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A Code of Conduct Is Imperative for Ocean Carbon Dioxide Removal Research

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As the impacts of rising temperatures mount and the global transition to clean energy advances only gradually, scientists and policymakers are looking towards carbon dioxide removal (CDR) methods to prevent the worst impacts of climate change. Attention has increasingly focused on ocean CDR techniques, which enhance or restore marine systems to sequester carbon. Ocean CDR research presents the risk of uncertain impacts to human and environmental welfare, yet there are no domestic regulations aimed at ensuring the safety and efficacy of this research. A code of conduct that establishes principles of responsible research, fairness, and equity is needed in this field. This article presents fifteen key components of an ocean CDR research code of conduct.

Keywords: carbon dioxide removal, ocean, policy, research governance, geoengineering

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INTRODUCTION

Industrial development has unequivocally altered the Earth's climate, unleashing widespread changes in natural systems that have increasingly inequitable outcomes for humans (IPCC, 2021). Limiting global warming to the 1.5° C goal at the heart of the 2015 Paris Agreement — or even to the Agreement's "avoid at all cost" upper limit of 2° C — requires that drastic and rapid emissions cuts be supplemented with carbon dioxide removal (CDR) to eliminate historically emitted anthropogenic carbon dioxide that continues to warm the planet (Rogelj et al., 2018). However, CDR techniques may have profound adverse social and environmental impacts, such as disruption to ecosystems and food webs, pollution, and high energy costs. To avoid exacerbating the already-inequitable impacts of climate change, climate mitigation must be pursued *via* methods that maintain biodiversity and support social equity (Pörtner et al., 2021). Research codes of conduct help ensure these goals can be equally upheld throughout the process of developing solutions (Hubert, 2021).

Although attention surrounding CDR has traditionally focused on land-based techniques to reduce atmospheric carbon dioxide levels, interest in various ocean-based CDR solutions is now skyrocketing among policymakers, funders, scientists and entrepreneurs (Boettcher et al., 2021). Ocean CDR approaches differ widely in their potential scales, the ways they aim to manipulate or restore ocean systems, and the degree of human intervention they require. Vast, relatively unpeopled ocean spaces have inspired an array of proposals from political leaders, investors, and marine researchers. Some of these proposals rely on intensive technological manipulations of ocean chemistry or biology, representing a form of climate engineering; these include fertilizing the ocean with iron, redistributing nutrients or organic matter within the ocean to stimulate algal blooms through artificial upwelling, adding minerals to rivers, beaches or ocean water to enhance ocean alkalinity through mineral weathering, and using electrical currents to generate alkalinity in seawater, which can locally induce additional CO_2 absorption by the ocean. Other proposed ocean CDR methods, such as the restoration of populations of large marine animals, including epipelagic fishes and whales, and the cultivation of vast quantities of kelp or other seaweeds in the open ocean, could involve less intensive manipulation. Amid this explosion in interest, the National Academies of Sciences, Engineering, and Medicine (NASEM) released a *Research Agenda for Ocean Carbon Dioxide Removal and Sequestration* in early December 2021, which sets priorities for research and development of several of these CDR pathways (National Academies of Sciences, Engineering, and Medicine, 2021a).

Because many proposed ocean-based CDR approaches share certain features with other types of climate engineering — including potential impacts over vast spatial scales, long timelines, and the risk of unintended planetary-scale effects (National Academies of Sciences, Engineering, and Medicine 2021b)— a code of conduct for ocean CDR research must be developed immediately. Codes of conduct establish sets of norms and best practices, encouraging responsible research among public and private actors (Hubert, 2021). By encouraging researchers to assess, minimize, and publicize the impacts of their experiments, a code of conduct could reduce the harm done by field experiments. And by promoting principles that would encourage the growth of a rigorous body of research — such as rules requiring the disclosure of funding or the peer review and publication of results — a code of conduct could help researchers transparently and honestly determine the efficacy of ocean-based CDR technologies, which they must do if those technologies are to play a meaningful role in climate mitigation. Indeed, the NASEM ocean CDR panel identified as its top immediate priority the development of a code of conduct to prevent "ill-considered" studies: those that would fail to advance scientific knowledge or pose significant social and environmental risks (National Academies of Sciences, Engineering, and Medicine, 2021a). Ultimately, policymakers could use an ocean CDR code of conduct as a starting point for future regulations that are managed by institutions accountable to the public (Hubert, 2021).

A SEA OF RISKS, UNCERTAINTIES, AND OPPORTUNITIES

Existing national and subnational regulatory frameworks do not ensure that ocean CDR research will be carried out in a manner that minimizes harm and transboundary impacts. Jurisdiction over the ocean varies depending on distance from shore: nations, and to a lesser extent, subnational regions (e.g. states or provinces), regulate areas within 200 nautical miles from shore, while the high seas do not fall under the jurisdiction of any one nation (UN General Assembly, 1982). This creates a patchwork of regulation over ocean activities that is both complicated and incomplete. Alarmingly, regulation on ocean CDR research and development — the critical oversight needed to guide relevant research toward demonstrating efficacy, ensuring equity, and reducing environmental and social harm — is lacking domestically and internationally. In the United States, there are no domestic regulations aimed at ensuring that ocean CDR is effective and safe. Some ocean CDR research activities may fall under existing regulatory schemes such as those related to emission of pollutants into water or impacts to protected species, but these regulations have not yet been applied to CDR (Webb et al., 2021).

Further, much of the world's ocean — including, for example, parts of the Southern Ocean most attractive for deployment of interventions such as ocean iron fertilization — lie beyond national jurisdiction, in zones that are especially vulnerable to ungoverned, independent research. International instruments may govern some of the activities associated with ocean-based CDR, such as discharge of minerals for ocean alkalinization or injection of CO_2 into sub-seabed geological formations. However, there are no binding international instruments that expressly regulate these methods (Webb et al., 2021). Much of the existing, non-binding international framework is specific to ocean iron fertilization, reflecting the comparatively longer history of scientific research into the biogeochemistry surrounding that pathway (National Academies of Sciences, Engineering, and Medicine, 2021a).

Moreover, a full appreciation of the risks, tradeoffs, opportunities and potential co-benefits of ocean CDR research — let alone its full deployment at scales large enough to affect the Earth's climate — cannot be directly obtained from the more mature body of research on land-based CO_2 sequestration because of fundamental differences in how marine environments function (Steele et al., 2019; Canadell et al., 2021). The fundamental physical and biogeochemical properties of the ocean — including its vast scale and high degree of connectivity — make it very different from the terrestrial or coastal settings in which CDR has traditionally been deployed. Chief among these is that water is a fluid, allowing the ocean and nearly everything in it to move across political boundaries. Even CDR experiments conducted close to shore within a nation's exclusive economic zone could plausibly have international or global impacts. In addition, the majority of proposed ocean CDR techniques leverage natural biogeochemical processes, and the likelihood of harmful ocean consequences from these approaches is still unclear. Depending on their scale, field experiments involving these techniques could affect both near and distant marine ecosystems in the same ways as projected for large-scale ocean CDR deployment. Existing literature suggests these consequences could include:

- induction of hypoxic or anoxic water-column conditions due to increased deep-water bacterial activity, possibly as a result of ocean iron fertilization or the intentional sinking of large quantities of macroalgal biomass (Oschlies et al., 2010),

- shifts in phytoplankton diversity and abundances that would have difficult-to-anticipate ecosystem effects (Oschlies et al., 2010; Bach et al., 2019),
- "nutrient robbing," or depletion of macronutrients by phytoplankton or cultivated macroalgae that starves natural plankton and algae nearby (Oschlies et al., 2010; Bach et al., 2019),
- entanglement of marine life (Campbell et al., 2019),
- potential alteration of weather patterns (National Academies of Sciences, Engineering, and Medicine 2021a), local ocean currents, and/or mesoscale ocean circulation patterns (Campbell et al., 2019),
- toxic effects on marine life, including microbiota, from the release of trace metals associated with silicate minerals applied to enhance alkalinity (Hartmann et al., 2013),
- in the case of certain proposed CDR methods, rapid reversals in ocean chemistry following termination (Feng et al., 2016), and
- poorly understood feedbacks involving climate-active marine trace gases that could erode the climate benefit of an ocean CDR intervention (Law, 2008).

KEY COMPONENTS OF AN OCEAN CDR CODE OF CONDUCT

Given the critical need for research coordination amid this sea of risks and uncertainties, we reviewed other codes of conduct to identify crucial responsible research principles that should be included in an ocean CDR research code of conduct. We investigated research fields that have similarly uncertain implications for human or environmental welfare, including nanotechnology, gene editing, and geoengineering. Sixteen research codes of conduct from eight fields reveal fifteen common principles to guide research of new technologies (**Figure 1**). These principles require researchers to assess and minimize potential environmental harms before, during, and after experiments. They also promote a tiered research structure, requiring researchers to demonstrate the potential efficacy of a technology — in the lab, *via* modeling, or in small field trials — before scaling up to larger *in situ* experiments. The principles promote public and stakeholder engagement and consideration of fairness and equity, recognizing researchers' obligation to involve the full community of people who may be impacted by the research, and the overall need to involve the global community in decisions about climate engineering (**Figure 1**).

Principles for code interpretation, including definitions of the purpose and scope of the code, are likewise important (**Figure 1**). The scope of a code of conduct can be limited to specific technologies, or the code's application can depend on the overall purpose or intent of the research. Because new ocean-based CDR techniques continue to be described, the set of available technologies is presently unbounded, and a purpose-focused code of conduct (e.g., Hubert, 2017) would better fit this fast-evolving area of research. A purpose-focused code of conduct will require a definition of CDR, so those applying the code can determine whether a research activity's purpose is to investigate CDR methods. The code may adopt an existing definition of CDR, such as those used by the Intergovernmental Panel on Climate Change (IPCC) or NASEM. IPCC defines CDR as "[a] nthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products," including "anthropogenic enhancement of biological or geochemical sinks" but excluding "natural CO_2 uptake not directly caused by human activities" (Rogelj et al., 2018). NASEM similarly defines CDR as methodologies that "remov[e] or captur [e] CO_2 from the atmosphere or some reservoir in close contact with the atmosphere" and durably store it (National Academies of Sciences, Engineering, and Medicine, 2021a). In contrast to the

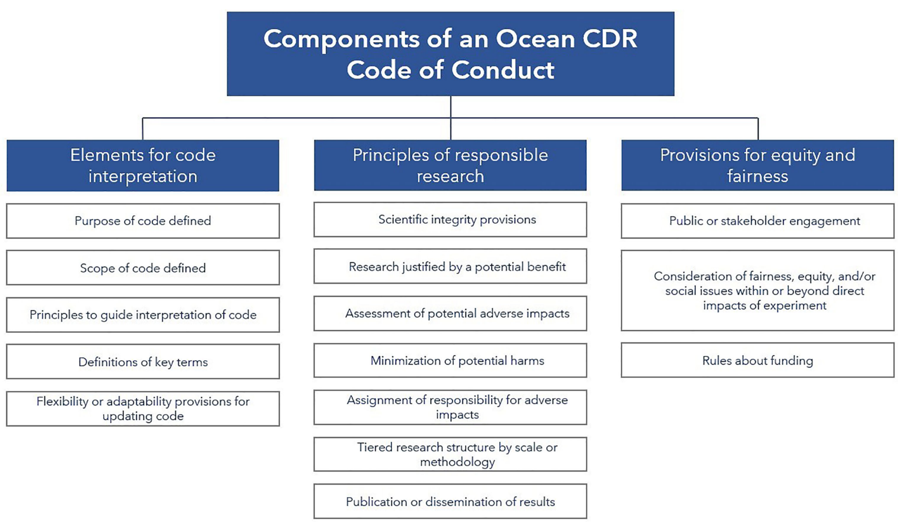

FIGURE 1 | Key components for inclusion in a research code of conduct for ocean CDR.

IPCC definition, the NASEM definition includes pathways that may require less direct anthropogenic manipulation, such as ecosystem protection (National Academies of Sciences, Engineering, and Medicine, 2021a).

There are already two well-developed research codes relevant to ocean CDR that contain most of these principles: the Geoengineering Research Governance Project's *Code of Conduct for Responsible Geoengineering Research* (Hubert, 2017) and NASEM's *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance* (National Academies of Sciences, Engineering, and Medicine, 2021b). Additionally, the Aspen Institute recently released a report on developing a code of conduct for ocean-based CDR, which raises questions for researchers to consider that are consistent with the principles we identified (Aspen Institute Energy & Environment Program, 2021). These documents indicate the ocean CDR research community is open to implementing an ocean CDR research code of conduct. And until the appropriate groups are assembled to develop a code of conduct for the oceans, researchers and practitioners can voluntarily adopt guidance based on existing codes.

CONCLUSION

While some ocean CDR solutions may indeed prove to be effective pathways for the sequestration of atmospheric CO_2 while safeguarding biodiversity and supporting equitable human development, the outcomes of most of these approaches are not yet fully understood. Many of these proposed interventions may be powerful enough to affect the Earth's climate, creating the potential for research surrounding ocean CDR to effect tragic or unexpected outcomes. Because codes of conduct help ensure coordination, transparency, and equity of research on technologies with the potential to affect human and environmental welfare, we believe the development of an ocean CDR research code of conduct is a fundamental prerequisite to the design or conduct of any large-scale field experiments of ocean CDR technologies.

A code of conduct will only be effective if it is adopted by the ocean CDR community. Across research disciplines, the most important factor in code uptake is engagement with the parties to whom the code of conduct applies. Code development should involve diverse stakeholders, including researchers, practitioners, funders, environmental NGOs, regulators, and publishers. As ocean CDR research progresses, stakeholders should periodically revisit and update the code of conduct and consider drafting guidelines specific to each type of ocean CDR technology.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

RL, SE, and LS contributed to conception and design of the literature review. RL and SE wrote the first draft of the manuscript. RL, SC, JC, SE, and LS wrote sections of the manuscript. All authors contributed to manuscript revision, read, and approved the submitted version.

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