# Broaden Research on Ocean Alkalinity Enhancement to Better Characterize Social Impacts

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# Broaden research on ocean alkalinity enhancement to better characterize social impacts

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ABSTRACT. Ocean alkalinity enhancement (OAE) is being considered as a way of achieving large-scale removals of carbon dioxide from the atmosphere. Research on the risks and benefits of

different OAE approaches is expanding apace, but it remains difficult to anticipate and appraise the range of potential impacts to human communities that OAE might generate. These impacts, however, will be critical to evaluating the viability of specific OAE projects. This paper draws on the authors' involvement in interdisciplinary assessment of OAE to 1) identify the factors that currently limit characterization of potential social impacts; and 2) propose ways of reconfiguring OAE research to better consider these.

SYNOPSIS. Research on ocean alkalinity enhancement (OAE) should be reconfigured to better characterize social impacts.

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[see attached file]

## 1. Introduction

Failure to reduce greenhouse gas emissions in line with climate stabilization targets has brought attention to methods of carbon dioxide removal (CDR)[1]. Some proposed CDR approaches involve enhancing the oceans' ability to sequester and store carbon. Ocean alkalinity enhancement (OAE) is one such approach and encompasses methods to increase seawater alkalinity to provoke a more rapid uptake of atmospheric $CO_2$. Some OAE approaches involve accelerating rock weathering processes by adding pulverized materials (for example lime or olivine) to coastal zones or the open ocean[2]. Others utilize electrochemical methods to make seawater more alkaline[3,4].[1]

Until recently, research on OAE has been largely theoretical, focused on computational simulations to assess the carbon removal potential of different methods. These assessments estimate the global climate effects of these interventions, rather than their local or regional impacts[2]. Small-scale field studies have recently begun[5–9], and scientists and start-ups are now

[1] Other proposed approaches for carbon removal via alkalinity enhancement include those that either make use of (i) upwelling of waters that are artificially alkalized at depth[47] or (ii) electrochemically splitting surface seawater into acid and alkaline components and pumping the acid into the deep ocean, in order to increase alkalinity in surface water[48]. Land-based enhanced weathering would also result in an addition of alkaline materials to the ocean but is generally considered separately from approaches that involve a direct alteration of marine geochemistry.

progressing plans to develop and deploy different OAE options[3,10]. Several large CDR funders (e.g., XPRIZE and Frontier) have signaled the potential for large investments to flow into OAE projects, and pilot deployments are already beginning[11,12].

The OAE field trials and pilot projects increasingly underway will likely shape how OAE technologies are configured for larger-scale deployment. Open questions for mineral-based OAE methods include: how will alkaline materials be generated or processed? How will materials be transported to coastlines and distributed into seawater? For electrochemical methods, how will inputs and energy sources vary? What kinds of effluents and waste products will be produced and how and where will they be distributed or processed? As research progresses, scholars and policymakers are calling for attention to 'responsible' research on CDR; like other CDR technologies, OAE has the potential to introduce ecological and social changes that may vary according to how a given OAE approach is configured[10].

In this paper, we argue that developing OAE 'responsibly' requires close attention to the social outcomes of different approaches, but that our ability to anticipate these outcomes is constrained by several factors[13,14]. We draw on interdisciplinary social science research on OAE including 1) engagement with relevant groups (e.g., local industries and NGOs) in areas where OAE field experiments have occurred (Bergen, Norway and Gran Canaria, Spain); 2) participatory evaluation of OAE life-cycle assessments (e.g., with industries of relevance to OAE such as cement and concrete); and 3) interviews with experts involved in OAE R&D (e.g., researchers in academia and OAE start-ups). (A full description of these activities is provided as *Supplementary Information*). We identify four structural challenges that currently limit anticipation or identification of social impacts of OAE and offer recommendations on how to configure OAE research and development to better anticipate and characterize potential social impacts.

## 2. Defining 'social impacts'

We define 'social impacts' here as effects that OAE might bring to human communities, particularly those proximate to the supply chain (e.g., sites of deployment, mineral extraction, transport and processing). We note that impacts can be positive and/or negative; we refer here to 'co-benefits' to emphasize positive impacts.

By 'social', we refer to the range of impacts on human communities, spanning aesthetic, historical, cultural, economic, and health effects (drawing upon United States National Environmental Policy Act, NEPA, 40 C.F.R. 1508.8[15]). 'Social' impacts, as we understand them here, are always interwoven with environmental and economic processes. Scholarship on socio-ecological systems and ecosystem services has demonstrated that ecological functions are key to a range of economic and cultural outcomes, such as provision of food and water, regulation of erosion or waste treatment, and cultural services like recreation, educational and spiritual values[16–18].

By 'impacts', we mean consequences that result either 1) 'directly' from a project (at the same time or location as project activities) 2) 'indirectly' (later in time or outside a project location), or 3) 'cumulatively' (in combination with both project and non-project activities, past, present and future (drawing again on NEPA 40 C.F.R. 1508.8). For OAE, 'impacts' might also be both (1) impacts associated with changes to marine chemistry, and (2) impacts associated with broader project operations and infrastructure. Those impacts associated with changes in marine chemistry remain to be characterized and might fall outside the scope of existing risk assessment frameworks given the novelty of the intervention. Impacts arising from the development of supply chains and infrastructures could, in principle, be easier to characterize within existing regulatory frameworks, but current research on OAE has not yet mapped them or identified potential mitigation pathways[19]. Crucially, this latter category of impacts could, as we will argue here, prove particularly important to understanding the overall social impacts of OAE, and deserve attention although they might not be 'novel'.

Table 1 summarizes the different classes of social impacts that OAE activities might generate; we emphasize that these are examples of *potential* impacts rather than a definitive or comprehensive summary, and some may be consequential while others might not. We emphasize that the likelihood of any of these impacts varies significantly depending on the specific configuration of OAE activities. The factors limiting more specific understanding of these impacts are discussed in the following section.

*Table 1. Categories of social impacts potentially associated with OAE*

| Possible social impacts | Associated with changes to marine chemistry | Associated with other project-related activities |
|---|---|---|
| **Direct** (at same time or location as project) | e.g., increases to local shellfish grower production and income | e.g., job creation from the OAE supply chain |
| **Indirect** (later in time or outside project location) | e.g., changes in food provisioning from aquaculture or fisheries in surrounding areas | e.g., various social and environmental impacts due to expansion of mining activities |
| **Cumulative** (combined effects from past, present, and future activities) | e.g., cumulative human health effects of additional trace metals from different OAE projects | e.g., local tourism and aesthetic impacts from increased industrial infrastructure and vessel traffic |

## 3. Factors constraining our understanding of potential social impacts

Below, we discuss four factors that complicate assessment of the social impacts of OAE.

### 3.1 Limited understanding of the impact of OAE on marine ecosystems

Limited knowledge about the impact of additions of alkalinity for marine ecosystems preempts a characterization of how human communities might in turn be affected by OAE. For example, some methods of OAE might result in sudden localized reductions in dissolved $CO_2$, which would limit photosynthesis and negatively affect important phytoplankton communities (and thus fisheries), but the pattern or significance of these effects is not yet clear. Similarly, we lack adequate knowledge about the potential impact of trace elements present in minerals proposed for OAE, although some interviewees expressed confidence in capabilities for removing trace elements from resulting processed materials. Principal options include calcium-rich minerals like quicklime and hydrated lime derived from limestone, and magnesium-rich minerals like olivine, brucite, or forsterite derived from ultramafic rocks[4,20]. While dissolved calcium and magnesium ions appear unlikely to have adverse effects, trace elements such as iron, silica, nickel or chromium may very well do so[3,9]. A recent study[2] has cautioned, for instance, that the application of natural silicate feedstocks (e.g. olivine-bearing rocks and basalt) could have deleterious impacts on marine zooplankton (and subsequently on marine biological pumps and ocean trophic structure), given that even small amounts of iron, nickel and silicon have the potential to induce blooms that deplete oxygen at lower levels[4,7]. Depending on the choice of material for OAE applications, the manner of their processing, and the rate of application, trace elements could also bioaccumulate in ways that represent a direct health risk for people. Such impacts would have obvious consequences for livelihoods, and many ramifications for coastal and/or marine-dependent communities—ranging from impacts to marine resources, tourism, or fishing that coastal communities rely upon for food, livelihoods, and wellbeing. The nature of these changes cannot be understood in general terms: for example, these might vary according to species and source of alkalinity, meaning that the same conceptual approach might have crucial differences in impacts between different human communities.

Electrochemical approaches might pose fewer risks, but they also raise potential environmental impacts that require further empirical study. The impacts might result from how these methods intake seawater, and from outflow effluents and other byproducts. Intake pumps and filters can harm local marine life; effluents resulting from electrochemical approaches may reduce dissolved organic carbon, which could have impacts for autotrophic organisms[3,21]. Electrochemical processes could also generate hazardous byproducts, such as chlorine gas or hydrochloric acid, and these may pose health challenges if produced in locations where safe management and disposal is lacking.

Additional effects of OAE on carbon export also remain ambiguous. A key knowledge gap in the geochemistry of mineral-based OAE is the amount of alkaline material that might be dissolved before the occurrence of secondary precipitation of $CaCO_3$ (calcium carbonate). This secondary precipitation would result in either zero net uptake of $CO_2$ from the atmosphere (for carbonate mineral-based OAE) and a reduction in uptake (for silicate-based OAE), or a net release of $CO_2$ if alkalinity of seawater is reduced past its initial state[9,20]. The thresholds at which such secondary precipitation arise are currently unclear, with further research needed to understand which other factors (e.g., precipitation nuclei, presence of organic materials) might induce such runaway precipitation.

An inadequate understanding of the ecological changes triggered by OAE not only limits our ability to characterize social impacts linked to potential environmental hazards, but also impedes a proper characterization of benefits. The possibility of using OAE to reverse ocean acidification is the most obvious example, as it constitutes a key ‘selling point’ for this CDR method[22]. Counteracting acidification could mitigate climate change impacts to calcifying organisms and thus protect particularly vulnerable ecosystems like coral reefs. This would deliver a broad range of benefits—from increasing food security to the preservation of cultural values—for those communities most directly affected by their destruction[23–25]. More broadly, it would assist economic sectors, such as aquaculture and tourism, threatened by rapidly acidifying oceans. Yet we currently lack an adequate understanding of how to reverse acidification in practice, since we cannot yet calibrate the parameters of sustainable ecosystem remediation through deliberate alkalinization[26].[2] As a result, specifying the socio-ecological benefits that might arise from OAE remains almost as difficult as anticipating the harms that might result from its deployment.

### 3.2 Limits of current research formats

Our interviewees emphasized that modelling, the cornerstone of current attempts to evaluate ocean alkalinity enhancement, operates with scales and at levels of resolution that limit its value as a tool to identify community-level or even regionally specific social impacts. The spatial grid of current Earth System models is ill-suited to illuminate the sort of localized dynamics that will matter most to localized groups. Modelling instruments often tend to assume that alkalinity will increase uniformly across oceans, rather than be concentrated in specific locations.

In the meantime, laboratory and field experiments are beginning to characterize potential environmental risks and benefits[27,28]. These methods are essential to produce an adequate knowledge base for future decisions on the further development of OAE methods, but also have inherent limitations when addressing the impacts that OAE might have in particular socio-ecological contexts. Mesocosm studies can only go so far in mimicking natural ecosystems, not least because they are run on timescales of weeks to months and cannot capture longer-term effects. According to our interviewees, mesocosm studies might obfuscate environmental risks; for example, it remains unclear whether the thresholds at which secondary precipitation occurs in mesocosm studies arise due to the experimental system (e.g., a lack of mixing of water in mesocosm containers).

A further limitation of experimental research methods flagged by our interviewees is their inability to assess cumulative impacts of different OAE interventions. Even if the impact of a single OAE project were negligible, the effects of two dozen projects in overlapping areas might be significant[29].

### 3.3 Indeterminacy of proposed technological configurations

OAE still remains a conceptual proposition. At this stage, we still lack full specification of the components that might make up systems for OAE deployment. Relevant dimensions of such systems that our interviewees discussed included the sourcing of raw materials and the technologies used for their processing, the desirable particle size (relevant for dissolution rates), the application of equilibrated or non-equilibrated alkalinity, the choice of distribution methods (such as via reactors or ships—or aircraft[31]), or the measures used to ensure that materials will be distributed in a way that avoids creating 'hotspots' of alkalinity or secondary precipitation. These dimensions will be critical for the characterization of social outcomes.

The range of possibilities, and the limited scope of pilot and demonstration projects, makes it difficult to specify a complete socio-technical configuration, and thus to anticipate potential social impacts. We have found that spelling out a full socio-technical configuration, even in a highly speculative fashion, helps reveal a broad range of often unexpected social considerations. The extractive dimensions of OAE offer a case in point. Mineral-based approaches could require extensive additional mining operations, or they could create a use for existing wastes and

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[2] Evidence suggests that some coastal fish have higher mortality if exposed to chronic increases in alkalinity, such as the lime and hydrated lime that have been applied to control invasive species afflicting shellfish aquaculture.

byproducts (e.g., mine tailings). This distinction will be key, as mineral resource extraction gives rise to a range of environmental and social hazards, yet it is rarely considered in current appraisals of OAE[32]. These impacts would affect most directly those communities in areas proximal to mining activities, and include ground vibrations, noise pollution, impacts to soil and air quality due to dust (and/or water use to avoid these impacts), impacts to surface water and groundwater, air and water pollution, trucking traffic, sedimentation, erosion, land subsidence. These in turn might affect wildlife habitat, forestland and recreational land, human habitat, physical, mental, and social wellness, food security, and cultural and aesthetic resources[3,33]. Our understanding of these impacts will be limited without efforts to specify a full industrial and socio-technical configuration of OAE systems[13].

### 3.4 Challenges in identifying relevant publics and co-location effects

While the geography of OAE deployment remains highly uncertain, it is likely that the social impacts and benefits of OAE will be unevenly distributed, and will be dependent on the level of development, economic vulnerability, regulatory capacity, and reliance on local marine environments in areas of deployment. 'Location' is itself an ambiguous parameter: alterations in marine environments do not lend themselves to a straightforward spatial or social demarcation, and geographically distant constituencies might see themselves as 'affected' by modifications of coastal or open ocean environments.

Experimental work and pilot studies offer an opportunity to identify concerned groups and expand the range of groups invited to deliberate on OAE. Initial guidance on the governance of OAE emphasizes the importance of public engagement, but what 'public engagement' means depends on who is designated as a relevant 'public' group. In our own work, we found that early-stage research and innovation projects rarely arrive with a clearly defined set of affected groups. In doing engagement work alongside experimental OAE studies, our largest challenge was ascertaining who to bring to the table[10].

In addition to convening public groups in areas proximal to research or deployment zones, a productive means of engagement might be to target OAE's possible overlaps with existing economic, conservation, and other activities in coastal regions with which OAE might be co-located. The potential for production of potable water via reject brines in desalination plants was of interest, for example, to local groups in Gran Canaria, Spain, where potable water is a scarce resource with associated environmental burdens. Similarly, some OAE approaches under consideration might be integrated with beach nourishment and/or wetland restoration initiatives, which could provide ecosystem services ranging from carbon sequestration to shoreline stabilization and erosion prevention[35]. In engagement work we conducted alongside mesocosm experiments, we found different groups interested in these possibilities.

## 4. Broadening the research agenda to better characterize social dimension of OAE

As we have suggested, there are too many unknowns at present to fully characterize the social impacts that OAE will generate. Too much remains uncertain or simply unknown about fundamental technical and scientific aspects of this class of technology to hypothesize about the social distribution of risks and benefits. Yet as the portfolio of OAE research and development expands, it is possible to capitalize on these experimental activities to improve our ability to envision how OAE might affect human communities. Below we offer a set of recommendations for how to broaden the OAE research agenda to better capture these effects. These recommendations are inspired by similar calls to integrate social science into energy and ecosystem research[36–38]. They also build on a growing literature on the need for interdisciplinary assessments of novel marine CDR technologies[13,39].

### 4.1 Utilize place-based research to investigate local perspectives on OAE

Place-based biophysical research, such as mesocosm studies and other field experiments, offers a unique opportunity to explore how local communities perceive the prospect of OAE, and how OAE might relate to their own priorities on climate and environmental change. Research conducted in association with the experimental use of olivine in the Dominican Republic, for example, has suggested that perceptions of OAE might be shaped by the historical experience and adaptation needs of small island development states[40]. Our own research along mesocosm studies indicates that the siting of outdoor experiments serves as a prompt to identify relevant groups, from non-governmental organizations involved in coastal conservation to start-up companies engaged in 'blue economy' initiatives. Even if experimental studies are conducted somewhere different to where OAE might eventually be deployed, engaging local communities gives a flavor of the broad range of societal considerations that influence perceptions of OAE, and gives local groups a voice in how research and development should be designed and aligned with local priorities[10].

### 4.2 Consider social dimensions of OAE in modelling efforts

Earth System and Integrated Assessment Models remain key to our ability to assess the potential and limits of OAE, but some interviewees highlighted that they are blunt tools for appraising social implications. As noted above, this is partly due to the scales of resolution at which these models tend to operate. A standard grid in an Earth System Model is a poor unit of assessment to elucidate the social distribution of risks and benefits in deployment scenarios. Integrated Assessment Models, on the other hand, incorporate societal trends, but generally do so via a set of choices that limit the range of contextual political considerations. It is thus important to find other ways to incorporate social dimensions in modelling efforts. The trend in OAE Earth System modelling towards greater complexity and higher resolution opens the door to increasingly interdisciplinary discussions of the parameters that should drive OAE simulations. Furthermore, modelling outputs could be used as a catalyst for public engagement and deliberation, as they offer concrete—if speculative—OAE deployment scenarios linked to specific climate change mitigation pathways.

In our own work, we have used expert deliberations to identify constraints and opportunities for mineral-based methods. Those deliberations generate new parameters for further modelling, for example by constraining the regional availability of the relevant minerals based on current political and regulatory constraints on expanding extraction. Similarly, we can use available social scientific research on governance capacity in different regions of the world to further constrain deployment scenarios (akin to how the World Bank's governance index is used to guide investment or development decisions). This might identify regions where, despite their geophysical suitability, OAE should not be pursued in early stages of research and deployment, given the significant risk of poor governance and subsequent negative socio-environmental externalities.

### 4.3 Extend engagement and socio-technical feasibility research into land-based components of OAE systems

The social dimensions of OAE become even more salient when considering the land-based components of future OAE systems. Sharing a full accounting of the energy and material requirements of proposed OAE systems, for example, would be important information to bring to public and community engagement on OAE. This kind of full accounting is also essential if we want to identify the relative advantages and disadvantages of OAE as compared with alternative forms of carbon removal, particularly at scale. In a future regional scenario, for example, OAE approaches might offer important advantages over other CDR approaches by avoiding competition with other uses of land, nutrients, or freshwater[30].

In our own research, we have used the example of mineral-based OAE to advance characterization of OAE as a socio-technical system spanning marine and land-based components. Structuring deliberations around the full set of system components can serve as a means to 'opening up' discussions with different groups about OAE's potential costs and benefits. In our expert workshops, issues raised included important non-biogeochemical impacts that might otherwise be overlooked, such as the viability of additional limestone extraction, or the conditions for safe carbon capture and storage (a requirement if the operation is to achieve a net removal of carbon dioxide). Extending research into land-based components of OAE is also essential for mapping the cumulative impacts of multiple projects in a particular location[41,42].

### 4.4 Evaluate social dimensions in addition to MRV

OAE currently lacks robust methods for monitoring, reporting and verification (MRV) of carbon removal. As MRV criteria and technical infrastructures begin to be considered in earnest, it is potentially tempting to incorporate social criteria alongside other MRV metrics. However, we assert that social dimensions of OAE should be considered in parallel rather than subsumed into these metrics. Otherwise, highly heterogeneous social contexts of deployment will likely be 'flattened' into simplistic accounting measures. Here we can draw inspiration from efforts to create alternative forms of 'carbon accountability' in relation to REDD+ or 'blue carbon' initiatives[44,45]. Participatory evaluation offers mechanisms for including local communities, and serves as further opportunity to research social contexts of deployment[46]. If (or when) OAE is integrated into voluntary or regulated private carbon markets, buyers of credits will have to sift through and compare multiple options, and it will be important to capture context-specific social variables, rather than simply the carbon removal efficacy of the intervention.

A final note: While OAE and marine CDR more broadly have the potential to offer positive impacts for people, they also raise many place-based considerations. In essence, climatic benefits from technologies like OAE might have benefit to a global community—but the negatives could also accrue to specific communities. These local/global tradeoffs are ethically difficult. As OAE research expands, it will be imperative that we enrich our understanding of its local consequences, if we are to ensure that risks and benefits are not distributed in ways that compound existing vulnerabilities and entrench environmental injustice. Rather than waiting for scientific uncertainties to be resolved before embarking on a full appraisal of OAE, we need to begin integrating attention to social aspects into research efforts, so that we can give due consideration to these significant but under-researched issues.

ASSOCIATED CONTENT

Supplementary information: Description of empirical activities associated with this perspective piece (PDF)

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**Author Contributions**

*SN conceptualized and wrote the first draft and led editing and revising of the manuscript. JL contributed to conceptualization, writing, editing and revising of the manuscript. JV and PR contributed to editing and revising of the manuscript.*

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ABBREVIATIONS

CDR, carbon dioxide removal; MRV, monitoring, reporting and verification; OAE, ocean alkalinity enhancement.

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