

OCEAN ALKALINITY ENHANCEMENT

Current state of knowledge and potential role of
philanthropy

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Ocean Alkalinity Enhancement: Current state of knowledge and potential role of philanthropy

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ABOUT THIS DOCUMENT

Climate Change has become the largest challenge for marine biodiversity and ecosystem integrity. Marine ecosystems experience increasing stress as atmospheric CO₂ concentrations raise global temperatures and acidify the oceans. Despite global efforts to mitigate emissions and decarbonize the economy, it is unlikely that extreme ecosystem effects can be fully averted without carbon dioxide removal (CDR) mechanisms.

The benefits, risks and costs of ocean CDR to address the preceding stressors must be better understood. In this context, there is an increasing urgency to understand the impacts associated with a variety of CDR proposals that have emerged and will continue to emerge. Moreover, it is critical to understand how to design a productive and science-based discourse that assesses knowledge gaps and provides the kinds of insights that would allow the international community to make informed decisions about the piloting and deployment (or not) of candidate technologies.

A group of experts and funders convened to discuss the state of knowledge in the field of ocean alkalinity enhancement. At the request of the marine philanthropic funder Oceanskind, CEA Consulting organized a convening of a dozen experts in the field, as well as a handful of philanthropic donors seeking to better understand the potential and limitations of ocean alkalinity enhancement (OAE). OAE is an umbrella term for a variety of proposals to add alkalinity to the ocean in such a way that CO₂ is removed and/or sequestered from the atmosphere; the specific objectives of the meeting included:

1. Discuss the potential role of OAE as a mechanism to strengthen ecosystem resilience and/or boost greenhouse gas (GHG) mitigation;
2. Share insights around current state of knowledge regarding OAE effectiveness, risks and uncertainties;
3. Brainstorm opportunities to advance the field, with particular focus on potential philanthropic engagement.

This document merges a thorough literature review with insights gained during the convening. In the last decade, specific aspects of OAE have received some attention in the specialized CDR literature (such as in AGU100 journals) but significant knowledge gaps remain. This document makes an attempt at discussing current knowledge and knowledge gaps relating to the local and global application of OAE and to provide recommendations to the broader philanthropic community that is considering supporting the advancement of the field. The remainder of this document is structured as follows:

Section I highlights current stressors to marine organisms and the need to alleviate them.

Section II introduces four distinct OAE proposals and trade-offs associated with their deployment.

Section III summarizes the known effects of alkalinity enhancement on calcifying marine ecosystems.

Section IV discusses governance considerations associated with the science and technology of OAE.

Section V summarizes opportunities for philanthropic engagement, as surfaced during the meeting.

I. INTRODUCTION

Impacts of climate change to marine ecosystems

Greenhouse gas (GHG) emissions are changing the chemistry and physics of the world's oceans. Since the Industrial Revolution, hundreds of billions of tons of carbon have entered the ocean/atmosphere system, resulting in surface and eventually subsurface ocean warming, reduction in Arctic sea ice extent, rising sea levels, deoxygenation and ocean acidification (IPCC 2019). The interactions between multiple stressors is still not fully understood, nor is the relative importance of each stressor in relation to others (Cabral et al. 2019). However, the combined impact from all anthropogenic impacts on the ocean and marine ecosystems threatens to irreversibly modify marine biogeochemistry and the essential ecosystem services provisioned by a well-functioning ocean system, and climate change is by far the most impactful and fastest growing threat to virtually all marine ecosystems (Gattuso et al. 2015; Halpern et al. 2019; see Appendix A for details).

Macro-level impacts of climate change on ocean chemistry, food webs, and genetics are slowly becoming apparent. Extensive research has focused on climate change impacts on specific marine species, and also more recently on the systems-level impact of climate change on marine ecosystems. Some impacts identified by recent research include the large (15% increase in size in 8 years) expansion of nutrient-free ocean “deserts” in both the Atlantic and Pacific oceans (Hoegh-Guldberg and Bruno 2010), slowing meridional overturning circulation (MOC), which has major implications for both climate and nutrient cycling in the ocean, as well as changes in marine organisms’ genetics, physiology, morphology, distribution, productivity, and phenology (Scheffers et al. 2016). Acidification of the ocean resulting from dissolved carbon dioxide from the atmosphere is predicted to result in dangerously low carbonate saturation states, especially in polar regions, if warming and covalent greenhouse gas emissions are not kept to a level consistent with 2 degrees Celsius or less total warming. Resulting risks include the possible extinction of habitat-building species, including corals (Hoegh-Guldberg and Bruno 2010), disappearance of other ocean habitats (e.g., sea ice-based ecosystems), declining primary

productivity of the ocean (Behrenfeld et al. 2007) and therefore food provisioning services of the ocean (Allison et al. 2009). In short, if climate change continues unabated, there are risks to the overall function of the ocean including the fundamental biogeochemistry that drives productivity and critical ecosystem functions.

Emission trajectories point to the need for carbon removal technologies

The likelihood of remaining at or below 1.5 degrees Celsius of warming is extremely low, even including the most optimistic mitigation pathways. Most emissions projections from both IPCC analyses and scenario modeling from other groups still result in emissions that would exceed the threshold of 2 degrees Celsius before the end of the century. International policy, as shown in Figure 1, has lagged behind the scope and urgency of mitigating GHG emissions to biologically and ecologically safe limits. Since the 1997 Kyoto protocol, a wide range of GHG mitigation strategies have been proposed, developed, and scaled, including renewable energy generation, electrification of transport, and efficiencies in aviation. However, adoption of emissions reduction technologies including renewable electricity generation, electrification of transport technology, and decarbonization of fossil energy (i.e., carbon capture and storage (CCS)) has lagged behind the pace needed to mitigate the worst impacts of climate change. A major challenge for the global response to climate change remains that policy responses are not proportional to the scope of the climate problem, enhancing the argument for technological interventions beyond emissions reduction to help mitigate both causes and effects of climate change (“Climate Action Tracker” n.d.) (Figure 1).

Since the early 1980s, dozens of proposals have been brought forward to address the causes (GHG emissions) and effects (temperature, acidity, aridity, flooding) of climate change. These proposals can be broadly classified as:

1. **GHG emissions reduction** via transition to non-fossil energy sources, greater energy efficiency,

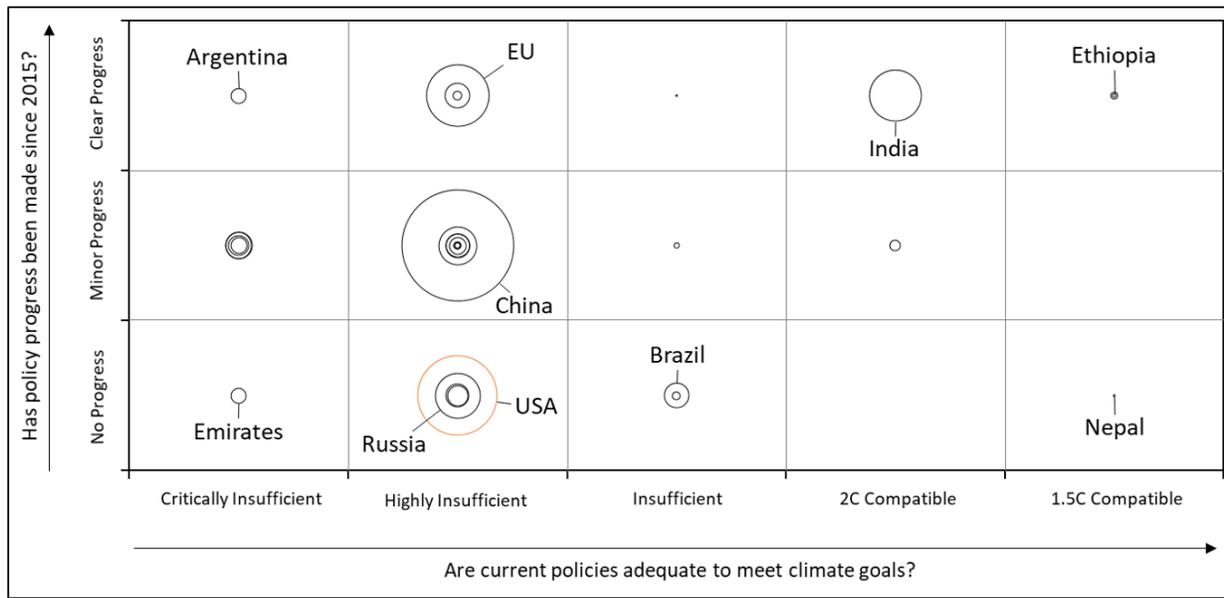


Figure 1: Status and trend of international climate policies (CEA analysis based on climateactiontracker.com).

- and removal and storage of CO₂ from point sources.
- Carbon Dioxide Removal (CDR)** wherein post-emissions, legacy CO₂ is proactively removed from the atmosphere.
 - Solar Radiation Management (SRM)** involving the reduction of incoming or the increase in outgoing solar/thermal energy.

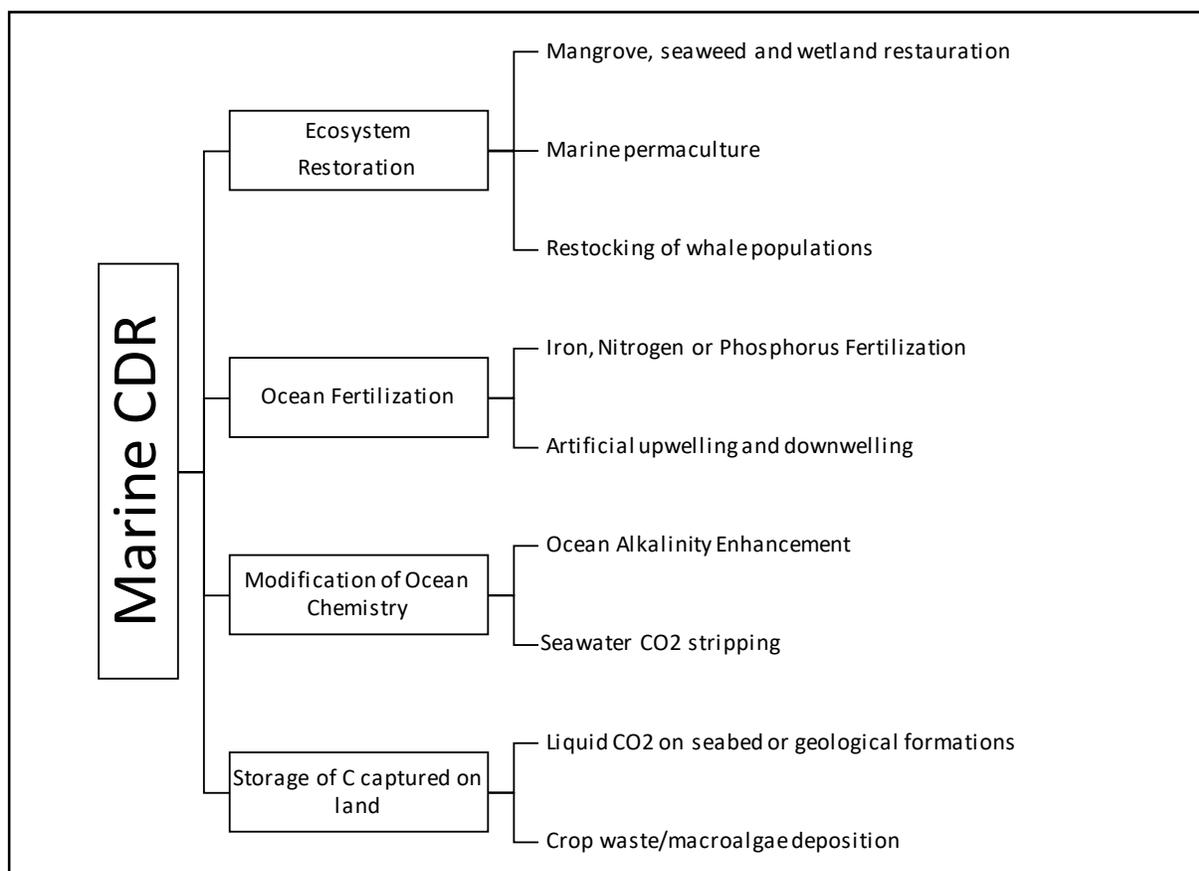
There is a common understanding among scientists and decision-makers that there will not be one silver bullet to turn back the clock on GHG emissions, and each of these categories deserves attention. The remainder of this document focuses on the subset of CDR approaches that require the ocean. In particular, one promising and understudied approach is the focus here: Ocean Alkalinity Enhancement.

Marine CDR proposals

The large role the ocean already has and will play in moderating excess atmospheric CO₂ and climate has attracted a suite of proposals to enhance this role in the context of proactive CO₂ management. Marine CDR proposals focus on approaches that require the coastal and marine environment for their solution. Broadly speaking, these proposals can be subdivided into four categories, namely (i) ecosystem restoration to increase naturally occurring photosynthesis; (ii) fertilization of existing ecosystems to boost photosynthetic activities and accelerate the

downward transport of organic carbon; (iii) restoration of chemical oceanographic attributes to pre-industrial times; and (iv) physical storage of carbon in the form of liquid CO₂ or biomass, irrespective of the source of production. A growing body of literature is assessing the technical readiness, theoretical impact, cost effectiveness and potential environmental side effects of such marine CDR proposals (Gattuso et al. 2018; Boyd and Vivian 2019). However, due to lack of research, especially at relevant scales, the evaluation and intercomparison of proposals is not straightforward. While technical studies may attempt to highlight the importance and relevance of a given approach, it is currently problematic to accurately assess their true potential, cost, and impact (Boyd and Vivian 2019; Gattuso et al. 2018). Meanwhile, a number of comparative meta-analyses have emerged in recent years, each providing important insights into the potential impacts and trade-offs of land- and/or ocean-based CDR proposals (Gattuso et al. 2018; NASEM 2018; Keller et al. 2014; Keller et al. 2018a; Lawrence et al. 2018; The Royal Society 2018; National Research Council 2015; Boyd and Vivian 2019). Based on these meta-analyses—and based on specific technical analyses for each proposal reviewed—a picture of largely untested proposals emerges, with a high degree of uncertainty regarding their potential contribution to GHG drawdown and their potential role in enhancing ecological resilience.

Figure 2: Examples of Marine CDR pathways¹



Ocean Alkalinity Enhancement (OAE) is one of the more promising proposals as it imitates naturally occurring phenomena that reduce both ocean acidification and atmospheric CO₂ levels. In the past decade, numerous proposals have emerged that may provide scalable and cost-effective options, with potentially low (known or presumed) environmental side effects (see Section II). This is not unexpected given that mineral weathering and alkalinity addition to the ocean is the primary way by which the Earth naturally removes and stores excess CO₂ on very long timescales (Archer et al. 2009). Nonetheless, OAE's potential has often been underrepresented in broader CDR discussions. As one example, a 20-year US CDR R&D agenda by the National Academies of Science, Engineering, and Medicine omitted OAE (and other marine CDR) from its analysis (NASEM 2018).

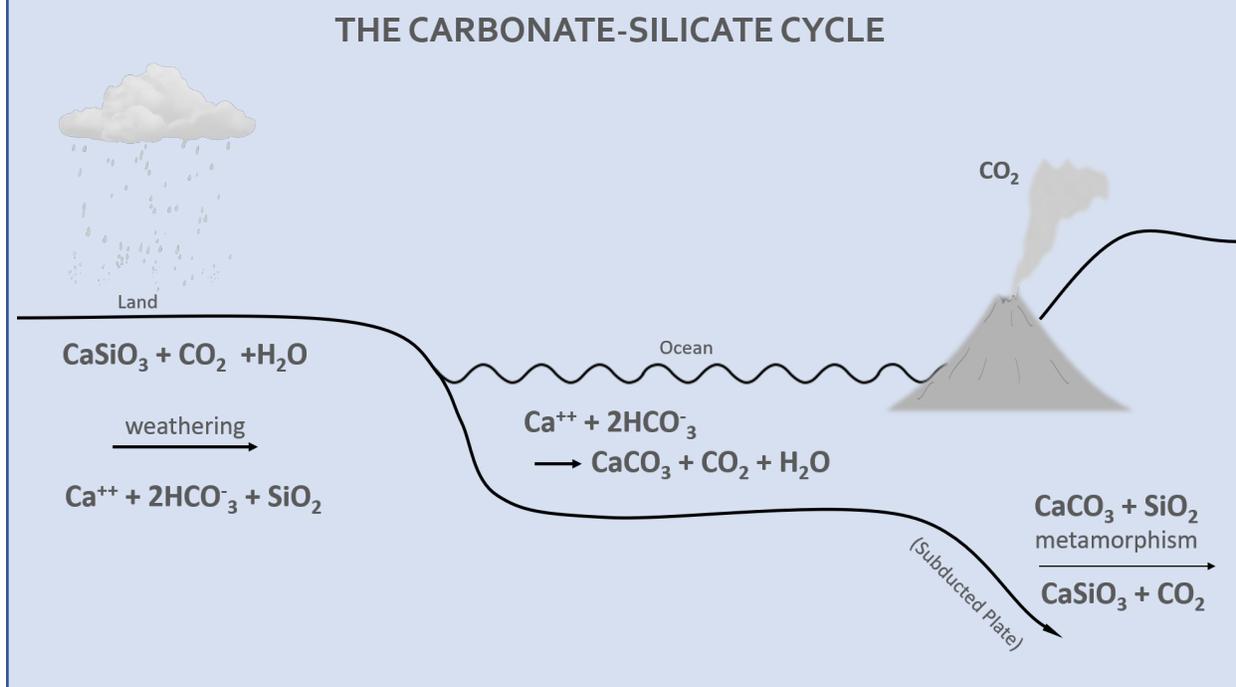
Objective, hypothesis-driven research is required to advance the field of ocean alkalinity

enhancement; the US lags behind EU efforts and increased international coordination would benefit the field. Various research groups in the EU have been set up with the specific mandate to evaluate CDR proposals, including marine approaches, based on their potential and risk to the environment (and to inform policy makers): See Appendix C. Such cross-institutional working groups are almost absent in the US. Several strong entities have emerged focusing on specific aspects of CDR but there is no formalized platform, organization or dedicated community of practitioners in the US that systematically evaluates findings from the CDR literature and whose recommendations are taken into consideration by national lawmakers or international governance bodies. A potential exception is the National Academies of Science, Engineering, and Medicine, a private, non-profit society of scientists charged with providing independent, objective advice to the nation on matters related to science and technology (assuming their above omission of ocean CDR from their policy statement was an aberration). In addition to US universities, a group of NGOs (consisting of Carbon180, WRI, EDF, Great Plains

¹ Note that various taxonomies have emerged in the literature to distinguish between CDR approaches (e.g. chemical vs. physical vs. biological or natural vs. technological).

Box 1: Ocean's role in the carbonate-silicate cycle

Oceans are a crucial component in the carbonate-silicate cycle, which plays a key role in stabilizing Earth's climate over long timescales. In this cycle, volcanic rock is weathered by wind and rain, releasing calcium, magnesium, potassium, or sodium ions that are eventually carried to the oceans. In the ocean, calcifying organisms use calcium ions and bicarbonate ions (resulting from the reaction of CO_2 with seawater) to form calcium carbonate, a building material of shells and skeletons. As these organisms die, their bodies sink to the ocean floor where a fraction of the calcium carbonate is buried. Over time, layers of shells and sediment are cemented together and turn to rock, storing the carbon in stone—limestone and its derivatives. The slow cycle returns carbon to the atmosphere through volcanoes: Earth's land and ocean surfaces sit on several moving crustal plates. When the plates collide, one sinks beneath the other, and the rock it carries melts under the extreme heat and pressure. The heated rock recombines into silicate minerals, releasing carbon dioxide. When volcanoes erupt, they vent the gas to the atmosphere and cover the land with fresh silicate rock to begin the cycle again.



Institute, Sierra Club, The Nature Conservancy and NRDC, among others) is increasingly considering CDR approaches as necessary additions to meeting climate mitigation goals. These organizations have started to assess and communicate the potentials and negatives of CDR approaches (including OAE) but formal collaborations to this specific end have not been created. International efforts exist, including GESAMP's working group 41² or IPCC's working group III.³ These groups have only recently started focusing on ocean CDR and might become important platforms for the advancement of science necessary to evaluate OAE for the global community.

² GESAMP is a group of independent scientific experts that provides advice to the UN system on scientific aspects of marine environmental protection; WG 41 focuses on marine geoengineering approaches.

³ IPCC's WG III focuses on climate change mitigation, assessing methods for reducing greenhouse gas emissions, and removing greenhouse gases from the atmosphere

II. TECHNICAL ASPECTS OF OCEAN ALKALINITY ENHANCEMENT

Ocean alkalinity increases with excess atmospheric CO₂. When excess atmospheric CO₂ passively diffuses into the ocean, much of that CO₂ is quickly hydrated to form carbonic acid. Carbonic acid dissociates into bicarbonate ions (HCO₃⁻) and protons (H⁺), the latter causing seawater to become more acidic. A proportion of the extra protons combines with carbonate ions (CO₃²⁻) to form HCO₃⁻, therefore increasing the concentration of HCO₃⁻ and decreasing CO₃²⁻ in seawater (the latter causing a decline in the carbonate saturation state) (upper half of Figure 3). The ocean typically absorbs 25-30 percent of the CO₂ that is released in the atmosphere, and as levels of atmospheric CO₂ increase, so do CO₂ and acidity levels in the ocean.

To counter this, adding chemical base (alkalinity) to seawater can be useful in three ways.

First, CO₂-reactive forms of alkalinity can consume and convert surface seawater CO₂ to dissolved inorganic carbon in the form of bicarbonate and carbonate ions, thus decreasing the surface ocean's partial pressure of CO₂ (pCO₂). This thereby either reduces emissions of excess CO₂ from the ocean (e.g., in upwelling areas) or forces net atmospheric CO₂ uptake by the ocean.

Secondly, elevating ocean alkalinity counters seawater acidity and its biological effects by i) consuming acidity and elevating pH, and/or ii) increasing the calcium carbonate saturation state of seawater, critical to the maintenance of calcification in shell-forming organisms including coral and shellfish.

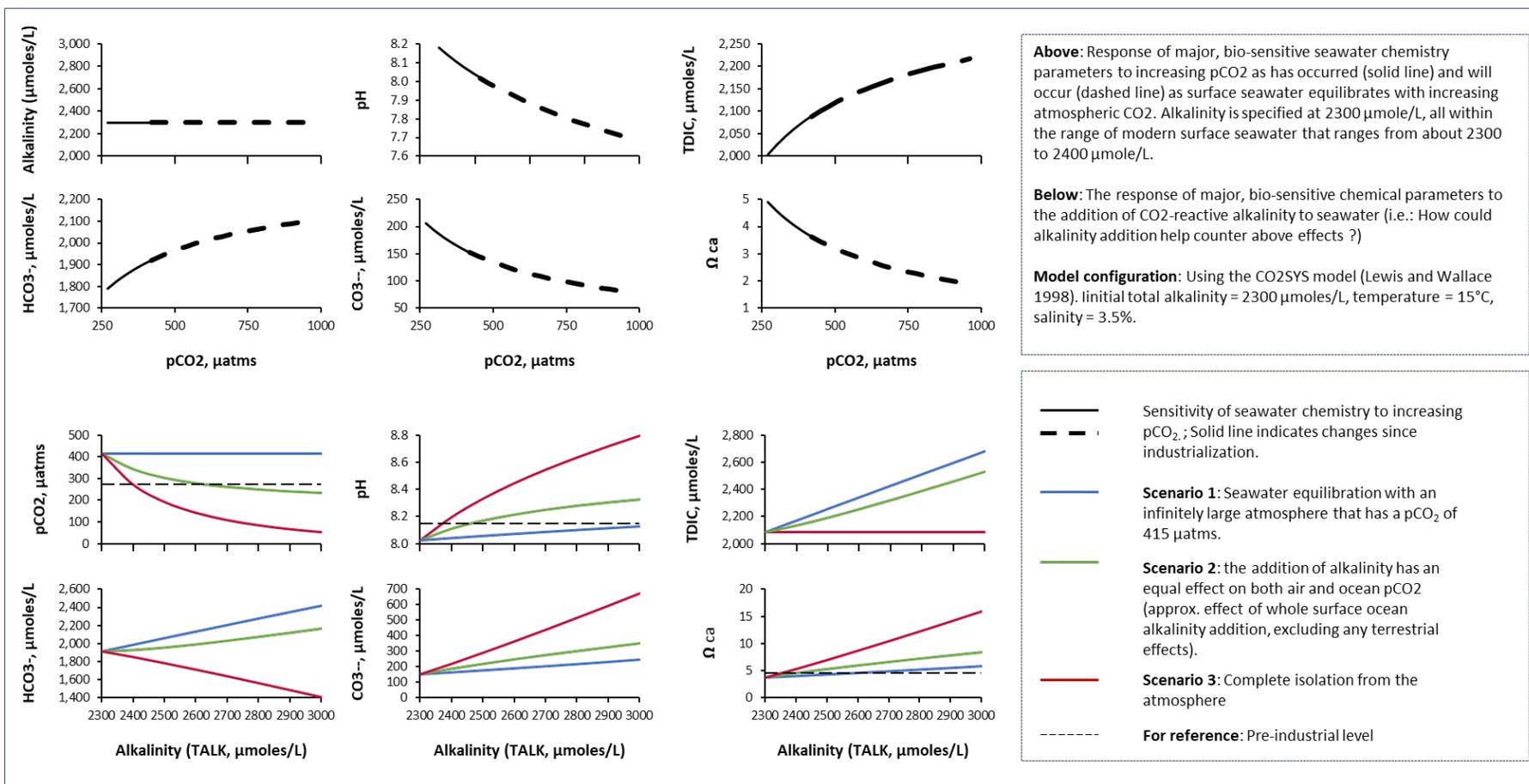
Third, adding or forming dissolved alkaline bicarbonate and carbonate ions to/in seawater provides a vast, naturally occurring and relatively stable carbon storage medium for anthropogenic CO₂. Seawater's resident bicarbonate and carbonate pool is already by far the largest carbon storage reservoir in contact with the atmosphere, dwarfing the carbon contained in air, terrestrial biota, and soils.

In summary, and in theory, if reactive alkalinity (e.g., hydroxides) at a safe concentration were evenly distributed in the surface layers of the

ocean, it could decrease the ecological stress that acidification is causing while simultaneously increasing the CO₂ adsorption and storage capacity of the ocean. In practice however, this proposal is complicated by the fact that conventional sources of reactive alkalinity are not produced at the temporal and spatial (global) scales required, and can be expensive and carbon intensive to produce and distribute. Renforth and Henderson (2017) provide a comprehensive overview of proposals to date. Table 2 reviews the approaches, including their cost drivers and current limitations. Among these limitations, beyond theory and a few laboratory studies, little is known about the actual net biogeochemical and ecological effects of adding alkalinity to marine systems.

When alkalinity is added to seawater, acidity is consumed, carbonate saturation is increased and atmospheric CO₂ is sucked out of the atmosphere. If CO₂-reactive forms of alkalinity (soluble oxide, hydroxide or carbonate bases) are added, they rapidly react with seawater CO₂ to largely form non-CO₂-reactive bicarbonates, the primary form of seawater alkalinity. Because such reactions consume acidity (CO₂), seawater pH is thus elevated, as is carbonate saturation state. Additionally, the chemical conversion of seawater CO₂ to alkaline bicarbonate means that the pCO₂ of the water declines. If seawater is in contact with the atmosphere and its pCO₂ drops below that of the atmosphere, air CO₂ spontaneously diffuses into the water until air/seawater pCO₂ and chemistry equilibrium is reached. The net effect of the preceding is that CO₂ is removed from the atmosphere to the ocean, while seawater alkalinity, pH, carbonate saturation state, and inorganic carbon concentrations are higher than they were initially. The preceding responses and their sensitivities to alkalinity addition are shown in the lower half of Figure 3. Note that significant changes in these parameters occur within that natural range of surface seawater alkalinity. In particular, dramatic changes in seawater alkalinity are not needed to restore mean seawater pH and carbonate saturation state to pre-industrial values. Note also that adding non-CO₂-reactive alkalinity (soluble bicarbonate bases equilibrated with air) to seawater does all of the preceding while having little or no direct effect on seawater pCO₂ or air CO₂ removal.

Figure 3: Response of seawater chemistry parameters to increasing pCO₂ and to addition of CO₂-reactive alkalinity to seawater.



Once the newly alkalized seawater is equilibrated with the atmosphere (if circumstances allow it to do so) the bicarbonate (and some carbonate) ions formed simply enter the existing, large reservoir of these compounds in the ocean, where estimated residence times are near 200,000 years. Ultimately, they are removed from seawater via biological formation of solid calcium carbonate (shell formation) that precipitates nearly half of the carbon to the sea floor while the rest returns to the ocean/atmosphere system as CO_2 : $\text{Ca}^{2+} + 2\text{HCO}_3^- \rightarrow \text{CaCO}_3 \downarrow + \text{CO}_2 \uparrow + \text{H}_2\text{O}$ (i.e., bio-calcification is an alkalinity-consuming and CO_2 /acid-generating process).⁴ Alkalinity delivered to the ocean via continental mineral weathering, alkalinity generated by anerobic metabolism (in sediments), and hydrothermal cycling of seawater through mineral substrata below the ocean add further complexity to the biogeochemistry of marine alkalinity.

Four approaches of Ocean Alkalinity Enhancement

Direct addition of alkaline, silicate rocks

The reaction of alkaline, silicate minerals with CO_2 and its subsequent delivery of alkalinity to the ocean plays a major role in consuming excess CO_2 and rebalancing ocean chemistry on geologic time scales (Archer et al. 2009). It has therefore been proposed that this process can be sped up by dramatically increasing the reactive surface area of such minerals (via grinding to small particles) and placing these either in soils or the ocean. This then accelerates the natural process of silicate weathering, producing long-lived, dissolved calcium and magnesium bicarbonates that are either generated in the ocean or delivered via rivers following upstream, enhanced mineral weathering. Land-based mineral weathering naturally consumes about 1 Gt of CO_2 /yr. and delivers this carbon to the ocean mostly as bicarbonate alkalinity. The primary issues of accelerating this process are the costs and environmental impacts of extracting, grinding and distributing silicate minerals, and the downstream biogeochemical impacts of silica and trace metals that can accompany this alkalinity as well as the effects of the alkalinity itself (reviews by Hartmann et al. (2013); Renforth and Henderson (2017))

⁴ Although biogenic calcification is considered a sink of carbon, bio-calcification is an alkalinity-consuming and CO_2 /acid-generating process

Thermal calcination to produce hydroxides (used for ocean liming)

Lime has been an alkaline agent for centuries and its application for ocean carbon removal goes back to the mid-1990s. For centuries, lime products have been used as an essential commercial and industrial alkali and ingredient in cements and mortars. Because lime is a strong chemical base capable of neutralizing acids, it is also used to treat soil, drinking water, wastewater and industrial acid streams. Kheshgi (1995) first considered its use in the alkalization of seawater for the purpose of alkalinity enhancement and atmospheric CO_2 removal. Calcination is typically an energy- and carbon-intensive process during which limestone (calcium carbonate (CaCO_3)) is burned and decomposes into pure lime (calcium oxide (CaO)) that is then spontaneously converted to calcium hydroxide (Ca(OH)_2) when added to water. Once in water, this hydroxide rapidly reacts with CO_2 , forming dissolved calcium bicarbonate ($\text{Ca}^{2+} + 2\text{HCO}_3^-$) and, to a lesser extent, dissolved calcium carbonate ions ($\text{Ca}^{2+} + \text{CO}_3^{2-}$). The net result is that calcium hydroxide (or any soluble, mineral hydroxide) addition to seawater increases the removal of excess CO_2 from the ocean/atmosphere system and stores this carbon in a stable, dissolved bicarbonate/carbonate alkalinity. This simply adds to the existing, vast global carbon pool of these alkaline compounds in the ocean, by far the largest single carbon reservoir on the Earth's surface. To remove 1 GtC (3.7 GtCO_2) from the atmosphere per year, approximately 6.5 Gt of limestone are needed to produce 4.5 Gt of lime (Renforth and Henderson 2017; Kruger and Renforth 2012). By comparison, global cement production in 2018 was 4.1Gt ("Statista - The Statistics Portal for Market Data, Market Research and Market Studies" n.d.). However, calcination is not the only source of mineral hydroxide alkalinity, "lime," for OAE (see "Electrochemical Methods" below).

Accelerated weathering of limestone (CaCO_3)

As in silicate rock addition (above), Harvey (2008) proposed the idea of adding mineral calcium carbonate (limestone) directly to the ocean as a means of accelerating natural carbonate mineral weathering to effect CDR. However, CaCO_3 dissolution and alkalinity generation only naturally occur in subsurface ocean waters (CaCO_3 is unreactive in surface waters because they are uniformly supersaturated in CaCO_3), and hence the effect on surface ocean/atmospheric CO_2 would

Table 1: Overview of Ocean Alkalinity Enhancement approaches. Blue font indicates the alkaline output produced that will be added to the ocean.

Approach	Required machinery	Inputs	Outputs	Cost drivers	Pros	Potential limitations
Direct addition of alkaline rocks	<ul style="list-style-type: none"> facilities for rock extraction, grinding and transport, and land or ocean distribution 	<ul style="list-style-type: none"> rocks containing carbonate or silicate minerals 	<ul style="list-style-type: none"> ocean alkalinity in the form of dissolved mineral bicarbonates and carbonates SiO₂ and trace metals 	<ul style="list-style-type: none"> rock extraction, grinding, transport and distribution 	<ul style="list-style-type: none"> low tech, low cost could be incorporated into sand/beach renewal/protection could benefit land ecosystems/agriculture negative-emissions scheme 	<ul style="list-style-type: none"> very slow reaction rates requiring large masses of fine particles carbonate minerals not effective in surface ocean benefits/impacts little studied
Manufactured sources of alkalinity: Accelerated weathering of limestone	<ul style="list-style-type: none"> AWL reactor for flue gas scrubbing facilities for limestone extraction, grinding and transport 	<ul style="list-style-type: none"> limestone or waste limestone fines CO₂-rich gas, e.g., from power plant seawater 	<ul style="list-style-type: none"> CO₂-poor gas dissolved calcium bicarbonate and carbonate 	<ul style="list-style-type: none"> pumping seawater limestone CAPEX of AWL reactor 	<ul style="list-style-type: none"> low tech, low cost point-source emissions reduction and ocean C storage scheme analogous to existing SO₂ mitigation 	<ul style="list-style-type: none"> needs lots of seawater, limestone requires semi-concentrated CO₂ source benefits/impacts little studied
Thermal calcination for hydroxide production	<ul style="list-style-type: none"> facilities for limestone/dolomite extraction, grinding, transport kiln for calcining transport of hydroxide produced 	<ul style="list-style-type: none"> limestone or dolomite fuel - fossil or solar heat 	<ul style="list-style-type: none"> calcium or magnesium hydroxide CO₂, esp. if fossil energy used 	<ul style="list-style-type: none"> Energy for calcination limestone CCS, esp. if fossil energy used raw materials transport 	<ul style="list-style-type: none"> existing technology large amount of raw materials available potentially a negative-emissions scheme 	<ul style="list-style-type: none"> energy and limestone intensive CO₂ intensive esp. if fossil energy used benefits/impacts little studied
Electrochemical production of hydroxide	<ul style="list-style-type: none"> electrolysis cells water pumping facilities for rock extraction, grinding, transport 	<ul style="list-style-type: none"> Non-fossil electricity salt electrolyte (NaCl or other) water - fresh, seawater, alkaline rocks 	<ul style="list-style-type: none"> H₂ and O₂ or Cl₂ dissolved calcium, magnesium or sodium hydroxide SiO₂ and trace metals if silicate minerals used 	<ul style="list-style-type: none"> electricity water (pumping) raw materials transport 	<ul style="list-style-type: none"> cost countered by value of H₂ produced potentially very high global capacity negative-emissions scheme 	<ul style="list-style-type: none"> more technologically challenging potentially slow to scale benefits/impacts little studied

not be felt for at least hundreds of years, until that deep water naturally advected to the surface.

Rau and Caldeira (1999) took a different tack. Knowing that greatly elevated CO_2 in seawater forces CaCO_3 to dissolve and consume most of the CO_2 , they proposed directly contacting CO_2 -rich waste gas streams with seawater and limestone to facilitate mineral dissolution, and CO_2 conversion to calcium bicarbonate. Thus, the concept of accelerated weathering of limestone (AWL) was born. It is a low-tech method to capture and sequester CO_2 from fossil fuel-fired power plants and other point sources such as cement manufacturing. In its simplest form, an AWL reactor is constructed at the site of a coastal waste gas stream that is then brought into contact with seawater and limestone within the reactor. If the concentration of CO_2 in the waste gas stream is $>1\%$, the limestone spontaneously reacts with and consumes the CO_2 to primarily form dissolved calcium bicarbonate, already the dominant form of alkalinity (and carbon) in the ocean. Pumping of seawater into and out of the reactor can be energy-intensive, but many coastal plants already pump large volumes of seawater for condenser cooling. Under such circumstances, costs of $\$10/\text{t}$ CO_2 mitigated or lower might be possible, especially if low cost (e.g., waste) limestone is available and nearby (Rau 2011). Otherwise and more commonly, AWL cost is estimated to be $\$<40/\text{tCO}_2$. Such estimates are tentative given that AWL research has thus far been largely confined to small-scale experiments.

Electrochemical methods

House et al. (2007) proposed an electrochemical scheme whereby the alkaline sodium hydroxide produced in a chlor-alkali process was added to the ocean to effect CDR (see "liming" above), while the produced hydrogen and chlorine gases were reacted in a fuel cell to generate electricity and hydrochloric acid. The authors proposed that silicate minerals would then be used to consume this acid and convert it to a benign, soluble salt (e.g., magnesium chloride (MgCl_2)) that could then also be safely added to the ocean. The net effect would be to accelerate silicate weathering and CDR while also regenerating some of the electricity initially used in the process. Rau (2008) modified this approach by adding calcium carbon directly into a seawater electrolysis cell so excess hydroxide was again produced that absorbed CO_2 and generated stable, dissolved alkalinity

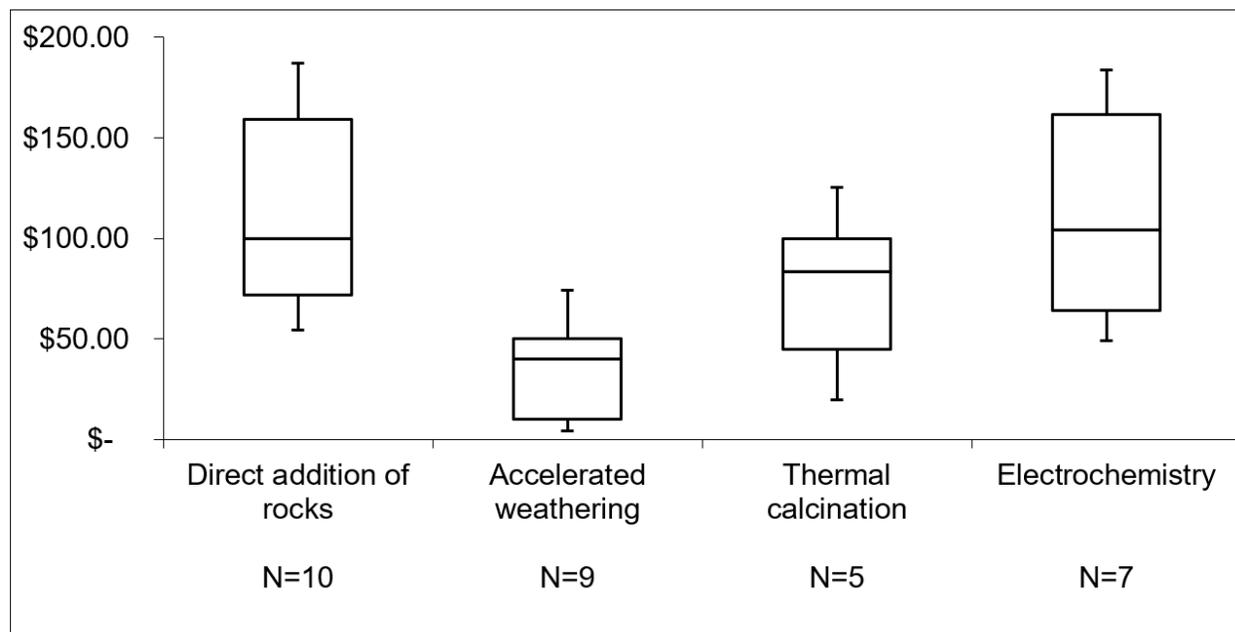
(calcium/sodium bicarbonates) and hydrogen (H_2). Subsequently, a similar electrochemical cell configuration was used to directly react silicate minerals to effect CDR and generate H_2 and bicarbonate alkalinity (Rau et al. 2013).

When powered by renewable electricity, all of the preceding systems produce either negative-emissions electricity or hydrogen gas, and the estimated global CDR capacity of this approach appears to be much larger (and less land intensive) than bio-energy with carbon capture and storage (BECCS), the only other negative-emissions energy system thus far widely considered (Rau et al. 2018). In addition to mineral extraction, grinding, and transport, and the potential downstream biogeochemical impacts, the primary issue with such approaches is the need for significant amounts of low-cost renewable electricity.

Open questions

Cost estimates range widely because of variation in technologies used, the geographic availability of the required alkalinity sources and because of uncertainties in predicting real economics in the absence of full-scale testing, deployment, learning and refinement. A key consideration in the choice of negative-emissions technologies is the cost, typically calculated as USD per net ton of CO_2 mitigated or removed. The general consensus in the academic literature is that OAE approaches are cost-competitive with comparable approaches, but that much additional work is required to increase confidence in current cost estimates. Figure 4 provides an overview of cost assessments provided in 15 (meta-) analyses, providing a total of 43 cost estimates across the four OAE approaches presented above. The cost of net tCO_2 removal calculated for OAE ranges from USD $\$3$ - 200 (in both cases outliers that can't be seen in the box plot figure), with median values between USD $\$55$ (accelerated weathering) to USD $\$107$ (thermal calcination). The major cost driver in almost all of the proposals is energy and raw materials. The source of energy (fossil vs. non-fossil) also determines the net effectiveness of CO_2 removal, thereby influencing the net cost. The most cost-effective accelerated weathering proposals, for example, assume the use of renewable energy and mining waste fines and the proximity to both coastal waters and powerplants with CCS facilities. These assumptions naturally drive down the expected scalability of a proposal. None of the techno-economic assessments reviewed were

Figure 4: Cost estimates from technoeconomic analyses (CEA analysis based on technoeconomic analyses; see Appendix D for details).



based on actual observations in the field and it would not be surprising for current cost estimates to significantly increase once operational costs are fully accounted for (including inefficiencies, liabilities, and cost drivers that have not yet been quantified, such as the transport and distribution of alkalinity). On the other hand, OAE is at an early stage and future breakthroughs in energy efficiency and synergies with other industrial systems could significantly reduce costs at scale (Rau et al. 2018).

An important consideration will be how these technologies may interact with other climate mitigation proposals, and the wider socio-economic systems. In this context, key questions will include the following: How will these proposals interact and compete with the existing mineral extraction industry, and other emissions reduction and negative-emissions approaches? What are the cost reduction potentials? Where are the best resources and places to start undertaking these technologies? What are the societal consequences? What policies and markets are required to make OAE (R&D) attractive? Are there viable links to carbon finance and what would effective monitoring processes look like for accurate carbon accounting?

At what scale can alkalinity addition help protect ocean life from acidification? In 1976, the U.S. Environmental Protection Agency (EPA) published the recommendation (still in place today) that “for

open ocean waters where the depth is substantially greater than the euphotic zone, the pH should not be changed more than 0.2 units from the naturally occurring variation” (Carnegie Science 2007). Given that average ocean pH was about 8.2 prior to the industrial revolution (US EPA 2016), this would imply to keep Ocean pH above 8.0. Feng et al. (2016) estimate that the regional addition of 1-10 Gt of lime per year may be able to reverse pH decline in the Great Barrier Reef, Caribbean Sea, or South China Sea. However, the model simulations were undertaken using a grid of 100’s of km, and much higher resolution ocean circulation modelling is required for specific environments. Paquay and Zeebe (2013) assess the alkalinity requirements on a global level and estimate that an annual input of 5-26 Gt of lime would be required to keep ocean surface pH above that level. These estimates are based on simple configuration of the *Long-term Ocean-atmosphere-Sediment Carbon cycle Reservoir Model* (LOSCAR). However, while countering ocean acidity at the global scale with OAE may appear daunting, small scale applications of OAE (e.g., to selected coral reefs, oyster beds, Marine Protected Areas, etc.) could be helpful, if not critically important. Further research is needed to find out.

Is the extractive sector ready to mine and process alkaline rock at scale? For the purpose of comparison, GHG mitigation efforts are usually evaluated against their ability to mitigate 1Gt of

carbon per year (Davis et al. 2013).⁵ In order to reach that scale, Renforth and Henderson (2017) estimate that, in a perfectly efficient system, between 1 and 3.5 Gt of raw material will need to be extracted for every Gt of CO₂ captured. Conservatively speaking, this might imply the need of 5 billion tons of rock extracted per year for the sole purpose of ocean alkalinity enhancement, thereby doubling the quantity used in today's cement production, or a 10% increase on current rock extraction for aggregate. In the past decade, the kind of sustained growth necessary for this scale (15-20% per year for the next 25-50 years) has only been seen in China but has been slowing down a little in past years. An open question is whether the extractive industry is purely driven by demand signals or also constrained by regulatory frameworks and supply dynamics. On the other hand, the alkalinity for OAE need not come from rocks; it can also come from globally abundant salts such as NaCl (e.g., seawater) from which sodium hydroxide (NaOH) is commercially, electrochemically derived. Bottom line: OAE is not globally limited by alkaline rock resources, but rather by the ability to scale up extraction or the production of alkalinity, and the willingness to bear the environmental and monetary cost of doing so.

How much additional capacity is required in the shipping industry to distribute alkaline material?

Global seaborne trade reached 10.7 Gt per year in 2017 (UNCTAD 2018); adding 5Gt of lime to global trade will require new ships and shipping routes. To a certain extent, existing capacity might buffer some of the increased demand: container shipping of major shipping lines have started utilizing information technology in processes such as yield management, shipping quotations, cargo volume management, the design of new shipment services, and operation of empty legs; a 50 percent increase in shipping material might not require a 50 percent increase in shipping capacity. Kruger and Renforth (2012) estimate that a 1Gt annual distribution of lime will require only an additional hundred bulk carriers (300,000 dead-weight tonnage (DWT) each) to absorb additional shipping demand of lime. In 2018, the UNCTAD secretariat calculated a maritime shipping capacity of 2Gt DWT, 800M of which was made out of dry bulk carriers (UNCTAD 2018). The addition of one

hundred *Malagamax*⁶ carriers of 300,000 DWT would represent a 4 percent increase in dry bulk carrier capacity. Given that this shipping segment grew by 3 percent between 2017 and 2018, this would seem like a trivial addition, particularly when considering a slow ramp-up of OAE application over several decades.

Where should OAE be applied? Theoretical models of OAE global effectiveness to maximize CO₂ removal or acidity neutralization assume that alkalinity would be evenly distributed across the surface layer of the world's oceans, though it is unclear how that could actually be achieved. One study (Lenton et al. 2018) has shown that global CO₂ and acidity removal is relatively insensitive to geographic location of surface ocean alkalinity addition as long as enough alkalinity is added to some portion of the surface ocean. Possibly ideal locations for OAE are upwelling areas with high pCO₂, high acidity and high average wind speeds. Strategically placed in such locations, OAE would consume excess seawater CO₂ prior to degassing to air and where horizontal transport could allow long residence time in the surface ocean's mixed-layer (to prevent loss of contact with air), and allow dispersal of alkalinity (and its benefits) away from the point of input. On the other hand, to counter the local effects of acidification on say a coral reef, upstream addition of alkalinity would have to be based on the direction, intensity and seasonality of currents bathing the reef.

⁵The assumption is that 19 such wedges would be required to reach net-zero emissions globally.

⁶A 300,000 DWT carrier; the name refers to the largest vessel that can pass through the Straits of Malacca.

III. BIODIVERSITY AND ECOSYSTEM INTEGRITY

Effect of alkalization on ocean biogeochemistry

Effects of ocean alkalization on ocean biogeochemistry and marine ecosystems have mainly been explored through theoretical and modeling exercises and much less so in laboratory or in-situ experiments. A growing body of literature addresses the potential for trace substances of alkaline material to interact with biota close to the point of alkalinity addition and whether unintended biogeochemical effects of OAE might adversely affect marine biota. Examples include the following:⁷

- It has been hypothesized that calcifiers would benefit from addition of CaCO_3 derivatives, especially given the existing, widespread application to saltwater aquaria to benefit corals and shellfish within. On the other hand, the use of silicates and concomitant release of mineral dissolution products including alkalinity, Si, Fe, and Ni could benefit silicifiers (diatoms) and N_2 -fixers (cyanobacteria) and increase ocean productivity (Bach et al. 2019). For example, in certain areas where silica is the limiting nutrient for diatoms, Köhler et al. (2013) predicted that a shift in phytoplankton species composition towards diatoms will occur if silica-rich olivine is used as an alkaline agent.
- The addition of impure alkaline substances can release heavy metals (e.g., cadmium, nickel, chromium from silicate minerals) which, if in high enough concentrations, could impact ocean biogeochemical cycling and marine ecosystem services (Hartmann et al. 2013; Hauck et al. 2016). For example, Montserrat et al. (2017) discuss the potential effect of olivine addition on nickel concentration and its detrimental effect on the physiology of marine organisms, although they observe that ecotoxicology of nickel is mainly found in freshwater organisms.
- Hauck et al. (2016) estimated that the relative contributions to total CO_2 uptake by olivine dissolution are 57% alkalinity, 37% iron, and 6% silicic acid. Given the contentious nature of iron fertilization (Strong et al. 2009), the

elevated iron content in olivine could produce undesirable effects, despite its potentially net-positive effects on downward carbon transport. However, such effects could seemingly be avoided by adding olivine only to iron-replete regions (i.e., most of the ocean, especially coastal regions).

- Cripps et al. (2013) found that the addition of lime leads to an altered acid-base balance in relatively robust crustaceans, such as the European green crab. Yet such effects could be beneficial in countering the alteration of such balance effected by ocean acidification.
- González and Ilyina (2016) use the Max Planck Institute Earth system model to suggest that modern ocean pH and carbonate saturation state values are strongly exceeded in several regions under alkalinity enhancement simulations designed to counter a very high CO_2 emission scenario. They also find pronounced differences in regional sensitivities to OAE, with the Arctic Ocean and tropical oceans emerging as hot spots for biogeochemical changes.

The target effect of ocean alkalinity enhancement has been poorly studied to date. In their recent review of OAE implications for marine ecosystems, Bach et al. (2019) note that “perhaps the most fundamental outcome of more than two decades of ocean acidification research is that carbonate chemistry perturbations affect calcifying organisms disproportionately. Thus, it is meaningful to pay special attention to calcification when considering impacts of increased alkalinity on marine organisms and ecosystems.” However, the target effect of ocean alkalization on calcifying organisms has been tested only in a small handful of studies. Specifically, alkaline treatments on mollusks (Cripps et al. 2013; Waldbusser et al. 2015), corals (Comeau et al. 2012; Albright et al. 2016), and one species of calcifying algae (Gore et al. 2018) have generally resulted in increased calcification rates in response to alkalinity-induced elevation of calcite and aragonite saturation states. Other known benefits include the decrease in seawater pCO_2 and thus potential increases in the ocean uptake of atmospheric CO_2 . Heavy metals, silica, and other compounds that might serve as bio stimulants or inhibitors can be found in naturally occurring alkaline rocks and can be expected to leach into seawater as the alkalinity generated

⁷ For the most recent and complete overview of potential OAE impacts on ocean ecosystems, see Bach et al. (2019).

from them increases. Mining, processing, and distributing to the ocean alkaline materials such as olivine and limestone may therefore result in increased concentration of impactful elements/chemicals in the water column.

Only a subset of alkaline materials has been tested in coastal areas or laboratories for their impact on biota. The majority of studies that have addressed the impact of adding alkaline materials on marine organisms have used a treatment of calcium bases or sodium hydroxide (D’Olivo and McCulloch 2017; Lenton et al. 2018; Albright et al. 2016; Cripps et al. 2013). Treatments of sodium hydroxide have been tested in situ in the ocean, while other alkaline substances have not been studied at that scale. Only the chemical (dissolved CO₂ and carbonate precipitation) impacts of adding olivine to seawater have been studied, and then only at laboratory scale (Montserrat et al. 2017). In situ ocean research on OAE has thus far been limited to a single, small, coral reef study (Albright et al. 2016). The impact of alkalization on non-calcifying organisms remains an important unknown. There is not yet enough information about what additional environmental impacts or benefits alkalization would have (Feng et al. 2016). Further research is needed to address the preceding before large scale deployment can be contemplated.

Effects on Corals / Coral Reefs

Calcifying corals seem to benefit from the addition of alkaline materials, but effects are hyper-local and variability in species’ response is understudied. The primary mechanism through which alkalization is assumed to benefit corals is the increased saturation states of calcite and aragonite in the local marine environment (Feng et al. 2016; Albright et al. 2016; D’Olivo and McCulloch 2017). Increased coral calcification rates are roughly proportional to the degree of alkalization, but considerable variation in response exists across species (McCulloch et al. 2012). Albright et al. (2016) conducted an alkalization experiment in a natural setting and found that “only corals directly within the alkaline plume” displayed increased calcification/growth. These finding suggests that alkalization must create a large enough plume to cover an entire coral community to provide benefits to the entire ecosystem at the local level. The variability in responses of different species to ocean alkalization remains understudied. Comeau et al. (2013) found that variation in species

calcification rate response to carbonate saturation state raises the possibility that alkalization might disproportionately benefit a few organisms, thereby resulting in shifting species dominance in coral reefs. On the other hand, OAE might restore coral community structure changes that have presumably occurred due to the ongoing loss of carbonate saturation state (acidification).

Additional stressors impact the viability of coral reefs, and alkalization alone may not be sufficient to influence their viability. Coral reefs are subject to multiple stressors, primarily temperature changes, overfishing, nutrient and debris pollution. In particular, sea surface warming resulting from climate change is likely to be a more important stressor for coral reefs than acidification in the short and medium term (Feng et al. 2016; D’Olivo and McCulloch 2017). Therefore, whether alkalinity enhancement provides additionality or ultimately changes ecosystem survival outcomes remains unknown, but it seems clear that ocean alkalization would have to be coupled with stronger emissions reductions policies and possibly other restorative technologies in order to preserve enough of the ocean for healthy coral growth (Lenton et al. 2018).

Effects on Phytoplankton

The impacts of alkalization on marine plant life remain understudied but insights of ocean acidification studies can be cautiously applied to speculate on OAE impacts. Ocean acidification is expected to alter plankton community structure and biogeochemistry in the future ocean (Dutkiewicz et al. 2015). This, in turn, could change the composition of sinking organic matter and the efficiency of the biological carbon pump (Basu and Mackey 2018). However, the majority of research has been lab-based and studies on the response of entire plankton communities to ocean acidification are still relatively rare and it is presently unclear how acidification could affect the functioning of entire ecosystems and biogeochemical element cycles. In the absence of dedicated studies addressing the effect of alkalinity enhancement on physiological, neurological, and ecological attributes, it can be cautiously hypothesized that alkalinity enhancement mitigates the ecological imbalance and biological effects of ocean acidification. Recent insights include the following:

- Calcifying phytoplankton such as the coccolithophore *Emiliana huxleyi* quickly react

to increased $p\text{CO}_2$ levels (increased acidity). Examples include slowing down growth rates (Iglesias-Rodriguez et al. 2008) and changes in carbonate plate - malformation (Jones et al. 2013) and increase in volume (Iglesias-Rodriguez et al. 2017). There are however large discrepancies between and even within species suggesting diverse adaptations within the group (Iglesias-Rodriguez et al. 2008; Langer et al. 2006; 2009). The effect of OAE in coccolithophores remains an open question.

- Increasing dissolved $p\text{CO}_2$ and decreasing seawater pH affect photosynthetic marine organisms in very different ways. For example, Gao et al. (2019) report that $p\text{CO}_2$ limits growth of calcifying algae and enhances growth for diatoms and nitrogen fixers (diazotrophs), while interactions with other environmental variables, such as trace metal, may neutralize or even reverse these effects. This means that increased acidification will have an impact on algal diversity, a suggestion that can also be observed in naturally occurring pH gradients (Ziveri et al. 2014).
- The bioavailability of important trace metals is likely impacted by changes in ocean chemistry. An example is Iron (Fe), a biologically important element whose chemistry is most sensitive to pH. As oceanwaters acidify, decreasing the hydroxide ion concentration, Fe's speciation and solubility will be altered. Shi et al. (2010), for example, suggest that bioavailability of dissolved Fe is decreased through ocean acidification.
- Food-web effects are complex and difficult to predict but biomass and size structure of copepods (zooplanktonic organisms) for example have seen to be negatively affected (Cripps et al. 2014; Taucher et al. 2017)
- Many factors in addition to acidification influence algal composition, growth rates, and productivity. Stress factors (such as pollution, UV, sea surface temperature) and limiting factors (such as nitrate, phosphate, and iron) play crucial roles and synergies must be better understood to judge the isolated effect of ocean acidification (Iglesias-Rodriguez et al. 2016; Oviedo et al. 2014; Feng et al. 2016; Gattuso et al. 2015; Halpern et al. 2019).

- Note: Most non-calcifying macro-algae actually benefit from ocean acidification. Potentially they would do less well under more alkaline conditions (Koch et al. 2013). However, this detrimental effect has not been studied experimentally.

Ocean alkalinity enhancement is more than just the reversal of ocean acidification. OAE is, in all likelihood, a point-source technology that, unless added in pure form, comes with additional elements and compounds. Thus, three effects of ocean alkalization on phytoplankton can be expected: first, increased calcification rates of calcifying algae; second, potentially increased or decreased algal productivity when/if elements/compounds being added are rate-limiting to growth or where their concentrations inhibit growth; third, some potential reactions to the rate of alkalinity-induced changes in seawater $p\text{CO}_2$ /pH. One of the few studies focused on the effect of alkalinity enhancement is Gore et al. (2018). The authors explore the effect of one calcifying algae (*Corallina spp.*) species to elevated pH levels and find that calcification rates increase by 60%.

Effects on Marine Bivalves

Like corals, mollusks studied exhibited increased calcification rates under alkalization. As calcifying organisms, mollusks stand to benefit from ocean alkalization in similar ways to corals. A solid body of literature suggests that ocean acidification is impacting the growth, survival rates, and biomass across bivalve species and across geographies (Waldbusser et al. 2013; Waldbusser et al. 2015; Ekstrom et al. 2015; Green et al. 2009; Barton et al. 2012). Vulnerability of shellfish to rising atmospheric CO_2 levels varies regionally and across life stages. For example, the vulnerability of bivalves to acidification is highest during larval states and increases in estuarine systems and enclosed bays due to the multiple sources of pollution, acidification, and other anthropogenic stressors that decrease the organism's natural resilience to single stressors (Waldbusser et al. 2011; Ekstrom et al. 2015).

Alkalinity enhancement in early life stages is a tested remedy to increase survival rates in certain bivalves. Waldbusser et al. (2015) provide experimental evidence that bivalve larvae are most affected by carbonate saturation state (rather than pH or $p\text{CO}_2$), respiration rate was affected in

very low pH levels (<7.4) and initiation of feeding was most sensitive to $p\text{CO}_2$; similar findings are presented by Thomsen et al. (2015). The high impact of carbonate saturation levels is confirmed by Green et al. (2013), who provide evidence that carbonate saturation state is a significant chemical recruitment cue for settling bivalves in both direct observation laboratory studies and field manipulations. They showed that in the field, bivalve recruitment can be increased by a factor of three in a 30-day field study by raising the pH (~0.3). Commercial shellfish farmers have started to respond to failing recruitment by periodically adding alkaline calcium hydroxide to bivalve longlines (Comeau et al. 2017) or adding sodium carbonate to oyster hatchery water to increase pH and carbonate saturation state and enhance bivalve health (Barton et al. 2015).

Open Questions

Does ocean alkalinity enhancement really mitigate current risks to calcifying organisms and their ecosystems? Ocean pH effects on calcification, photosynthesis, and neurophysiological functions differ between taxa and life stages, and such differential responses can lead to important ecological shifts in populations and communities. Iglesias-Rodriguez et al. (2016) suggest that two of the main challenges in predicting the ecological effects of ocean acidification are (1) integration across these levels of organization, from seawater chemistry to multi-species interactions, and (2) assessing the synergistic effect with other climate stressors that operate in parallel. As Feng et al. (2016) and D’Olivo and McCulloch (2017) write, warming is likely to have a larger influence on the survivability of corals in the short to medium term than seawater acidity. In addition, other threats including overfishing, nutrient pollution, and debris pollution threaten coral reefs (Gattuso et al. 2015). Hoegh-Guldberg and Bruno (2010) suggest warming alone poses extinction risk to corals. As such, an open question remains what role OAE can play in mitigating the cumulative human impact on marine ecosystems and whether, if applied locally and in a controlled fashion, the effort and cost are justified by the benefits to ecosystems.

Research has focused on specific species rather than ecosystem effects of alkalization. An incomplete understanding of the effects of ocean alkalization on marine biota has been specifically called out as a risk by researchers considering the potential and viability of ocean alkalization

proposals (González and Ilyina 2016; Iglesias-Rodriguez et al. 2016). Another understudied side effect of ocean alkalization is how heavy metals that are naturally occurring in both natural and human produced alkaline substances might impact marine organisms, biogeochemical cycling, and ecosystem services when leaked into the water along with alkaline material treatment (Hartmann et al. 2013; Hauck et al. 2016). Studies conducted so far have used pure alkaline substances, not impure materials that might be used if ocean alkalization was undertaken at a large scale, so these impacts of ancillary pollutants on marine life remain a large risk and unknown for ocean alkalization.

Cessation impacts are poorly understood and represent a potential threat. It could be posited that more gradual changes in pH provide a better opportunity for organisms to modify their acid-base regulation and adapt to a changing environment. In the case that alkalinity enhancement is undertaken and then halted, the change in pH thereafter may be larger and occur over a shorter time scale than if no alkalinity enhancement was undertaken (González et al. 2018). Coastal ecosystems are perhaps the most appropriate for testing alterations in pH because they are subjected to greater pH fluctuations than the open ocean and because they contain the greatest density of ecologically and commercially valuable calcifying species—corals and shellfish. However, how organisms would react to that change remains unknown, and the comparison to organisms’ reactions/ability to adapt in the counterfactual where no alkalization is undertaken, and pH continues to fall more gradually as CO_2 emissions continue to accumulate, is important to consider. Marine organisms, especially those with short life cycles and fast reproduction, may already have some adaptations to conditions of higher acidity—how those react to subsequent exposure to alkaline conditions remains an open question for continued study.

What are the impacts of alkalization on calcifying and non-calcifying organisms in the ocean? Lack of scientific knowledge on environmental side effects of ocean alkalization remains a knowledge gap that should be explored (Feng et al. 2016) with “higher resolution models and field experiments,” where appropriate, to provide a better understanding of risks. Much more research is required to inform OAE deployment decision-making in this regard.

What is the effect of non-calcium based alkaline

substances on calcification and how might impurities in naturally occurring alkaline substances impact marine ecosystems? Studies so far have used pure sodium hydroxide (Albright et al. 2016), sodium carbonate (Gore et al. 2018) or calcium hydroxide (Cripps et al. 2013; Comeau et al. 2017). An open question remains whether other forms of alkalinity have the same net positive impact on calcifying organisms. An alkaline substance obtained through intensive mining or as the by-product of industrial processes may be more likely to contain impurities, some of which may cause negative impacts on marine life. What effect would those impurities/trace elements have if added to marine environments as part of ocean alkalization efforts?

Ocean alkalization will result in increased supersaturation levels of CaCO_3 , resulting in greater carbon storage, but what might the ecosystem impacts be? The surface ocean is supersaturated in calcium carbonate by a factor of 3-5 above the point where carbonate precipitation (and subsequent loss of CO_2 and alkalinity) should spontaneously occur. Research has shown that the threshold for spontaneous precipitation is at least 3 times higher than present seawater saturation state. This means that seawater could stably store much more carbon in alkaline form than it currently does. However, this needs to be confirmed through further laboratory assessment both in the presence of carbonate seed crystals and without, and at a range of temperatures.

IV. GOVERNANCE CONSIDERATIONS

“Governance” is a broad term that here includes: i) parameters for and oversight of scientific research at universities as well as in private and public sector enterprises; ii) legislative, legal and regulatory dimensions of testing and deploying OAE technologies; iii) market developments associated with OAE development and deployment; and iv) public understanding and attitudes, including various forms of civic engagement, that shape opportunities and constraints to explore OAE options and make decisions about its deployment as an experimental pilot or a solution at scale. In this chapter we provide a broad overview of the systems that are currently in place to govern scientific research and experimental deployment of ocean CDR in general, and OAE specifically.

Governance of scientific research

Epistemic-based Governance

Traditional scientific institutions have driven much of the research agenda around SRM and CDR concepts. In the past decade, multiple synthesis reports have emerged that attempted to make a vast and emerging, highly technical field of (ocean) CDR and SRM more accessible to both researchers and policy makers. The most prominent groups that currently facilitate such efforts include the National Academies of Sciences, Engineering, and Medicine (NASEM); The Royal Society; as well as EU-based groups including GEOMAR’s CDR-MIP project. These much-cited and multi-disciplinary efforts, however, remain decadal publications whose focus and content are limited in scope. For the most part, these reports do not have a ready-made audience of interested stakeholders nor are designed and produced to inform or be of relevance to any particular decision-makers. Efforts are now beginning that seek to understand how the relatively insulated research community may or should relate to policy processes and other mechanisms that govern scientific research and that may use the results of this research in policy settings.

A growing community of academic and NGO actors sharing interests in bridging between research and decision-making may support deliberative mechanisms that spring up in international organizations, but this community is nascent and needs more thorough and consistent coordination. Increasingly, a group of universities and NGOs are emerging with in-depth understanding of marine CDR proposals and the necessary capacity to assess and communicate the potentials and negatives of CDR approaches (including OAE). Academic institutions with the specific focus of building governance systems in the U.S. include the Consortium for Climate Governance (C2G), the Institute for Carbon

Removal Law & Policy at American University, and the Climate Engineering Governance Initiative at ASU, among others.

While the core academic research community and specialized NGO community is well-networked, a fuller and more inclusive collaboration is needed to productively guide an “ocean CDR” conversation in ways that encompass technical, economic, legal, policy, and social dimensions. The *New Carbon Economy Consortium* (NCEC) is a good example of an historical collaboration with these goals. NCEC was a multi-sectoral alliance spearheaded by Arizona State University and Carbon 180, involving top research universities, national labs, non-governmental organizations, and commercial partners that conducted an overarching assessment of all carbon removal technologies for technical feasibility and commercial viability, and took an early look at the challenges of governance in this emerging space.

International Organization-based Governance

International bodies are slowly emerging to coordinate Ocean CDR research, interpret findings and make recommendations. In recent years, the UN system has given rise to working groups with the general potential to provide a governance system of (ocean) CDR research:

- **GESAMP Working Group (WG) 41:** GESAMP is a group of independent scientific experts that provides advice to the UN system on scientific aspects of marine environmental protection; WG 41 focuses on marine geoengineering approaches, including both SRM and CDR proposals. The group’s focus is the assessment of each proposal’s potential to decrease effects of climate change and the risks that are inherent to each proposal. GESAMP takes a precautionary approach that follows academic standards of peer-reviewed scientific research. In a recent report (Boyd and Vivian 2019), the WG 41 has synthesized existing knowledge

on eight specific marine geoengineering proposals, including OAE, with the ultimate aim of providing recommendations to states party to the London Protocol on which proposals might be candidates to be listed in annex 4, and therefore governed by the geoengineering provisions of the London protocol.

- **The IPCC Working Group III** focuses on climate change mitigation, assessing methods for reducing greenhouse gas emissions, and removing greenhouse gases from the atmosphere. As part of this mandate, CDR approaches have come into the group's focus.

U.S. National Government-based Governance

Current and past bodies of the U.S. Government might prove useful as models for how to systematically advance understanding of risks and benefits of OAE proposals.

- **The Office of Technology Assessment:** Between 1972 and 1995, the United States Congress Office of Technology Assessment (OTA) synthesized knowledge on existing technologies of interest to congressmembers and the issues they aimed to address. OTA provided research, counsel, and recommendations about legislative options that Congress could act upon to deal with emerging issues having significant scientific or technological components. These issues covered a wide range, including security, defense, environment, health, food, medicine, information technology, international sustainable development, and other topics. OTA frequently offered information and guidance to policymakers on emerging technologies and emerging challenges, such as climate change. Requests to OTA were vetted by a bipartisan Congressional committee to ensure broad interest and shared commitment. OTA reports became public resources used and cited by all sectors and generally regarded as the bottom line on whatever topic was under investigation. OTA was de-funded but not de-authorized as a result of partisan disagreements about its importance and relevance. Currently, an active conversation is occurring in Congress to restore OTA under its original authorization, updating some features and perhaps renaming the body to create independence from the original agency.
- **The Office of Science and Technology Policy**

(OSTP), an agency within the Executive Office of the President ("the White House"), is currently tasked with providing "the President and others within the Executive Office of the President with advice on the scientific, engineering, and technological aspects of the economy, national security, homeland security, health, foreign relations, the environment, and the technological recovery and use of resources, among other topics." OSTP is sometimes regarded as the Executive Branch analog to the Legislative Branch's OTA, but they are not the same. OSTP tends to focus more on coordinating working groups and research activities across federal agencies, relying on a mix of permanent, detailed, and appointed staff to carry out its activities. Its focus is typically tied to a current administration's policy priorities. OSTP published a decadal report on ocean science and technology priorities from 2019-2030 (OSTP 2018), but omitted CDR and SRM proposals within its report. OSTP's mandate would fit with developing scientific understanding and consensus about OAE, however its focus depends on executive guidance from the President and other high-level advisors. Despite being staffed by professionals with scientific backgrounds, OSTP is not generally regarded as being an independent voice. The current U.S. Administration explicitly rejects climate-related research as legitimate, and it is unlikely that OSTP would take on OAE as a topic.

- **The Climate Program Office** in the National Oceanic and Atmospheric Administration (NOAA) and NOAA's Ocean Acidification Program may be natural candidates to consider for either leading research activities or possibly providing funding for universities to undertake specific research. However, federal agencies have decreased funding of climate change-related research in the current administration and NOAA might not be an exception.
- **ARPA-E or the Navy** might also be natural partners for ocean CDR research and pilots, particularly with respect to hyper-technological aspects of CDR proposals that have energy-using/generating potential, such as the Navy's seawater-to-fuels program (Willauer et al. 2014) and electrogeochemical OAE (Rau et al. 2018).

Governance of experimental deployment

Governance implications or considerations vary widely depending on the scale of proposed ocean alkalinity enhancement experiments or eventual deployment. National, provincial, or municipal level regulatory frameworks and participatory bodies (e.g., local councils, other forums for local level discussions) may prove sufficient for micro, local, and regional scale experimentation with OAE. The considerations and implications of larger-scale experiments, and deployment (if further research indicates it should be done) differ. Governing those larger scale experimentations, communication of the science around marine geoengineering efforts, and enabling social licensing for such large-scale initiatives may require not only new legal frameworks, but also new institutions. Furthermore, the four different OAE proposals discussed above might have very different legislative implications, depending on their “polluting” potential (i.e., the chemical composition of alkaline materials that are ultimately added to seawater). C2G’s recent policy brief on ocean CDR governance suggests that “marine CDR could occur within recognized exclusive economic zones, territorial seas, or the global commons. Each raises different sets of governance issues” (C2G 2019). C2G then lists 10 relevant fora, processes, and communities which do or could contribute to this, including the Convention on Biological Diversity (CBD), the London Protocol, UN Convention on the Law of the Sea (UNCLOS), and the UN Framework Convention on Climate Change (UNFCCC).

It must be considered that experimental deployments may occur in novel ways that lie outside of what might be traditional research. This is made more likely by the fact that OAE is a very specific approach that has not yet matured enough to fall under a unique legislative or regulatory framework, and that means OAE research could take place in laboratory and open sea trials under entirely other names. Efforts aiming to protect or restore ecological systems from the impacts of ocean acidification and thermal stresses linked to climate change can entail strategies that fall under the definition of OAE or SRM. The Great Barrier Reef, for example, is under enormous threat from heating oceans and acidification of seawater, and restoration efforts include a floating “sun shield,” marine cloud brightening, and water mixing deployed locally (McDonald 2019). As ocean-based ecological crises come to light,

more examples of experimental OAE deployments that are governed under ecosystem protection or restoration mandates (rather than SRM per se) should be expected. This raises a critical governance challenge that may not have been apparent when only considering the roll-out of scientific research. Choices made on a case by case basis under a variety of governance regimes could occur, resulting in cumulative effects that may be hard to discern. A larger, integrated, anticipatory governance structure may be required to avoid a sort of slippery slope that leads to unintended consequences.

Global Governance Regimes

A decade of unregulated ocean fertilization trials gave rise to the London Convention and its associated London Protocol. In response to concerns about ocean iron fertilization field experiments during the last decade, the parties to the 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) passed a resolution in 2008. The resolution noted that the scope of the Convention and associated Protocol encompassed regulation of such activities. The Resolution called upon the Parties to 1) assess scientific research proposals under their respective jurisdictions in the context of ocean fertilization on a case by case basis; 2) establish an assessment framework to evaluate such proposals, and 3) restrict ocean fertilization to “legitimate scientific research.” The Parties also agreed to review the resolution at appropriate intervals in light of new and relevant scientific information and knowledge” (London Convention 2008). In 2010, the Parties passed a resolution establishing a detailed assessment framework for ocean fertilization research. The resolution also called for consultation and notification of potentially affected parties and reporting to all parties (London Convention 2010).

New amendments regulate ocean CDR beyond iron fertilization. In 2013, an amendment to the London Protocol was passed, which would legally bind its Parties to utilize an assessment framework for “marine geoengineering” including iron fertilization and other “deliberate interventions in the marine environment to manipulate natural processes” (London Protocol 2013). The parties are to only issue permits for such activities if an assessment establishes that marine pollution is prevented or reduced to a minimum, and its outcome is not contrary to the aims of the

Protocol (London Protocol 2013). However, the amendment requires acceptance by two-thirds of the parties to the Protocol (which currently has 51 parties) to come into force, yet has only been adopted three parties to date, meaning that it may be a protracted period before the amendment becomes operational (Harrison 2017). Moreover, adding OAE to the amendment's annex 4 of regulated marine geoengineering activities would require acceptance by two thirds of the parties to the Protocol, which could also be a protracted process (Dixon et al. 2014). If OAE were to be added to annex 4, existing provisions of the London Protocol regarding the distinction between legitimate scientific experimentation vs. deployment, assessment of risk, consultation of experts, and mediation of transboundary conflicts/ impacts would apply.

The Convention on Biological Diversity has also passed a series of resolutions related to marine geoengineering. In a 2009 resolution focused on ocean fertilization, the parties called for a precautionary approach to such activities, requiring “an adequate scientific basis on which to justify such activities, and a global regulatory framework for activities other than “small scale scientific research,” subject to rigorous scientific assessment (Convention on Biological Diversity 2008). As the case with the London Convention/ Protocol, resolutions passed by the parties to the CBD are not legally binding on the parties.

Several provisions of the United Nations Law of the Sea Convention (UNCLOS) would also be pertinent to OAE research and/or deployment. While Articles 238 and 239 emphasize the right to conduct marine research, and seek to foster it, it is subject to regulation by coastal states in their respective territorial seas, continental shelf and exclusive economic zone under Articles 245 and 246. Moreover, Article 194 requires the parties to take measures to prevent, reduce and control marine pollution in all areas of the world's oceans. Moreover, the draft text of the agreement to protect biodiversity beyond national jurisdiction, (BBNJ, (UNCLOS 2019)) currently being developed by the parties to UNCLOS, contains several provisions that might be pertinent to OAE, including restrictions of activities in contemplated marine protected areas on the high seas (Section 4.4), and a mandate for environmental assessment by States of “planned activities under their jurisdiction or control in areas beyond national jurisdiction” (Sec. 5.1).

Linkages between potential ecosystem risks of OAE and its contribution to other international law commitments should be considered for its governance. Beyond the London Protocol/London Convention framework which primarily establishes a process to mitigate the risks associated with geoengineering experiments, clarity is needed as to how OAE might fit into legally binding requirements of other instruments. For example, whether and how OAE efforts are accounted for within national carbon budgets/NDCs and in the carbon market is unaddressed (Mace et al. 2018). This omission makes a strong argument for governance of OAE and marine geoengineering CDR proposals more broadly under the Paris Agreement framework, including under its Rulebook developed in 2018. The language of the Paris Agreement would clearly appear to permit its parties to formulate governance mechanisms for OAE. Under Article 4, the Parties are to maintain Nationally Determined Contributions, which require the development of “mitigation measures.” The Paris Agreement's parent agreement, the UNFCCC, defines “mitigation” to include enhancement of sinks (UNFCCC 1992), which would clearly encompass OAE approaches. This would permit development of specific accounting and monitoring rules under the Paris Agreement in this context. Moreover, the Paris Agreement's Preamble calls upon its parties to take into account the impact of response measures on the furtherance of principles of human rights, sustainable development, and protection of the environment. Developing a unified framework for governance of OAE and avoiding polycentric regulation for OAE experiments within existing international law contexts is a critical challenge for allowing the development of OAE technology and experimentation to fill crucial knowledge gaps.

Domestic Governance Regimes

Domestic legal frameworks in the United States and other nations where mining or deployment might occur provide insufficient guidance for the development of knowledge surrounding OAE, technological development, transparency, and risk mitigation. We found no US federal or state guiding policy frameworks for proposals for CDR in general, or OAE specifically, and the current policy landscape appears unlikely to yield new policy or governing bodies to address OAE risks, governance of science, governance of technology, and social licensing (i.e., social acceptance of or support for the activities). Domestic policy and related regulatory frameworks that affect OAE but are not

specifically about OAE pertain to legal compliance with various environmental, public health, waste, and other laws that apply to all relevant activities. (These issues also pertain to technology assessment, but in a different way.) These legal dimensions, and how the intersection of technology assessment and legal developments may co-evolve in this space, have not been explored to any significant extent but merits serious investigation.

Public attitudes and social licensing

OAE research and deployment should be accompanied by deliberate public outreach to empower stakeholders with information. There is plenty of evidence that the term “geoengineering” provokes fear and anger in the public domain (Hulme 2012; Burns and Flegal 2015; Buck 2016; Bellamy and Lezaun 2017) and ocean CDR is no exception: oceans remain a sacred environment that should not be tinkered with and it is the public’s perception and outcry that have ultimately halted a decade’s worth of iron fertilization trials. Social licensing might therefore be the biggest obstacle for ocean alkalinity enhancement as it moves from theory to experiment to scale and it will be crucial to accompany scientific research with well-designed and deliberate public outreach. Multiple scales and types of stakeholders are likely to weigh in as the OAE conversation grows more public and as uncertainties become more widely appreciated, requiring both scientific and political framing (Scheufele and Tewksbury 2007; Graffy 2008). Governance systems should anticipate public engagement as a design feature rather than a barrier; well-designed public engagement can gather information that could otherwise be lost, builds trust in institutions, may result in more public support, and can improve substantive outcomes as well as demonstrate public accountability (Bice and Moffat 2014; Eberhard Falck et al. 2015). Ensuring transparency about known benefits, costs, and risks, and about viable strategies for anticipating and responding to results of marine experiments may be critical. Attention to the distribution or magnitude of benefits and risks of any OAE activities, adhering to standards of fairness or justice, and engaging in meaningful examination of options for solving the larger societal problems, of which OAE may be one of multiple strategies, are key guiding principles for conceptualizing the social licensing dimensions of ocean alkalization research, field study and potential deployment.

V. PHILANTHROPIC ROLE IN ADVANCING THE FIELD OF OAE

A key focus of the convening was to identify actionable recommendations for philanthropy to further the field of ocean alkalinity enhancement. Following four sessions of presentations and discussions, philanthropic investment opportunities were identified and prioritized in a 2-step facilitated session.

1. As a first step, a vision was articulated as an overarching goal for the field of ocean alkalinity enhancement:

“By 2030, a transparent and facts-based process has led to the common notion that i) OAE is an effective, low-cost, and low-risk approach to reduce ocean acidification and/or reduce atmospheric CO₂, or ii) OAE is an ineffective, costly, and/or high-risk approach to reduce ocean acidification/reduce atmospheric CO₂ and should not be further considered.”

2. As a second step, participants were asked to brainstorm specific activities that would allow us to move from our current situation to the vision as outlined above.
3. As a third step, suggestions were shared, clustered, and refined to produce five categories of activities that were deemed important for the vision to be reached. These included i) scientific research, ii) public funding, iii) technological development, iv) public outreach, and v) public education.
4. As a fourth step, working groups discussed the relative importance of each activity presented within the topical categories and mapped priority ideas to a matrix of estimated costs and philanthropic fit (Table 2).

Table 2: : Priority areas of engagement for philanthropy – Ocean Alkalinity Enhancement

	Fit for philanthropy		
	Low Fit	Medium Fit	High Fit
\$>20 Million	Large-scale demonstration pilots to validate effectiveness at scale	Technology development to lower cost to < \$50 per net ton removed	
\$5-20 Million		Medium-scale experiments including offshore mesocosms	Public Education Assess market incentives and pathways of OAE Assess policy Levers that enable OAE at scale
\$0-5 Million		NAS Study on OAE Establish international network of experts to exchange and coordinate research/technology Promote ocean CDR research outside of U.S. (UK, Japan, EU)	Improve understanding of OAE’s ecological impact (through lab/mesocosm and modeling) Build community of practitioners including universities, NGOs, and public institutions Improved techno-economic analysis Public outreach and engagement to ensure social licensing and public funding

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APPENDICES

Appendix A: Threats of Climate Change to Marine Ecosystems

Figure App 1 (Halpern et al. 2019); a) Annual change in all 14 impacts comprising the cumulative impacts for each ecosystem, with outer bars above zero indicating increasing impacts and inner bars below zero indicate decreasing impacts. (slr=sea level rise; oa=ocean acidification; sst=sea surface temperature). b) Cumulative impact of each threat to ecosystem type (for 2013).

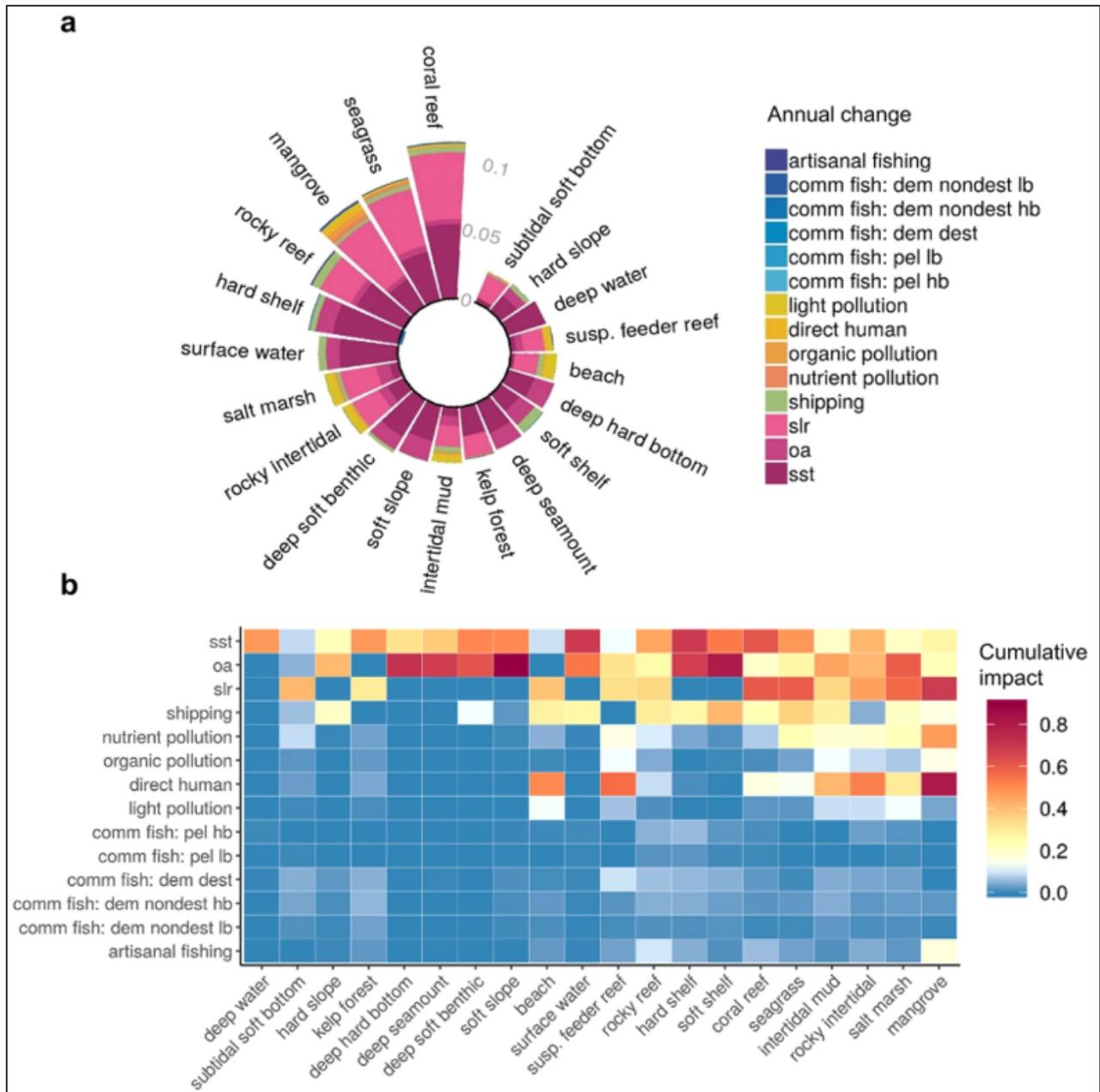


Table App 1: Expected effects of climate change on marine ecosystems

Threat category	Biodiversity	Productivity	Ecosystem integrity
<p><i>Warming: 2018 set a new record of ocean heating, surpassing 2017 as the warmest year on record for ocean heat content. The past five years (2014 – 2018) have ranked as the five warmest years for ocean heat content, confirming a trend that ocean warming has been accelerating since the 1990s. New research suggests that the rate of ocean warming is faster than previously predicted. A series of analyses indicate that the ocean is absorbing excess heat 40 percent faster than the IPCC estimated in its Fifth Assessment Report in 2013. The average global sea surface temperature—the temperature from the upper few meters of the ocean—has risen about 0.12 degrees Celsius per decade over the past 50 years, with a higher rate of warming in recent years.</i></p>	<p>Shifting stocks: As waters warm due to climate change, fish and other marine species are migrating into new territory, usually poleward, at a rate averaging 70 km (43 mi) per decade. For example, in the U.S. Atlantic, three commercially important species—American lobster, red hake, and black seabass—moved northward by an average of 190 km (119 mi) between 1982 and 2015. These shifts are expected to continue or accelerate in the future. The tropics are hotspots of ocean warming-driven local extinctions, while higher latitudes will likely see gains.</p> <p>Coral biodiversity: Polyps in corals suffer from heat waves, leading to coral bleaching. The combination of climate change and local stressors is now driving unprecedented rates of coral reef decline. Coral reefs have declined by ~50% in the past 30 years, with projections that 70-90% will disappear by 2050 at the current rate of warming. Changes in carbonate chemistry and warming of tropical waters may hamper or prevent coral reef growth within decades, with erosion outpacing reef building sometime this century.</p>	<p>Reduced fisheries productivity: IPCC estimates a decline in global wild catch of around 3 million tons per year (4%) in a 2 degree scenario. Productivity is shifting, with reductions and potential for local extinctions in the tropics and high latitudes, with a reduction in catches of up to 30% expected in some regions by 2050 (e.g., SE Asia). Some upwelling areas may have lower productivity, or low oxygen events.</p> <p>Shifting stocks and management challenges: Shifting stocks creates a challenge for fisheries governance given that current fisheries management lacks “future-proofing” policies to account for fluctuating or changing distributions of marine species. One study projected that new transboundary stocks will be present in roughly 30% of global EEZs by 2100. Stocks that straddle national boundaries may experience a scenario of “double jeopardy,” facing unsustainable competitive harvesting from multiple countries.</p>	<p>Kelp ecosystem impacts: Globally, many kelp ecosystems (Northern CA, Tasmania) appear to be suffering from changes that appear to be linked to increasing temperatures (e.g., loss of urchin predators and proliferation of barrens). Regional variation exists; some kelp habitats are expanding while others contract.</p> <p>Polar ecosystem impacts: Warming air and ocean temperatures are continuing to accelerate change across the polar regions. A recent study found that the Arctic surface temperatures have been warming at twice the rate of the rest of the planet for the past 50 years. The Arctic has been warmer over the last five years than at any other time since records began in 1900. This warming has led to dramatic reductions in sea ice thickness and extent, as well as accelerated melting of glaciers. The 2018 Arctic Report Card found that the Arctic experienced the second-lowest overall sea-ice coverage ever recorded; the lowest-recorded winter ice in the Bering Sea; the second-warmest air temperatures; and earlier plankton blooms due to early melting of sea ice in the Bering Sea.</p>

Acidification: As the ocean absorbs gigatons of the excess CO₂ that humans produce every year, seawater has become increasingly acidic. The rate of acidification is unparalleled—more than 10x faster than anything experienced in the last 55 million years. The ocean has acidified by 26% since pre-industrial times and if CO₂ emissions continue under a “business as usual” scenario, acidity is projected to increase by 120% by 2060.

Wildlife phenology: Shifting timing of reproductive events or migration can affect biodiversity. For example, a meta-analysis of seabird populations worldwide showed that they have not adjusted their breeding seasons over time or in response to sea surface temperature. Changes in prey availability, migratory pathways, mating timing, etc., all have implications for marine biodiversity.

Impacts on many species: Many studies suggest reduced survival, impaired ability to form and maintain calcification, reduced growth rates and development, altered behavior and sensory systems, and decreased abundance. Animals and plants with calcium carbonate-based shells (e.g., mollusks) will likely be the first to be affected, and across species, early life stages (e.g., larvae) are particularly sensitive to ocean acidification. Around half of all benthic species (e.g., corals, mollusks, echinoderms) have lower growth and survival rates under projected future acidification. Reduction or even loss of species that are key links in marine food webs – such as pteropods, small swimming

Shifting stocks and food security: Commercially valuable species (e.g., Cod, Tuna) will shift ranges towards higher latitudes, resulting in different resource distribution within and among countries. Climate impacts on fisheries are expected to reduce food security and exacerbate inequality

Aquaculture and commercial fisheries losses: Adverse economic impacts from ocean acidification are already being experienced. For example, since 2005, oyster farmers along the U.S. West Coast have seen massive die-offs of up to 80% of their oyster larvae because of ocean acidification, which causes young oysters’ shells to disintegrate. In northern Chile’s upwelling region, ocean acidification has led to a 25% reduction in growth rate of cultured scallops.

Deoxygenation: Concentrations of oxygen in the ocean are declining due to three main factors that relate to climate change: (1) heat-related stratification of the water column (less ventilation and mixing), (2) reduced oxygen solubility as temperature increases, and (3) impacts of warming on biological processes that produce or consume oxygen such as photosynthesis and respiration. Deep sea areas are likely to be among the hardest hit ecosystems. The number of hypoxic “dead zones” has been grown significantly since the 1990s, leading to mortality and/or displacement of fish and invertebrates.

Shifts in ecosystem competition: Calcifying phytoplankton communities are expected to suffer decreased production capacity and reproductive viability. In contrast, some species can tolerate ocean acidification and may even thrive under more acidic conditions. Some species will experience positive effects (e.g., due to enhanced photosynthesis in seagrasses, seaweed, algae, and non-calcifying phytoplankton, or loss of competitors or predators).

Sea level rise: The global sea level has been rising over the past century, though the rate of change has accelerated in recent decades. The rate of global sea-level rise nearly doubled from 1.7 mm annually throughout most of the twentieth century to 3.1 mm (0.12 inch) per year since 1993. By 2100, global sea level could rise 65 centimeters (21 inches) if the rate of sea-level rise continues to accelerate at the observed rate.

snails that are an important food source for many larger animals, could have cascading impacts across ecosystems. Pteropod shells are already dissolving in some parts of the ocean.

Coastal ecosystem-dependent species: Sea level rise will primarily affect biodiversity through habitat loss. Habitat displacement or destruction due to sea level rise could substantially reduce local and regional biodiversity, particularly for low-lying coastal habitat types (salt marshes, mangroves, mud flats), which are important nursery areas for marine animals. Similarly, polar wildlife (walrus, penguins, polar bears) will be affected by the loss of ice cover.

Coral reef fishery decimation: Corals are home to diverse fish assemblages, and many commercially important fish species. Ocean acidification is the other major CO₂-related threat facing coral reefs. Ocean acidification reduces the growth of coral skeletons, slows recovery from acute events, increases erosion of reefs, and reduces the strength of the reef structure. An estimated 30-60% of coral reefs have died since preindustrial times. Even if the goals of the Paris Climate Agreement are achieved (of limiting temperature to below 2 degrees Celsius), roughly 70-90% of current distribution of coral reef habitat will disappear by 2050. These impacts will ripple through both natural and human communities: coral reefs serve as incubators for roughly 25% of all marine fish species, supporting fish stocks that provide food for more than one billion people.

Coastal inundation and loss of flood protection: The impacts of sea-level rise hold consequences for both natural and human communities as structured coastal ecosystems (including coral reefs, saltmarshes, mangroves, and seagrasses) currently reduce wave height by an estimated 30-90%. At least 40% of the global population lives in coastal areas which are vulnerable to rising seas.

Changing weather patterns: As Arctic waters warm and become increasingly ice-free, new implications are emerging for the rest of the world—from climatic and environmental impacts to geopolitical and commercial considerations. Growing scientific evidence has linked the loss of land and sea ice in the Arctic, and associated interference in the thermohaline circulation, to extreme weather events over the northern hemisphere—from severe winter storms in the eastern United States in 2018 to the intense cold wave in Europe in March 2018.

Tipping points in vulnerable ecosystems: Model-based projections suggest that the polar seas will be the first regions to cross the threshold into “undersaturation.” This is already occurring in some parts of the Arctic Ocean, and by 2100, it’s likely that the entire region will be undersaturated.

Coastal habitat loss: Mangroves and tidal flats suffer from sea level rise and damage from intensified storms. A global modeling analysis suggests that a 50-centimeter sea-level rise by 2100 would result in a loss of roughly 50% of coastal wetlands across the planet. While mangroves are able to adapt to rising waters to some extent, the inability to retreat due to upstream development or topography limits that ability.

Appendix B: List of Marine “Geoengineering” proposals as evaluated by GESAMP

Table App 2: Marine “geoengineering” techniques evaluated by GESAMP’s working group on Marine Geoengineering

Categories	Techniques
Ocean Fertilisation	Iron
	Macro-nutrients – Nitrogen and Phosphorus
	Fertilisation for fish stock enhancement
Carbon Storage in the Ocean	Liquid CO ₂ placed in mid/deep ocean water depths
	Liquid CO ₂ placed on the seabed
	Liquid/Solid CO ₂ placed into unconsolidated deep-sea sediments
	Mineralisation of CO ₂ in rocks beneath the seabed
	Depositing crop wastes in the deep ocean
	Macroalgae cultivation for sequestration
Ocean pumping	Artificial upwelling
	Ocean Carbon Capture and Storage
	Artificial downwelling
Enhancing ocean alkalinity	Adding lime directly to the ocean
	Adding carbonate minerals to the ocean
	Accelerated weathering of Limestone to produce alkalinity
	Electrochemical enhancement of carbonate and silicate mineral weathering
	Brine Thermal Decomposition (BTD) of desalination reject brine
	Open ocean dissolution of olivine
	Coastal spreading of olivine
	Enhanced weathering of mine waste
	Amending soils of managed croplands with crushed reactive silicates
Methane	Methane capture and destruction/degradation
Increasing Ocean Albedo/Reflectivity	Microbubbles
	Foams
	Ice
	Reflective particles/material e.g. small beads
	Marine cloud brightening
Other techniques with potentially similar side-effects to marine geoengineering	Ocean Thermal Energy Conversion (OTEC)
	Deep water source cooling

Source: (Boyd and Vivian 2019)

Appendix C: Examples of working groups Europe focused on CDR and SRM

- In Kiel, Andreas Oschlies at GEOMAR coordinates the German Research Foundation's (DFG) *Priority Programme on Climate Engineering* which focuses on risks, challenges and opportunities of geoengineering proposals to "create a scientific basis for a responsible approach to the issue", including ocean CDR.
- Also at Kiel's GEOMAR institute, David Keller oversees the *Carbon Dioxide Removal Model Intercomparison* (CDR-MIP) Project which brings together a suite of Earth System Models (ESMs) and Earth System Models of Intermediate Complexity (EMICs) in a common framework to explore the potential, risks, and challenges of different types of proposed CDR.
- The Max Planck institute in Munich coordinates the EU-funded *Implications and Risks of Engineering Solar Radiation to Limit Climate Change* (IMPLICC) Project which aims to increase the level of knowledge about the feasibility and implications of geoengineering concepts including ocean CDR
- Stefan Schaefer at IASS Potsdam coordinated the *European Transdisciplinary Assessment of Climate Engineering* (EuTRACE) project which pools EU experts to assess the potential, uncertainties, risks and implications of various CDR and SRM options and engages policy-makers in a dialogue about the group's findings and implications.
- Piers Forster at the University of Leeds coordinates the UK Research Council funded *Integrated Assessment of Geoengineering Proposals* (IAGP) project that evaluates the effectiveness and side-effects of geoengineering proposals.

Appendix D: Technological potential and cost effectiveness of selected CDR proposals

Table App 3: USD/tCO₂ removed – techno-economic analyses used for cost/effectiveness analysis

Direct addition of rocks		Accelerated weathering		Thermal calcination		Electrochemistry	
\$/tCO ₂ removal	Source	\$/tCO ₂ removal	Source	\$/tCO ₂ removal	Source	\$/tCO ₂ removal	Source
72	Renforth P et al., 2013	10	Renforth, P 2017	2.3	DOE 2003	190	Renforth, P 2017
159	Paquay et al., 2013	40	Renforth, P 2017	23	IPCC, 2014	104	Renforth, P 2017
70	González MF& Ilyina 2016	<38	Rau 2011	100	Renforth, P 2017	187	Renforth, P 2017
200	Renforth, P et al. 2013	50	McLaren, 2012	95	Renforth, P 2017	28	NRC (1993)
100	Minx, J. C. et al. 2018	170	NIST Accelerated Weathering Laboratory 2017	126	Renforth, P 2017	14	Renforth, P 2017
		6	Renforth, P et al. 2003	72	Renforth, P 2017	100	Rau 2008
		9	Renforth, P et al. 2003	159	Renforth, P 2017	136	Bourgeois, R 2006 (DOE)
		21	Renforth, P et al. 2003	38	Renforth, P 2017	3-163	Rau et al. 2018
		48	Renforth, P et al. 2003				

Figure App 2: Cost curve of a selection of CDR and SRM approaches for which techno-economic assessments are most available. CEA analysis based on 119 techno-economic analyses. Note that results are highly uncertain and only reflect preliminary results in a poorly studied field.

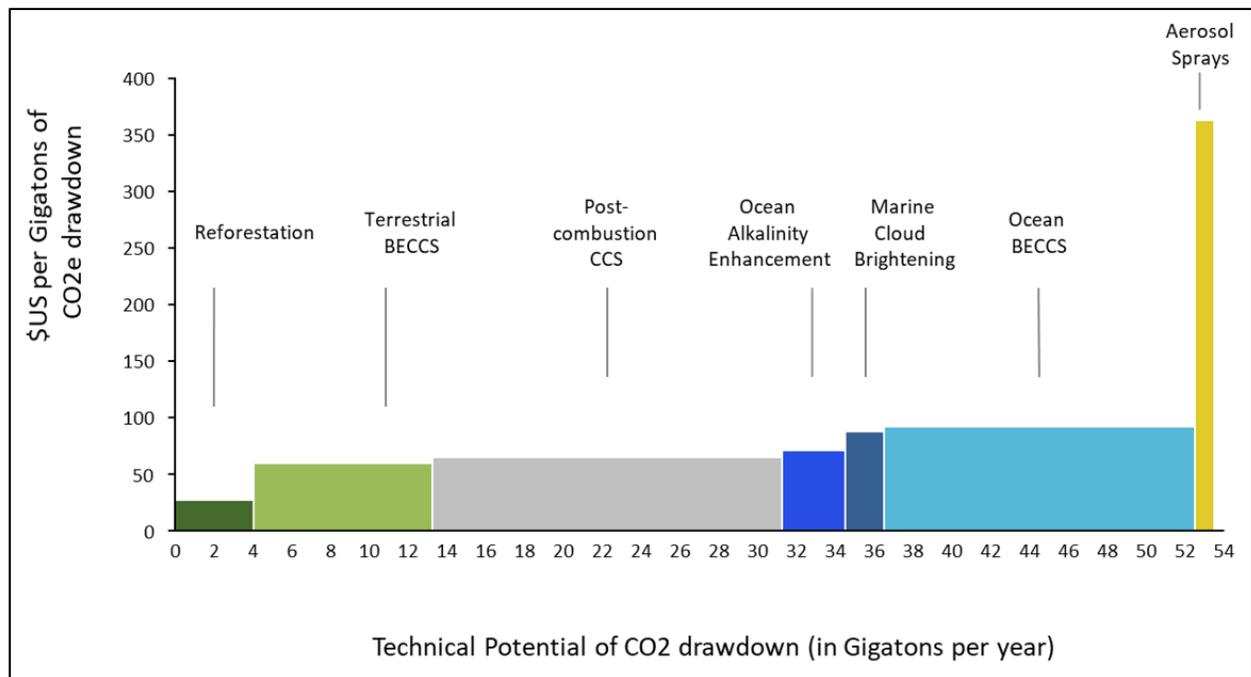


Table APP 4: Evaluation of ocean CDR approaches across key decision criteria for research and scaling (courtesy of David Keller).

Knowledge of ocean-based NETs from previous assessments (Fuss et al. 2018; Lawrence et al. 2018; Gattuso et al. 2018; Keller 2018; Keller et al. 2018b; NASEM 2018; The Royal Society 2018; Renforth and Henderson 2017; Schäfer et al. 2015; Wright, Teagle, and Feetham 2014; L’Orange Seigo, Dohle, and Siegrist 2014) that was used to determine the level of investigation for different NET approaches. Note that *for most NET approaches there have been multiple technology proposals* to achieve the action that reduces atmospheric CO₂. For physical potential; low: <4 Gt C yr⁻¹; medium: > 4 and < 10 Gt C yr⁻¹; high: > 10 Gt C yr⁻¹. For economic feasibility (10-20-year costs to implement) low: > 100 US\$ tCO₂⁻¹; medium: ≤100 and ≥ 5 US\$ tCO₂⁻¹; high: ≤5 US\$ tCO₂⁻¹. Environmental impact (including risks and benefits) indicates the degree to which the ocean could be altered from present. For the level of investigation **low** indicates that the NET will be investigated in only a few WPs, **medium** indicates that the NET will be investigated in multiple Work Packages (WPs) in either Core Theme (CT) 1 or 2, **high** indicates that the NET will be investigated in multiple WPs across both CTs 1 and 2, and **very high** indicates that the NET is investigated in all science WPs and has two WPs dedicated to it; all ocean-based NETs will be included in discussions with stakeholders.

NET approach	Physical CDR potential	Economic feasibility	Political / legal constraints	Public acceptance	Environmental impact	Social impact	Technology Readiness Level	Level of investigation (investigated in WP)
Ocean alkalization	High	Tech. specific; low-medium	Unclear	Unknown	Likely to be medium; impacts on biology not clear	Low, unless large mining operations are required	2-3	Very High (WPs 1-7)
Direct CO ₂ removal from seawater with CCS	Unknown; theoretically high	Unknown; likely low	Unknown	Unknown	Unknown	Unknown	1-2	High (WPs 1-4, 7)
Marine biomass for biochar or bioenergy	Unknown; likely low	Unknown; likely low	Low (in regards to seaweed farming)	Unknown; positive for biochar	Unknown; likely high	Unknown	1-2	High (WPs 1-4, 7)
Artificial downwelling	Unknown	Low	Unknown	Unknown	Unknown	Unknown	1-3	Medium (WPs 2,3, 7)
Blue carbon sink enhancement	Low	High	Low	Unknown	Low, likely many co-benefits	Likely beneficial	1-3	Medium (WPs 1-3, 7)
Terrestrial biomass dumping	Unknown	Unknown	High	Unknown	Unknown; theoretically high	Unknown	3	Low (WPs 2, 3, 7)
Artificial upwelling	Low	Unknown; likely low	Unknown	Unknown	High	Unknown; potentially high	1-2	Low (WPs 2, 7)
Ocean fertilization	Low to medium	Tech. specific; low-high	High	Unclear	High	Unclear	1-3	Low (WPs 1, 2, 7)

Appendix E: Meeting Agenda

Meeting agenda; each content session includes 30 minutes of group discussions.

Time	Min	Topic	Detail	Presenter
8.30-9:00	30	Coffee		
9:00-9.30	30	Welcome and introductions	Introductions, objectives, desired outcomes	<ul style="list-style-type: none"> • Jason Thompson
9:30-10.45	75	Panel discussion: Technical aspects of ocean alkalinity enhancement proposals	Panelists will walk attendants through the “value chain” of OAE proposals, from mining, to calcination, to distribution. A focus will be on knowledge and knowledge gaps in each step.	<ul style="list-style-type: none"> • Greg Rau • Phil Renforth (Remote) • Greg Dipple
10:45-11:45	60	Presentations: OAE proposals in practice: pilots and models	Two short presentations will highlight the experience with OAE pilots so far, as well as insights from earth models about local and global applications.	<ul style="list-style-type: none"> • Jess Adkins • David Keller (Remote)
11:45-12:45	60	Lunch		
12:45-14:15	90	Presentations: Known or potential positive and negative biological and ecosystem impacts of alkalinity addition	Three short presentations will highlight the potential and limitations of OAE for the protection of key ecosystems (phytoplankton, corals, oysters).	<ul style="list-style-type: none"> • Rebecca Albright • Debora Iglesias Rodriguez • George Waldbusser
14:15-15:00	45	Panel discussion: Governance, government, and social licensing	Panelists will speak to the evolving question of governance of ocean carbon dioxide removal and the importance of social licensing in the piloting and development phase of OAE technologies.	<ul style="list-style-type: none"> • Wil Burns • Elisabeth Graffy
15:00-15:15	15	Coffee		
15:15-17:00	105	Facilitated group session: Research, funding, and partnering needs	The group will map out a pathway for future OAE research and technology development and identify stages of funding needed for each phase	<ul style="list-style-type: none"> • Antonius Gagern
17:00-17:30	30	Wrapping up	Reflection on objectives and decisions on next steps.	<ul style="list-style-type: none"> • Matthew Elliott
17:45-19:00	75	Hike to Half Moon Bay State Beach		
19:30- xx	N/A	Drinks and dinner at Beach House, Half Moon Bay		

Appendix F: Meeting Participants

Name	Org	Email Address	Short Bio
Antonius Gagern	CEA Consulting	antonius@ceaconsulting.com	Antonius is a Senior Associate at CEA Consulting and leads the firm's work on Ocean Carbon Dioxide Removal. Previous to joining CEA, Antonius was the environmental economist at Rare. He holds an M.Sc. in Tropical Marine Ecology (Bremen University) and a Ph.D. in fisheries economics from the Institute of Science and Technology, Autonomous University of Barcelona).
Matt Elliott	CEA Consulting	matthew@ceaconsulting.com	Matt Elliott is a Principal at CEA Consulting, where he co-leads the Philanthropic Services practice. Matt has also served as Conservation Director of the Sea Change Investment Fund, and an external consultant for EDF and NRDC among other organizations. He holds bachelor's degrees in Environmental Science and Public Policy from Harvard University and a master's degree in Environmental Change and Management from Oxford University.
Debora Iglesias-Rodriguez	UC Santa Barbara	iglesias@lifesci.ucsb.edu	Debora Iglesias-Rodriguez is a biological oceanographer with a broad focus on mechanisms controlling diversity and function in marine biota, and the Vice Chair of the Ecology, Evolution and Marine Biology program at UCSB. Previously, she studied genetic diversity in coccolithophores and their distribution and ran a research group at the National Oceanography Centre (Southampton, U.K.), focusing on marine bioluminescence and the effect of ocean acidification on marine plankton. She holds a B.Sc. in Biology & Biochemistry (Univ. Santiago de Compostela) and a Ph.D. on carbon utilization in phytoplankton (Swansea Univ., U.K.).
Elisabeth Graffy	Arizona State University	egraffy@asu.edu	Elisabeth Graffy is Professor of Practice in the School for the Future of Innovation in Society and in the Consortium for Science, Policy, and Outcomes (CSPO) at Arizona State University. She co-directs the Energy and Society program within ASU-LightWorks and the Environmental Humanities Initiative in the Julie Ann Wrigley Global Institute of Sustainability. Elisa focuses particularly on issues undergoing disruptive change at the intersection of science, politics, and culture. Elisa holds a doctorate in environmental studies (public policy) and master's degree in agricultural economics from the University of Wisconsin-Madison, as well as a bachelor's degree in politics from Princeton University.
Jess Adkins	Caltech	jess@gps.caltech.edu	Jess Adkins is a chemical oceanographer studying past climates through geochemical investigation, in particular the last few glacial/interglacial cycles. In recent years, Jess has increasingly focused on practical applications of ocean alkalinity enhancement. In this context, he discovered a catalyst for enhanced weathering reactors and is exploring ways to involve maritime shipping companies in the large-scale deployment of OAE. He holds a B.S. in chemistry from Haverford College and a Ph.D. from the MIT/WHOI Joint Program in Oceanography.

Greg Dipple	University of British Columbia	gdipple@eoas.ubc.ca	Gregory Dipple is a Professor in the Earth Ocean and Atmospheric Sciences department at the University of British Columbia. He studies the processes and driving forces for mineral reactions with a focus on fluid-rock interactions. Over the past decade, his primary research interests have migrated from deep crustal metamorphic processes to, most recently, carbon sequestration at and near the surface of the Earth. Dipple holds a Ph.D. from Johns Hopkins University in Geological and Earth Sciences and a B.Sc. from Indiana University.
George Waldbusser	Oregon State University	waldbuss@coas.oregonstate.edu	George Waldbusser is a biological oceanographer and associate professor in the Ocean Ecology and Biogeochemistry program at Oregon State University. He has been working on applications of the study of ocean acidification, specifically how OA impacts shellfish for the past 13 years. George holds a bachelor's degree in science from St. John's University, a Master's in Science in biological oceanography from the University of Connecticut, and a Ph.D. in biological oceanography from the University of Maryland.
Greg Rau	University of California	ghrau@sbcglobal.net	Greg Rau is a biogeochemist, researcher at the University of California, Santa Cruz, and visiting scientist at the Lawrence Livermore National Laboratory. For the past 40+ years, Dr. Rau has been actively engaged in carbon biogeochemistry research. Since 1998 this work has included studying methods of CO ₂ management, building on geochemical processes that naturally consume this gas. He is also listed as inventor on five US patents. Rau holds a Ph.D. in Biogeochemistry/Watershed Ecology from the University of Washington.
Rebecca Albright	California Academy of Sciences	ralbright@calacademy.org	Rebecca Albright is a coral ecologist and biogeochemist, and the curator for invertebrate Zoology at the California Academy of Sciences. Her research has focused on ocean acidification impacts on coral reef biology and ecology. She also ran the first and only field experiments to study alkalization impacts on coral reefs in conjunction with Ken Caldeira. Albright holds a B.Sc. in biological sciences from Duke University and a Ph.D. on ocean acidification and coral reefs (University of Miami).
Wil Burns	American University	wil@feronia.org	Wil Burns is a Professor and Co-Director of the Institute for Carbon Removal Law & Policy at American University, focusing on climate geoengineering and the role of loss and damage in international climate regimes. He also serves as a Senior Fellow at the Centre for International Governance Innovation (CIGI) in Canada, and as Co-Chair of the International Environmental Law Committee of the International Law Association. Previously, he served as Assistant Secretary of State for Public Affairs for the State of Wisconsin and worked in the non-governmental sector for twenty years, including as Executive Director of the Pacific Center for International Studies, on the implementation of international wildlife treaty regimes. He holds a PhD in international law from the University of Wales-Cardiff School of Law.

Giana Amador	Carbon180	giana@carbon180.org	Giana Amador coordinates the research and operational work of Carbon180, an organization focused on developing policy, promoting research, and advancing solutions that transform carbon from a liability to an asset. Prior to joining Carbon180, Giana focused on renewable energy policy in the United States. She received her B.S. in Environmental Economics & Policy and B.S. in Society & the Environment from UC Berkeley.
David Keller	Geomar	dkeller@geomar.de	David Keller is a biological oceanographer at GEOMAR and modeler focused on climate systems, including modeling on carbon removal through ocean alkalization and other means. David studies various proposals for carbon removal using earth system models to model the future state climate and present day, and theorize the impacts of different CDR undertaken at differing scales. He also leads the Carbon Dioxide Removal Model Intercomparison Project (CDR-MIP) testing different models to reduce the range of uncertainty about future climate states. David holds a Bachelors in science in marine biology and biological oceanography from Millersville University and a Ph.D. in Marine, Estuarine, and Environmental science from the University of Maryland.
Phil Renforth	Heriot-Watt University	p.renforth@hw.ac.uk	Dr. Phil Renforth is an engineer and geochemist and an Associate Professor at the Research Center for Carbon Solutions. His research focuses on how reacting carbon dioxide with rocks and minerals may be able to help prevent climate change (key focus on enhanced weathering, negative emission technologies, and alkaline waste. Phil currently leads two UKRI research grants on the Greenhouse Gas Removals Program. He holds a Ph.D. in Geo-environmental Engineering.
Paul Rouse	Carnegie Climate Governance Initiative	prouse@c2g2.net	Paul Rouse is science advisor at Carnegie Climate Governance Initiative (C2G), a visiting fellow in politics and international relations at the University of Southampton and a fellow of the Royal Society of Arts. He has headed up the environmental, energy, and food security agenda for the U.K. Economic & Social Research Council, including thinking on geoengineering research and engagement activity with the SPICE initiative. Rouse left the science policy community in 2018 to undertake a Ph.D. at the University of Southampton on the governance of geoengineering.
Jan Mazurek	ClimateWorks Foundation	Jan.Mazurek@climateworks.org	Jan Mazurek directs ClimateWorks' Carbon Dioxide Removal (CDR) Fund. She has worked on energy and environmental policy at the federal and state level for more than 25 years. Prior to ClimateWorks, then-Governor Schwarzenegger (R-CA) appointed her to serve as Senior Policy Advisor to the California Air Resources Board (CARB). Before CARB, Mazurek was a member of the Obama-Biden Presidential Transition Team, advising on U.S. Environmental Protection Agency toxics, pesticides, and children's health issues. She has published two books with the MIT Press and Johns Hopkins University presses, respectively, and more than 100 other publications, including op-eds in major U.S. newspapers. She holds a doctorate from UCLA's Luskin School of Public Affairs.
Jason Thompson	Oceankind	n/a	Jason serves as the Chief Technology Officer (CTO) of Oceankind, a new Ocean conservation foundation created by a Palo Alto-based family to focus on radical solutions to marine environmental challenges.

Eric Smith		n/a	<p>Eric Smith is an Investment Officer for the Grantham Environmental Trust where he co-manages Neglected Climate Opportunities. He leads investments in businesses and technology in agriculture and oceans that can sequester or mitigate greenhouse gas emissions at scale. Eric was previously a venture fellow with SJF Ventures and worked for BlackRock on climate finance, in addition to providing advisory and audit services to forest based carbon projects. He is a graduate of the dual degree program at Duke University, having received his MBA and Master of Forestry, and served as a Peace Corps Volunteer in Costa Rica.</p>
Walt Reid	Packard Foundation	n/a	<p>Walt is the Director of the Conservation and Science Program at the David and Lucile Packard Foundation. Previously, he was a Consulting Professor with the Institute for the Environment at Stanford University. Dr. Reid was responsible for the creation of the Millennium Ecosystem Assessment, which he directed from 1998-2005. Prior to that he was Vice President of the World Resources Institute in Washington D.C. He is a member on several boards of ecosystem and biodiversity-related scientific journals. Walt earned his doctorate in Zoology (Ecology and Evolutionary Biology) from the University of Washington and his bachelor's degree in Zoology from the University of California, Berkeley.</p>

Appendix G: Presentations

Session 1: Technical aspects of OAE – Greg Rau, Greg Dipple, Phil Renforth

In an introductory panel discussion, **Greg Rau, Greg Dipple, and Phil Renforth** provided a broad overview of the concept of Ocean Alkalinity Enhancement and a detailed breakdown of OAE proposals. Three key points were made during the session, details are reflected in Section II of this proceedings document:

1. OAE imitates the major geologic process through which planet Earth regulates atmospheric temperature, namely the weathering of alkaline rocks. “Acid-base reactions between CO₂ and alkaline rocks have stabilized atmospheric chemistry, driven marine carbon capture, and prevented extreme temperature change on Earth for millennia.” OAE proposals aim to increase the rate at which this naturally occurring phenomena can take place in order to counteract anthropogenically enhanced CO₂ emissions.
2. No major technological breakthroughs would be required to employ OAE at scale. A 10% increase in current global rock extraction (and application of resulting alkalinity) could theoretically lead to very significant reductions of atmospheric CO₂, in the order of 3-5 Gt per year. Costs per net CO₂ reduction are estimated at 10-100\$/ton and therefore comparable to other CDR proposals.
3. OAE is still at a concept phase and many questions remain untested and unanswered. They include questions of chemical and physical oceanography (e.g., carbonate saturation, surface ocean's partial pressure of CO₂) and biology (e.g., what are the effects of OAE side products, including trace metals, on physiological functions of marine biota).

Session 2: OAE proposals in practice: pilots and models – David Keller and Jess Adkins

David Keller shared insights of earth systems modeling as relevant to ocean alkalinity enhancement. Idealized modeling results suggest that alkalinity additions could both reduce atmospheric CO₂ and limit or reverse climate change, but the scale required is beyond current capacity (mining, shipping): Moving from a high emissions scenario to a moderate emissions scenario relying upon OAE would require 4,010 Gt of finely ground olivine per year. David highlighted important limitations of current earth systems modeling, particularly the lack of integration with food web and carbon cycle responses.

1. Food web effects: using olivine as alkalizing agent, for example, would add iron and silicate to the system, thereby acting as fertilizers for primary producers. This might cause either diatom (“green ocean,” more C sequestered) or coccolithophore (“white ocean,” more coccolithophores, less C sequestered) blooms.
2. Carbon cycle responses might oppose the removal of CO₂ in the medium term (decades to centuries) due to reduced atmospheric partial CO₂ pressure (the ocean carbon sink becomes a carbon source).

Jess Adkins zeroed in on two research frontiers in OAE deployment and efficiency that will become crucial once OAE moves from the demonstration phase to scaled application.

1. One major constraint in OAE is the dissolution rate of limestone, which increases with grain size. At the same time, costs of limestone increase exponentially as grain size diameter decreases, making OAE in practice either costly or very expensive. Jess presented recent results from laboratory testing that indicate how the use of a catalyst (Carbonic Anhydrase) can speed up limestone dissolution by 20 percent.
2. Another cost driver in OAE deployment will be the distribution of alkaline agents. Jess summarized his current effort to partner up with the shipping industry: Global maritime trade contributed to 3% of global GHG emissions and vessels feature flue gas exhausts with 5% CO₂ (sufficient to dissolve limestone in seawater without a catalyst). Since cargo ships usually have 5-20% of empty container capacity, they could carry enough limestone to offset their emissions during trips.

Session 3: Ecosystem implications – Debora Iglesias Rodriguez, Rebecca Albright, George Waldbusser

In this session, three presentations highlighted the knowledge and knowledge gaps relating to the ecosystem implications of ocean alkalinity enhancement.

- 1. Debora Iglesias Rodriguez – Phytoplankton:** No OAE manipulations have been conducted to test primary producers' response to OAE but the past 20 years of research on ocean acidification might allow the following cautious speculations:
 - Calcifying phytoplankton quickly react to increased $p\text{CO}_2$ levels (slow growth, malformations) and is likely to benefit from alkalinity enhancement if it decreases $p\text{CO}_2$.
 - Diatoms feature silicate shells and will likely benefit from alkalization when alkaline agent is olivine or other silicate rock.
 - Synergistic and antagonistic effects of $p\text{CO}_2$, carbonate saturation state, pH and trace metal availability (all effects of OAE), are difficult to predict and effects will be different for different species groups.
- 2. Rebecca Albright – Corals:** Rebecca highlighted the known stressors of ocean acidification on corals (calcification rates, early post-settlement growth of larvae, fertilization success, cementation, reef accretion, respiratory stress, acidosis, metabolic suppression) to conclude that the “cost of living” for corals is significantly increased with increased acidification. Rebecca summarized findings from an in-situ test of OAE on corals. From this research it could be concluded that coral calcification rates increased by almost 7 percent, closely tracking the change in aragonite saturation state (Ω_{arag}). A key unknown is how unevenly OAE might benefit certain species of corals and to what extent its application might harm ecological structures on the reef.
- 3. George Waldbusser – Bivalves:** Given the commercial importance of shellfish aquaculture in the United States and globally, ocean alkalinity enhancement has been thoroughly tested on a variety of shellfish species, particularly on the larval stages. George provided an overview of findings and open questions from research and in-situ application:
 - Shellfish appear to benefit from direct addition of alkaline substances in their environment as measured by larval survival rates (can increase by a factor of 2-3 compared to baseline). Similar to coral responses, increased $p\text{CO}_2$ has negative effects on metabolism and energy budget.
 - Shellfish has a high sensitivity to metals (Ni, Cu, Zn, Cd, Pb) which may be found in trace quantities in alkaline rock. Additional research is required to parse out the species-specific effect and potential implications of larger-scale OAE.
 - Non-carbonate alkalinity appears to play a large role in shallow coastal systems (through sulfur cycling and bromide production) and would interact with OAE applied for bivalves. More research is needed in this field, too.

Session 4: Governance, government and social licensing Wil Burns and Elisabeth Graffy

In this session, two presentations shed a light on the governance and social licensing aspects of ocean CDR generally, and OAE specifically.

Wil Burns provided a broad and detailed overview of the legal and governance structures that currently apply to any OAE testing, demonstration, and application at scale; the presentation highlighted that applicable legislation provides a relatively solid blueprint for different stages of OAE research and development. Highlights include the following:

- **Research:** The 1972 London Dumping Convention and the 2013 Resolution LP.4(8) on the Amendment to the London Protocol state that scientific research proposals should be assessed on a case by case basis using an assessment framework and cannot be intended for commercial gain. UNCLOS also explicitly provides the right of all states to “conduct marine scientific research subject to the rights and duties of other States.”
- **Deployment:** The CBD, 10TH COP (2010) decided that no climate technologies can be deployed, “until there is an adequate scientific basis on which to justify such activities and appropriate consideration of the associated risks” on an environmental, social, economic, and cultural level. UNCLOS also stipulates

that States shall take all practical measures to “prevent, reduce, and control pollution of the marine environment from any source” defined, among others, as substances “which results or is likely to result in such deleterious effects as harm to living resources and marine life.” The Paris Agreement (2015) and UNFCCC (1992) support mitigation measures and to protect “sinks and reservoirs” while respecting, promoting, and considering human rights obligations.

Elisabeth Graffy provided an overview of potentially relevant US environmental laws associated with these activities, shared a framework for understanding and managing the science-policy interface around novel or contentious issues, and led discussion about how concerns about climate change combined with strategic policy entrepreneurship may affect how decision-making on OAE could occur:

- OAE activities may impact air, land, water, biodiversity, worker safety and human health. These issues are governed by existing policy, legal, and regulatory regimes that apply universally to all activities that trigger them. Although it is theoretically possible that OAE could be exempted from compliance with domestic regulations through special legislative provisions (which can happen but is rare), the need for compliance with domestic laws should be assumed. For example, mining and processing minerals for OAE will be subject to normal mining regulations, regardless of the purpose of the mining.
- Contrary to a common and simplistic perception that scientific information is simply shared with policymakers to inform them, Elisa presented a more dynamic framework explaining the intersection of science and policy from emergence of an issue to legislation and implementation. The framework explains how disruptions create opportunities for new policies and new stakeholders, and where such negotiations take place in the process. This approach helps to clarify why public discussion can seem chaotic and where research can have productive input into policy development.
- Using the case of the Great Barrier Reef and several examples raised by other presenters earlier in the day, Elisa illustrated that OAE activities are already being piloted and deployed under policy frames like decarbonization of supply chains or shipping, as well as ecosystem protection and restoration. Notions that OAE governance is entirely in the future or will occur in some controlled sequence directed by the research community are not realistic. Governance thinking should assume a patchwork trend and should strive to assess the status quo and its implications in a straight-forward manner in order to avoid slippery slopes or unintended cumulative effects.