CO₂ per year (Butenschan et al., 2021). Caserini et al., (2021) estimated the potential discharge of slaked lime into the Mediterranean Sea using existing ship networks to be 186 Mt per year, which could result in an additional CO₂ uptake of 122 Mt CO₂ per year by the Mediterranean Sea. Caserini et al., (2021) also reviewed an alternative scenario where 1000 new ships are dedicated to lime disposal. The authors estimated their discharge potential to be 1.3 Gt per year, corresponding to a removal of 1.1 Gt CO₂ per year (Caserini et al., 2021).

3.1.3 Coastal OAE Scenarios

OAE can be conducted by adding alkaline minerals in coastal zones. Coastal zones can include exclusive economic zones (EEZs), which indicate waters extending seaward to 200 nautical miles from the coastline (Feng et al., 2017), as well as coastal shelves (<100m from shore) (Palmieri & Yool, 2024), and the surface (~80 meters) coastal water column (Fakhraee et al., 2023).

Feng et al., (2017) and Kwiatkowski et al., (2023) simulated OAE scenarios in global ice-free EEZs using olivine. Feng et al., (2017) investigated the carbon uptake potential of coastal seas in EEZs beginning in 2020 by adding 0.25 mol of olivine per mol of CO₂ emitted until 2100 under a high emissions (RCP8.5) scenario. Feng et al., (2017) also investigated the influence of olivine grain size and ran OAE scenarios using different sizes of olivine (10, 100, or 1000 μm in size). The results indicate that small grain sizes (10 μm) could reduce the atmospheric carbon content by

approximately 868 GtC by 2100 relative to the control RCP8.5 scenario, while the largest grain size examined (1000 μm) has little carbon sequestration ability on this timescale (42.5 GtC) (Feng et al., 2017). Similarly, Kwiatkowski et al., (2023) modelled the carbon uptake potential of a coastal OAE scenario where 11.7 Gt per year of olivine (alkalinity addition of 0.32 Pmol per year) was added to EEZs from 2006 to 2010 under historical conditions. The carbon uptake associated with this scenario was 2.95 GtC per year (10.8 Gt CO₂ per year) in 2010, which is higher than the control scenario using historical data (2.59 GtC) (Kwiatkowski et al., 2023). In an additional OAE scenario that accounted for iron and silicate addition from olivine dissolution, the carbon uptake increased to 4.16 GtC per year (15.3 Gt CO₂ per year) in 2010 (Kwiatkowski et al., 2023).

Similarly, Fakhraee et al., (2023) and Palmieri and Yool (2024) modelled OAE in coastal environments. Fakhraee et al., (2023) explored the impacts of large-scale OAE within the surface coastal marine water column using synthetic (calcium oxide (CaO) and magnesium oxide (MgO)) and natural (basalt and olivine) alkaline feedstocks beginning in 2030 at three different application rates: low (100 g m⁻² y⁻¹), moderate (300 g m⁻² y⁻¹), and high (500 g m⁻² y⁻¹) under moderate (RCP4.5) and high (RCP8.5) emissions pathways. By 2100, the carbon uptake during OAE is 5.7-20.4 Gt CO₂ per year for CaO and 6.7–23.0 Gt CO₂ per year for MgO under a moderate emissions scenario for low through high application rates (Fakhraee et al., 2023). The CDR rates increase under a high emissions scenario due to increased efficiency of carbon storage at higher background pCO₂ (Fakhraee et al., 2023). Under both emissions pathways, gross carbon dioxide removal per unit mass of natural alkaline feedstocks is significantly lower than the synthetic alkaline feedstocks (Fakhraee et al., 2023). Similarly, Palmieri and Yool (2024) model a coastal OAE scenario from 2020 to 2100 under a high emissions pathway (SSP85) using a TA addition rate of approximately 29 Teq per year to global shelves. The results indicate that applying OAE from 2020 to 2100

decreases atmospheric CO₂ by approximately 10 ppm and increases air-to-sea CO₂ uptake by approximately 8% relative to the baseline SSP85 scenario (Palmieri & Yool, 2024).

In sum, models indicate that OAE has a substantial CDR potential when conducted globally, regionally, or in coastal areas. Global OAE modelling scenarios using calcium- and magnesium-based alkaline materials or simulated TA addition indicate that the oceanic carbon reservoir would increase while the atmospheric carbon reservoir would decrease (Burt et al., 2021; Gonzalez & Ilyina, 2016; Gonzalez et al., 2018; Ilyina et al., 2023; Jin & Cao, 2023; Keller et al., 2014; Kohler, 2020; Kohler et al., 2013; Lenton et al., 2018; Sonntag et al., 2018; Yang et al., 2023). Regional modelling scenarios similarly indicate that conducting OAE in seas, such as the Mediterranean basin, or different ocean areas, such as the Southern Ocean, can enhance oceanic carbon uptake compared to unmitigated simulations (Burt et al., 2021; Butenschan et al., 2021; Caserini et al., 2021; Feng et al., 2016; Ilyina et al., 2013; Jin & Cao, 2023; Lenton et al., 2018). Further, coastal modelling scenarios suggest that OAE conducted in EEZs, coastal shelves, or coastal water columns could lower atmospheric CO₂ concentrations while increasing the oceanic carbon content (Fakhraee et al., 2023; Feng et al., 2017; Kwiatkowski et al., 2023; Palmieri & Yool, 2024). Model estimates of the CDR potential of global, regional, and coastal OAE differ depending on the alkaline material used, the application amount and location, the simulated emissions scenario, and other model parameters.

3.2 Long-Term CO₂ Uptake and Storage Stability

To understand the permanence of carbon uptake under OAE, many studies model termination scenarios where OAE stops after a given period. Overall, studies that simulate global OAE termination scenarios find that once OAE stops, the ocean no longer takes up carbon at an enhanced rate and begins to parallel oceanic carbon uptake under an unmitigated scenario

(Gonzalez et al., 2018; Jin & Cao, 2023; Keller et al., 2014). For example, Gonzalez et al., (2018) modelled a termination scenario where global OAE stops after 50 years (2020-2070). The termination OAE scenario involved adding 114 Pmol alkalinity under a high emissions pathway (RCP8.5) to try and achieve atmospheric CO₂ concentrations under a moderate emissions pathway (RCP4.5). The results indicate that after OAE termination, the ocean carbon sink is no longer enhanced, and atmospheric CO₂ concentrations grow parallel to those under the RCP8.5 scenario (Gonzalez et al., 2018). Similarly, Jin and Cao (2023) find that terminating an OAE scenario under RCP8.5 conditions to achieve RCP4.5 atmospheric CO₂ concentrations after 55 years (2020-2075) weakens the oceanic uptake of CO₂ and atmospheric CO₂ begins to increase past the targeted RCP4.5 concentrations. Additionally, Keller et al., (2014) find that when OAE terminates after 50 years (2020-2070), the ocean stops taking up CO₂ at an enhanced rate but continues to store the CO₂ taken up during the implementation of OAE.

Further, Ilyina et al., (2013) modelled a global OAE scenario where alkalinity is added in a 2:1 molar ratio to CO₂ (TA:CO₂) that starts in 2020 and terminates after 10 years under a high emissions pathway (RCP8.5). Under this OAE termination scenario, atmospheric CO₂ decreases by 30 ppm relative to the unmitigated scenario with moderate emissions (IPCC's A1B) in 2100 (Ilyina et al., 2013). This decrease is small compared to the continuous scenario that decreases atmospheric CO₂ by 450 ppm (Ilyina et al., 2013). Once the OAE has stopped, atmospheric CO₂ concentrations revert to rising at the rate determined by fossil fuel emissions (Ilyina et al., 2013). However, atmospheric CO₂ concentrations remain approximately 10 ppm below the unmitigated scenario (IPCC's A1B) at the end of the simulation (3050) when emissions cease (Ilyina et al., 2013). Similarly, Keller et al., (2014) find that in 2100, atmospheric CO₂ concentrations will be 48 ppm lower than in the unmitigated RCP8.5 scenario when simulating a termination scenario where

global OAE under the RCP8.5 scenario stops after 50 years. Jin and Cao (2023) further find that terminating an OAE scenario after 55 years under RCP8.5 results in atmospheric CO₂ concentrations reaching 747 ppm, compared to 964 ppm and 538 ppm under the unmitigated RCP8.5 and RCP4.5 scenarios, respectively, by 2100. The results of Ilyina et al., (2013), Keller et al., (2014), and Jin and Cao (2023) thus indicate that terminating OAE stops enhanced oceanic carbon uptake but can result in lower atmospheric carbon concentrations compared to an unmitigated scenario.

Further, Feng et al., (2017) model a termination scenario where coastal OAE through olivine addition under the RCP8.5 scenario stops after 50 years (2020-2070). Terminating OAE after 50 years using olivine with a small grain size (10 µm) results in 554 GtC of atmospheric drawdown by 2100 relative to the control run (Feng et al., 2017). Thus, while CO₂ uptake can continue after OAE terminates, it reduces atmospheric CO₂ substantially less than the continuous OAE scenario, which removed 868 GtC (Feng et al., 2017).

In conclusion, modelled OAE termination scenarios suggest that once OAE is terminated, the ocean no longer uptakes CO₂ at an enhanced rate (Gonzalez et al., 2018; Jin & Cao, 2023; Keller et al., 2014). However, some scenarios suggest that while terminating OAE stops enhanced oceanic carbon uptake, it results in lower atmospheric carbon concentrations compared to unmitigated scenarios (Feng et al., 2017; Ilyina et al., 2013; Jin & Cao, 2023; Keller et al., 2014).

3.3 Climate Impacts

Due to the impact OAE has on atmospheric CO₂ concentration, it influences the climate system. Modelling studies on OAE have shown its potential to mitigate warming under various emissions scenarios (e.g., Gonzalez & Ilyina, 2016; Jin & Cao, 2023) and influence precipitation

patterns (Jin & Cao, 2023; Sonntag et al., 2018). Due to its impact on warming, OAE has also been shown to potentially reduce sea ice melting and associated sea level rise (Gonzalez & Ilyina, 2016).

3.3.1 Temperature

Global OAE scenarios produce varying estimates of the influence on global mean SAT. Under a high emissions pathway (RCP8.5), Gonzalez and Ilyina (2016) found that OAE could mitigate the annual mean global SAT to a 1.5 K increase over this century. Similarly, Sonntag et al., (2018) found that OAE produces a mean average cooling of 1.55 K over 2081 to 2100 compared to the reference RCP8.5 scenario. Gonzalez and Ilyina (2016) and Sonntag et al., (2018) discuss that these temperature changes are similar to what is projected under a moderate emissions (RCP4.5) scenario (1 K) but slightly lower, likely due to OAE only reducing atmospheric CO₂ concentrations and not influencing other greenhouse gases (GHGs).

Further, Lenton et al., (2018) found a global OAE scenario under a high emissions pathway (RCP8.5) creates a global mean SAT cooling of 0.16 K from 2081 to 2100. This estimate is similar to the value produced by Keller et al., (2014), who found a global OAE scenario under RCP8.5 resulted in a mean SAT cooling of 0.26 K by 2100. Additionally, coastal OAE has been found to influence global SAT as well. For example, Palmieri and Yool (2024) found a global coastal OAE scenario to decrease global mean SAT by an average of 0.06°C over the 2090s under a high emissions pathway (SSP85).

Gonzalez et al., (2018) and Jin and Cao (2023) found that modelling global OAE scenarios under RCP8.5 conditions to reach the atmospheric CO₂ concentrations under RCP4.5 resulted in SAT closely following the temperature under RCP4.5. For example, Jin and Cao (2023) found the average global SAT for global OAE under this scenario to be 15.2°C in 2100, which is the same temperature projected under RCP4.5.

The spatial distribution of changes in SAT under global OAE scenarios is heterogeneous. Numerous studies found SAT cooling under global OAE was more pronounced in higher latitudes, particularly in the Arctic, under a high emissions scenario (RCP8.5) (Gonzalez & Ilyina, 2016; Lenton et al., 2018; Sonntag et al., 2018). For example, Gonzalez and Ilyina (2016) found the global OAE scenario prevented approximately 2.8 K of warming over the Arctic and subpolar regions in the Northern Hemisphere compared to the reference RCP8.5 scenario.

The termination of global OAE scenarios can influence the global average SAT. Under a global OAE termination scenario (55 years), Jin and Cao (2023) found average global SAT increases to 16°C, which remains lower than the unmitigated RCP8.5 scenario (16.9°C) in 2100. Further, in a scenario where global OAE terminates after 50 years, Gonzalez et al., (2018) found differences in CO₂ forcing drive varying regional patterns of surface warming compared to the reference RCP8.5 scenario. Specifically, in northern polar regions and over high latitudes of North America and Europe from 2070 to 2100, the warming rates after OAE termination are nearly 50% higher than those under the reference RCP8.5 scenario, reaching up to 0.15 K of warming per year (Gonzalez et al., 2018).

3.3.2 Precipitation

Due to its impact on atmospheric CO₂ and climate, OAE can influence future precipitation patterns. Jin and Cao (2023) found that a global OAE scenario designed to achieve atmospheric CO₂ concentrations of those under a moderate emissions pathway (RCP4.5) results in global precipitation trends stabilizing at the RCP4.5 level (1067 mm in 2100). However, under the OAE termination scenario (55 years), the global average precipitation exceeds those under RCP4.5 and RCP8.5 (1058 mm) scenarios and reaches 1059 mm (Jin & Cao, 2023).

Similarly, Sonntag et al., (2018) found a global OAE scenario reduces increases in global mean precipitation over the century compared to the reference RCP8.5 scenario but is slightly higher compared to the reference RCP4.5 scenario. The spatial precipitation pattern under OAE indicates a consistent drying of mid to high latitudes; however, regions in the tropics with high precipitation further increase and those with weak precipitation further decrease compared to the reference RCP8.5 scenario (Sonntag et al., 2018).

3.3.3 Sea Ice and Sea Level Rise

As OAE affects the amount of atmospheric CO₂ and global average SAT, it can influence sea ice melting and sea level rise. Gonzalez and Ilyina (2016) found that under a global OAE scenario, summer sea ice only reduces by approximately 15% of its current value compared to disappearing as projected under a high emissions pathway (RCP8.5). Further, Gonzalez and Ilyina (2016) found that under the global OAE scenario, projected sea level rise is reduced by approximately 75% compared to the reference RCP8.5 scenario.

In sum, model scenarios indicate that OAE could mitigate increases in future warming (e.g., Gonzalez et al., 2018; Jin & Cao, 2023; Keller et al., 2014; Palmieri & Yool, 2024). Model scenarios indicate the cooling associated with OAE scenarios is more pronounced over the Arctic (Gonzalez & Ilyina, 2016; Lenton et al., 2018; Sonntag et al., 2018). In addition to temperature changes, OAE is expected to influence global precipitation patterns (Jin & Cao, 2023; Sonntag et al., 2018). Further, OAE could limit sea ice melt and associated sea level rise compared to unmitigated high emissions scenarios (Gonzalez & Ilyina, 2016).

3.4 Knowledge Gaps and Recommendations for Future Research

Several knowledge gaps remain regarding various aspects of OAE. Feng et al., (2017) discuss that while the best solution to address climate change is to stop emitting CO₂, this is unlikely to happen anytime soon and, consequently, OAE warrants further research as a potential complementary CDR technique. Numerous authors discuss the need for more OAE scenarios to be run in models under different conditions and parameters and subsequently compared to allow for the Earth system response, including the CDR potential and climate impacts, to be evaluated in a robust multi-model framework (Caserini et al., 2021; Fakhraee et al., 2023; Keller et al., 2014; Lenton et al., 2018; Palmieri & Yool, 2024). For example, Keller et al., (2014) discuss the need for less heavily parameterized and higher-resolution models to investigate the regional effects of OAE. Similarly, Jin and Cao (2023) discuss the need for additional studies on regional OAE and its side effects, as the authors state that OAE will likely be implemented regionally rather than uniformly across the global ocean. Further, Feng et al., (2017) and Sonntag et al., (2018) discuss the importance of modelling portfolio scenarios that combine CDR and SRM methods to understand their interactions, as a combination of these methods could be applied in the future.

Although outside the scope of this review, numerous knowledge gaps remain regarding the impacts of large-scale OAE on the marine environment. For example, Caserini et al., (2021) discuss that research is needed to assess the diffusion and dissolution of alkaline materials in the ocean and understand OAE's impact on ocean biogeochemistry. Further, Butenschan et al., (2021) and Fakhraee et al., (2023) highlight the need to comprehensively investigate the influence of changes to ocean biogeochemistry, including OA, driven by OAE on marine biodiversity and ecosystems. For example, Feng et al., (2017) state that the ecological impact of the influx of trace materials from OAE, such as silica or iron from olivine dissolution, remains uncertain and must

be investigated to ensure marine organisms are not adversely affected. Additionally, Lenton et al., (2018) suggest observational studies, such as mesocosm experiments, are needed to address uncertainties regarding OAE's impact on the marine environment.

Further, OAE's broader environmental impacts and feasibility must be examined. For example, Fakhraee et al., (2023) discuss that the emissions and land use required during the mining, processing, transporting, and depositing of various alkaline materials must be considered, particularly in evaluating their carbon and ecological footprints. While some life cycle assessments exist for OAE (e.g., Foteinis et al., 2022; 2023), further research is needed to comprehensively assess the costs and benefits of the OAE production chain and processes (Butenschan et al., 2021). In addition to the environmental impacts of OAE, its feasibility in the real world outside of model experiments must be considered, as these scenarios often overlook the practicalities of deployment (Feng et al., 2017; Keller et al., 2014). For example, Feng et al., (2017) discuss the need for future studies to investigate varying deployment strategies for OAE, as the continuous and homogenous application of alkaline materials used in models is unlikely to be feasible in real-world applications due to logistical and technical constraints.

In conclusion, future research should aim to create a robust multi-model framework that addresses the uncertainties and knowledge gaps remaining regarding OAE's impact on the climate system (Caserini et al., 2021; Fakhraee et al., 2023; Keller et al., 2014; Lenton et al., 2018; Palmieri & Yool, 2024). Research is also needed to understand OAE's potential impact on marine biodiversity and ecosystems (Butenschan et al., 2021; Caserini et al., 2021; Fakhraee et al., 2023; Feng et al., 2017; Lenton et al., 2018). Further, OAE's environmental impact must be investigated to analyze the costs and benefits (Butenschan et al., 2021; Fakhraee et al., 2023).

4.0 mCDR: Implications for International Governance

Currently, OAE is not explicitly governed under any international framework. Ocean fertilization is the only mCDR approach with a direct governance framework; however, it is not yet legally binding (Bach et al., 2024; Gambardella, 2019; McGee et al., 2018). Many other international frameworks have indirect ties to mCDR governance due to their connection with the ocean and its biodiversity, conservation, or resources (McGee et al., 2018; Roschel & Neumann, 2023). Numerous issues and uncertainties challenge the international governance of mCDR, including those relating to social acceptability and ethical desirability, future research conditions, and international law (Cox et al., 2021; Gattuso et al., 2021; McGee et al., 2018; Roschel & Neumann, 2023). The overarching recommendation to address the current and future challenges to international mCDR governance is to ensure transdisciplinary research is a priority and a pre-emptive framework is developed (Bach et al., 2024; McGee et al., 2018; Roschel & Neumann, 2023).

4.1 Relevant International Frameworks

Several international frameworks could be relevant in the governance of mCDR activities. These regimes include the London Protocol under the International Maritime Organization (IMO), the Paris Agreement and United Nations Framework Convention on Climate Change (UNFCCC), the United Nations Convention on the Law of the Sea (UNCLOS), and the Convention on Biological Diversity (CBD) (Gambardella, 2019). While a few of these regimes have developed recommendations or regulations regarding mCDR activities, there are no legally binding international frameworks for mCDR (Bach et al., 2024; Gambardella, 2019; McGee et al., 2018). Within discussions and recommendations on mCDR governance, the precautionary principle

appears to be at the forefront (McGee et al., 2018; Roschel & Neumann, 2023). For example, the London Protocol and the CBD pursued similar governance aims of restricting early large-scale mCDR research, preventing environmental harm, and creating limited exceptions for scientific research that aligns with the precautionary approach (McGee et al., 2018).

Multiple international frameworks may be implicated in mCDR governance due to the impact of mCDR activities on marine biodiversity and ecosystems and their associated natural, cultural, or economic value. For example, OAE, in particular, could be indirectly governed by the regulations under the Convention on the Conservation of Migratory Species of Wild Animals, the Convention for the Protection of the World Cultural and Natural Heritage, the Agreement for the Implementation of the Law of the Sea Convention Relating to the Conservation and Management of Straddling Fish Stocks and Highly Migratory Fish Stocks, and the United Nations Fish Stocks Agreement due to its potential impact on marine life (McGee et al., 2018; Roschel & Neumann, 2023).

4.1.1 The IMO and London Protocol

The IMO cemented its role as a leader in the connection between climate change and the ocean by including marine geoengineering (both CDR and SRM) in its purview through amendments to the 1996 Protocol on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Protocol) (Gambardella, 2019). The London Protocol is the only international framework that explicitly governs marine geoengineering and is an emerging actor in mCDR governance (Cox et al., 2021; Roschel & Neumann, 2023). The London Protocol aims to regulate marine geoengineering activities that could cause harm to the ocean via dumping, defined as the deliberate disposal of wastes or other materials at sea (Gambardella, 2019; Roschel & Neumann, 2023).

In 2010, an amendment was made to the London Protocol to regulate mCDR activities related to ocean fertilization, which is an mCDR technique that aims to increase the biological productivity of the ocean by adding nutrients such as iron (Gambardella, 2019; McGee et al., 2018). This amendment acknowledged that ocean fertilization falls within the purview of the London Protocol, as it could be considered ocean dumping due to the deliberate placement of materials into the ocean (McGee et al., 2018). The amendment prohibited ocean fertilization activities other than for legitimate scientific research and provided an annex containing a framework for assessing scientific research involving ocean fertilization (Gambardella, 2019; McGee et al., 2018).

In 2013, parties to the London Protocol adopted an initial framework to govern marine geoengineering activities more broadly in a further amendment to the London Protocol (Gambardella, 2019). The 2013 amendment aims to prevent environmental harm rather than regulate mCDR techniques for climate mitigation (Boettcher et al., 2021). Specifically, the 2013 amendment allows legitimate research activities but restricts the placement of matter into the sea specifically for marine geoengineering (Roschel & Neumann, 2023). Thus, the IMO, through the London Protocol, applied the precautionary principle to prevent damage and risks to the marine environment through the large-scale application of marine geoengineering activities (Gambardella, 2019).

Currently, only ocean fertilization is explicitly addressed in the framework set out by the 2013 amendment; however, a process is underway to add additional types of marine geoengineering techniques (Roschel & Neumann, 2023). The addition of other marine geoengineering approaches would allow the amendment to provide a regulatory structure for the potential future governance of marine geoengineering activities that involve the placement of

substances into the ocean, such as OAE, that could otherwise be considered dumping (Roschel & Neumann, 2023). However, neither the 2010 nor the 2013 amendments to the London Protocol have entered into force (Bach et al., 2024; Gambardella, 2019). To become binding, two-thirds of the contracting parties would have to adopt the amendments (Gambardella, 2019).

4.1.2 The CBD

The CBD is an emerging actor in mCDR governance (Cox et al., 2021; Roschel & Neumann, 2023). The CBD adopted a decision in 2008 which called for a moratorium on large-scale ocean fertilization, aligning with the precautionary principle (Bach et al., 2024; Gambardella, 2019). Specifically, the CBD requested states not to conduct ocean fertilization experiments until there is a sufficient scientific basis to justify such activities (McGee et al., 2018). The decision also highlighted the need to consider broader environmental risks and socio-cultural impacts (Roschel & Neumann, 2023). However, the decisions adopted under the CBD have no binding force and are instead considered as recommendations (Gambardella, 2019; McGee et al., 2018).

After issuing the recommendations on ocean fertilization, the CBD later broadened their scope to encompass all climate-related geoengineering activities in 2010 (McGee et al., 2018). Specifically, the CBD provided a non-binding ban on all CDR or SRM activities, including marine-based techniques, which could negatively impact biodiversity, thus promoting the precautionary approach (McGee et al., 2018; Roschel & Neumann, 2023). However, this decision created an exception for small-scale, controlled scientific research (McGee et al., 2018).

4.1.3 The UNFCCC and Paris Agreement

The 2015 Paris Agreement aims to limit global temperature change to below 2°C above pre-industrial levels, with the aspirational goal of limiting temperature increase to only 1.5°C

above pre-industrial temperatures (McGee et al., 2018). The Paris Agreement does not explicitly discuss CDR techniques; however, Article 4 states that a balance between anthropogenic emissions and GHG removals by sinks can be achieved in the second half of the century (Gambardella, 2019; UNFCCC, 2015). Thus, the Paris Agreement implies a commitment to achieve net zero using CDR to elevate carbon sinks (Boettcher et al., 2021; Gambardella, 2019). The implicit role of CDR in the Paris Agreement is further highlighted as models suggest that the goals outlined in the Agreement can likely only be achieved through a mix of CDR and emissions reductions (Boettcher et al., 2021; McGee et al., 2018).

Considering CDR's implicit role in reaching the Paris Agreement temperature targets, McGee et al., (2018) discuss that the international governance of CDR technologies must complement the goals of the Paris Agreement. In the case of mCDR, it may be necessary to revisit the necessity of the precautionary principle that has accompanied discussions on mCDR technologies, such as ocean fertilization under the London Protocol, and consider if it impedes achieving the targets set out by the Paris Agreement (McGee et al., 2018). Currently, the Paris Agreement focuses the precautionary principle on preventing the adverse outcomes of climate change from a 2°C temperature increase above pre-industrial levels rather than the additional risks that could accompany CDR (Gambardella, 2019).

4.1.4 UNCLOS

While UNCLOS does not explicitly govern mCDR, it has implicit governance implications due to the potential impact of these techniques on the marine environment (Roschel & Neumann, 2023). UNCLOS mandates protecting and preserving the marine environment, such as regulating pollution (Roschel & Neumann, 2023). UNCLOS defines marine pollution as introducing substances or energy into the marine environment that will likely result in deleterious effects

(Gambardella, 2019). The Convention also stipulates that all measures necessary to prevent, reduce, and control pollution of the marine environment must be taken (Gambardella, 2019). Consequently, the Convention could indirectly apply to mCDR activities that involve adding materials to the ocean environment (Gambardella, 2019). The Convention also calls for states to fulfill an obligation of due diligence regarding monitoring activities that might cause marine pollution from technologies under their jurisdiction (Gambardella, 2019). Thus, if mCDR activities result in marine pollution, state responsibility might be engaged if the state fails to implement all necessary measures to avoid pollution based on available scientific knowledge (Gambardella, 2019).

In sum, there are no legally binding international governance regimes for mCDR (Bach et al., 2024). The London Protocol and CBD outlined explicit amendments and recommendations, respectively, regarding mCDR; however, they are not legally binding (Bach et al., 2024; Gambardella, 2019; McGee et al., 2018). UNFCCC and UNCLOS have implicit governance implications regarding mCDR governance due to their connections to climate change and international ocean law (Boettcher et al., 2021; Gambardella, 2019; McGee et al., 2018; Roschel & Neumann, 2023). Various international frameworks will likely be relevant in mCDR governance due to linkages with conservation and resource management (Gambardella, 2019).

4.2 Issues and Uncertainties

mCDR will face several challenges regarding social acceptability, future research, and governance. Public acceptance of mCDR will likely be low due to the sensitive and interconnected relationships different communities have with the oceans (Cox et al., 2021). Research on various aspects of mCDR will need to be rapidly scaled to match the assumptions under international climate policy regarding the need for CDR to meet climate goals (Cox et al., 2021; Gattuso et al.,

2021; McGee et al., 2018). However, mCDR research is constrained by unclear governance on mCDR and the current fragmented international ocean governance framework (Loomis et al., 2022; Roschel & Neumann, 2023).

4.2.1 Societal and Ethical

Regarding the social acceptability of mCDR, Cox et al., (2021) found these technologies will face a greater public acceptance challenge than tCDR techniques. This challenge is due to public attitudes as the ocean is often perceived as fragile, vital to human life, interconnected, and challenging to experiment on in a controlled and accurate manner (Cox et al., 2021). To support public acceptance of mCDR, Cox et al., (2021) suggest that ensuring reliable and contained experiments are conducted and that any risks are communicated transparently is crucial. Further, Cox et al., (2021) discuss that since mCDR technologies are in the initial stages of development, they are sensitive to framing effects that influence their acceptability and feasibility. Specifically, framing can influence how policymakers and the public view mCDR and its role in climate policy and must thus be controlled to promote robust decision-making (Cox et al., 2021). To moderate the framing of mCDR, Cox et al., (2021) suggest that including diverse actors, discussing alternative options, considering social criteria, and communicating uncertainties and risks are necessary.

In addition to assessing the social acceptability of mCDR, understanding the impacts of mCDR approaches on well-being and human systems is crucial. Bach et al., (2024) state that mCDR approaches have implications on more than just the climate system, as they could impact food production (fisheries), biodiversity conservation, livelihoods, equity, and environmental justice. Regarding environmental justice, Nawaz and Lezaun (2024) discuss that it is crucial to acknowledge that some groups may be disproportionately impacted and identify vulnerable and

disadvantaged groups early to avoid exacerbating inequalities through uneven impacts from mCDR.

4.2.2 Research

International climate policy has already established an assumption that CDR will be crucial to achieving temperature stabilization (McGee et al., 2018). However, before mCDR is considered in international climate policy, responsible research into the science, governance, social acceptability, and ethics is needed (Cox et al., 2021; Gattuso et al., 2021; McGee et al., 2018). For example, through a series of interviews with experts on mCDR from a variety of disciplines (e.g., academia, non-governmental, private sector, etc.), Nawaz and Lezaun (2024) found that the need to accelerate research on mCDR has emerged as urgent. Loomis et al., (2022) similarly discuss that an assessment of the risks, trade-offs, opportunities, and potential co-benefits of mCDR research is needed, especially because the possibility of harmful ocean consequences from mCDR approaches remains unclear. Loomis et al., (2022) additionally state that mCDR research must be conducted responsibly, as in-situ experiments could affect near and distant marine ecosystems and biodiversity depending on their scale. Further, Roschel and Neumann (2023) state that research must go beyond the technical feasibility and cost-effectiveness of mCDR and investigate what the appropriate governance of these techniques could or should be from multiple perspectives (e.g., environmental, social, ethical, etc.). Currently, there is limited research on mCDR from a social science perspective (Cox et al., 2021).

4.2.3 Policy and Governance

The global ocean governance framework is fragmented and set up in a sectoral regime (Roschel & Neumann, 2023). Jurisdiction over the ocean varies depending on the distance to shore:

nations regulate areas within 200 nautical miles from shore (EEZs), while the high seas do not fall under the authority of any one state (Loomis et al., 2022). Hence, coastal states may regulate mCDR in their territorial seas and EEZs, as states have sovereign rights concerning natural resources, environmental protection, and scientific research (Boettcher et al., 2021). Overall, there is a patchwork of regulation over the ocean and related ocean activities that is complicated and incomplete (Loomis et al., 2022).

The interplay between different international rules and regimes will be important in the context of mCDR. Loomis et al., (2022) state that regulation on mCDR is lacking internationally, as there is no critical oversight to guide research activities. Specifically, while some mCDR activities may fall under the scope of existing international frameworks, this has not been concretely established (Loomis et al., 2022). Further, McGee et al., (2018) discuss that assessing how existing frameworks and emerging regimes will interact and overlap to form a comprehensive governance structure for mCDR will be crucial.

In the context of mCDR, the challenges of international ocean governance become apparent. Roschel and Neumann (2023) discuss the example of the London Protocol and CBD, which seek to limit ocean fertilization as an mCDR approach until the risks are carefully researched, understood, and considered. The authors highlight that the need to dually regulate ocean fertilization stems from preventing environmental impacts from a specific input (London Protocol) and treating this approach as a potential threat to biodiversity (CBD) (Roschel & Neumann, 2023). Roschel and Neumann (2023) highlight that these two frameworks have different mandates, geographic scope, parties to their Conventions, various levels of binding force, and their processes are unintegrated. Thus, the example of ocean fertilization highlights the complexities

and fragmented nature of the current international ocean governance frameworks regarding mCDR (Roschel & Neumann, 2023).

A further challenge in the international governance of mCDR will be determining how to manage the risks of harm to the marine environment and how to respond to such harm. Boettcher et al., (2021) discuss that preliminary attempts to govern mCDR, as seen in the London Protocol and CBD, focus on preventing environmental harm rather than using the ocean for carbon uptake and climate mitigation. McGee et al., (2018) further state that additional developments in international mCDR governance would likely require developing regulations and institutions to provide mechanisms for environmental impact assessments, systems for monitoring results, mechanisms for consultation and participation, and rules for responsibility and liability of transboundary harm to the territory of other states or the oceans as a global commons. However, the slow pace at which international regulations are developed and implemented will likely provide a further challenge to creating a global mCDR governance regime (Bach et al., 2024).

The transboundary effects of mCDR activities present a further challenge for international governance. Boettcher et al., (2021) provide an example of performing OAE in territorial waters to reduce the effect of OA on a coastal ecosystem and associated tourism and shellfish industries. While this activity is conducted in territorial waters, it does pose the risk of transboundary harm to the marine environment as the alkaline materials could travel throughout the ocean (Boettcher et al., 2021). Thus, opposing states could claim that the activity is inconsistent with international law, as the rules of customary law obligate states to prevent significant transboundary harm and follow the precautionary approach (Boettcher et al., 2021; McGee et al., 2018).

While experts predict OAE could be ready for deployment by 2050, it is considered high-risk and is one of the least preferred techniques out of numerous land- and ocean-based CDR and

SRM approaches (Sovacool et al., 2022). Through surveys and interviews with experts in the field of mCDR, Sovacool et al., (2022) found that public perceptions and social acceptance, legal and regulatory obstacles, market demand, and environmental or planetary risks will likely be substantial barriers to OAE implementation. Additionally, Sovacool et al., (2022) found that storage and disposal constraints, challenges to system integration, financing, and other factors are moderate barriers to OAE implementation. Thus, OAE has technical-related barriers (e.g., upscaling, storage, and system integration) and non-technical barriers (e.g., environmental and planetary risk, social acceptance, legal and regulatory challenges) (Sovacool et al., 2022). Similarly, after assessing different mCDR approaches, Gattuso et al., (2021) found OAE has low global governability. Gattuso et al., (2021) discuss that OAE's low governability is primarily due to its low public acceptability and potential adverse environmental impact, which have been at the forefront of frameworks set out by the London Protocol on mCDR.

In conclusion, mCDR will likely face numerous governance considerations stemming from societal, research, and policy concerns. Due to humankind's interconnected relationship with the ocean, the public acceptance of mCDR is likely to be low, and the impact of mCDR approaches on well-being must be considered (Bach et al., 2024; Cox et al., 2021; Nawaz & Lezaun, 2024). While mCDR may be used to reach international climate policy goals, considerable research is needed to assess the risks, trade-offs, opportunities, and co-benefits of mCDR approaches from multiple perspectives (Cox et al., 2021; Gattuso et al., 2021; Loomis et al., 2022; McGee et al., 2018). Substantial governance challenges regarding mCDR stem from the fragmented nature of the international ocean governance regime and managing the risk of transboundary harm (Bach et al., 2024; Boettcher et al., 2021; Loomis et al., 2022; McGee et al., 2018; Roschel & Neumann, 2023). Understanding the interplay between different rules and regimes and how a new mCDR

governance framework could evolve in alignment with international climate policy goals will be necessary (Boettcher et al., 2021; McGee et al., 2018; Roschel & Neumann, 2023). Consequently, mCDR governance faces technical and non-technical challenges (Gattuso et al., 2021; Sovacool et al., 2022).

4.3 Recommendations for Future Governance

The beginning stages of mCDR governance appear to follow a patchwork approach of sectoral and conservation regulation as a reactive response to the emerging topic of mCDR (Sovacool et al., 2022; Roschel & Neumann, 2023). While the initial action by international organizations has been to implement the precautionary principle surrounding mCDR, it could be necessary to revise this approach and consider whether this path complements the goals set out in international climate policy, particularly under the Paris Agreement (McGee et al., 2018). Rather than solely focusing on preventing environmental harm, Roschel and Neumann (2023) suggest a comprehensive approach to governing mCDR that considers benefits, trade-offs, and risks between climate mitigation, ocean protection, and other policy goals is best.

To further align mCDR with current climate policy frameworks, Bach et al., (2024) discuss a monitoring, verification, and reporting (MVR) scheme for carbon accounting as integral to mCDR feasibility. Monitoring potential side effects and climate change mitigation is a core component of the carbon accounting framework under the UNFCCC (Bach et al., 2024). Thus, future research should assess the development of an MRV framework for mCDR to align with UNFCCC while addressing the unique challenges of mCDR technologies, such as carbon leakage in the ocean-atmosphere climate system (Bach et al., 2024).

There is a strong need for transdisciplinary research regarding mCDR (Bach et al., 2024; McGee et al., 2018). Research on mCDR must be transdisciplinary and inclusive by consulting scientists, lawyers, social scientists, and ethicists, as this combination will offer the best prospects of properly informing societal deliberation into research and application of mCDR (McGee et al., 2018). Incorporating social sciences and engagement with society and policymakers alongside field experiments at ranging scales would promote the development of a comprehensive governance structure for mCDR (Bach et al., 2024). Committing to an inclusive governance approach would ensure that mCDR research and deployment is accompanied by social acceptance and support, ethical desirability, and political buy-in (Bach et al., 2024; Nawaz & Lezaun, 2024). To promote an inclusive approach to mCDR governance, Cox et al., (2021) discuss applying discourse mapping to mCDR to help identify which types of knowledge are being centered and which are being neglected. Specifically, Cox et al., (2021) state that discourse mapping could help anticipate the tensions between knowledge types in decision-making and enhance diversity and inclusivity early on when designing the governance of mCDR.

Regarding research governance, Loomis et al., (2022) discuss the need for a code of conduct for mCDR to ensure coordinated, transparent, and equitable research. Loomis et al., (2022) discuss that a code of conduct for mCDR research should define the elements of the code (e.g., purpose, scope, etc.), set out principles of responsible research, and provide provisions to ensure equity and fairness are considered. Overall, Loomis et al., (2022) discuss that an mCDR code of conduct should aim to minimize harm while responsibly investigating efficacy and promoting public and stakeholder engagement throughout the process.

A robust and foresighted governance framework that integrates existing structures or creates a new, overarching regime that allows for rigorous oversight and synthesis of best practices

appears mandatory for mCDR (Roschel & Neumann, 2023). Getting ahead of the emerging discourse on mCDR is necessary to ensure the best possible outcomes and alleviate pressure in future decision-making (Roschel & Neumann, 2023; Sovacool et al., 2022). Considering the trade-offs, risks, and benefits and their global distribution in anticipation of future challenges and climate policy discussions can promote a comprehensive path to address mCDR and its role in climate mitigation (Roschel & Neumann, 2023). mCDR governance should require the co-production of knowledge through the participation and research design and completion by relevant stakeholders involving industry, non-governmental organizations, and global communities to ensure an inclusive approach to mCDR governance (Bach et al., 2024).

In sum, transdisciplinary and inclusive research on mCDR and its governance is needed to promote social acceptability, ethical desirability, and political support (Bach et al., 2024; McGee et al., 2018; Nawaz & Lezaun, 2024). To align mCDR governance with international climate policy goals, prioritizing the precautionary principle may need to be reconsidered in favour of a comprehensive approach that considers the benefits, trade-offs, and risks between climate mitigation, ocean protection, and other policy goals (McGee et al., 2018; Roschel & Neumann, 2023). Overall, a robust, foresighted, and inclusive approach to mCDR governance that considers the benefits, risks, and trade-offs is needed to outline mCDR's role in international climate policy (Bach et al., 2024; Roschel & Neumann, 2023; Sovacool et al., 2022).

5.0 Discussion and Conclusion

All studies found the modelled OAE scenarios to reduce atmospheric CO₂ concentrations through enhanced oceanic carbon uptake. The estimated CDR potential of OAE varies depending on model parameters, including the scale of OAE (e.g., global or regional), the type of alkaline material used, the amount of alkaline material deposited, the length of OAE, and the emissions scenarios simulated (e.g., Jin & Cao, 2023; Keller et al., 2014). However, despite OAE's promising CDR potential, numerous knowledge gaps remain regarding its environmental and climate impacts (e.g., Butenschan et al., 2021; Caserini et al., 2021; Fakhraee et al., 2023; Keller et al., 2014; Lenton et al., 2018). Additionally, OAE will likely face significant barriers concerning international governance (e.g., Sovacool et al., 2022). Future scientific research will be required to comprehensively assess the costs and benefits of OAE from an environmental perspective, and transdisciplinary cooperation will be needed to develop a comprehensive governance regime for OAE and mCDR on a broader scale (Bach et al., 2024; Butenschan et al., 2021; Feng et al., 2017, McGee et al., 2018; Roschel & Neumann, 2023).

Global OAE scenarios using calcium- and magnesium-based alkalinity sources were found to enhance oceanic CO₂ uptake. For example, global scenarios of OAE using calcium-based alkalinity sources (e.g., calcium carbonate, lime, and hydrated lime) suggest between 166 GtC (Keller et al., 2014) to 940 GtC (Gonzalez & Ilyina, 2016) can be removed from the atmosphere by 2100, depending on the amount of alkaline material added and other model parameters. Further, global OAE scenarios that modelled an increase in alkalinity without specifying a specific alkaline source found OAE to increase oceanic CO₂ uptake. For example, modelling increases in oceanic TA corresponded to an increase in oceanic carbon uptake of 143.1 GtC (Lenton et al., 2018) and

157 GtC (Burt et al., 2021) over 80 and 75 years, respectively, under different emissions scenarios. Overall, studies modelling global OAE scenarios suggest that OAE has a strong CDR potential.

Similarly, modelled scenarios of regional and coastal OAE were found to increase oceanic CO₂ uptake. Certain locations of regional OAE were found to produce equivalent or higher oceanic uptake of CO₂ compared to global OAE. For example, OAE scenarios conducted in the Southern Ocean or Subpolar North Pacific region produced similar uptakes to global OAE scenarios when the same amount of alkaline material was deposited (Burt et al., 2021; Ilyina et al., 2023; Lenton et al., 2018). Regarding regional application locations, several studies found that oceanic CO₂ uptake could be enhanced by using existing shipping transportation networks to deposit alkaline materials and conduct OAE (Butenschan et al., 2021; Caserini et al., 2021; Kohler et al., 2013). Coastal OAE was found to increase oceanic uptake of CO₂ in the surface coastal water column, on coastal shelves, and in ice-free EEZs (Fakhraee et al., 2023; Feng et al., 2017; Kwiatkowski et al., 2023; Palmieri & Yool, 2024).

The termination of OAE scenarios can influence long-term oceanic CO₂ uptake and storage. Specifically, while the carbon sequestered by the ocean remains in the marine environment after OAE is terminated, the ocean stops sequestering atmospheric CO₂ at an enhanced rate (Gonzalez et al., 2018; Jin & Cao, 2023; Keller et al., 2014). However, some studies suggest that after terminating OAE, atmospheric CO₂ concentrations may remain slightly lower compared to unmitigated scenarios (Feng et al., 2017; Ilyina et al., 2013; Jin & Cao, 2023; Keller et al., 2014).

Corresponding with the decrease in atmospheric CO₂, modelled OAE scenarios indicated impacts on the climate system. Global offshore and coastal OAE scenarios were found to reduce global mean SAT compared to unmitigated scenarios in numerous studies (Gonzalez & Ilyina, 2016; Gonzalez et al., 2018; Jin & Cao, 2023; Keller et al., 2014; Lenton et al., 2018; Palmieri &

Yool, 2024; Sonntag et al., 2018). Under global OAE scenarios, the SAT decrease was generally more pronounced at higher latitudes, particularly in the Arctic (Gonzalez & Ilyina, 2016; Lenton et al., 2018; Sonntag et al., 2018). Corresponding with the decrease in global mean SAT, sea ice melt and associated sea level rise are projected to decrease under OAE (Gonzalez & Ilyina, 2016). In addition to changing projected mean SAT, long-term precipitation patterns are expected to change under OAE. For example, compared to unmitigated high emissions scenarios, OAE could increase overall precipitation (Jin & Cao, 2023; Sonntag et al., 2018).

There are several knowledge gaps regarding the CDR abilities of OAE and its potential side effects on the climate system and marine environment. Overall, future research should focus on modelling OAE using different earth system models and model parameters and creating a robust multi-model comparison framework to quantify the CDR potential and associated climate impacts of OAE (Caserini et al., 2021; Fakhraee et al., 2023; Keller et al., 2014; Lenton et al., 2018; Palmieri & Yool, 2024). Additionally, while this review only investigated the CDR potential and climate impacts associated with OAE, several other aspects of OAE require additional research. For example, the influence of OAE on ocean biogeochemistry and associated impacts on marine biodiversity remains uncertain and thus requires further research (Butenschan et al., 2021; Caserini et al., 2021; Fakhraee et al., 2023; Feng et al., 2017; Lenton et al., 2018). Further, the environmental and carbon footprint of different OAE scenarios must be investigated to comprehensively understand the costs and benefits associated with OAE when considering the large-scale production of alkaline materials and deposition process (Butenschan et al., 2021; Fakhraee et al., 2023).

While OAE appears to be a promising CDR technique that could be deployed to help limit global warming (Lenton et al., 2018), there is little explicit international governance on mCDR

and no explicit governance on OAE. While the London Protocol has made amendments to include some types of mCDR and marine SRM under its purview and the CBD has set out recommendations for mCDR research, they are not legally binding (Bach et al., 2024; Gambardella, 2019; McGee et al., 2018). Further, UNFCCC and UNCLOS have implicit governance implications regarding mCDR due to their linkages with climate change and international ocean law (Boettcher et al., 2021; Gambardella, 2019; McGee et al., 2018; Roschel & Neumann, 2023). Numerous other international organizations have indirect connections to mCDR governance, specifically frameworks that govern the ocean's conservation and resources (Gambardella, 2019).

mCDR approaches will likely face substantial barriers to effective international governance due to low public acceptance. Due to humankind's interconnected relationships with the ocean, societal acceptance of mCDR will likely be low (Cox et al., 2021). Additionally, the broader implications of mCDR approaches on society, such as their impacts on food production, biodiversity conservation, livelihoods, and environmental justice, must be considered (Bach et al., 2024). Specifically, transdisciplinary research on mCDR is needed to comprehensively assess its effectiveness, trade-offs, risks, and opportunities and its social acceptability and ethical implications (Cox et al., 2021; Gattuso et al., 2021; Loomis et al., 2022; McGee et al., 2018; Roschel & Neumann, 2023).

The major governance-related challenges of mCDR relate to the fragmented nature of the international ocean governance regime and managing the risk of transboundary harm (Bach et al., 2024; Boettcher et al., 2021; Loomis et al., 2022; McGee et al., 2018; Roschel & Neumann, 2023). Understanding how current international governance frameworks overlap and the potential for developing a new governance structure will be important for the future of mCDR research and

potential deployment (McGee et al., 2018). Overall, public perceptions and social acceptance, legal and regulatory obstacles, market demand, and environmental or planetary risks will likely be substantial barriers to OAE implementation (Gattuso et al., 2021; Sovacool et al., 2022).

A comprehensive and foresighted approach to mCDR governance that considers benefits, trade-offs, and risks between climate mitigation, ocean protection, and other policy goals, such as those set out under the Paris Agreement, will likely be needed (McGee et al., 2018; Roschel & Neumann, 2023). To develop a comprehensive mCDR governance regime, there is a strong need for transdisciplinary and inclusive research that includes a broad range of professionals, such as scientists, lawyers, social scientists, ethicists, industry leaders, NGOs, and global communities (Bach et al., 2024; McGee et al., 2018). Developing appropriate research codes of conduct and an MRV framework will likely also be imperative to creating a successful governance regime for mCDR (Bach et al., 2024; Loomis et al., 2022). Overall, the governance of mCDR should require the co-production of knowledge through the participation of various stakeholders (Bach et al., 2024).

Overall, initial modelling studies on OAE indicate that OAE has the potential to enhance oceanic CO₂ uptake and reduce the amount of CO₂ in the atmosphere, with corresponding decreases in global average SAT (Gonzalez & Ilyina, 2016; Jin & Cao, 2023; Keller et al., 2014; Lenton et al., 2018; Sonntag et al., 2018). However, OAE should only be used as a tool to help mitigate climate change alongside emissions reductions (Feng et al., 2017). Future research should focus on comprehensively assessing the potential impacts of OAE on the marine environment through robust multi-model comparison frameworks and quantifying its ecological and carbon footprints (Butenschan et al., 2021; Caserini et al., 2021; Fakhraee et al., 2023; Feng et al., 2017; Jin & Cao, 2023; Keller et al., 2014; Lenton et al., 2018). From an international governance

perspective, transdisciplinary research is needed to develop a comprehensive and inclusive governance regime for mCDR techniques to address the current and future challenges facing mCDR (Bach et al., 2024; Loomis et al., 2022; McGee et al., 2008; Roschel & Neumann, 2023).

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7.0 Appendices

7.1 Research Question 1 Dataset

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7.2 Research Question 2 Dataset

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7.3 Incorporating Proposal Feedback

The initial scope for this MRP was substantially larger. This project was originally going to assess the governance of CDR on national and international scales through a systematic scoping review. However, after receiving comments on my proposal from my second reader, Nic Rivers, I narrowed the scope of this MRP. Specifically, Nic pointed out that my initial research question was very broad, and the search string and methods appeared to address more of the environmental, social, ethical, and economic implications of CDR rather than governance. To address these comments, the scope of this project was narrowed and separated into two distinct research questions. The first research question synthesized the academic literature on the CDR potential and climate impacts of one CDR approach: OAE. OAE was chosen as it is of interest to my team at Environment and Climate Change Canada, and I will be providing my MRP to my team as a backgrounder on the topic. The second research question assessed the discourse on international mCDR governance, specifically identifying the key actors, frameworks, challenges, and opportunities. Narrowing the scope of my MRP and separating the research questions allowed me to synthesize research on both topics in sufficient detail and provide a comprehensive assessment of the current state of knowledge.